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Controls on dryland mountain landscape development along the NW Saharan desert margin: Insights from Quaternary river terrace sequences (Dadès River, south-central High Atlas, Morocco)

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A B S T R A C T

This study documents river terraces from upstream reaches of the Dadès River, a major fluvial system draining the south-central High Atlas Mountains. Terraces occur as straths with bedrock bases positioned at 10 m altitudinal intervals up to 40 m (T1-T5) above the valley floor, becoming less common between 50 and 140 m. The rock strength, stratigraphy and structure of the mountain belt influences terrace distribution. Terraces are absent in river gorges of structurally thickened limestone; whilst well-developed, laterally continuous ter-races (T1-T4) form along wide valleys occupying syncline structures dominated by weaker interbedded lime-stone-mudstone. Terrace staircases develop in confined canyons associated with weaker lithologies and influence from structural dip and stratigraphic configuration.

Terraces comprise a bedrock erosion surface overlain by fluvial conglomerates, rare overbank sands and colluvium. This sequence with some OSL/IRSL age control, suggests terrace formation over a 100 ka climate cycle with valley floor aggradation during full glacials and incision during glacial-interglacial transitions. This integrates with other archives (e.g. lakes, glaciers, dunes), appearing typical of landscape development along the NW Saharan margin south of the High Atlas, and similar to patterns in the western-southern Mediterranean. The 100 ka climate cycle relationship suggests that the terrace sequence documents Late-Middle Pleistocene landscape development.

Consistent altitudinal spacing of terraces and their distribution throughout the orogen suggests sustained base-level lowering linked to uplift-exhumation of the High Atlas. Low incision rates (<0.2 mm a^{-1}) and general absence of terrace deformation suggests dominance of isostatically driven base-level lowering with relief generation being Early Pleistocene or older.

1. Introduction

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River terraces are bodies of fluvial sediment with a step-like mar-gin and flat topped surface that grade topographically towards a val-ley centre and in a downstream direction (Stokes et al., 2012a). They are commonly preserved along river valley margins around the world and are considered to have regional lithostratigraphic importance (Bridgland and Westaway, 2008a,b; 2014). A terrace forms when a river incises, abandoning the former floodplain and channel belt (Leopold et al., 1964). Successive periods of fluvial sediment aggradation, river incision and floodplain-channel abandonment can form inset river terrace staircases (Starkel, 2003). The fluvial sedimentation is generally a function of climate-related sediment supply and flood regime, whilst river incision is determined by base-level low-ering, normally driven by combinations of tectonics, climate and eustacy (e.g. Bridgland and Westaway, 2008a; Vandenberghe, 2015). Global database compilations of river terrace research have high-lighted the importance of terraces as archives of Late Cenozoic (mainly Quaternary) environmental change and their relationship to unravelling the development of topographic relief (Bridgland and Westaway, 2008a,b; 2014). Much of this research is focussed on large, mid latitude northern hemisphere river systems that have evolved un-der fluctuating glacial, periglacial and humid climatic conditions due to their ice sheet proximity and connectivity. With few exceptions (see Bridgland and Westaway, 2008a and references therein), there is a no-table research gap from lower latitude regions where fluvial systems have evolved in environments with negligible-minimal direct ice sheet influence under drier continental conditions. One such area is NW Africa and its inland arid region south of the High Atlas Mountains (Fig. 1).

The NW Saharan Desert margin is bordered by the 3–4 km relief of the High Atlas Mountains of Morocco. Its topography, and the lower relief ~2 km Anti-Atlas Mountains to the south (Fig. 1), marks

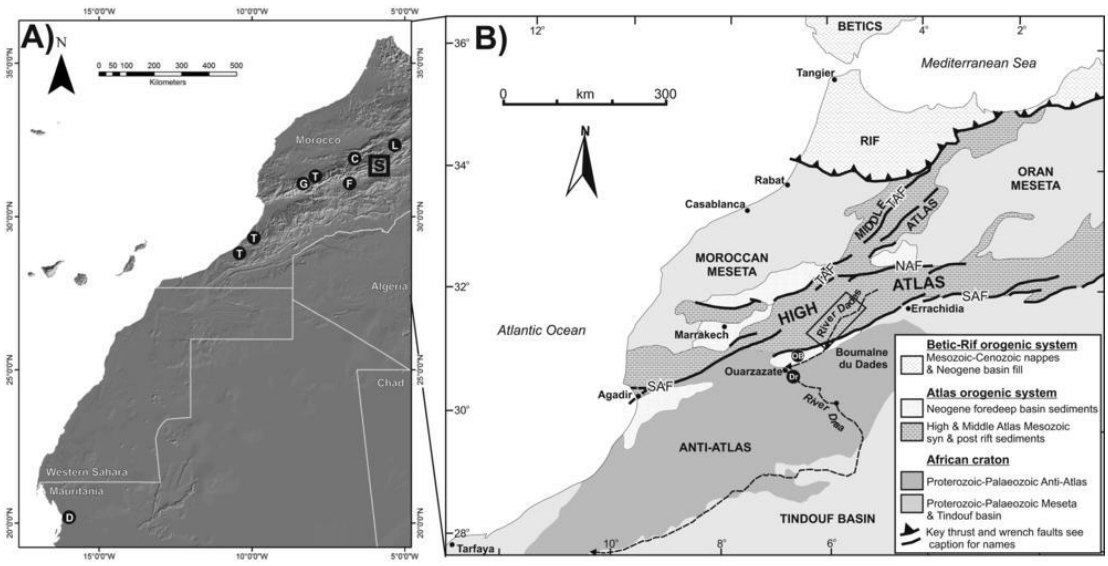

Fig. 1. A) Topography of NW Africa and Quaternary landscape study locations referred to within text (D = dune studies; T = terrace studies; G = glacier moraine study; F = fan stud-ies; C = glacial cirque study; S = Dadès River study area; L = mountain lake study). B) Tectonic and geological configuration of Morocco and the south-central High Atlas region. Note River Dadès study region (black rectangle: Figs. 2 and 3). OB = Ouarzazate Basin; Dr = Draa gorge and capture region; NAF/SAF/TAF = Northern/Southern/Tell Atlas Fault systems. Modified from Michard (1976) and Carte Géologique du Maroc (1985).

the southern limits of ongoing Alpine tectonic collision between Africa and Europe (Dewey et al., 1989) and is a key area of climate interchanges between the Atlantic, Mediterranean and continental low latitude regions of Central-West Africa (Tjallingii et al., 2008). The mountain landscape origins relate to accelerated Plio-Quaternary up-lift (Frizon de Lamotte et al., 2000) and global climate cooling and fluctuations throughout the Quaternary (Plaziat et al., 2008). Quater-nary sediments and landforms occur throughout the region (Plaziat et al., 2008) but river terrace research is limited, being geographically restricted to coastal areas of the Anti-Atlas (e.g. Weisrock et al., 2006) and localised parts of the northern High Atlas

(Delcaillau et al., 2016). Coastal river terrace studies are either regional treatments, using river-marine terraces for numerical uplift modelling (e.g. Westaway et al., 2009) or are localised studies high resolution dating studies of a single Late Pleistocene terrace level site for detailed climatic insights (e.g. Weisrock et al., 2006). These Atlantic drain-ing rivers have a strong climate-eustatic base level control, have developed in low mountain relief and are influenced from humid At-lantic weather. However, these coastal systems are not typical of in-land, where drainage has evolved under considerably drier continental climatic conditions, greater relief variability and absence of eusta-tic base level control. The southern flanks of the High Atlas provide an excellent area to study river terraces and their role for unravelling Quaternary fluvial landscape development typical of the dryland con-tinental interior of NW Africa. Here, rivers are 1) sourced from some of the highest mountain relief, 2) are routed southwards from moun-tain through to lower lying desert climatic regions and 3) cross all of the key tectonic components of the High Atlas orogenic system.

In this study we focus on a 60-km-long upstream reach of the Dadès River (Fig. 1), a principal river system draining the south-central High Atlas in the characteristic dryland continental interior of NW Africa. The terraces are used to explore the interplay of geo-logical, climate and tectonic base level controls on Quaternary flu-vial landscape development. The relationship of the terrace sequence to the rock strength, structure and stratigraphic sequence of the High Atlas orogen is assessed as a passive geological control on terrace formation. Terrace-climate relationships are examined using an OSL/IRSL dated terrace sediment sequence, providing insights into the timing of fluvial aggradation and incision patterns and their relationship to a 100 ka climate cycle. The terrace sequence is then used to explore spatial and temporal patterns of base-level lowering through incision rate quantification and its relationship to the timing and mechanisms of tectonic relief generation of the High Atlas orogen.

2. Geological and geomorphological background

2.1. Regional geology and drainage evolution

The Dadès River is one of the larger drainage systems in NW Africa forming the principal perennial river that drains the south-central High Atlas Mountains of Morocco (Fig. 1B). On entering the Ouarzazate Basin, the Dadès River flows westwards along the north-ern margin of the Anti-Atlas. At Ouarzazate town, the Dadès River joins the Draa River, turning SE with routing across the Anti-At-las through the Draa Gorge before turning WSW to join the Atlantic Ocean.

This drainage configuration relates to the long term tectonic de-velopment of NW Africa. The High Atlas is an ENE-WSW oriented Alpine orogenic system formed by African-European plate suturing (Dewey et al., 1989; Frizon de Lamotte et al., 2008). Relief generation of 2–4 km has involved the inversion of a Mesozoic intracontinental rift system by regional thrust faulting and folding (e.g. Gomez et al., 2000) and thermal-related isostatic uplift related to a mantle plume un-derlying the High Atlas (e.g. Missenard et al., 2006). The mountain belt displays common characteristics of a collisional orogenic system (Figs. 1B and 2): a high relief ‘axial zone’, bordered by thrust front (Northern and Southern Atlas faults [NAF/SAF]) and peripheral fore-land basins around the relief margins (Chellai and Perriaux, 1996; El Harfi et al., 2001). The stages and timing of High Atlas relief gen-eration are debated but generally considered to have occurred in two stages during the Early and Late Cenozoic (Frizon de Lamotte et al., 2000).

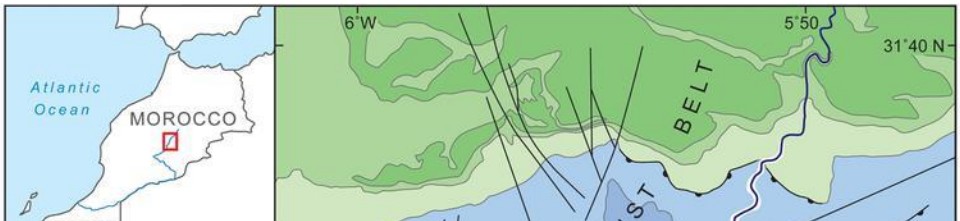

Fig. 2. A) Geology of the study area within the High Atlas orogenic system, illustrating key lithostratigraphic units and major tectonic and stratigraphic structures. B) North-South orogenic cross-section. Map and cross-section modified from Carte Géologique du Maroc (1975, 1990; 1993). See Table 1 for stratigraphic and lithologic information.

