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Bedrock structural control on catchment-scale connectivity and alluvial fan processes, High Atlas Mountains, Morocco.

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Abstract

Lithology is acknowledged as an important internal catchment control on flow processes to adjacent alluvial fans. In contrast the role of inherited structural configuration (e.g. bedrock attitude) to catchment connectivity and sediment transport is rarely considered. We examine 4 young (<100 year old), active tributary-junction alluvial fan systems from the Dadès Valley in the High Atlas of Morocco in terms of their catchment-scale connectivity, sediment transfer and resulting alluvial fan processes. The catchments occur on the same lithologies (limestones and interbedded mudstones) but experience different passive structural configurations (tilted and structurally thickened beds). The fan systems react differently to historic peak discharges (20-172 m^3/sec). Catchments containing tectonically thickened limestone units develop slot canyons that compartmentalise the catchment by acting as barriers to sediment transfer, encouraging lower sediment to water flows on the fans. Syn-dip catchments boost connectivity and sediment delivery from translational bedrock landslides as a result of steep channel gradients, encouraging higher sediment to water flows. In contrast translational landslides in strike-oriented drainages disrupt longitudinal connectivity by constricting valley width, whilst the gradients of the main channels are supressed by the attitude of the limestone beds, encouraging localised backfilling. This diminishes the sediment to water content of resulting flows.

Keywords: coupling, connectivity, bedrock landsliding, tributary junction, alluvial fan

Alluvial fan studies typically use a combination of different approaches including morphometrics, geomorphology and sedimentology to either address potential engineering hazards (e.g. Wilford *et al.* 2004) or to examine long-term (Quaternary) landscape response to a range of external forcing mechanisms such as climate (Cesta &Ward 2016), base level (Harvey *et al*. 1999; Harvey 2002; Mather *et al*. 2000; Pope *et al.* 2016) and active tectonics (Whipple & Trayler 1996; Allen & Hovius 1998; Yildirim *et al.* 2016). Two of the most consistent geomorphological relationships derived from such alluvial fan studies are between catchment area and alluvial fan gradient and area (Harvey 1997). The strength and persistence of these relationships in part reflects the fact that the smallest, steepest and higher relief catchments have a reduced capacity to store sediment, and better slope-channel coupling, and thus are more likely to deliver higher sediment to water flows (typically debris flows) to the alluvial fan depositional area. Alternatively, larger and lower relief catchments tend to have more capacity to store eroded sediment and accumulate higher water discharges, reducing the sediment to water nature of flows (typically fluvial flows) delivered to the alluvial fan environment (Mather *et al.* 2017 and references therein). Even within valley constrained tributary-junction settings these observed relationships persist, albeit more weakly (Al–Farraj & Harvey 2005; Wang *et al.* 2008; Stokes & Mather 2015). Whilst it is acknowledged that lithology can play an important role in modifying the above relationships (e.g. Blair 1999; Whipple & Trayler 1996; Arzani 2012) the significance of existing bedrock attitude (e.g. tilting, folding) of the underlying bedrock is less understood. Yet particularly in arid, mountainous bedrock landform systems the inherited tectonic structure of the bedrock may be a significant control on catchment geomorphology and thus the nature of connectivity between the landscape components within that catchment (Friyirs 2007) and the nature of sediment conveyance through that system (e.g. Hartshorn et al, 2002; Emberson et al 2016) and ultimately to the alluvial fan, influencing its depositional processes. The degree of connectivity (coupling) in turn dictates the sensitivity of that landscape to environmental change (Harvey 2001; Hooke 2003; Friyirs 2007; Fuller & Marden 2011).

To explore the role of tectonically deformed strata in catchment connectivity between the various landform units (slopes, channels) and alluvial fan processes more clearly, we ideally need to select a study area where we can remove the influence of climate change, human activity and active tectonics (seismicity) from the systems we examine. Whist this is technically not feasible, what we can do is examine an area that will minimise these variables. This would include a study area that has been significantly affected by tectonics in the past (i.e. has tectonic structure but is essentially currently stable /passive) on a similar range of lithologies but with differing structural configuration and under the same climate/human variables. A study by Stokes & Mather (2015) on a suite of active tributary-junction alluvial fans within the Dadès River of the eastern High Atlas Mountains of Morocco indicates that this would provide such a study area. The location of fan generating catchments in this study area was found to be related to specific structural settings (tilted and structurally thickened stratigraphic units) within a geological sedimentary sequence dominated by interbedded limestones and mudstones. The range of processes operative on the studied tributary-junction fans was variable (fluvial to debris flow) and complicated further by a range of diverse catchment configurations that reflect the underlying, inherited tectonic configuration of the bedrock. These include the development of slot canyons in areas of limestone tectonically thickened by thrusting, and bedrock landsliding in areas of tectonically tilted bedrock related to regional fold structures. Here we seek to explore the relationship between these passive-tectonic structural bedrock controls (tilted strata, tectonically thickened strata) on catchment-scale connectivity within the catchment and how this is reflected in the associated alluvial fan flow and depositional processes. This will be achieved using 4 'type' tributary-junction alluvial fan systems within the River Dadès catchment (Fig 1). The findings are presented in a conceptual integrative model that can provide a framework for other alluvial fan studies.

Study area geology

The Dadès River is a 5th order perennial river that drains the south-central High Atlas Mountains of Morocco (Fig. 1a) before entering the Ouarzazate basin to the south. The bedrock within the selected study area predominantly comprises Jurassic marine limestone and mudstone lithologies (e.g. Krencker *et al*. 2014) of the Mesozoic rift system that dominates the central and eastern High Atlas (Warme, 1988). The River Dadès study reach, along which the tributary alluvial fans, cuts SW through an open asymmetric syncline before a minor route deviation takes it to the southeast at the Tarhia n' Dadès gorge (located between Fans 1 and 4, Fig 1c). There it cuts a short 0.5km long, 150m deep and 20-50m wide route through a Lower Jurassic limestone ridge (Stokes *et al.* 2008).

The evolution of the modern Dadès River system is considered to relate to the capture of the internally drained Ouarzazate basin by an Anti-Atlas drainage (Stäblein, 1988). This capture probably occurred in the Middle-Late Pleistocene based upon preliminary fan surface exposure dating from mountain front sites north of Ouarzazate town (Arboleya *et al.* 2008). The resulting base-level lowering, together with uplift of the High Atlas has resulted in regional drainage network incision and erosion in the Ouarzazate Basin (Pastor *et al.* 2012) but its influence on erosion upstream in the High Atlas is probably limited (Boulton *et al.* 2014). The main High Atlas topography was largely generated during the Cenozoic as a consequence of on-going collision between Africa and Europe (Beauchamp *et al.* 1999). An overall lack of deformation across Thrust Front areas in Quaternary river terraces, suggests that the High Atlas in the Dadès River region is characterised by low rates of tectonic activity, at least from the Middle-Late Pleistocene to Recent (Stokes *et al*. submitted). This observation is supported by modern low seismic activity. Historical earthquakes that do occur tend to be concentrated along the South Atlas thrust front region and are infrequent and of low (4.9) magnitude (Medina & Cherkaoui, 1991).

Study area climate and geomorphology

The flood hydrology of the Dadès River is determined by a semi-arid mountain climate. Precipitation in the upper elevation of the catchment ranges from 200mm pa upstream (M'smerir, Fig. 1c) to 150mm pa downstream (Boulmalne du Dadès, Fig 1c) (Schulz *et al.* 2008; Dłużewski *et al.* 2013). The tributary fans that form the focus of this study are ephemeral tributary catchments developed within the lower elevation, more arid zones. Average daily discharges in the Dadès are 33.3m^3/s but with marked seasonal variation (Fig. 1b), linked to annual winter–spring snow/rain precipitation in watershed regions derived from Atlantic low pressure incursions (Schulz & de Jong, 2004) and rarer convective storm events from the tropics (Fink & Knippertz, 2003; Knippertz *et al.* 2003). The ephemeral tributary streams commonly store and supply large volumes of coarse clastic sediment to tributary junction alluvial fans in the Dadès River valley dependent upon the tributary catchment bedrock lithology, stratigraphy and structure (Stokes & Mather 2015). Bedrock weathering and sediment supply is enhanced by the absence of vegetation cover that is exacerbated by the arid climate and historic to current grazing practices.

Stokes & Mather (2015) examined the development of the active tributary fan catchments in this study area. They identified that the ephemeral tributary systems capable of generating a tributary alluvial fan tended to possess higher reliefs, longer lengths, lower gradients and larger areas. It was also identified that the fan generating catchments tended to be underlain by a combination of more erodible geological strata (tectonically tilted and interbedded mudstones and limestones). From that study it was clear that the strongest morphometric relationships (such as fan catchment area and gradient) often seen in classic mountain front alluvial fan settings still existed, but at a weak (though statistically significant) level in this confined upland drainage system. The weak relationships observed could in part be explained by the 'build and reset' relationship between the ephemeral tributary streams which supply the sediment to the fans, and the perennial flow of the River Dadès which 'resets' (erodes/removes) the tributary fans every 10 years or so when a large flood event flushes through the system (Fig. 1b). Thus the large part of the tributary-junction fan sediments are typically of short time duration (<100 years) and reflect the current, inherited catchment configuration (the catchment developing over longer, Quaternary timescales).

Approach and methodology

4 study fans have been selected for this paper (Fig. 1c) from the study reach examined by Stokes & Mather (2015). These fans have been selected as they are the larger and best preserved examples of the fan depositional systems and span both the full range of observed fan depositional processes and catchment erodibility (Fig. 2) and geomorphology (Fig. 3). These fans formed the focus of a field survey in May 2011. Relative age of flow processes on the fans was determined using previous field survey and the Google Earth Professional archive imagery (Mather *et al*. 2015) and the catchments where examined by a combination of remote imagery analysis using Google Earth and ArcGiS integrated with field observations for terrain analysis. Relative erodibility of the catchment (Fig. 2) is based on rock strength from a combination of mapping, logging and Schmidt hammer readings from field survey and geological data taken from the regional geological maps (Carte Géologique du Maroc, 1990; Carte Géologique du Maroc, 1993) and is fully explained in Stokes and Mather (2015). Field topographic survey (Fig. 4) was undertaken using a Trupulse 360® for morphological survey and a Trimble GeoXH ® for positioning information. Cross-profiles were taken across the most complete distal portion of each selected tributary fan. Long profiles where taken from the Dadès river along the active channel up the tributary fan, over the backfill and into the bedrock dominated element of the catchment system. Surveys were terminated after the first significant tributary system to enter the catchment (typically >1km into each catchment). To facilitate analysis of potential peak discharges within the catchments the competence approach of Clarke (1996) was utilised (Stokes *et al.* 2012; Mather & Stokes 2016). Historic flood estimates were derived from appropriate sites recognised within the lowermost portion of the backfilled catchment sediments and uppermost fan apex in an attempt to assess the peak discharge reaching the fan for the catchment. Values for fluid density were determined from an assessment of the fan deposit sedimentology in order to determine the most representative discharge range.