Analysis of the High Atlas drainage pattern by Babault et al. (2012) describes rivers that are longitudinal (strike-orientated) or transverse to the mountain belt structure. This research suggests that early drainage is inherited from growing upper crust fault-fold structures, with later drainage development configured to amplified N-S regional slopes as topography grows. The modern Dadès River is oblique to the orogen structure, suggesting it is a longer lived longitudinal drainage system (Babault et al., 2012) but one that contains large scale knick zones linked to more recent Plio-Quaternary uplift and relief genera-tion (Boulton et al., 2014).

At continental scale, the modern Dadès-Draa system (Fig. 1B) is related to capture of the internally drained Ouarzazate Basin by an Anti-Atlas drainage (Stäblein, 1988). The capture is probably a Mid-dle-Late Pleistocene occurrence based upon fan surface dating from sites north of Ouarzazate town (Arboleya et al., 2008).

2.2. Geology and geomorphology of the Dadès River

The headwaters of the modern Dadès River lie at altitudes of 2800–3400 m (above sea level), with the river entering the Ouarzazate Basin at ~1550 m (Fig. 3A). The study area (Fig. 3B) encom-passes key geological and morphological components of the High At-las orogenic system (Figs. 2 and 3): 1) high relief (3400–2000 m) fold-thrust belt (FTB), 2) intermediate relief (1900–1600 m) wedge top basin (WTB), 3) intermediate relief (1900–1600 m) thrust front (TF) and 4) low relief (1600–1500 m) foredeep basin (FB) (orogen terminology *sensu* DeCelles and Giles, 1996).

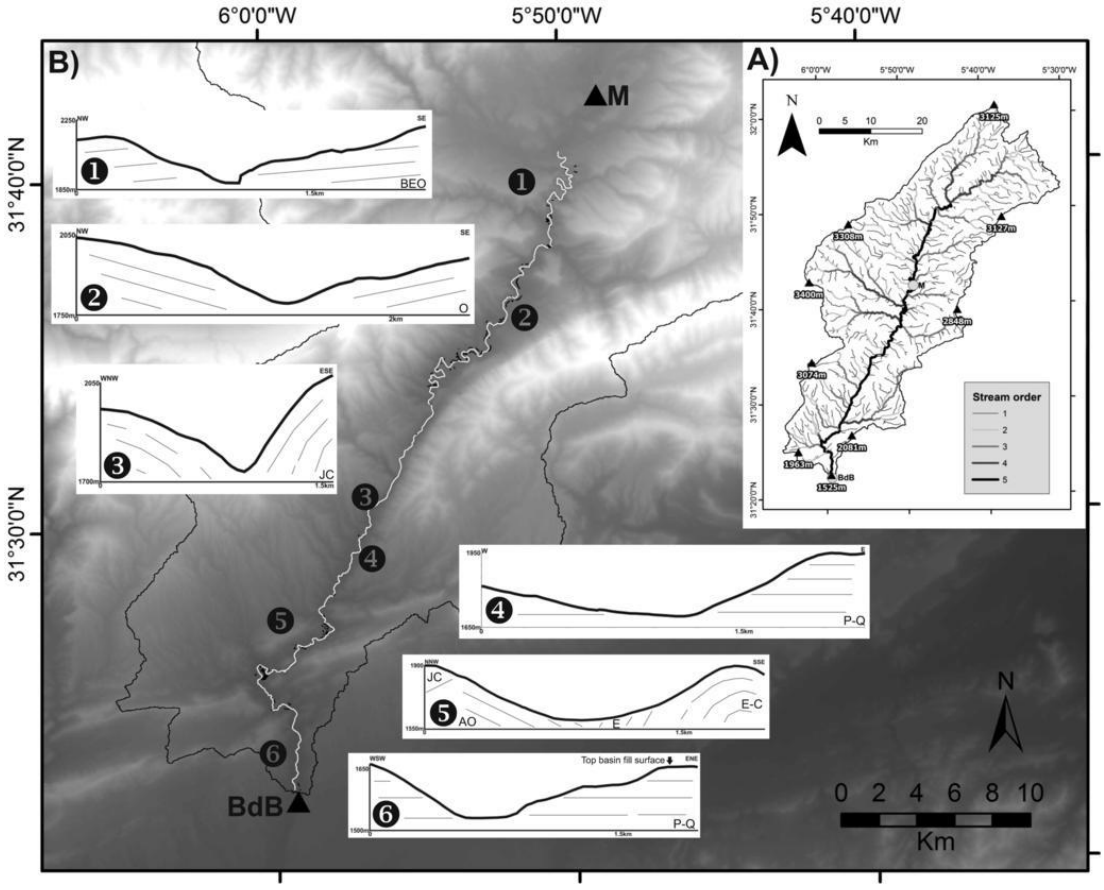

Fig. 3. A) Dadès River catchment, relief and Strahler stream ordering. B) Detailed study area showing the drainage divide (black line), the Dadès River trunk drainage study region (white line) between the towns of Boumalne du Dadès (BDD) and M'smerir (M), river terrace distribution (red dots) and cross valley profiles (1–3 = proximal, mid, distal FTB; 4 = WTB; 5 = TF; 6 = FB) annotated with geology and regional bedrock dip configuration (P-Q = Plio-Quaternary; AO = Aït Ouglif Fm; E-C = Eocene-Cretaceous; BEO = Bin El Ouidane Fm, O = Ouchbis Fm, JC = Jbel Choucht Fm: See Fig. 2 and Table 1).

The FTB forms the mid to upstream parts of the study area (Fig. 3). Jurassic marine limestone and mudstone lithologies are dominant (Carte Géologique du Maroc, 1990, 1993), corresponding to a Meso-zoic rift system that forms the central-eastern High Atlas (Warme, 1988). This bedrock is affected by a series of regional fold and thrust fault structures (Fig. 2). In the upstream FTB the Dadès River cuts through the SE limb of a symmetric open anticline in a series of deeply incised (>100 m depth) high sinuosity canyons (Figs. 2, 3 and 4A). Downstream, the folding changes to an asymmetric syncline with the Dadès River routed southwest along the fold axis in an open valley configured by the syncline (Figs. 2, 3 and 4B). A route deviation to the southeast occurs at the Tarhía n' Dadès gorge (Figs. 2, 3 and 4C) where the Dadès River cuts a short 0.5 km long, 150 m deep and 20–50 m wide route through a Lower Jurassic limestone ridge (Stokes et al., 2008). In the downstream distal part of the FTB, thrust faulting has structurally thickened Lower Jurassic limestones causing the Dadès River to cut a deeply incised (>200 m), ∼5 km long and 20–100 m wide gorge, the Dadès Gorge (Figs. 2, 3 and 4D; Stokes et al., 2008).

The Dadès River emerges from the Dadès Gorge into the Aït Se-dratt WTB (Figs. 2, 3 and 4E). Plio-Quaternary terrestrial fan and fluvial conglomerates are organised into a syncline that has devel-oped between the FTB and the TF (Carte Géologique du Maroc, 1990, 1993). Sediment provenance, palaeocurrents and stratigraphic-struc-tural organisation suggests a complex FTB transverse and parallel palaeo-drainage routing influenced by thrust faulting and folding (Cavini, 2012), corresponding in part to an ancestral Dadès River. The modern Dadès River is routed southwest, transverse to the WTB in a relatively open asymmetric valley flanked by high cliffs on western banks and lower slopes/cliffs on eastern banks (Figs. 3B and 4E).

In the TF region, the Dadès River passes through a structurally complex ENE-WSW striking, southwards verging folded and oblique thrust faulted sequence of Mesozoic-Cenozoic lithologies (Carte Géologique du Maroc, 1975; Tesón and Teixell, 2008). The river dis-plays marked orientation changes as it passes through the TF region, showing a dominant configuration to the ENE-WSW strike of de-formation, with shorter NNW-SSE valley reaches that are transverse to the TF strike (Figs. 2 and 3B). The strike and transverse orientated valleys are relatively open (Fig. 4F) but short gorge reaches exist where the river routes through Jurassic and Palaeogene lime-stones (Fig. 4G). Cross-sections and stratigraphic-structural analyses by Tesón and Teixell (2008) suggest that the TF region has undergone low rate (0.3 mm/a^{-1}) tectonic shortening of 7–8 km.

Finally, the Dadès River emerges from the TF passing southwards into the (Ouarzazate) FB (Figs. 2, 3 and 4H). Here, Plio-Quaternary terrestrial fan and fluvial conglomerates form the dominant lithol-ogy, with some stratigraphic affinity to similar sediments in the WTB (Cavini, 2012). The sediments form a top surface ∼100 m above the Dadès River valley floor (Fig. 3B), with the surface revealing relict fan-shaped morphologies fed from drainage outlets along the TF/FB margin. Further west in central and western parts of the Ouarzazate Basin, the surface is incised forming a stepped landscape with up to 5 inset fan/terrace surfaces (Görler et al., 1988; Stäblein, 1988; Arboleya et al., 2008). Some higher-older surfaces display folding and fault scarps (Sébrier et al., 2006; Arboleya et al., 2008) suggesting Quaternary deformation. Seismic activity is infrequent and low magnitude, with historical shallow earthquakes of magnitude <4.9 distributed throughout the TF/FB margin regions (Medina and Cherkaoui, 1991). *2.3. Quaternary-recent characteristics of the Dadès River and surrounding region*

The modern Dadès River is a perennial 5th order trunk drainage (Fig. 3A) fed by ephemeral tributaries (Stokes and Mather, 2015). The modern channel occupies a highly sinuous valley, incised by < 3 m into a flat up to 500 m wide alluvial floodplain of weakly cemented gravels capped by sands and silts. Canyon and gorge reaches often lack the alluvial floodplain instead

comprising bedrock reaches with sometimes thin and transient alluvial covers. Flood hydrology is influ-enced by a semi-arid mountain climate with a marked altitudinal zona-tion where annual precipitation varies from 200 mm upstream (M's-merir village) to 150 mm downstream (Boumalne du Dadès town) (Schulz et al., 2008; Dłużewski et al., 2013) (Fig. 3). Average daily discharges are 33.3 m^3/s but with seasonal variation linked to annual winter–spring precipitation in drainage divide regions derived from Atlantic low pressure incursions and rarer convective storm events from the tropics (e.g. Fink and Knippertz, 2003). The ephemeral trib-utaries commonly store and supply large volumes of coarse clastic sediment to alluvial fans in the Dadès River valley dependent upon the tributary catchment bedrock lithology, stratigraphy and structure. The fans build out onto the valley floor and are often eroded through interaction with low frequency-high magnitude flooding (Stokes and Mather, 2015). Bedrock weathering and sediment supply are further enhanced by the absence of vegetation cover.

Throughout the study area, alluvial terraces are observed along the sides of the Dadès valley and its larger tributaries. Their only documentation is on recent geological maps (e.g. Carte Géologique du Maroc, 1993) where up to 5 levels (q1–q5) are intermittently recorded using the classical stratigraphic subdivision nomenclature (Plaziat et al., 2008): Younger Quaternary = Soltanien [q1]; Middle Quaternary = Tensiftien [q2]; Older Quaternary = Amirien [q3], Sale-tien [q4], Moulouyen [q5]. The maps lack detail on mapping proce-dure, height information, age assignment and any terrace environmen-tal significance. During the Quaternary, arid climate conditions dom-inate, fluctuating between cool and dry glacials and warm and dry in-terglacials (Lamb et al., 1994; Valero-Garcés et al., 1998). Despite the aridity, periods of humidity with elevated precipitation existed, becoming regionally elevated during the major climate transitions (Tjallingii et al., 2008). During the glacials high relief areas (2–4 km) saw plateau icefield, valley glacier development, periglacial activity (Wiche, 1953; Hughes et al., 2011) and fluctuating high mountain lake levels (Lamb et al., 1994; Valero-Garcés et al., 1998); contrasting with enhanced aeolian dune activity in low relief and lower latitude west-ern Sahara Desert regions (Lancaster et al., 2002).

3. Approach and methods

3.1. Terrace mapping, stratigraphy and sedimentology

River terraces were analysed using integrated field and remote sensing approaches in-between the towns of Boumalne du Dadès (downstream) and M'smerir (upstream) (Fig. 3). Remote sensing utilised 1 arc second SRTM derived digital elevation data, Google Earth imagery, topographic and geological maps collectively visu-alised and interrogated in Arc GIS. River terraces were identified using standard morphological and geological criteria (Stokes et al., 2012a; Mather et al., in press). Ter-race surfaces were often unclear due to burial by slope/fan deposits but valley side erosion commonly revealed a flat to gently dipping downstream terrace surface contact with overlying slope material. Terrace risers were normally steep and cliff-like, whilst terrace bases revealed sharp lithological contrasts between the fluvial conglomerate and underlying bedrock. Contacts between conglomerates and overly-ing slope deposits utilised differences in sediment textures, fabrics and stratigraphy (Mather et al., in press).

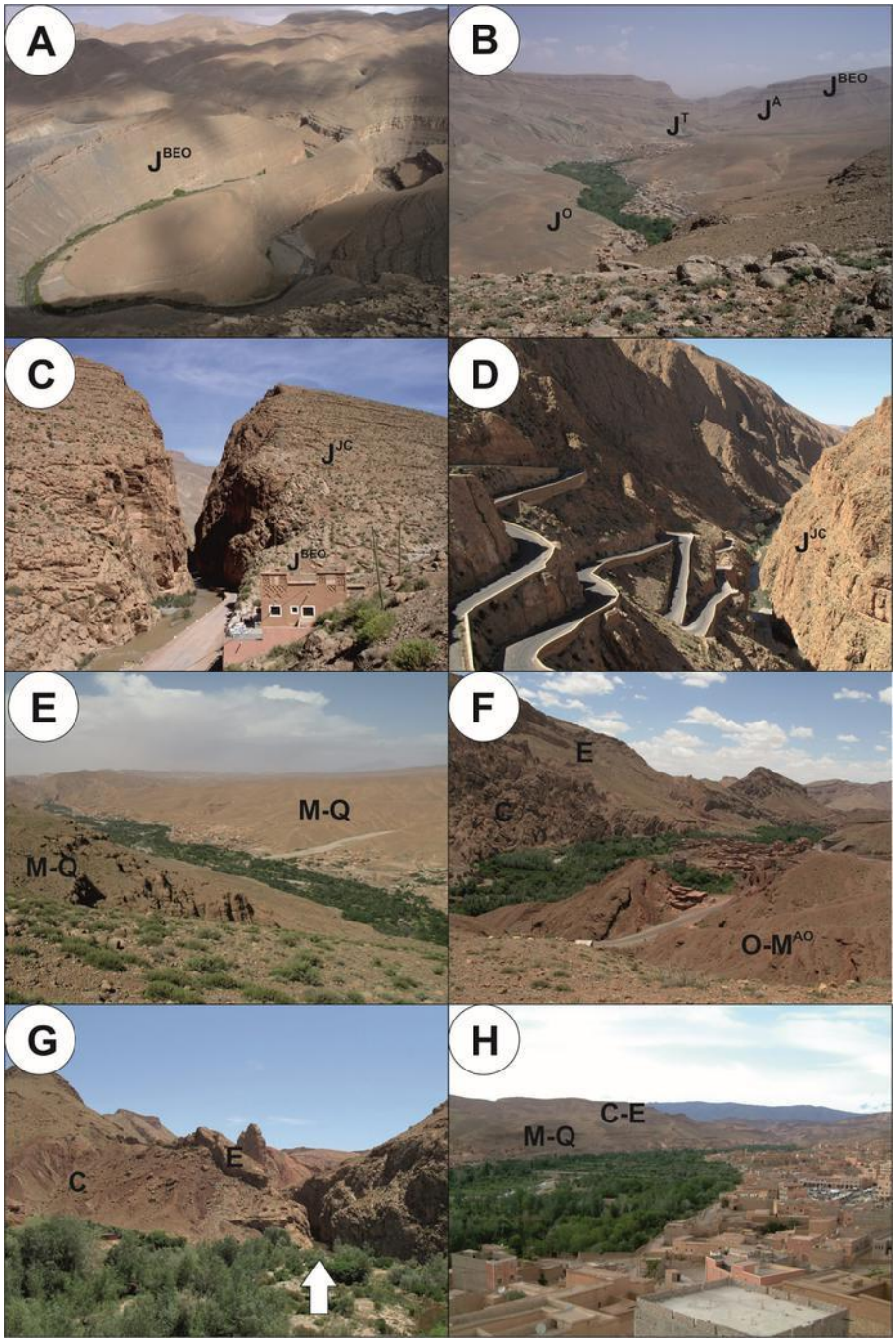

Fig. 4. Bedrock geology and geomorphology study area field imagery: A) High sinuosity bedrock canyon in strong Middle Jurassic bedrock, proximal FTB region. B) Open valley form developed in mixed-weak strength Lower Jurassic bedrock, mid FTB region. C) Tarhía n' Dadès Gorge and D) Main Dadès Gorge developed in strong Lower Jurassic bedrock, distal FTB region. E) Open valley form developed in mixed-weak strength Mio-Quaternary bedrock, WTB region. F) Open valley form developed in mixed-weak Mio-Quaternary bedrock, upstream TF region. G) Gorge (arrowed) changing to open valley form (foreground) developed in mixed-weak (Cretaceous) and mixed-strong (Eocene) bedrock, TF region. H) Open valley form developed in mixed-weak Mio-Quaternary bedrock, FB region. See Table 1 for stratigraphy, lithology and rock strength characteristics and notation.

Terraces were mapped using a Trimble Geo-XH GPS to record breaks and changes in slope associated with inner valley terrace mar-gins (i.e. closest to the modern river). Outer valley terrace margins were normally estimated/extrapolated using slope morphology differ-ences between the bedrock geology, the slope deposit and the ter-race. Terrace heights were surveyed using a Trupulse 360B laser range finder, recording the elevation of the lowest point of the terrace base above the modern river, in accordance with other strath terrace stud-ies in mountain belt settings (e.g. Stokes et al., 2012b). Terrace bases were unclear in areas of Plio-Quaternary basin fill (e.g. FB and WTB settings) due to similarities in sediment textures, fabric and structures. Here, terrace heights were based on survey estimates using differences in slope geomorphology (e.g. Mather et al., in press). The locations and elevations of the terraces, together with those of the modern river long profile were compiled into an Excel database (Supplementary Information) and represented as a scatterplot terrace height-range di-agram (Fig. 5). Using the database and the height-range diagram, a terrace stratigraphic framework was constructed. Normally, a ter-race stratigraphic framework is constructed using combinations of variables including: sedimentology, soils, terrace height, provenance, desert pavement etc. (e.g. Meikle et al., 2010; Stokes et al., 2012b). Here, the terrace stratigraphy was constructed using terrace base el-evation and assuming the simplest palaeo-profile fit, since all other variables showed insufficient contrast or are absent between levels. Terrace stratigraphic nomenclature uses a letter and numbering sys-tem with T1 the lowest and youngest level, with subsequent higher al-titude/older terraces levels corresponding to T2 and T3 etc. Terraces above T6 (50 m above modern channel) are rare fragmentary occur-rences that make correlation difficult. These levels are referred to us-ing height only but the terrace numbering system allows future studies to assign further levels (e.g. T7 etc.) if required.

Field mapping enabled type localities to be selected for detailed study, including sites with 1) well-preserved river terrace staircases in contrasting geological-geomorphological contexts, 2) clear and rep-resentative internal terrace stratigraphy and sedimentology, 3) suit-able material for OSL sampling and 4) evidence for tectonic deforma-tion. Sites with clear and representative internal terrace stratigraphy and sedimentology were described and logged using sediment facies analysis (Miall, 1978) to enable sedimentary process and environment interpretations.

3.2. Terrace dating

Terrace chronology was established using OSL/IRSL dating of quartz and feldspar, a technique routinely used for Quaternary river terrace studies (e.g. Martins et al., 2010). Sands suitable for OSL/IRSL dating were extremely rare and were restricted to the T2 terrace (~10 m above the modern river) located only in the upstream study area within mid and proximal parts of the FTB region. Three sites were sampled over a 10 km distance (Fig. 5; Supplementary Information) to ensure stratigraphic continuity and to test the tem-poral consistency of the T2 terrace age results. Sampling targeted fluvial sands that capped the coarse grained fluvial gravels (Fig. 9). These sands reflect overbank areas elevated adjacent to the active channel (Section 5). After logging the sections, sampling locations were prepared by removing weathered surface sediment under black out conditions. Steel tubes (~30 × 10 cm) were hammered into the sand units with tube ends sealed on removal, all under blackout conditions. Host sediment water content was visually estimated in the field. A bulk sand sample was obtained for laboratory dosimetry measurements.

The tube (180–250 μm sand fraction) and bulk samples were pre-pared for laboratory dosimetry measurement using standard chemi-cal cleaning preparation steps, followed by radionuclide concentra-tion measurement with final dose rate calculations using the conversions and calculations of Prescott and Hutton (1995) and Adamiec and Aïtken (1998) (Supplementary Information). A nominal water content of 5 ± 4% was used based on field

estimates and laboratory derived saturation moisture contents. Luminescence measurements were made using a Risø OSL reader (DA-20). Quartz luminescence followed the SAR protocol (Murray and Wintle, 2000) involving natural quartz purity dose checks (Duller, 2003) and preliminary preheat plateau tests (Supplementary Information). Feldspar luminescence followed the infrared stimulated luminescence (IRSL) approach (Buylaert et al., 2012), measuring normal and post IRSL signals at low and high tem-peratures (e.g. IR 50 and pIRIR 290). The SAR protocol (Thiel et al., 2011; Buylaert et al., 2012) was used for K-feldspar IRSL signal measurements and testing (Supplementary Information).