Alluvial fan catchment area characteristics

The 4 selected study catchments are located within the 2 main tectonic structural bedrock compressional features that dominate the study area. Fans 22 and 28 are located on the SE limb of an open symmetric syncline; Fans 4 and 1 are located on the gentler NW limb of a tight, asymmetric fold structure (Stokes *et al*. 2008), with Fan 1 positioned within the thrust-faulted / folded structurally thickened portion of the fold limb:

Fan 1 - a relatively large, syn-dip (bedrock dipping 50°- 90° to SE) catchment (Figs 2 and 3a) that cuts through weak lithologies in the upper catchment and a tectonically thickened and strong, massive limestone unit in its lower reaches. This catchment feeds a fluvial fan.

Fan 4 - a small, steep syn-dip (bedrock dipping 50°- 70° to SE) catchment dominated by weak lithologies (Figs 2 and 3b) and feeding a debris flow fan.

Fan 22 - a small, strike-parallel (bedrock dipping 10°- 20° to NE) drainage developed in mixed (weak, Intermediate to strong) lithologies (Figs 2 and 3c) and supplying a debris flow fan with some fluvial deposits

Fan 28 - a relatively larger, strike-parallel (bedrock dipping 10°- 20° to NW) mixed lithology catchment (Figs 2 and 3d) supplying a fluvial dominated fan

Fan 1

Fan system 1 has the largest catchment area (28.9km^2), highest relief (>1km) and longest length (10km) of the 4 fans in this study (Table 1). The main tributary is the lowest gradient of those surveyed with several knickpoints through the gorge section (Fig. 4a). The fan is backfilled into the catchment by some 300m, and the surveyed profile (Fig. 4a) was covered with bedload throughout although the depth and calibre was highly variable between reaches (Fig 5). The catchment is transverse to the strike of the underlying geology, developing syn-dip (Fig 3a). The geology of the catchment area is dominated by weak to intermediate lithologies (thinly interbedded limestones with mudstones) in the upper catchment and strong lithologies (tectonically thickened limestones) in the lowermost catchment (Figs 2 and 5). Geomorphologically this has led to some large-scale bedrock landsliding (covering 1.5% of the catchment area) in the upper catchment and slot canyon with associated topples and karst development in the lower catchment (Figs. 3 and 5). In addition to the landsliding there is some minor storage of gravel (1% of the catchment area) within the channels, mainly in the upper catchment reaches.

Fan 4

The catchment for Fan 4 is one of the smallest of those examined in this paper at 2.93km^2 (Table 1) and the steepest (Fig. 4a). It is developed down the dip (Fig. 3a) of dominantly weak material (Fig 2) on steeply dipping interbedded muds and thinly bedded limestones. Fan backfilling occurs up to 500m into the catchment but other storage is minimal (Table 1, <1% of the area). In the surveyed reach this bedload floored channel then passes relatively sharply into a bedrock dominated area (Fig. 6b). Within bedrock reaches there are significant knickpoints developed (Fig. 4a). There is evidence of older and higher valley fills which are currently being cannibalised by the modern system (Fig. 6a). 13% of the catchment is affected by landsliding (Table 1 and Fig. 3b). Of this landsliding 92% is older, shallow translational movement down-dip into tributary streams, and elevated above the main streams (Fig. 3b). However there has been some large-scale slumping of this into stream areas by more recent mass movement (Fig. 6c,d). Where this occurs it creates a restriction for the tributary flows (Fig. 6c) and presents a ready supply of cobble-boulder material for transport, the size of which is determined by discontinuities within the limestone (bedding and jointing).

Fan 22

The strike-oriented catchment area for Fan 22 is 5.28km^2 with a steep relief of ~1km and a length of >4km (Table 1). The catchment contains significant knickpoints in the limestone sections, with intermediate gradients developed in the softer mudstones in the lower catchment (Fig. 4a). Storage extent within the catchment is limited with the lowest gravel storage of the catchments examined here (Table 1, 0.4% of the catchment) and limited larger bedrock landsliding activity, containing one significant bedrock slump (3% of catchment area, Fig. 3c and Table 1). Fan backfilling occurs some 300m into the catchment, but then passes into a zone of intermittent bedload and bedrock dominated reaches (Fig 7). The coarse bedload (derived from the limestone units) locally forms 'boulder chokes' in the main tributary system, and these boulders locally armour the softer mudstone bedrock reaches (Fig. 7a). The catchment contains a mix of rock strengths (Fig. 2b) with the more resistant lithologies (thickly bedded limestones) in the upper catchment and weak to intermediate lithologies (mudstones and more thinly interbedded limestones and mudstones respectively, Fig. 7) in the lower catchment (Fig 2a). Active spring lines are evident along the contacts (Fig. 7b). There is evidence that the catchment has been pirated by smaller streams on its southern margins (Fig. 3c), reducing its original catchment area, although this predates the deposition of fan deposits examined in this study.

Fan 28

Alluvial fan system 28 is the furthest north of the catchments examined here (Fig. 1a and 2a). It forms one of the larger catchments (19.03km^2), is strike-oriented (Fig. 3d) and has a general channel slope similar to the upper surveyed reaches of Fan 1 (Fig. 4a) but with more significant knickpoints in the lower reaches. This slope mirrors the strike/oblique strike of the bedrock (Fig. 8b). This catchment also contains the most sediment storage in terms of gravel (1.8% of the catchment area) and landsliding (>11% of the catchment area, Table 1). Backfilling occurs some 300m into the valley canyon and then passes into an area of alternating bedload lined and bedrock reaches (Fig. 8b). The landslides are developed within the stronger, more limestone dominated units that are interbedded with mudstones (Fig. 2 and 8). Of the landsliding 90% is older translational sliding which terminates above the valley floor, and 10% represents the reactivated toes of the most down-dip elements of these slides, or recent rock topples (Fig. 3d and Fig. 8a,c and d). In the main, strike-oriented drainage, the homoclinal shifting (down-dip stream migration) and landsliding has led to a very asymmetric main valley and catchment (Figs. 3d and 8b). Active springs drain between the limestone and mudstone strata, following the structure.

Alluvial fan depositional area characteristics

In May 2011 a topographic field survey was undertaken across the alluvial fan tributary junction depositional areas, and up the fan into the backfilled fan catchments (Fig. 4). Here we will examine the flow processes operative on the respective fans when that survey was undertaken. All fans are associated with slack water deposits (SWD; *sensu* Patton *et al*. 1979) of the River Dadès both upstream and downstream of the fan. These deposits will only be described briefly from the best exposed (Fan 28) section.

Fan 1

The depositional fan and catchment backfill of Fan 1 is the lowest gradient of those surveyed (Fig. 4a). Observations of the surface morphology suggest flows which contain a mix of finer (sand-silt grade) and course (cobble grade) material (Fig 9a-c) being transported occasionally as mudflow (Fig. 9b) but predominantly as a 2 phase flow, with clear imbrication of and sorting of clasts, with clasts being transported as bedload (Fig 9d). The final stages of these flows includes some minor (<1m) incision into the fan surface (Figs 9c e and f) suggesting more normal streamflow conditions with some turbulence, depositing small depositional lobes at the fan toes (Fig. 9a,e,f) which are subsequently removed by erosion and trimming by the Dadès River, creating a periodically more truncated morphology to the fan toe region (Fig.9c).

Fan 4

Fan 4 is a more lobate tributary fan and the steepest of those examined here (Fig 4b). Its sedimentology is dominated by open framework coarse sediments on the active fan surface and a lack of any incision. It is clear from archive imagery (authors own and Google Earth) that the fan surface was covered by a large event pre May 2006. This material is dominated by an orange tinge to the surface of the clasts (Fig. 10a,c). Between August 2007 and May 2011 this was overtopped by a smaller, more recent event that is clearly visible in the January 2012 satellite imagery (Fig. 10d). Between Jan 2012 and December 2016 further sedimentation occurred down the central fan, which has buried the irrigation canal (Fig. 10e). The fan body is dominated by accretional lobes (Figs, 10 and 11). The morphology of the pre-2006 flow is distinctly lobate in appearance with a relief of some several metres in total (Fig. 4b – see right hand side of the cross profile and Fig. 11a), and 0.5-1m for the fronts of individual arcuate ridges that front these lobes (visible on the cross-profile of Fan 4, Fig 4b and Fig. 11a). The steep nose of the outer ridge of the pre-2006 flow (Fig. 11a) shows some collapse features, with large boulders rolling down the face and onto the adjoining SWD area. The open framework boulders form a layer up to 1m thick and comprise 0.5-1m boulders in the distal portions of the flow. Provenance of the material is limestone with some rare shale clasts that tend to break down in transport and are represented as shale ‘ghosts’. There is evidence for some stream re-working in the backfilled catchment valley, but water appears to percolate through the gravels on the fan surface. The surface of the flow in places contains pockets of finer (silt/sand) material (Fig. 11b). In section these flow deposits have a clear flow orientation and abundant steep, subvertical clasts that are matrix supported (Fig. 11d). Each flow has a non-erosive base and coarsens upwards into a matrix free top (Fig. 11). This sedimentology is consistent in both distal back fill (Fig. 11d) and the toe of the fan (Fig. 11c). Within sections parallel to transport direction some weak internal surfaces can be observed with size segregated gravels.

Fan 22

Fan 22 shows less dynamic change in morphological appearance through time when compared with the previous 2 examples, other than minor incision and infill of the main fan channel over the period 2003-2013 (Fig. 12). The fan and backfill gradient is intermediate for the fans surveyed (Fig. 4a) and the cross section has the smoothest relief of the 4 examples (Fig. 4b). Minor cuts through the older sediments indicate a mixture of both one phase (Fig. 12e) and two phase (Fig 12f) flows. The former are matrix supported with subvertical clasts whilst the latter tend to be more clast supported with imbrication.