3.3. Terrace-rock strength relationships

The relationship between rock strength and terrace distribution was assessed using published geological maps and insitu field strength testing. Within the study area, the Mesozoic and Cenozoic bedrock comprises a range of different sedimentary lithologies that possess different strength properties related to lithology textures (granular vs crystalline), cementation and discontinuity (joints, frac tures, bedding, etc.) characteristics. Following Stokes and Mather (2015) two strength-lithology types were identified based upon (i) qualitative strength properties (above) and (ii) quantitative in situ mass strength measurements using a Schmidt hammer (Goudie, 2006):

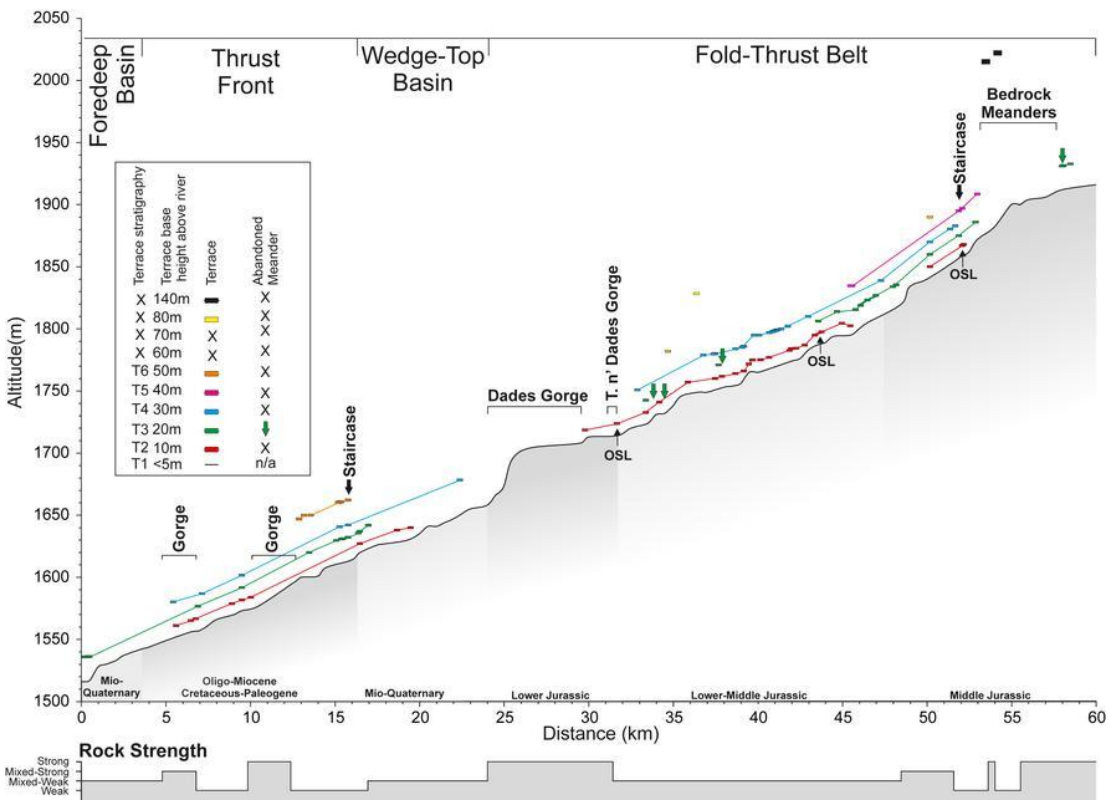

Fig. 5. River terrace, river gorge, bedrock and abandoned meander relationships to the orogenic system, bedrock stratigraphy and strength.

Type 1 — massive crystalline limestone or cemented clastic sedi-ments (conglomerates or sandstones) with Schmidt hammer values of 40–60. Rock surfaces display minimal discolouration. Rock weathers/ erodes into decimetre blocks, slabs or large clasts.

Type 2 — poorly cemented sandstone, siltstone, and mudstone with Schmidt hammer values of <30. Rock surfaces are discoloured, and rock mass possesses a well-developed fissile fabric conducive to granular weathering characterised by marked disintegration.

Stratigraphic units dominated by Type 1 or 2 lithologies were classified respectively as ‘Strong’ or ‘Weak’. Where a mixture of Type 1 and 2 lithologies occurred, then rock strength was classified as ‘Mixed-Strong’ or ‘Mixed-Weak’ depending on the Type 1 vs 2 dominance. Table 1 summarises the stratigraphy, lithology and rock strength relationships and downstream strength variability is plotted graphically alongside river terrace occurrences (Fig. 5).

4. River terrace distribution

Terraces were recorded at up to 140 m above the modern valley floor (Fig. 5). They are generally common features, often as laterally persistent levels along valley sides at up to 50 m (T6) (Figs. 5 and 6A,B), and then form infrequent fragmented levels and/or isolated oc-currences at ~80 m and ~140 m (Figs. 5 and 6C). The lowest T1 ter-race level is slightly incised (<3 m) by the modern Dadès River and occupies large areas of the valley floor, commonly used for subsis-tence agriculture (Figs. 5 and 6D). Above T1 there is a consistent vertical spacing of terraces up to 50 m at ~10 m intervals (T2 to T6) (Fig. 5). The stratigraphic relationship of the higher terrace lev-els above T6 (e.g. 50 m) is unclear and thus lacks correlation in this study. Google Earth and Excel databases of terrace locations, stratigraphy and bedrock geology-strength relationships are provided as Supplementary Information.

Table 1

Study area bedrock geology, stratigraphic configuration, distribution (Carte Géologique du Maroc, 1975, 1990; 1993) and rock strength characteristics (Section 3). FTB = Fold-Thrust Belt; WTB = Wedge-Top Basin; TF = Thrust Front, FB = Foredeep Basin. Valley length distribution superscript [a, b, c] = shared valley length of strike orientated valley exploiting contact between different stratigraphic units.

Time			Formation name	Lithologies	Orogen occurrence	Study area valley length distribution (km)	Rock strength
Cenozoic	Miocene-Quaternary (M-Q)		Aït Kandoula (AK)	Continental fluvial and fan conglomerate: cemented carbonate cobbles	WTB, FB	11.88	Mixed-Weak
	Oligo-Miocene (O-M)		Aït Ouglif (AO)	Continental fluvial conglomerate, sandstone and siltstone	TF	2.1[b]	Weak
	Eocene (E)		n/a	Continental and marine limestone and marl	TF	4.63[a]	Mixed-Strong
	Cretaceous (C)		n/a	Continental sandstone, shale and gypsum	TF	6.89[b]	Weak
Mesozoic	Jurassic Middle (J)	Bajocien	Bin El Ouidane (BEO)	Marginal marine platform oolitic limestone and marls	FTB	4.9	Mixed-Strong
		Aalenien	Azilal (A)	Continental and marginal marine silts, marls, sandstone and dolomite	FTB	3.5	Weak
	Lower	Toarcien	Tafraout (T)	Continental fluvial and marginal marine/coastal plain marl, silt and sandstone.	FTB	3.2	Mixed-Strong
		Pliensbachien	Jbel Choucht (JC)	Massive marine platform limestone.	FTB, TF	10.56[a]	Strong
		Pliensbachien	Ouchbis (O)	Interbedded deep marine rhythmic limestone and marl.	FTB	17	Mixed-Weak

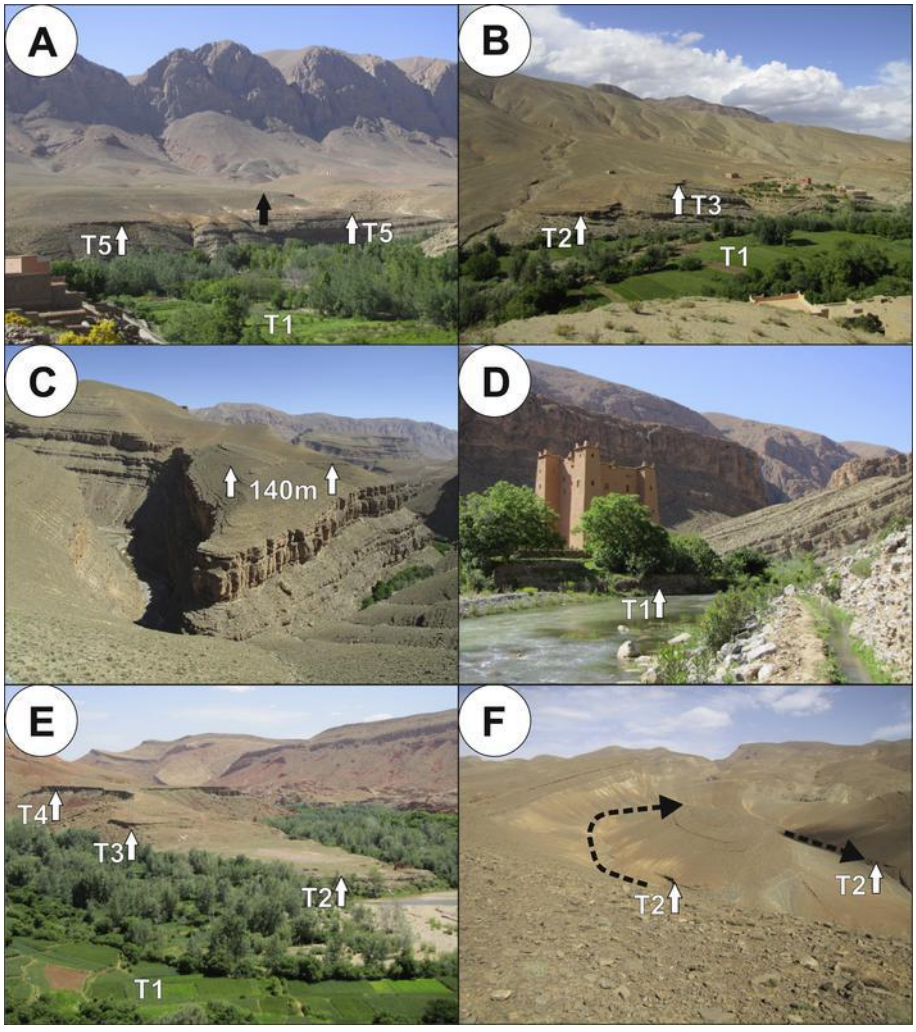

Fig. 6. River terrace field imagery: A) Laterally extensive T5 terrace levels (white arrows) buried by tributary fan slope sediments (black arrow), mid FTB region. B) T2-T3 terrace level remnants, inset by large relict tributary fan, mid FTB region. C) The highest documented terrace level remnants at 140m, proximal FTB region. D) T1 terrace level (arrow) ~2 m above modern river, immediately upstream of Tarhía n' Dadès gorge, distal FTB region. E) Well developed T1-T4 terrace staircase, downstream TF region. F) Abandoned bedrock meander containing T2 upstream-downstream terrace remnants buried by locally derived slope deposits, proximal FTB region.

Levels T1 to T4 form well preserved, extensive levels throughout much of the FTB region (Fig. 5) where they overlie steeply dipping to flat lying Lower Jurassic limestone-mudstones of the Ouchbis For-mation in a wide, open valley (Figs. 3B and 6A,B). In proximal, up-stream parts of the FTB there is a progressive increase in limestone as the bedrock geology changes to the Middle Jurassic (Figs. 2 and 4A). Here, terraces form one of the best developed staircases in the study area, comprising T1 to T5 that have developed on a bedrock spur as part of a pronounced valley meander (Figs. 5 and 7). Up-stream of this staircase decametre thick limestone units of the Mid-dle Jurassic Bin El Ouidane limestone dominate, with the valley form changing to a high sinuosity knick zone reach of bedrock meanders that lack terraces (Figs. 4A and 6C). Downstream, in the most distal part of the FTB region, terraces are absent from the Dadès and Tarhía n'Dadès Gorges, where vertical fluvial incision and limited valley

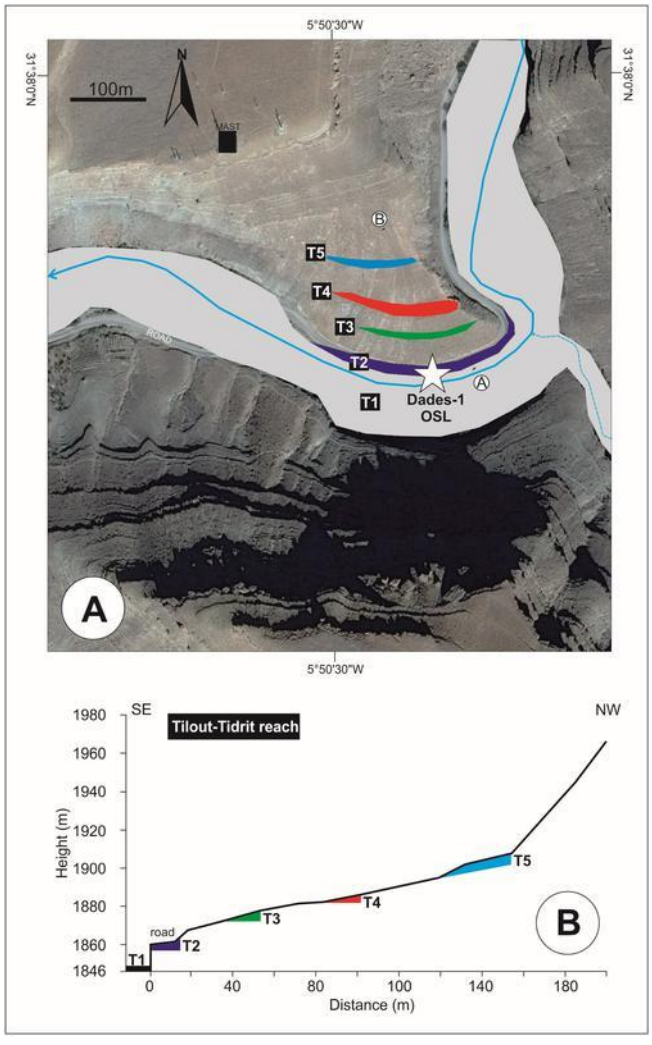

Fig. 7. Map (A) and topographic profile (B) of T1-T5 terrace staircase, upstream FTB region terrace staircase. See Fig. 8E and Supplementary Information for OSL sample information.

widening has occurred into strong Lower Jurassic Jbel Coucht lime-stone (Figs. 4C and D and 5). These gorges form marked lithologi-cal knick zones on the modern river profile (Fig. 5 and Boulton et al., 2014). Within the FTB region are four occurrences of km-scale aban-doned bedrock meanders (Fig. 5), associated with the T2 level located on the SE side of the river valley. T2 fluvial sediments occur at the up-stream entry and downstream exit points of the abandoned meanders (Fig. 6F). The meander cutoffs are infilled with slope colluvium but tributary stream incision through this fill often reveals the terrace and its basal Jurassic bedrock contact.

Within the WTB region terraces are unclear due to the lithological similarity with the Plio-Quaternary basin infill. Slope morphological changes suggest some fragmentary T2 terrace occurrences and an iso-lated T4 (Fig. 5).

Terraces become more common throughout the TF (Fig. 5). Up-stream areas show a well-developed staircase comprising T1 through T4 developed onto steeply dipping Neogene bedrock. Downstream is a more open valley, with a less well developed T1-T3 terrace stair-case developed onto steeply dipping Cretaceous bedrock (Fig. 6E). Mid and downstream TF areas comprise river gorge reaches cut into Jurassic and Palaeogene limestone lacking in river terraces (Fig. 4G).

Within the FB, terraces are again unclear due to the lithological similarities with the Plio-Quaternary basin infill. Slope morphological changes suggest fragmentary occurrences of T3. These terraces are in-set into a top basin fill surface (Fig. 3B).

The bedrock geology strength (Table 1) shows a relationship to valley morphology (Figs. 3B and 4) and terrace occurrence (Fig. 5). High strength bedrock (Table 1) lacks terraces, forming narrow val-leys with river gorge and canyon formation (Figs. 4A, C, D and 6C). Weak and Mixed-Weak bedrock are associated with wider valley forms and terrace occurrence, with well-developed T2-T4 levels along the lower valley sides but lacking higher-older levels. Mixed-Strong bedrock is often associated with the beginnings of narrower valley canyon development and the most well-developed terrace staircases (Figs. 5 and 7).

5. River terrace sedimentology and stratigraphy

River terraces are characterised by 1–3 m and rare 5–7 m thick conglomerate units (Figs. 8 and 9). The conglomerates are coarse grained and dominated by boulder-cobble size clasts of Mesozoic limestone that are set within a poor-moderately sorted matrix of lime-stone pebbles, gravel and sand (Fig. 8A and B). The largest clasts are well rounded and often display clear imbrication (Fig. 8A and B). The conglomerates are either massive or display weak horizontal stratifi-cation, with rare occurrences of metre scale low angle cross-stratifica-tion (Fig. 8A,B, C,D). Terrace basal contacts are sharp, revealing an angular unconformity with underlying tilted Mesozoic/Cenozoic sed-iments (Fig. 8A). The bases display an undulating topography, whose scale is determined by the dip and lithological variability of the un-derlying bedrock. Post-depositional carbonate cementation of clasts is common, especially at the terrace bases (Fig. 8A). Terraces are rarely capped by fine to coarse sand units up to ~2 m thick that are mas-sive, lacking sedimentary structures (Figs. 8E and 9). Sand grains are dominated by carbonate compositions but do contain some quartz and feldspar.

The terrace conglomerates are interpreted to have been deposited by high energy fluvial processes based upon their coarse grain size and down valley imbrication. Horizontal and low angle cross-strat-ification suggests deposition as gravel sheets and longitudinal bar forms (lithofacies Gm, Gp: Miall, 1978) within a braided river system (e.g. Hein and Walker, 1977). The lack of fines and soil development

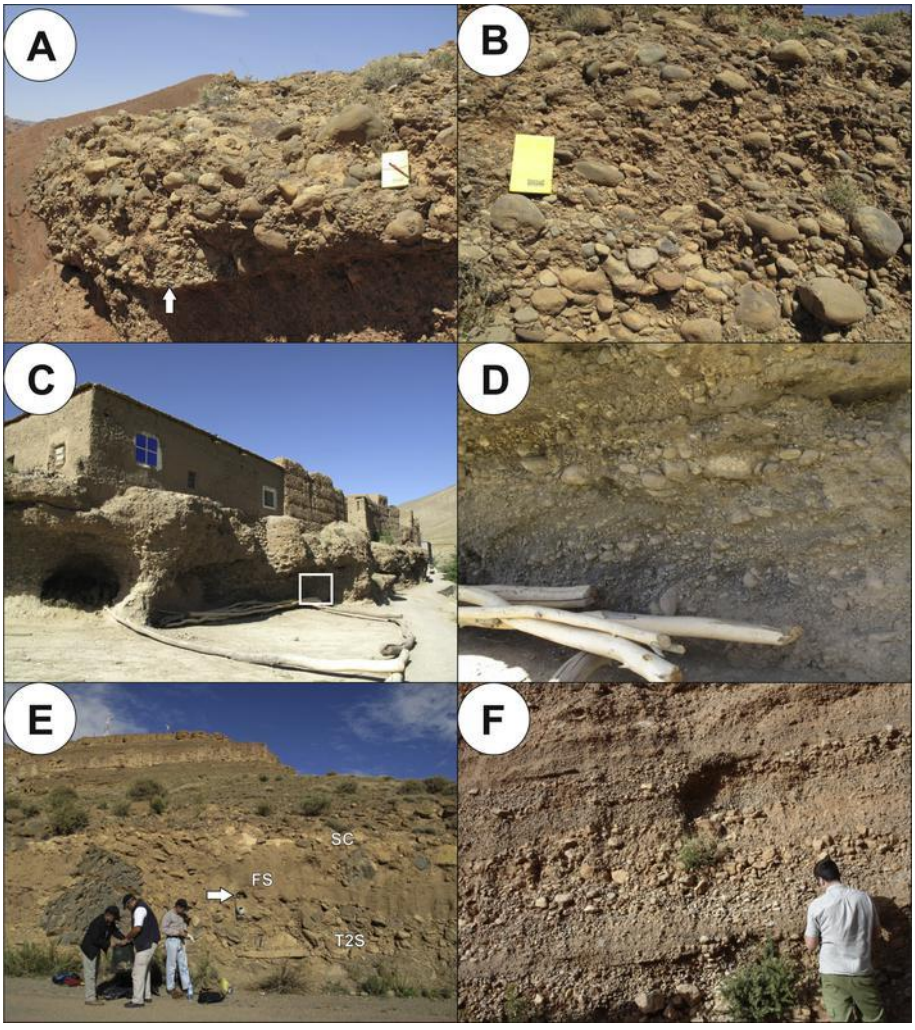

Fig. 8. River terrace sedimentology. A) T6 terrace in the upstream TF region illustrating the typical rounded and imbricated cobble conglomerate sedimentology, a carbonate ce-mented base (arrowed) and its sharp basal contact with underlying Neogene bedrock. B) T3 terrace in the upstream TF setting illustrated imbrication of rounded cobble clasts of Jurassic limestone. C) T2 terrace in mid FTB region showing thicker fluvial sediment accumulation and m-scale low angle cross bedding (white box = photo D). D) Detailed T2 sedimentology. E) Fine sands (FS) and slope colluvium (SC) capping the T2 terrace sediments (T2S), proximal FTB region. OSL sampling location arrowed (Section 6). F) Typical sedimentology of slope deposits that bury river terraces throughout the study area, noting poor sorting, soil development in fines and gentle dip towards valley. Example from down-stream T3 abandoned meander loop, mid FTB region (Fig. 5).

within the conglomerates suggests high sediment mobility and re-working, as part of a sustained period of valley floor aggradation. Thickness variations in terrace bodies can be accounted for by ei-ther local accommodation space variability or by valley morphologi-cal differences between the valley sides and palaeo-axis/thalweg. Con-glomerate carbonate cementation is typical of groundwater processes, with preferential cementation along terrace bases due to permeabil-ity differences between conglomerates and the bedrock (e.g. Nash and Smith, 2003). The overlying rare sands represent floodplain sedimen-tation or in overbank areas when flood waters overtop channel mar-gins with deposition in slack water areas (e.g. Benito et al., 2003). Sedimentary structures are common in floodplain and slack water de-posits (e.g. horizontal lamination or climbing ripples) but here their absence can be explained by insufficient grain size variability within the sediment laden flood waters. The quartz and feldspar content of the sands could be of aeolian Saharan dust origin but more simply is re-worked from Middle-Upper Jurassic continental sedimentary bedrock found upstream of the study area.