Fan 28

The longitudinal profile of Fan 28 and its backfilled feeder channel are similar to the previously describe Fan 22 example (Fig. 4a), and the canyon long profile is very similar to Fan 1. The cross-profile is heavily dissected (Fig. 4b) and the lower feeder channel shows a recent rock topple affecting sedimentation (Fig. 13). Currently the rock topple is being buried (compare Fig. 13b and c) and the toe of the fan shows further evidence of rapidly changing fan aggradation and erosion (Fig. 13 and Fig. 14c). To the north of the distal fan are well developed SWD which display clear climbing ripples (Fig. 14a). It is evident from 2006 field imagery (Fig. 14b) that the fan periodically impedes the Dadès River, which is responsible for the SWD deposition according to flow directions within the sediments (Fig. 14a). Sections through the fan deposits show evidence of clear sediment sorting and imbrication in flow parallel sections (Fig. 14d), although they may be matrix supported in places with some subvertical clasts. These deposits appear to indicate transitional flows that are both 1 and 2 phase in nature.

Alluvial Fan flood reconstructions

Based on the sedimentology and geomorphology presented above, it would appear that Fan 1 demonstrates the most typically fluvial characteristics of the fans examined here. The degree of sorting and imbrication in some sections suggests a water flow dominantly associated with high sediment concentration operating as a two phase flow (suspended and bedload) but transitioning to a more poorly sorted single phase flow (mixed, mass flow) at times. This transitional behaviour is typical of more hyperconcentrated flows (Pierson 2005; Mather & Hartley 2005; Mather & Stokes 2016). Similar features are observed in Fan 28, although here the flows appear to be more dominantly hyperconcentrated in sediment with poorer sorting.

Fan 4 flows have a morphology and internal structure consistent with debris flows (Wells and Harvey 1987; Blair & McPherson 1994; de Haas *et al.* 2016), with very little evidence of any two phase flow, other than at the start and end of the storm event. The coarsening upwards fabric, with many subvertical clasts and open framework top, but mainly clast supported (although some interstitial fines can be observed at depth) suggests a dominantly cohesionless debris flow (Postma 1986). The fan surface shows no channel development with any minor water flow draining through the cobbles, along with any fine sediment.

The deposits of Fan 22 show a greater mix of both two phase and single phase flows suggesting debris flow and hyperconcentrated flows are both in operation, but there is little evidence for fully turbulent flows (Table 2). The debris flows appear to contain more in the way of matrix than those seen in Fan 4, with no open work gravels or clear coarsening upwards. The matrix material appears to be derived from erosion of the local thick mudstone units adjacent to the fan producing flow materials that have mixed with hyperconcentrated flow deposits to form a more cohesive debris flow.

The above flow observations have been incorporated into flow modelling for maximum boulder sizes transported by flows on the fans using the Clarke (1996) competence method. The fluid densities have been based on observations from the sedimentology indicating the dominant flow conditions in each fan, with turbulent streamflow (Costa 1988) to hyperconcentated flow in Fans 1 and 28 and hyperconcentrated to debris flow in Fans 4 and 22 (Table 2). Flow depths generated would appear to fit observations in the field. In general the smallest catchments appear to generate the highest specific peak discharge range and for mean values there is a linear relationship between catchment size and flow discharge (Fig. 15) which is typical of flows generated in these environments (Mather & Stokes 2016). The sedimentology enables us to place an 'indicator' as to whether the peak flows are likely to be in the upper or middle of the calculated range (Fig. 15). Note that these are not absolute values but likely indicators only.

The flow reconstructions suggest that the discharges from the catchments, which most commonly occur from intense precipitation in autumn and winter, are typically less than 2 m flow depth but flowing at high velocities (up to 3m/s) as a result of the steep slopes. Both catchments 22 and 28 appear to have a base flow from the karst system from springs. When seeking to explain discharge and flow processes in terms of the surface catchment the karstic element should be considered (e.g. Schmidt & Morche 2006). This is particularly the case for the down dip, strike-orientated, asymmetric catchments which are likely to feed from up dip aquifers, which may serve to enhance the water to sediment ratio more than anticipated for individual catchments during a rainstorm event. This could explain what appear to be marginally higher estimates for flood discharges for Catchment 1 in the thickened limestones which are associated with more continuous karst systems.

Discussion

The selected tributary fans of the Dadès catchment show a surprisingly diverse sedimentology considering that they are derived from similar geological units (limestones and mudstones) under the same climate zone and landuse. Some of this can be explained by catchment size and its impact on sediment delivery (larger catchments generating more fluvial flows, smaller catchments generating more debris flows; Harvey 1984; Kostachuk *et al.* 1986). For example, Fans 22 and 28 are on similar geologies (Fig. 2) and Fan 28 is more fluvial than Fan 22, which is smaller. However when we examine other elements more closely, such as the flow reconstructions (Fig. 15), Fan 28 stands out as markedly different to the other fans, and it is noticeably steeper than the other fluvial fan (Fan 1, Fig 4). Equally some of the fans (Fans 4 and 28) are markedly more dynamic in terms of surface change than the other examples. In order to explain such differences we need to more closely examine the catchment and fan configurations in order to understand the nature of sediment delivery to the fan systems. This is most effectively achieved by reflecting on the impact of coupling or decoupling (*sensu* Harvey 2001) of the fluvial landscape elements on the relationship for sediment conveyance 1) between the tributary fan systems and the main trunk river (River Dadès) and 2) within the tributary-junction fan catchments. This coupling can be conceived as a series of longitudinal (downstream) or lateral (slope) linkages that can be 'disrupted' or 'boosted' by various landform configurations within the fluvial catchment (Fryirs *et al.* 2007). These landform configurations in this particular study are largely determined by the structural preconditioning of the bedrock by passive tectonics.

i) tributary alluvial fan and main trunk river (River Dadès) interactions

The tributary fan systems of the Dadès can be considered to be driven by top down (sediment supply) and bottom up (base-level changes), as discussed in Mather *et al.* (2017). The Dadès River system is currently incising, albeit slowly (<0.2mm a^{-1} over the last 100ka, Stokes *et al.* 2017) and essentially provides the base level for the tributary-junction alluvial fans. Thus given the age of the fan deposits examined here (<100 years) the impact of this can be largely ignored. However foreshortening of the fan by sediment removal by the Dadès River during periodic large magnitude flood events does instigate periodic distal fan incision within Catchments 1, 22 and 28, although this is only of the order of 1-2m at maximum (Fig 14c). What is clear from the archive imagery is that some tributary-junction fans (Fan 4 and Fan 28) have been much more dynamic in terms of observable change over the last 10 years. Yet they have all been affected by the same climate and weather patterns. Explanations for this variability could include variations in local precipitation within individual storm events and differential partial area contributions relating to the bedrock landscape (the authors have observed early, rapid runoff generation within a storm event from areas such as steep limestone bedding plane surfaces). More significantly the fans do, however, have different relationships with the main river. Fan 4 is located in a wider valley section (140m across), is unchannelled and mostly acts as a buffer between the slopes and the Dadès River, deflecting the active channel to the east. Alternatively Fan 28 feeds into a much narrower canyon section of the River Dadès (30m across) and more regularly impedes the River Dadès. Evidence from May 2006 for example (Fig. 14b) shows Fan 28 creating ponded areas within the Dadès River. This is not unusual for such systems, and has been reported from other arid systems elsewhere (Schick & Lekach, 1987). As the Dadès river 'resets' the sedimentation of many of the alluvial fans every 10 years or so during rare (<10 year) regional Atlantic trough events (Stokes & Mather 2015) this means that Fan 28 loses more of its sediment supply in each event, and may also be breached by smaller flood events in the River Dadès. Thus whilst process (debris flow versus fluvial) explains the difference in fan gradients between these 2 systems (Fig. 4a), regular removal of sediment in Fan 28 may also play a significant role and may modify the catchment area and fan morphometrics.

ii) within-catchment longitudinal (de)coupling

Top-down coupling within relatively small catchments (such as those in this study) is strongly affected by the magnitude and frequency of sediment production and transport (Harvey 2002). Within these catchments the effective connectivity or coupling laterally (between slopes and channels) and longitudinally (between channel reaches) is significant in effectively delivering sediment to the tributary-junction alluvial fan. In this context catchment size plays an important role. This is reflected in controls on catchment size highlighted by Harvey (2002) and Stokes & Mather (2015) in generating tributary-junction fans. Larger catchments are more likely to store sediment as a result of internal barriers or buffers, and very small catchments may be incapable of generating the sediment required to produce a tributary fan. In the Dadès River study area fan generating catchments are typically more than 0.88km^2 and less than 28km^2 in area (Stokes & Mather 2015).

Within fluvial catchments the downstream transmission of sediment from reach to reach is important and limited competence along a channel or differing transport capacities may lead to longitudinal disconnectivity in coarse sediment movement (Rice 1998; Hooke 2003) and will be dependent on the downstream continuity of critical power relationships (Bull 1979). Discontinuities in the effectiveness of sediment transport through a system are typically expressed by sedimentation zones (Church & Jones 1982; Church 1983). These may be permanent or may migrate downstream. All of the catchments examined contained a lowermost zone of backfilled fan deposits that passes upstream into a bedrock zone. Notably catchment 22 and 28 contain intermixed bedrock and bedload lined channel reaches above the main back-filled section of valley. This suggests discontinuity of sediment transport down the system. In catchment 22 the 'boulder chokes' act to armour the bed in the softer lithology bedrock reaches (Fig 7a) and as much of the coarsest material is trapped in boulder chokes, it does not make it to the alluvial fan, reducing its gradient. Incision and erosion of the mudstones in the lower fan generates the localised matrix supported debris flows.

In strike-oriented catchments such as catchment 28, locally the bedrock serves to hamper incision and the stream is forced to follow a lower gradient across the bedding plane (bedrock supressed channel gradient). This typically acts as a barrier to sediment transport and enhances the deposition of backfilled sediment reaches at these points. This may well explain the apparently low discharge figures modelled for this catchment (Fig. 15) with coarser bedload not being transmitted through the system effectively. Alternatively in syn-dip catchments such as catchment 4 the steep dip of the bedrock acts as a sediment transport booster in the main stream, which then rapidly delivers sediment to the fan and then backfills into the catchment at a remarkably constant slope (Fig 4a). This is in complete contrast to catchment 1, where the lowermost slot canyon is locally so narrow (Fig. 5) that it acts as a longitudinal barrier to sediment transport. This reduces the potential coarse sediment supply to Fan 1 and encourages channel storage in the upper catchment, with localised backfilling above the main gorge section. This in turn decreases sediment to water in flows reaching the fan, encouraging more fluvial flows.

ii) within-catchment lateral (de)coupling

Within all 4 catchments examined there is little in the way of slope sediment storage (talus, colluvium) but significant evidence for bedrock landsliding (Figs 3, 6 and 8). This is not unusual, especially in arid areas of marked relief where it may be the principal mechanism for sediment transfer from the slope (e.g. Mather et al 2014). Landslides are most frequent where slopes have been destabilised by rapid exhumation such as rapid vertical fluvial incision (e.g. Mather *et al.* 2003; Griffiths *et al*. 2005). Additional important controls are exerted by the erodibility and structural configuration of the catchment bedrock that will determine both the rates of incision (e.g. Anton *et al.* 2015) and distribution and significance of the landsliding (e.g. Griffiths *et al*. 2005; Chittenden *et al.* 2013; Nunes *et al.* 2015).