Terrace conglomerates and rare sands are commonly overlain by up to 5 m of coarse grained gravels (Figs. 8F and 9). These are poorly sorted and weakly stratified, with angular clasts whose composition reflects the local bedrock geology. The gravels mantle the valley sides in relict degraded patches and rarer continuous aprons with sediment building out over the river terraces, possessing a slope apron mor-phology. When observed in proximity to tributary junctions the grav-els have a fan-surface like morphology. Sediments are also associated with meander cut-offs, forming a slope infill of the abandoned val-leys (Fig. 6F). These texturally immature gravels are interpreted as lo-calised gravity driven slope deposits. At tributary junctions, the grav-els relate to debris flows as relicts of tributary junction fans, similar to those observed in the modern Dadès River (Stokes and Mather, 2015; Mather et al., in press). The terrace capping slope deposits are impor-tant for preserving the underlying fluvial sediments, acting as a valu-able stratigraphic marker to assess the relative timings of river activ-ity.

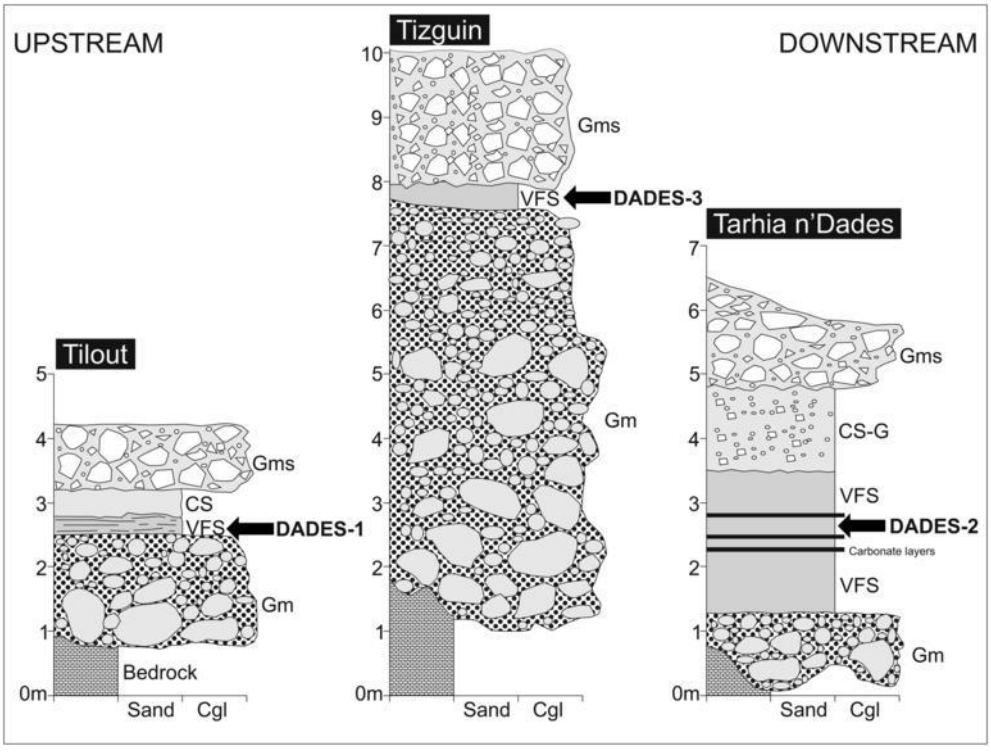

Fig. 9. Logs of terrace sections used for OSL dating. See Fig. 5 and Supplementary Information for locations. Cgl = cobble-boulder conglomerate/gravels; Gm = fluvial gravels; Gms = slope/tributary fan gravels; VFS = very fine sand; CS-G = coarse sand-gravel.

6. OSL/IRSL dating

Quartz and feldspar OSL/IRSL results are presented in Tables 2 and 3 with methods and a detailed technical discussion provided as Supplementary Information. The quartz age estimates (Dadès-1 = 69 ± 7 ka; Dadès 2 = 78 ± 4 ka; Dadès-3 = 76 ± 5 ka) show a mean age of 74 ka with a small 5 ka range (Table 2). De-spite the age consistency between locations, older timescale quartz OSL ages (e.g. >60–70 ka) are often considered to underestimate ab-solute ages (e.g. Buylaert et al., 2007) and are thus treated as minimum values. The feldspar age estimates (Dadès-1 = 104 ± 14 ka; Dadès 2 = 70 ± 6 ka; Dadès-3 = 102 ± 8 ka) reveal a mean age of 92 ka with a range of 9 ka (Table 3). However, these estimates show some degree of variability when compared to each other and their equivalent quartz OSL ages (see Supplementary Information for discussion).

7. Discussion

7.1. Geologic controls

Modelling studies suggest that bedrock benches beneath strath ter-races form when there is a change in ratio from vertical incision to

Table 2

Summary of equivalent dose values and calculated ages for quartz grains.

Sample	Natural De ± se (Gy)	Saturated[a] De ± se (Gy)	Dose Rate (Gy/ ka)	Age (Ka)
Dades-1	190 ± 17 (n = 17)	269 ± 29 (n = 16)	2.76 ± 0.1	69 ± 7
Dades-2	172 ± 5 (n = 27)	327 ± 21 (n = 19)	2.21 ± 0.1	78 ± 4
Dades-3	195 ± 6. (n = 28)	332 ± 18 (n = 20)	2.55 ± 0.1	76 ± 5

[a] Signal saturation equivalent at 2 × Do (Wintle and Murray, 2006).

lateral erosion (Hancock and Anderson, 2002). Within the study area, the potential for lateral bedrock erosion is greater in areas of weaker bedrock and restricted in stronger bedrock (Fig. 10). This is most no-table in middle parts of the FTB (Fig. 5), where mixed-weak strength interbedded limestone-mudstone of the Lower Jurassic Ouchbis For-mation (Fig. 4B) displays well-developed and laterally continuous T1, T2, T3 and T4 levels over some 20 km (Fig. 5). The structural config-uration of this bedrock into a syncline, and the routing of the Dadès River down the syncline axis (Fig. 2) enhance further the potential for lateral erosion. Bedrock on both valley margins dips towards the val-ley axis due to the fold limb arrangement (see ? on Fig. 3). This fa-cilitates valley margin erosion through slope undercutting and shal-low translational failures that exploit bedding plane dip and disconti-nuity configuration (Mather and Stokes, in press), a process reported in bedrock erosion field and modelling studies (e.g. Weissel and Seidl, 1997).

Fluvial bedrock erosion occurs through combinations of solution, plucking, cavitation and abrasion depending upon substrate lithology and discontinuities (Whipple et al., 2000). Within the study area, the dominance of Mesozoic carbonate substrate suggests some degree of solution (e.g. de Jong et al., 2008). However, field evidence from bedrock reaches (Stokes et al., 2008) and the basal contacts of ter-races (Section 5) suggest erosion is dominated by plucking/cavita-tion and abrasion. Terrace sediments are almost entirely composed of cobble size clasts of Lower-Middle Jurassic limestone (Section 5) with little

mudstone clast material. Similar grain size and compo-sition characteristics occur within the active thin alluvial covers in the modern Dadès River bedrock reaches. Limestone bedrock readily breaks down into decimetre blocks due to joint configuration (Stokes et al., 2008). The massive crystalline properties of the limestone pro-vide high rock strength, acting as an abrasion tool when transported as bedload over weaker mudstone bedrock. In terms of strath terrace formation, the bedrock bench corresponds to a period where bed-load and discharge are sufficient to abrade and widen the valley floor but sediment supply is insufficient to cause valley floor aggradation (Hancock and Anderson, 2002; Montgomery, 2004).

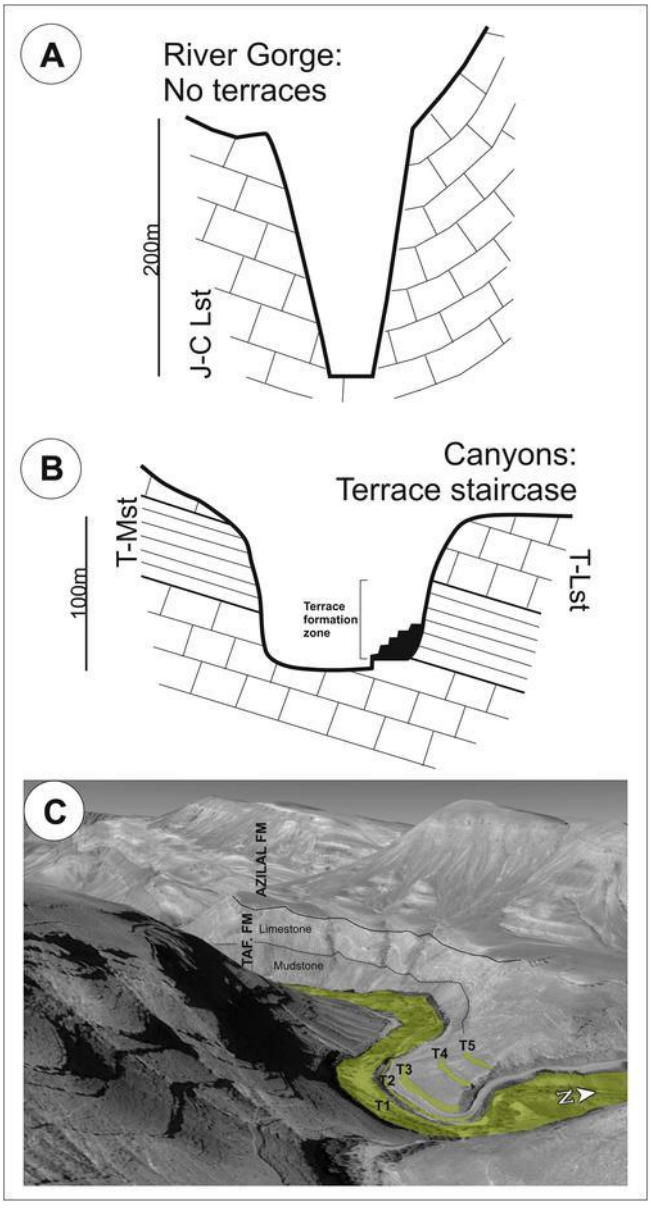

Fig. 10. A) River gorge reach of structurally thickened 'strong' limestone with no ter-race formation. B) Confined canyon reach where river terrace staircase development is controlled by the strength variability in a dipping stratigraphic sequence of Tafraoute Fm mudstone (T-MSt) and limestone (T-Lst). C) Oblique Google Earth image illustrat-ing rock strength, structure and stratigraphic sequence relationships to terrace staircase formation at the Tilout site (Fig. 7).