The largest of these landslides in the studied catchments appear to be largely relict down-dip translational features of unknown age that are suspended above the current system (Fig. 3). These were likely initiated during more humid climate periods in the Quaternary as reported in other bedrock landsliding examples (e.g. Soldati *et al*. 2004; Borgatti & Soldati 2010). They could only have been initiated after sufficient incision by strike-oriented catchment streams allowed adequate space for the down-dip movement of the bedrock (an incision depth of some 10s of metres). Subsequently a renewed phase of incision decoupled these landslides from the active system, but they have been locally reactivated in catchments 4 and 28 and recoupled with the fluvial system by recent stream undercutting. The apparent response to this landsliding in both catchments is however different. In the syn-dip catchment (Fan 4), the sediment is being rapidly delivered to the lower drainage area due to the boosting effect of the steep bedrock on channel slope, supplying high sediment to water debris flows. Alternatively, in catchment 28, the landslides have produced local slugs of sediment (Fig. 8c,d) but the longitudinal transmissions of this down channel has been hampered by connectivity barriers imposed by bedrock supressed channel gradients (discussed above) and the landslides themselves acting locally as barriers to longitudinal connectivity (e.g. Fig 8a). In comparison to Fan 4, the Fan 28 processes are thus dominantly more dilute, hyperconcentrated flows.

Conclusions

This study highlights the diversity of fan behaviour experienced on alluvial fan tributary fan systems which share common climate, landuse and lithological characteristics. In part the diversity of this behaviour can be explained by the interaction between the tributary-junction alluvial fans and the main Dadès River but for a fuller understanding we need to examine the individual fan catchment areas. The general observations from the catchments in this study are summarised in the conceptual model presented in Fig 16.

Complementing previous research we find that increasing catchment area and decreasing catchment gradient serve to decrease the sediment to water ratio and thus determine the fan system flow and depositional processes. From this study in the Dadès, however, it would also appear that a significant component of complexity is added by the passive tectonic attitude of the bedrock that determines the longitudinal and lateral connectivity within the catchment. Of particular note are:

1) in syn-dip catchments steep bedrock dip boosts connectivity by enhancing stream gradient. Where translational landslides are present this significantly boosts sediment to water content of flows and encourages debris flow processes on the alluvial fans,
2) strike-oriented catchments are associated with bedrock supressed channel gradients which inhibit the downstream passage of coarse material. Translational landslides may further constrict channel width and disrupt longitudinal connectivity. This tends to enhance water to sediment nature of flows arriving at the alluvial fan, encouraging hyperconcentrated flow processes on the associated fans
3) effective barriers to longitudinal connectivity are presented by the development of slot canyons in areas of tectonic thickening of massive limestone. These serve to compartmentalise the catchment and supress sediment to water characteristics of flows, leading to the most dilute fluvial flows observed in the tributary fans
4) the resulting configuration of the tectonics and dip serves to enhance base-flow subsurface contributions from the karst systems in some catchments. These springs have the potential to further dilute sediment to water flows during periods of prolonged rainfall and are often overlooked when considering processes in arid bedrock catchments

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Alluvial Fan				Alluvial Fan Catchment					
Fan ID	Area km^2	gradient	Dominant process	Area km^2	Relief km	Length km	gradient	Storage km^2	Landslides km^2
1	0.006	0.0138	F	28.90	1.343	9.968	0.13	0.29 (1%)	0.44 (1.5%)
4	0.013	0.0113	DF	2.93	0.949	3.336	0.28	0.02 (0.7%)	0.39 (13%)
22	0.015	0.0108	DF	5.28	0.939	4.127	0.23	0.02 (0.4%)	0.16 (3%)
28	0.008	0.0146	F	19.03	0.870	8.692	0.10	0.34 (1.8%)	2.11 (11.1%)

Table 1. General descriptive metrics of the alluvial fan systems discussed in this paper. Modified from Stokes and Mather (2015) with the inclusion of new data on bedrock landslides. F = fluvially dominated; DF = debris flow dominated. Storage indicates bedload material stored within fans/backfill of catchment.

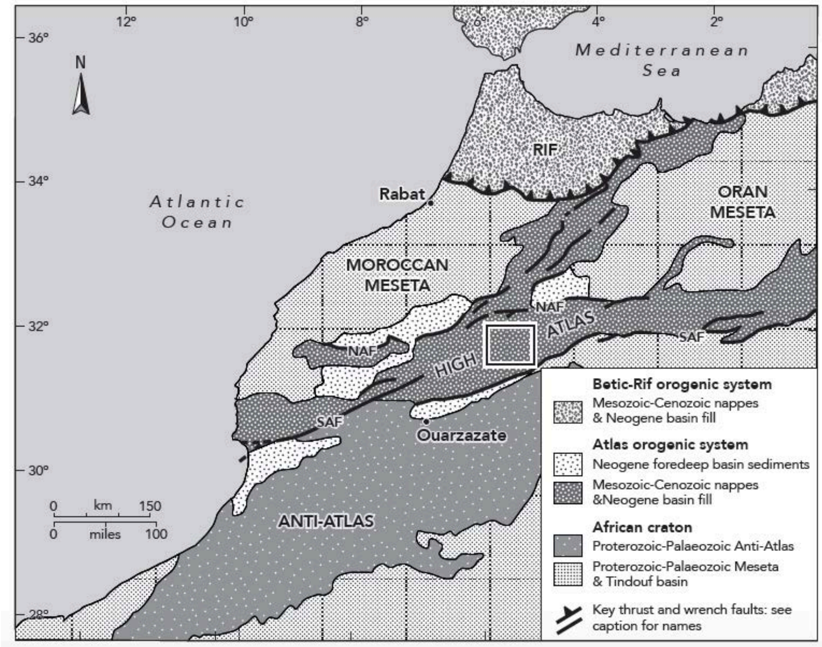
	Debris flow	**Hyper-Concentrated flow**	**Water flow**
Sediment concentration by weight (%)	70-90	40-70	1-40
Sediment concentration by volume (%)	47-77	20-47	0.4-20
Bulk density (kg/m^3)	1800-2300	1330-1800	1010-1330
Shear strength (dyne/cm^2)	>400	100-400	0-100
Fluid type	Viscoplastic?	Non-Newtonian?	Newtonian
Main sediment support mechanism	• Cohesion • Bouyancy • Dispersive stress • Structural support	• Bouyancy • dispersive stress • turbulence	• Electrostatic forces • turbulence
Viscosity (poise)	>>200	20-≥200	0.01-20
Fall velocity (% of clear water)	0	33-0	100-33
Sediment concentration profile	uniform	Non-uniform to uniform	Non-uniform
Main flow type	laminar	Turbulent to laminar	turbulent

Table 2. Flow type characteristics taken from Costa (1988) for the rheologic classification of water and sediment flows in channels with a silt and clay content of <10%.

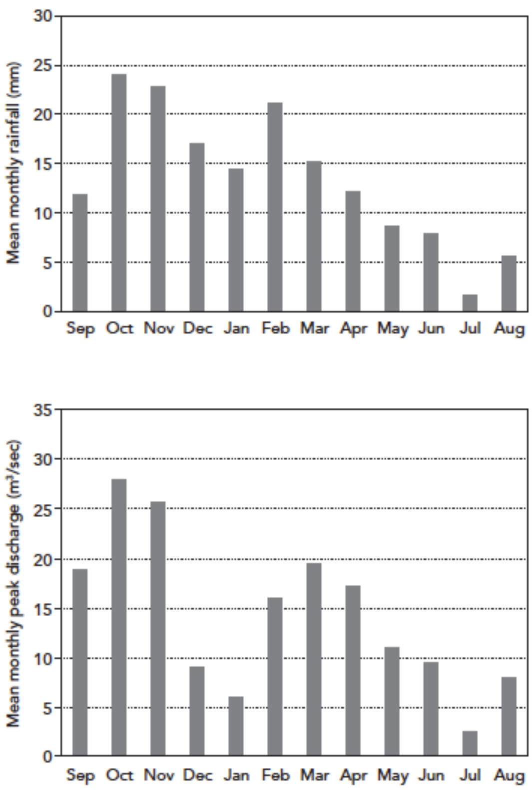
Figures

Fig 1. a) Location of study area. Adapted from Stokes and Mather 2015. Box in (a) is area displayed in (c). NAF, Northern Atlas Fault System; SAF, Southern Atlas Fault System. b) Mean monthly rainfall and peak discharge for the Ait Moutade gauging Station in the River Dadès from 1963-2003. Data from Schulz et al (2008). and c) Google Earth Professional (2016) image showing location of study catchments 1, 4 22 and 28 and Ait Moutade gauging station.

a)



b)



c)

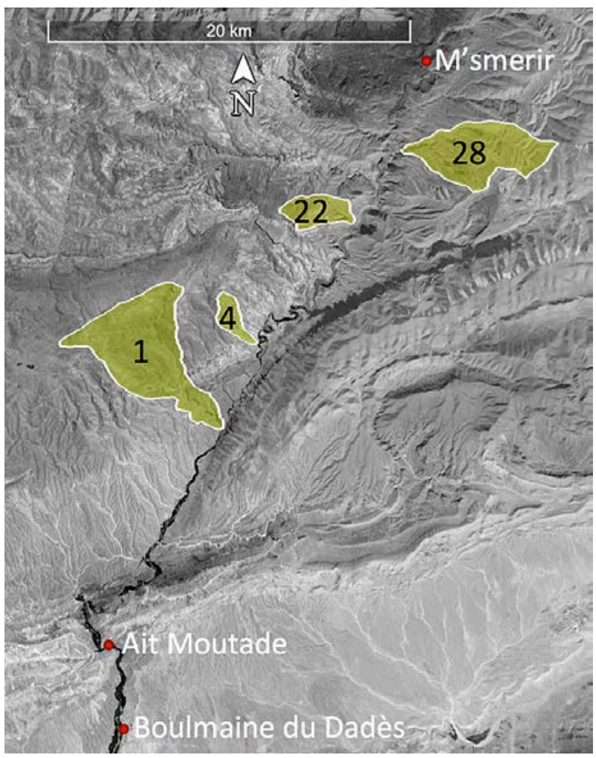
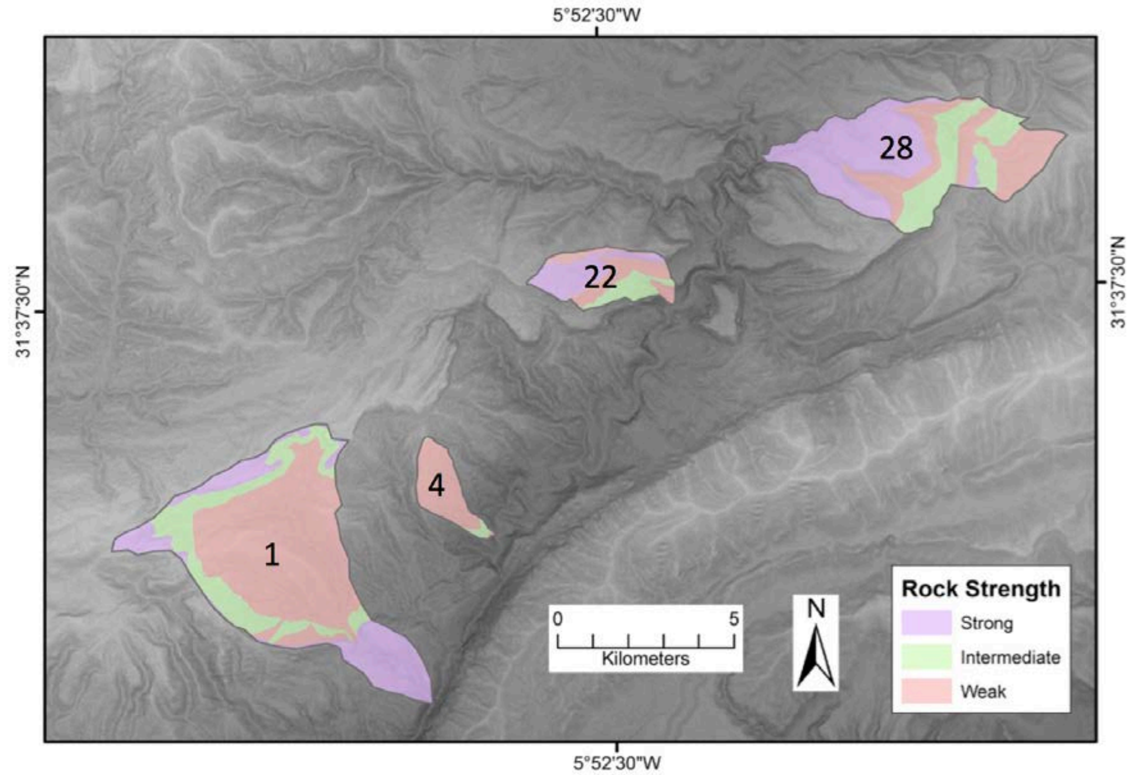


Fig 2. Tributary fan system catchment geology. a) rock strength information for the 4 study catchments (see Stokes and Mather 2015 for methodology) and b) catchment geology erodibility expressed as percentage catchment area of the 3 rock strength classifications of Stokes and Mather (2015). Solid symbols indicate fluvially dominated fans, open symbols indicate debris flow dominated fans, numbers indicate fans in this study

a)



b)

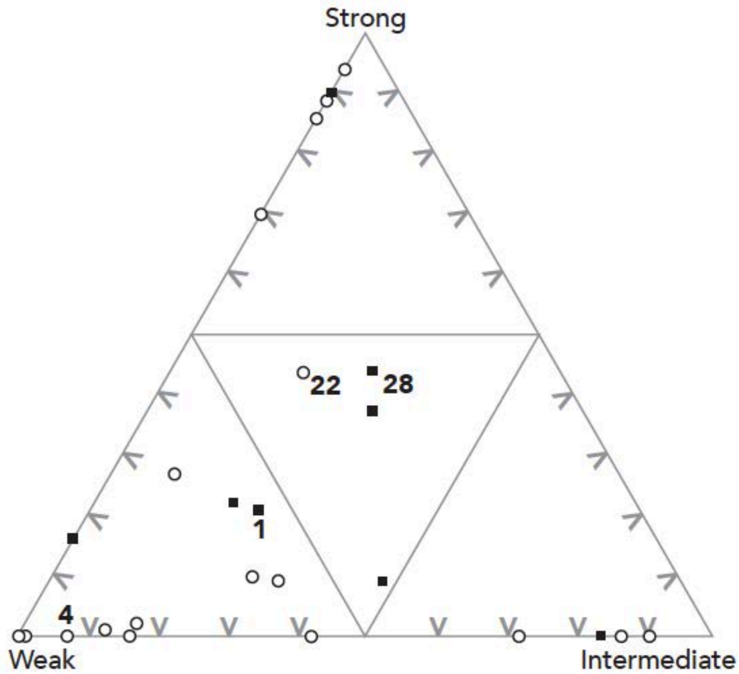
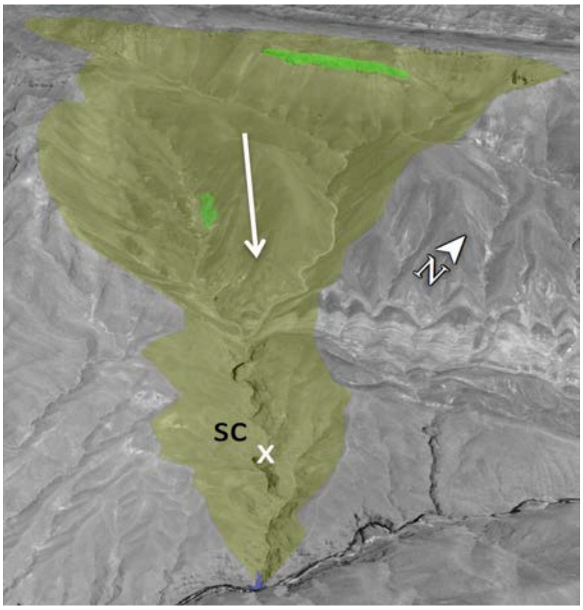
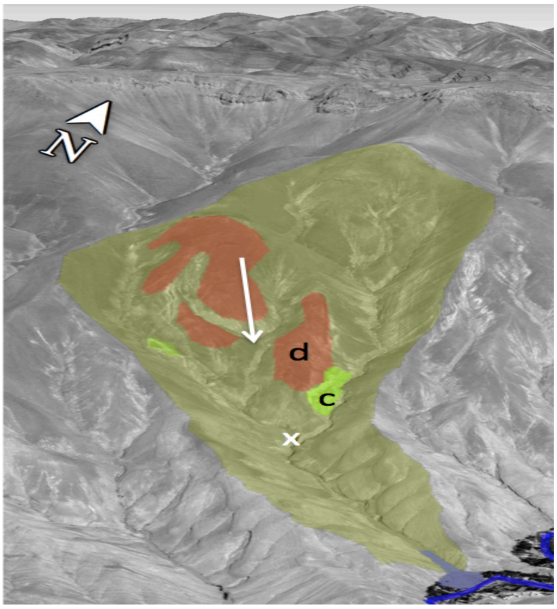


Fig 3. Catchment configuration for the study fans. Long profile survey (Fig. 4a) terminations are shown by X. Oblique terrain views (vertical exaggeration 1.5) and satellite images courtesy of Google Earth Professional (2016). Yellow indicates fan catchment, orange translational rock slides, green indicates bedrock slumps. White arrow indicates direction of geological dip. Fan is indicated in purple, main River Dadès by blue line in b,c,d. a) Fan 1, view 6.5km across. sc indicates slot canyon reach (shown in Fig. 5); b) Fan 4, view some 2km across, c,d Indicates landslide seen in Fig. 6c,d; c) Fan 22, view 4.5km across. c indicates area of drainage capture and d) fan 28, view 8km across. c,d are reactivated toes of translational landslides shown in Fig. 8c,d.



a)



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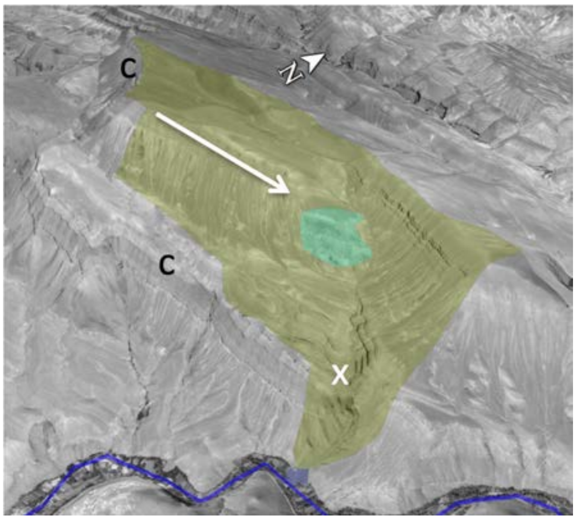

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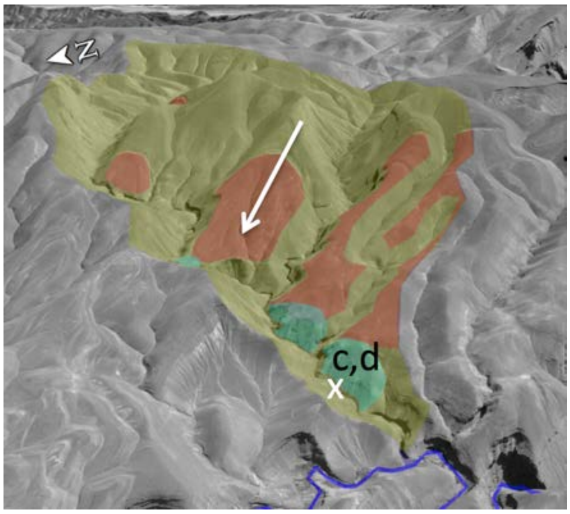


d)

Fig 4. Topographic survey for fans examined in this study (undertaken with Trupulse 360 ™ in field survey, May 2011). Solid lines indicate fluvially dominated fans, dashed lines indicate debris flow dominated. a) long profiles from River Dadès up main fan channel and into lower reaches of each catchment. Fans typically extend for 1-200m in length and are backfilled to <600m in each case and b) cross sections in medial-distal fan locations. Sections drawn with downstream River Dadès to left. Relative age of deposits determined from field and satellite imagery.