7.2. Climate controls

In this study, the typical terrace stratigraphic configuration, irre-spective of landform level, is a bedrock bench, overlain by coarse fluvial conglomerates with rare caps of overbank sands that are col-lectively buried by slope/tributary fan sediments (Fig. 11). This se-quence can be explained by climate-related behaviours of the river channel and its adjacent hillslopes (Fig. 11). The fluvial conglomer-ates correspond to the aggradation phase (Fig. 11), when there is el-evated coarse-grained sediment supply to the valley floor from the hillslopes, tributaries and upstream catchment areas due to effective slope-channel coupling (*sensu* Harvey, 2002) and sufficient discharge to mobilise coarse sediment (e.g. Bull, 1991). The overlying over bank sands can be explained in two ways: 1) as continued valley floor aggradation, but the final stages immediately prior to the onset of in-cision, where coarse-grained sediment supply is limited, or 2) in rela-tion to valley floor incision (Fig. 11) when the river channels have a reduced sediment supply, but where floodwaters can still overtop in-cised terrace surface (e.g. Wang et al., 2014). The latter is the simpler (and preferred) explanation being commonly observed in the modern Dadès River flood hydrology where flood waters overtop the valley floor T1 terrace depositing sand and silt. The terrace capping slope/fan deposits suggest valley floor incision (Fig. 11) with hillslope mater-ial burying the valley side terrace remnants but with insufficient river flood discharge to activate meaningful valley floor aggradation, a de-coupling of the channel and hillslopes (Mather et al., in press). The bedrock bench is cut early in the transition between the incision and aggradation phases (Fig. 11), a threshold period when flood regime and sediment supply is increasing to a sufficient level for bedload transport (tools) to cause lateral erosion into valley sides (Hancock and Anderson, 2002; Montgomery, 2004).

Terrace staircases record longer term patterns of fluvial down-cutting, with multiple ratio changes from vertical incision to lateral erosion. Studies routinely attribute terrace staircase formation to sus-tained base-level lowering driven by combinations of tectonic and/ or climatic changes (e.g. Starkel, 2003; Bridgland and Westaway, 2008a,b). Within the study area, terrace staircases comprising >4 lev-els occur in localised parts of the FTB and TF settings (Fig. 5). These staircases occupy locations of pronounced deviation in river valley di-rection, developing on valley margin spurs where the river has pro

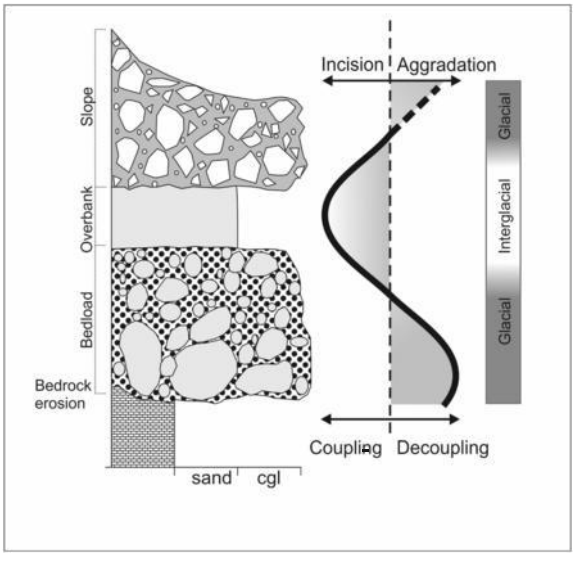

Fig. 11. A conceptual river terrace-climate model for the Dadès River illustrating the relationship between glacial-interglacial climates, valley floor incision-aggradation pat-terns and river channel-hillside coupling status.

OSL/IRSL dating of the T2 overbank sands, although limited in number, provides some insight into terrace incision timing (Fig. 11). Whilst quartz OSL ages were considered as minimum ages only (Table 2; Supplementary Information), the corrected feldspar ages (Table 3) of 104 ± 17 ka (upstream), 70 ± 6 ka (downstream) and 102 ± 8 ka (mid-reach) were considered more representative. These ages, including error bars, span the Marine Isotope Stage (MIS) 5 in-terglacial and MIS 4 glacial climate periods. River terrace research (e.g. Vandenberghe, 2015 and references therein) states that incision normally takes place during the climate transitions. This study agrees, with T2 incision most likely to have taken place during the MIS 6/ 5 cold-warm transition. By stratigraphic bracketing, this means that aggradation of the T2 fluvial gravels probably took place during the MIS 6 glacial and that slope colluvium was deposited over the T2 gravels and rare overbank sands during the MIS 4-2 glacial. The T2 stratigraphic configuration and timing has some affinities to sequences described by Weisrock et al. (2006) and Mercier et al. (2009) from the coastal region of the Anti-Atlas Mountains (Fig. 1). Using OSL, U-Series and radiocarbon dating, they proposed a major pre-MIS 5 fluvial incision and basal fluvial gravel aggradation phase, followed by MIS 5-3 fluvial-slope travertine-silt-sand aggradation and capped by a MIS 2 aeolian-slope silt deposit. Furthermore, studies of west-ern Mediterranean dated terrace records (e.g. Macklin et al., 2002; Santisteban and Schulte, 2007) suggest a complex pattern of fluvial aggradation and incision phases during the Middle-Late Pleistocene. Of note are reports of regionally synchronous MIS 6 aggradation and MIS 5 incision phases in southern Spain and NE Libya (Macklin et al., 2002). Thus, it seems that on the south side the High Atlas along the NW Saharan margin, the MIS 6 fluvial aggradation and onset of inci-sion at the MIS 6/5 transition have some degree of harmony with the Western Mediterranean region, acknowledging the restricted dataset in terms of sites and age control. Dated fluvial sequences are starting to emerge from northern Morocco in relation to early human occupa-tion research, describing fluvial aggradation in MIS 6/5e (e.g. Bartz et al., 2015). However, these are localised site specific archaeologically focussed studies where the fluvial geomorphological context is insuf-ficient to make meaningful comparisons to river terrace records.

If a similar climate relationship is considered for T1 that currently occupies large parts of the wider valley floor settings, this means that the coarse grained fluvial sediment corresponds to the Late Pleis-tocene glacial (MIS 2), whilst the onset and ongoing (small) incision phase is Late-Pleistocene-Holocene (MIS 2/1). Sands cap the T1 ter-race fluvial gravels and these are similar to the rare occurrences of the OSL/IRSL dated T2 sands. Interestingly, slope colluvium is not yet building out over the T1 terrace, with terrace top sedimenta-tion limited to localised tributary junction fan occurrences (Stokes and Mather, 2015). Much of the valley sides are bedrock, with only patches of colluvial veneer remaining. This suggests hillslope sedi-ment is almost exhausted and decoupled from the river channel (Fig. 11) with another phase of cold-climate (peri)glacial weathering re-quired to regenerate sufficient hillslope material to start to bury the T1 terrace (Mather et al., in press). Although glacial periods are dom-inated by aridity in NW Africa as illustrated by Saharan dune activ-ity (Fig. 1; e.g. Lancaster et al., 2002), high altitude lake records (e.g. Lake Isli [Fig. 1.], ~50 km north of the Dadès: Lamb et al., 1994; Valero-Garcés et al., 1998) show complex and detailed patterns of cold climate aridity-humidity variability which helps clarify the tim-ing of the T1 terrace formation. The lake record shows a marked change from elevated aridity, low lake levels (>35–28 ka) and ero-sion (28–20 ka) during the Full Glacial, changing to sustained humid-ity and high lake levels (20–11 ka) during the late Glacial Transi-tion (Valero-Garcés et al., 1998). Lake Isli is positioned on the Dadès River drainage divide and thus the downstream valley effects are prob-ably slope colluvium activity supplying excess sediment to the valley floor resulting in aggradation during the cold-arid Full Glacial (pre-20 ka), followed by slope erosion and valley floor incision during the late Glacial Transition period (post-20 ka) when the climate amelio-rates becoming more humid (e.g. Gibbard and Lewin, 2002). Further-more, although the Dadès catchment was not glaciated, the develop-ment of small ice fields and valley glacier advance in the Toubkal re-gion (Fig. 1) at ~76, 24 and 12 ka (Hughes et al., 2011) further il-lustrates the cold climate conditioning of the High Atlas landscape. In the Dadès catchment, periglacial activity would have been impor-tant for slope weathering and sediment supply to the valley floor but clear periglacial evidence are lacking from the terrace sediments (e.g. cryoturbations etc). The 24 ka Toubkal advance

approximates to the proposed T1 aggradation period, but the relationship of the 76 ka and 12 ka events to the terrace record remains unclear.

If the main periods of valley floor fluvial aggradation took place in the glacial periods (i.e. MIS 2 and 6) and major incision during warming transitions (i.e. 6/5 and 2/1), this suggests that fluvial land-scape dynamics in the south-central High Atlas are tuned to 100 ka Milankovitch cycles, showing affinity to other terrace-climate stud-ies from around the world (e.g. Bridgland and Westaway, 2008a; Vandenberghe, 2015). If this Milankovitch relationship is developed further, and that each of the well-developed, laterally continuous ter-race level (T1-T4) relates to a full climate cycle, it means that the Dadès River records some 400 ka of fluvial-landscape dynamics span-ning the Middle-Late Pleistocene (Fig. 12). It also suggests that rare terraces higher than T6, i.e. >50 m above the modern river, are Early Pleistocene in nature (Fig. 12) and they offer a significant potential for linking orogenic basin sedimentary records (e.g. WTB, FB) to incision of the FTB region.

High Atlas drainages, including the Dadès River, are routed down-stream into the Ouarzazate Basin. Here, remnants of large alluvial fans are recorded in west-central basin areas, with studies document-ing up to 5 inset fan surfaces (Stäblein, 1988; Littmann and Schmidt, 1989; Sébrier et al., 2006). This number of surface levels has some broad stratigraphic agreement with the upstream Dadès River ter-races (e.g. T1–T5). Furthermore, there is some degree of temporal agreement from cosmogenic exposure dating of the fan surfaces by Arboleya et al. (2008). They suggest that fan surface abandonment and incision is climatically controlled, occurring broadly over a se-ries of 100 ka cycles during the Holocene (MIS 1) and Mid dle-Late Pleistocene (MIS 5, 7, 9). Delcaillau et al. (2016) have de-scribed fan-terrace sequences from the Ourika valley on the north (Marrakech) side of the High Atlas. They consider climate as a key control on the incision and aggradation patterns but their study lacks age control, and thus clear climate relationships are lacking. -

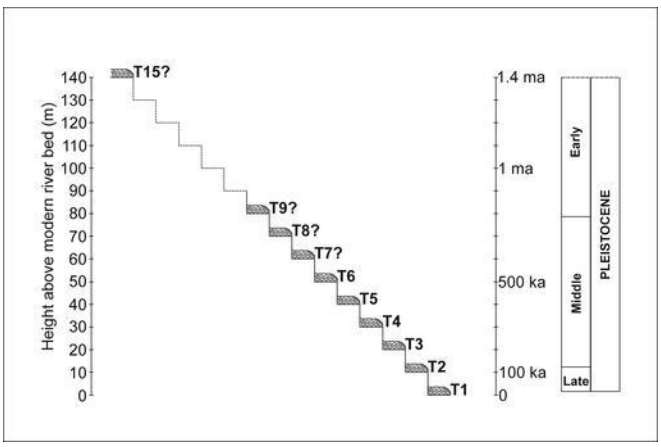

Fig. 12. Pleistocene temporal pattern of the Dadès River terrace sequence.