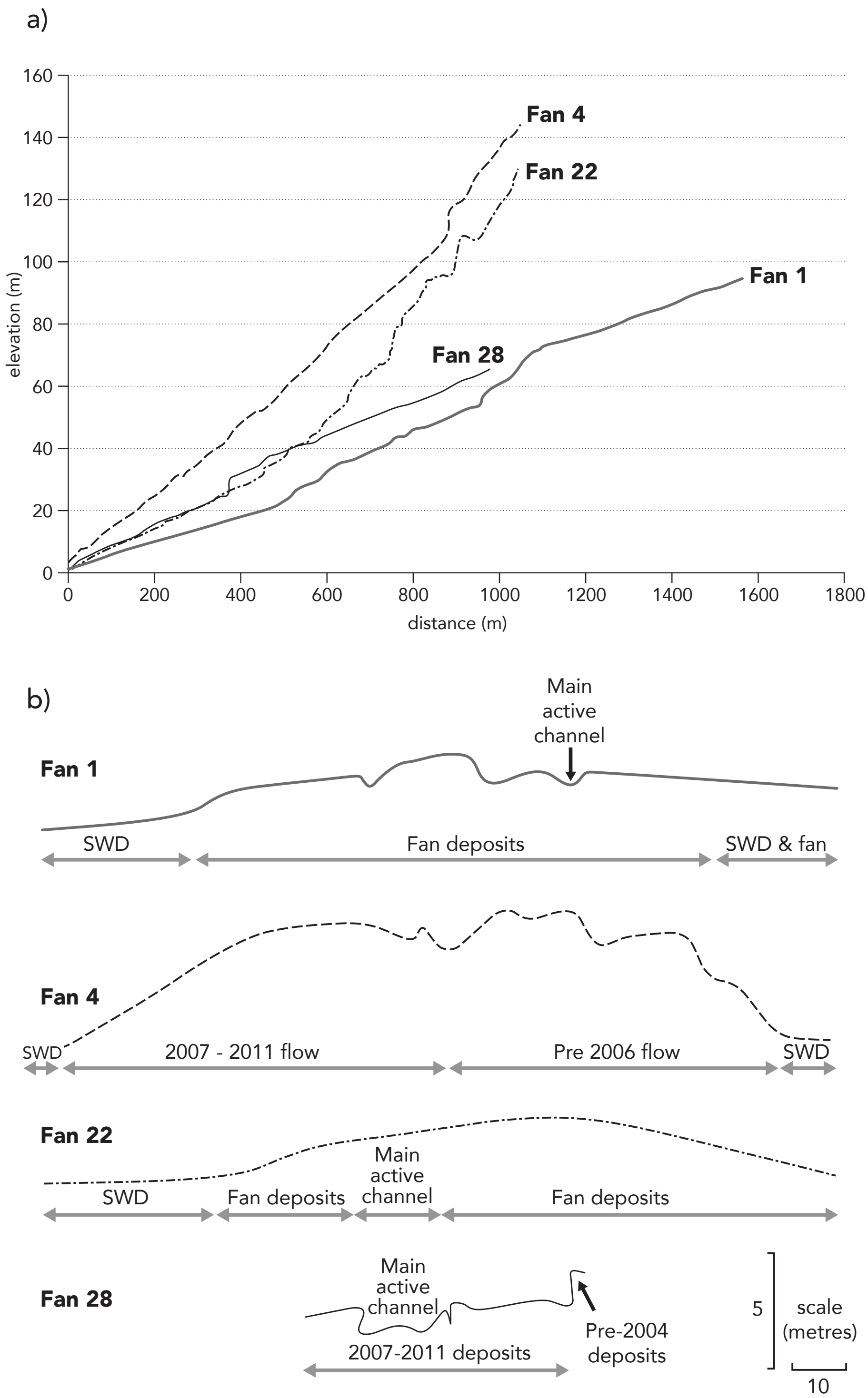
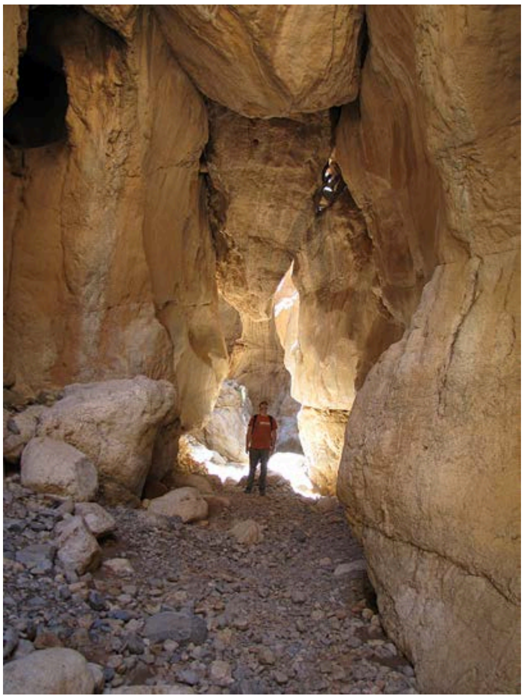


Fig 5. Fan 1 catchment characteristics. a) slot canyon section through massive limestone – cavern section with rockfall roof and b) slope deposits from canyon wall acting as local bottle neck for sediment transport through the main fan feeder channel. Person circled, for scale.

a)



b)

Fig 6. Catchment characteristics of Fan 4 from field survey. Persons circled for scale. a) view up feeder channel showing maximum extent of valley sediment storage - higher, older sediment fill (1) and lower, younger fill (2); b) view looking downstream in main drainage from bedrock dominated reach to top of backfill; c) view into base of landslide seen in (d) which has been reactivated due to stream incision and partially blocks the channel (c on Fig 3b) and d) view looking up catchment from tributary into recent landslide activity (d on Fig 3b).

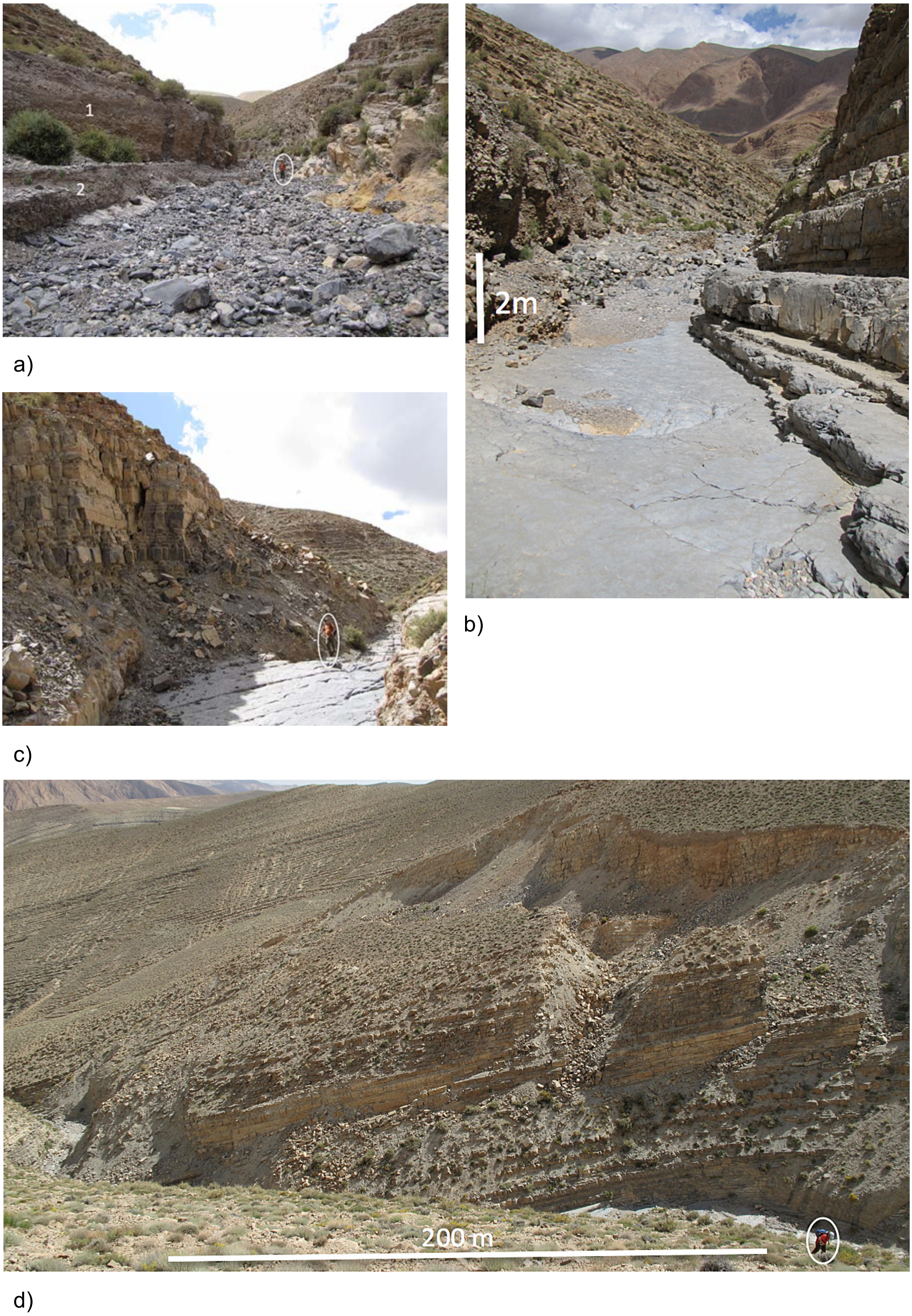
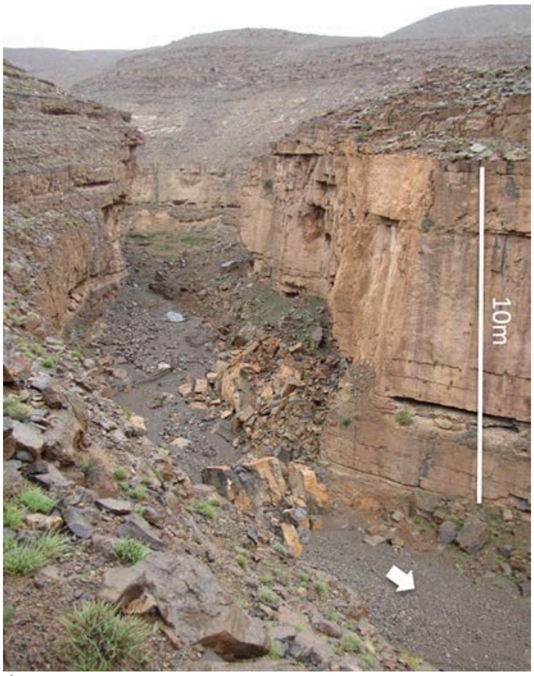


Fig 7 . Fan 22 catchment characteristics. Thick arrows indicate flow direction. a) 'boulder choke' and armouring from large boulders and b) limestone bedrock reach with emergent springs along mudstone and limestone bed contacts. Persons circled, for scale.

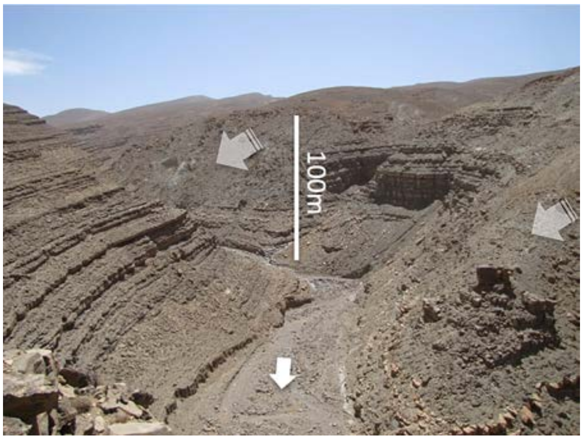
a) b)

Fig. 8. Catchment characteristics of Fan 28 from field survey (2011). Solid arrows indicate flow direction, Larger dashed solid arrows indicate direction of movement of translational landslides a) 2006/7 rockfall being progressively buried, b) asymmetric channel bedrock reach (dip of bedding to left of image), persons circled for scale. Note bedrock reach passes upstream into alluvial reach , c) translational landslides (right of channel) associated with a bedload rich reach and exacerbating asymmetric nature of the channel and d) detail of bedload rich reach within a landslide zone. Persons (circled) for scale.



a)

b)



c)

d)

Fig. 9. Sedimentology and Historic imagery of flow activity on Fan 1 from field survey (a-d) and Google Earth Professional archive (e-f). River Dadès flowing from right to left. a) April 2006 (herd of goats circled for scale) taken from downstream end and showing recent mudflow (b) with person circled for scale; c) May 2011, persons circled for scale. Note fan is trimmed (no depositional lobes); d) sedimentology observed in section on fan surface (arrowed in c) through 2006 deposits showing elements of fluvial flow (lower and upper part of section) which is fining upwards and imbricated whereas in the centre of the section there is a more matrix rich flow containing subvertical and suspended clasts; e) October 2013 showing incision on the fan surface and prograding lobes (p) and f) May 2016 showing progradation (p) after flood event. Scale bar 100m.

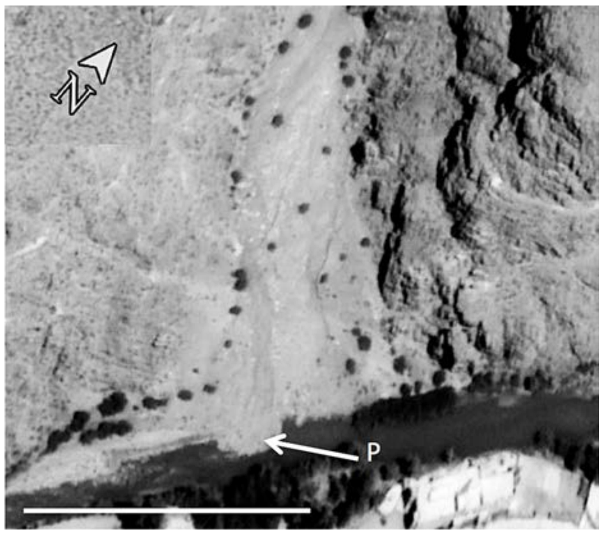
a)

b)

c)

d)

e)



f)

Fig. 10. Historic imagery showing activity on Fan 4 from field survey and Google Earth Professional archive. a) April 2006 field shot showing the reddened cohesionless debris flow in the field and from (b) August 2007 Google Earth; c) May 2011 field shot of the fan showing the pre 2006 flow buried by a more recent flow. Arrow indicates landslide scar seen in Fig. 6c; d) Jan 2012 Google Earth image. Note construction of wall defences (arrowed) to protect the irrigation channel at base of fan and e) May 2016 after further flows (post July 2013 according to Google Earth archive). Note wall has been breached to the south with flows through the trees into the irrigation channel. Former extent of wall indicated by dashed line. Scale bar 100m in all cases.

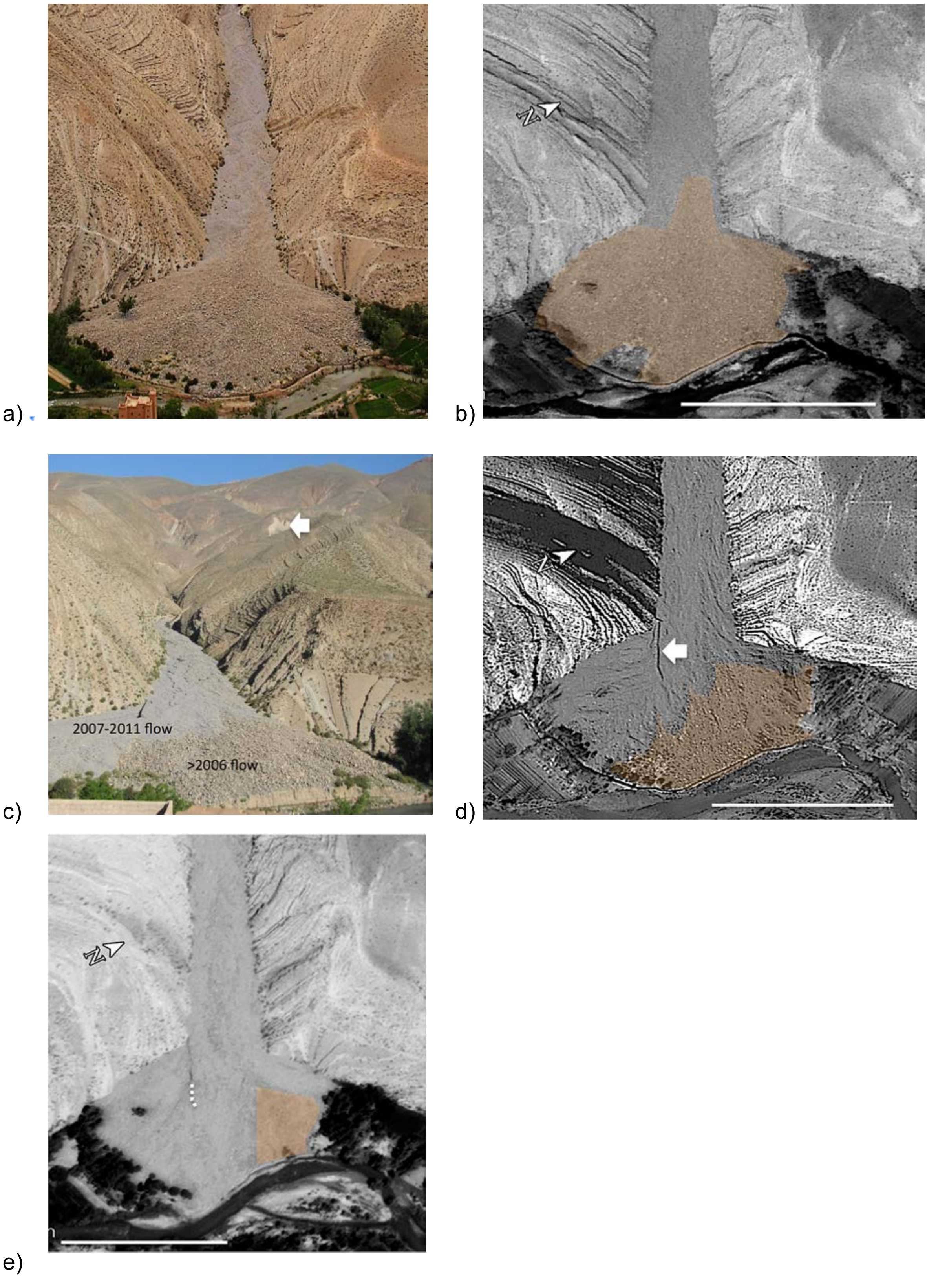
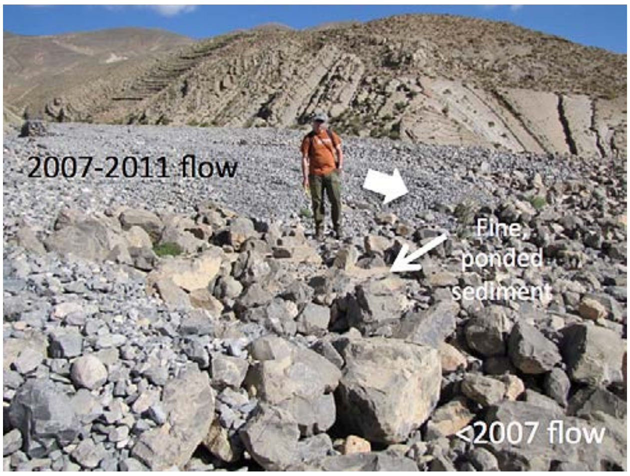


Fig. 11. Flow characteristics of Fan 4 from field survey. Solid arrows indicate flow direction. a) view looking down coarse openwork boulders of flow top and showing arcuate push ridges (highlighted by dashed lines) in the pre 2006 flow. Coarsest material found at margins of flow and ridges. Person circled for scale, b) lobate fingers of 2007-11 flow overlying pre 2006 event, c) flow transverse section through distal part of the pre 2006 event showing coarsening upward and open framework top, d) flow section in feeder channel, parallel to flow. Distinctive coarsening upwards openwork top with fines in subsurface, non erosive bases, subvertical clasts. Persons circled for scale.

a)



b)

c)

d)

Fig 12. a)-c) Historic imagery showing activity on Fan 22 courtesy of the Google Earth Professional archive. a) Dec 2003 incision of fan surface; b) Jan 2012 deposition mid-fan and c) July 2013 after further flows. Scale bar 100m. d) View down backfilled part of catchment and down fan surface, dashed white arrow indicates position and flow direction of river Dadès. e) matrix rich mass flow deposits and f) pre December 2003 clast rich debris-hyperconcentrated flow deposits, Thick solid arrows indicate flow direction.