This broad pattern of 100 ka cycles is illustrated in regional scale Quaternary climate modelling studies for NW Africa, where marked spatial and temporal patterns of changes in precipitation are recorded (Tjallingii et al., 2008). For the Sahara, aridity dominates but pre-cipitation becomes elevated during the climate transitions: 1) inter-glacial-glacial (e.g. MIS 5-4) and 2) glacial-interglacial (MIS 2-1) (Tjallingii et al., 2008), coinciding with the proposed periods of inci-sion in the Dadès River.

7.3. Base-level lowering controls

Whilst climate ultimately controls variations in sediment-water supply leading to changes in valley floor aggradation and incision (Bull, 1991), sustained base-level lowering is required to form an in-set sequence of river terrace levels (Vandenberghe and Maddy, 2001; Bridgland and Westaway, 2008a). If the rate of base-level lowering is small then complex fill terraces develop (Lewin and Gibbard, 2010), contrasting with

high rates of base-level fall which leads to strath ter-race and staircase formation (Starkel, 2003). Base-level lowering can be controlled by combinations of climate, river capture and tectonics.

Climate-related base-level lowering is normally attributed to eu-stacy, typically affecting downstream, coastal regions of river systems where falling sea level causes incision, whereas rising sea level causes aggradation (e.g. Stokes et al., 2012a and references therein). The con-tinental situation of the Dadès River (~900 km from modern sea level) means that eustatic base-level lowering affects are negligible.

River capture involves drainage rerouting and catchment area ex-pansion and loss respectively of the capturing and captured system (e.g. Stokes et al., 2002). The enlarged capturing system is at a lower base-level and once capture occurs, the base-level difference is trans-mitted upstream through the captured catchment (Mather et al., 2002). The Ouarzazate Basin has been captured by the Draa River in the Quaternary, whereby the internally drained Ouarzazate Basin was captured and re-routed southwards across the Anti-Atlas through the Draa Gorge (Stäblein, 1988; Arboleya et al., 2008). Capture-related impacts upon the drainage network are unclear due data collection absence. However, capture-related incision should account for some fluvial erosion in lower drainage system parts of the Ouarzazate Basin. Whether capture-related incision has transmitted upstream across the SAF and upstream into the High Atlas FTB region is un-clear but unlikely (Boulton et al., 2014).

Tectonic uplift is a commonly cited mechanism for long term base-level lowering in river terrace studies (e.g. Lavé and Avouac, 2001; Cunha et al., 2008), with fill terraces forming under low up-lift rate conditions and strath terraces forming under intermediate and higher uplift rate scenarios (Starkel, 2003).

The High Atlas topography has been generated during the Ceno-zoic linked to ongoing Africa-Europe collision. Despite debate, re-lief appears to have been generated during the Eocene-Oligocene and Plio-Quaternary (Frizon de Lamotte et al., 2000), through combined mechanical shortening (folding/thrusting) and mantle-related isostatic processes (e.g. Teixell et al., 2003; Missenard et al., 2006). The Dadès terrace record corresponds to the Plio-Quaternary uplift stage, record-ing the most recent phase of longer term drainage evolution. The up-lift has generated a regional NNW-SSE topographic gradient but the Dadès River is routed obliquely SW across this gradient exploiting the axes of km-scale fold structures within the Jurassic bedrock of the FTB region (Figs. 2 and 4). Fig. 5 reveals a marked parallel config-uration of the T1 to T4 terrace levels as they pass through all tec-tonic components of the High Atlas orogen. This includes the TF re-gion where elevated rates of active tectonic uplift could be expected. Field mapping and cross-section compilation by Tesón and Teixell (2008) demonstrates extensive folding and faulting in the TF region but this is restricted to Jurassic to Plio-Quaternary bedrock. Our ter-race mapping did reveal minor m-scale thrust faulting of terrace sed-iments but this was exceptionally rare, affecting the T3 level (Fig. 13). Faulting exploited bedding planes of tilted Neogene bedrock, with propagation up into the terrace sediments towards the NW (Fig. 13). Fault planes were low angle (~30°), with small (<2 m) verti-cal and horizontal offsets (Fig. 13). This lack of terrace deforma-tion, even in TF areas where it would be expected, suggests that the High Atlas in the Dadès River region was characterised by low rate tectonic activity, at least from the Middle-Late Pleistocene onwards. This is further supported by low modern seismic activity, where earth-quakes, concentrated along the SAF region, are infrequent and low magnitude (magnitude <4.9) (Medina and Cherkaoui, 1991). How-ever, there is uncertainty as to how deformation at the surface relates to the deformation at depth which generates earthquakes (Sébrier et al., 2006). Quaternary fan surfaces south of the SAF in the Ouarza-zate Basin do display a greater degree of surface faulting and fold-ing (Sébrier et al., 2006; Arboleya et al., 2008) but these are spa tially variable along different fault segments of the SAF mountain front. However, this surface deformation requires improved age con-trol to confirm deformation timing and its relationship to basin and mountain front incision.

River terraces with age control can be used to quantify fluvial incision rates which in turn can be developed further to inform on spatial and temporal patterns of uplift (e.g. Lavé and Avouc, 2001). In this study, the OSL dated fluvial overbank sands of the T2 ter-race provide some opportunity for quantifying incision. The Dadès-1 (104 ± 17 ka) and Dadès-3 (102 ± 8ka) samples were taken from sands immediately overlying coarse fluvial gravels at heights of 12.5 m and 17.75 m above the modern river level (Fig. 10), producing respective incision rate estimates and error ranges of 0.12 (0.10–0.14) mm a^{-1} to 0.17 (0.16–0.19) mm a^{-1}.

Higher rates of 0.3–1.0 mm a^{-1} were re-ported by Arboleya et al. (2008) from incised Quaternary fans in the Ouarzazate Basin, possibly reflecting 1) proximity to the Dadès-Draa capture site, 2) positioning along a more active SAF thrust segment or 3) rock strength differences between different components of the orogen.

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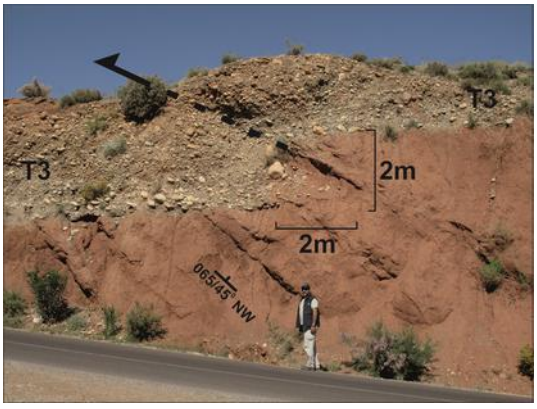

Fig. 13. T3 terrace deformation in the Thrust Front region (31°26′58.92N 5°58′12.63W), illustrating thrust faulting (dip = 30°; apparent strike = 065) of fluvial terrace gravels. Faulting is exploiting bedding plane dip of tilted Neogene bedrock (45/ 065 NW).

Compared to other studies that report incision rate from river ter-races in a collisional mountain tectonic context (e.g. Lavé and Avouac, 2001; Cunha et al., 2008) the rates reported here are low, suggesting the south-central High Atlas has evolved under low rock uplift rate conditions since the Late Pleistocene. Furthermore, the systematic alti-tudinal spacing of the T1-T4 terraces throughout the 60-km-long study area suggests that similarly low incision rates (<0.2 mm a^{-1}) have been maintained throughout the Quaternary, at least from the Middle Pleis-tocene onwards. The consistency in spatial and temporal distribution of the river terraces implies that the Dadès River is responding to some kind of regional tectonically driven, low rate base-level lowering process. Rather than fault/fold related mechanical uplift, the base-level lowering could be linked to isostatic uplift related to mantle upwelling under the High Atlas that has been widely associated with longer term geophysical-seismic studies of High Atlas topographic development (e.g. Missenard et al., 2006) and from regional quantitative tectonic geomorphological studies of drainage networks along the north and south of the central High Atlas (Delcaillau et al., 2010; Boulton et al., 2014).

8. Conclusions

1. Collectively, this study highlights the significant opportunity that river terrace sequences hold for providing insights into Quaternary flu-vial landscape development in NW Africa along the Saharan Desert margins. The study shows:

2. river terraces are widespread, yet little studied landforms through-out the High Atlas and the broader NW African desert mountain landscapes, a notable research gap of significant relevance for the geological, geomorphological and Quaternary science communi-ties;

3. terrace formation in the High Atlas, and more generally within col-lisional mountain belts, can be strongly influenced by rock strength and its relationship to the structural and stratigraphic configuration of the orogen;

4. dating of river terraces within dryland mountain landscapes in NW Africa is possible despite the rareness of fluvial sands with appro-priate mineral compositions suitable for dating longer time series (e.g. OSL);

5. with some age control, terrace formation can be linked to cli-mate-related incision and aggradational behaviour of the river channel and valley side slopes, operating over 100 ka climate cy-cles. For a given cycle, incision occurs during the cold-warm tran-sitions and aggradation during the full glacial. This is a pattern recorded elsewhere along the NW Saharan margin in the area south of the High Atlas, and appears synchronous with western/southern Mediterranean fluvial archives;

6. the terrace sequence suggests that fluvial landscape development spans the Late-Middle Pleistocene and possibly into the Early Pleistocene. This provides a significant future opportunity for a) understanding the Cenozoic development of the High Atlas Moun-tain topography through linkage and integration of geological and geomorphological records; and b) understanding spatial and tem-poral patterns of low latitude Quaternary climate change through integration with other limited regional climate archives (e.g. glaci-ers, lakes, dunes etc.) from the NW Saharan margin;

7. the spatial and temporal uniformity of terrace occurrence suggests a very low regional incision rate across all components of the High Atlas orogen (i.e. FTB, WTB, TF and FB);

8. the low regional incision rate coupled with a general absence of ter-race tectonic deformation suggests that base level lowering is prob-ably driven by mantle-related rock uplift rather than

mechanical fold and thrust related crustal shortening. This further implies that High Atlas relief generation is an Early Pleistocene or older phe-nomenon.

Table 3

Summary of equivalent dose values and calculated ages for K-feldspar grains.

Sample	De (Gy) IR50 ± se	De (Gy) pIRIR290* ± se	Ratio IR50: pIRIR290	Dose Rate ± se (Gy/ka)	Corrected* Age (Ka) pIRIR290	Uncorrected Age (Ka) pIRIR290
Dades-1	139 ± 24 (n = 8)	371 ± 58 (n = 5)	1: 1.4	3.6 ± 0.1	104 ± 17	109 ± 16
Dades-2	114 ± 8 (n = 9)	212 ± 10 (n = 9)	1: 1.9	3.0 ± 0.1	70 ± 6	77 ± 5
Dades-3	155 ± 24 (n = 16)	343 ± 28 (n = 16)	1: 1.7	3.4 ± 0.1	102 ± 8	108 ± 7

*Corrected for residual dose significant at 24Gy. No ages are presented for IR50. See supplementary Information for discussion.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2017.04.017.

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