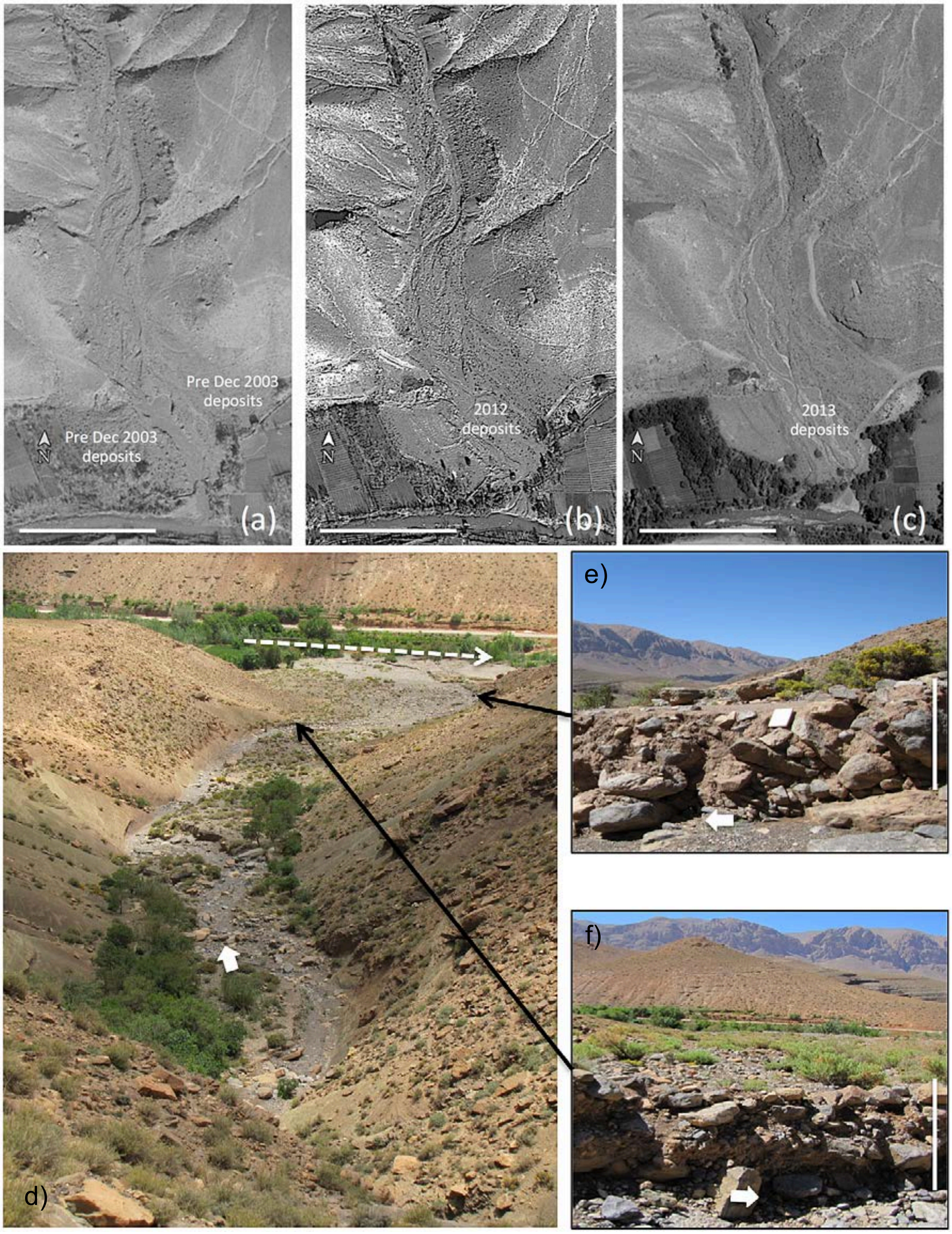
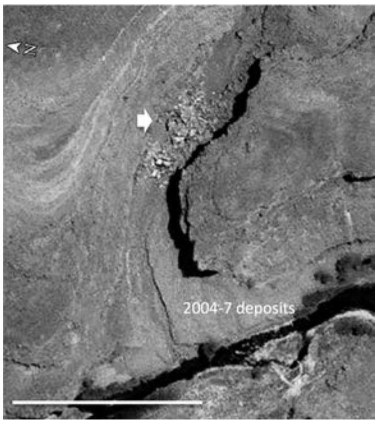
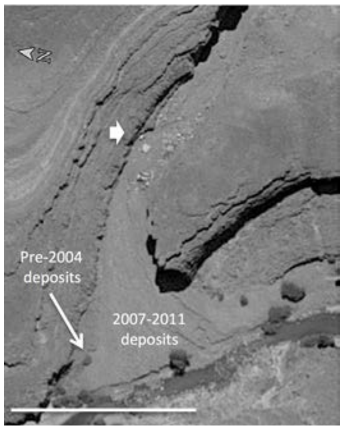


Fig 13. Historic imagery showing activity on Fan 28 courtesy of the Google Earth Professional archive. a) June 2004 incision of fan surface and upstream (north) toe of fan by River Dadès; b) Post April 2006, pre-August 2007 rock topple in canyon (arrowed). Active fan channel has migrated north and c) July 2013 – 2006/7 rock topple being progressively buried. Scale bar 100m, d) May 2012 field shot of the fan surface. 2004-7 rock topple arrowed. Now significantly buried by bedload. Letters indicate positions of corresponding photos in Fig. 14.

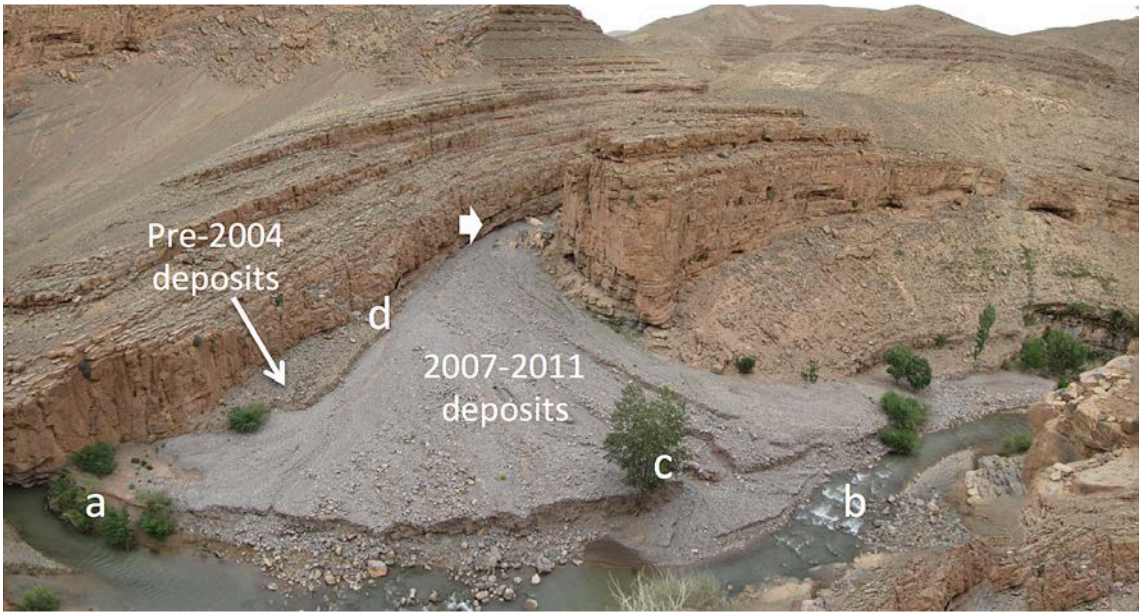
a)



b)



c)



d)

Fig 14. Flow characteristics of Fan 28 from field survey. Solid arrows indicate flow direction. a) climbing ripples in slack water deposits (a) on Fig. 13d); b) view to SE from May 2006 of Fan 28 impeding the flow of the Dadès (solid arrow). c) section through 2007-2011 deposits (looking into flow). Tree demonstrates rapid nature of aggradation and erosion. d) remnant from pre 2004 event showing imbrication suggestive of fluvial (but hyperconcentrated) deposition.

a)

b)

c)

d)

Fig. 15. Palaeodischarge calculations derived from Clarke (1996). Fans 1 and 28 lower discharge values based on fluid density for hyperconcentrated flow upper limit (1800 kg/m^3), upper values on turbulent stream flow in canyons (1150 kg/m^3). Fans 4 and 22 Lower discharge values based on fluid densities for debris flows of 2000 kg/m^3, the upper values represent the upper limits for hyperconcentrated flow (1800 kg/m^3). Trend line is for mean values.

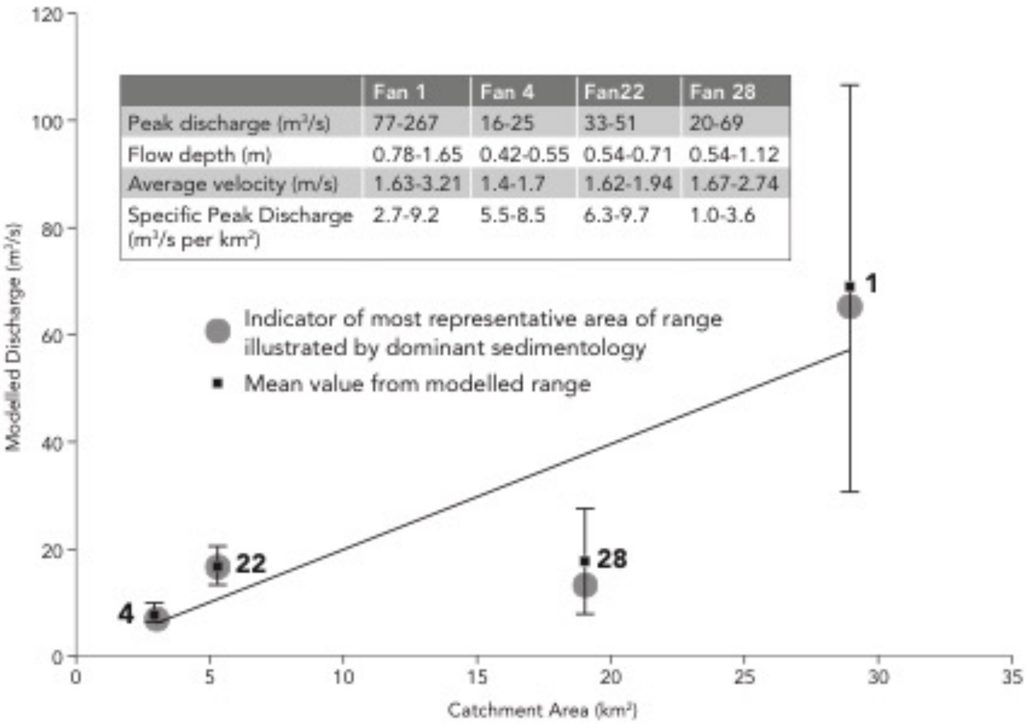


Fig 16. Summary of relationship between catchment features, sediment and water production and resulting flow processes on the observed fans expressed as morphology (aerial view, arrow indicates direction of main river flow) and sedimentology (vertical section view, flow right to left in each case, scale bar 20cm).