2016-10-21

River terraces and alluvial fans: The case for an integrated Quaternary fluvial archive

Mather, Anne

http://hdl.handle.net/10026.1/6673

10.1016/j.quascirev.2016.09.022
Quaternary Science Reviews
Elsevier BV

This is an accepted manuscript of an article published by Elsevier in Quaternary Science Reviews available at: http://dx.doi.org/10.1016/j.quascirev.2016.09.022

River terraces and alluvial fans: the case for an integrated Quaternary fluvial archive

[1]Mather, A.E., [1]Stokes, M., [2]Whitfield, E.

[1]School of Geography, Earth and Environmental Sciences, Plymouth University, Drake Circus, Plymouth, PL4 8AA, UK

[2]School of Natural Sciences and Psychology, Liverpool John Moores University, Byrom Street, Liverpool L3 3AF, UK

Abstract

The fluvial archive literature is dominated by research on river terraces with appropriate mention of adjacent environments such as lakes. Despite modern sedimentary basins comprising a significant (>88%) volume of distributive fluvial systems, of which alluvial fans (>1km, <30km in scale) are a significant part, interaction with these environments tends to be neglected and discussed in separate literature. This paper examines the dynamic role of alluvial fans within the fluvial landscape and their interaction with river systems, highlighting the potential value of alluvial fans to the wider fluvial archive community. Published literature is used to examine both thematic and geographical based benefits of alluvial fan research that can assist understanding of Quaternary fluvial archives. 3 regional case studies are presented that illustrate the interaction between alluvial fan and river terrace archives at Quaternary time-scales at 3 different stages of landscape evolution. These are i) continuous mountain front alluvial fans interacting with a non incising but laterally eroding axial fluvial system; ii) alluvial fans which transition into fluvial terraces as sedimentary basins shift from net aggradation to net incision and iii) tributary-junction alluvial fans that develop predominantly within incising river valley systems. A simple conceptual model is proposed to summarise the dynamic role of alluvial fans within this landscape context. The alluvial fans act as potential 'buffers' between hillslopes and river terrace records under 'top down' climate-driven high sediment supply and alluvial fan aggradation, and 'couplers' during periods of less sediment (in relation to water) discharge and alluvial fan incision. These dynamics will change with the addition of 'bottom up' controls such as main river incision, which will typically enhance the coupling effect of both systems.

1. Introduction

Research on fluvial archives within the Quaternary is dominated towards river terrace sequences (e.g. Stokes et al., 2012a and references therein), with key reviews of the Quaternary fluvial literature notable for their absence of alluvial fan inclusion (e.g. Bridgland et al., 2004; Thorndycraft et al., 2008; Bridgland and Westaway 2014; Piégay et al., 2015). Yet modern fluvial landscapes can contain significant (>88%) distributive fluvial systems (which include alluvial fans, Weissmann et al., 2015). This literature bias in part reflects 1) the focus within the fluvial literature on fill terraces (*sensu* Leopold et al.,1964) from lowland systems (where alluvial fans can occur, but are less likely to interact with the river terrace record), rather than the strath terraces (*sensu* Leopold et al., 1964) more common in upland catchments, and 2) the fact that most river terrace studies are more concerned with the burial affects of alluvial fans, hampering the identification of terrace tops (e.g. Stokes et al., 2012a) rather than utilising the archive within the landscape interpretation. Where alluvial fans occur within the landscape, they are usually treated as separate systems in separate literature (e.g. Rachocki and Church, 1990; Harvey et al., 2005; Ventra and Clarke in press). However, it is becoming increasingly clear that a ‘source to sink’ approach to fluvial systems (e.g. Busschers et al., 2007; Garzanto et al., 2015), and a ‘whole catchment’ tactic is essential if we are to better model landscape change and understand our fluvial systems more fully (e.g. Macklin and Lewin, 2008).

Distributive fluvial systems occur at a variety of spatial and temporal scales (Fig. 1) that include alluvial, colluvial or debris fan elements within the fluvial landscape (e.g. Harvey and Renwick, 1987; Harvey, 1996; 1997; Stokes and Mather, 2015; Weissmann et al., 2015; Wheaton et al., 2015). Within this paper we focus on >1km to <30km long distributive alluvial fan systems most commonly associated with Quaternary river terrace records in basin and mountain valley settings. Alluvial fans in a fluvial landscape add to the ‘whole catchment’ approach which enables us to better understand the river sequence record by providing an enhanced understanding of the nature of water and sediment delivery to our fluvial system of interest (e.g. Florshiem et al., 2004; Gómez-Villar et al., 2006; Wang et al., 2008; Stokes and Mather, 2015). Alluvial fans have similarities with associated river systems in terms of aggradation and incision patterns, stratigraphy and even morphology (e.g. Larson et al., 2015). Modelling studies have highlighted that tributary and hillslope inputs are significant to erosion and deposition patterns along the longitudinal profile of the main river and its associated river terrace accumulations (e.g. Merritts et al., 1994; Geach et al., 2015; Veldkamp et al., in review). Thus, field studies of tributary alluvial fans can better inform landscape evolution models that look at long-term (Quaternary) changes within fluvial systems. Alluvial fans warrant a higher profile within the fluvial archive community and integrated studies of alluvial fans with river terraces should be considered as a more standard approach when investigating fluvial landscape development. Alluvial fans inform on what is happening on adjacent slopes and the degree of coupling between adjacent hillslopes and river systems, and tributary and river channel reaches within fluvial systems. The former may be particularly significant where we are dealing with an exogenic river whose flow regime is largely dictated by a climate regime external to the point of terrace formation (e.g. a main river fed by glacial melt water) that is not reflective of the area in which the river terraces are deposited (which may be an arid, ephemeral flow environment). The degree of interconnectivity between the alluvial fan and river terrace record informs on a range of factors from slope sediment supply to tectonic activity (e.g. Mack and Leeder, 2001; Harvey, 2012). Here, we use the published literature to examine the relevance of alluvial fan deposits to river terrace records over a range of spatial and temporal scales in landscape evolution. It is beyond the scope of this paper to provide a review of the extensive alluvial fan literature, and this is done elsewhere (e.g. Harvey et al., 2005 and specialist volumes *op.cit*.). In this paper we focus on those studies examining integrated alluvial fan and fluvial system approaches to Quaternary archives to illustrate how this approach can contribute to our understanding of long term landscape evolution. Such studies are few. In order to achieve wider appeal we have utilised the best studied regional examples from contrasting settings (USA, SE Spain, Morocco) and supplemented these with new data from the lesser studied elements of these regions (SE Spain; Río Alías and Morocco; River Dades). We consider the role of alluvial fans in catchment sediment storage and the aggradational and incisional archive they contain. We have summarised the observations from these studies, and the wider published literature included within this article, to provide a new conceptual model of the dynamic interplay between alluvial fans and adjacent river systems under changing sediment supply, climate and river incision conditions.

2. Spatial and temporal considerations

In relation to river terraces, deposition adjacent to the river terrace setting may occur on a variety of spatial (and temporal) scales (e.g. Harvey, 2010; Weissmann et al., 2015 and Fig. 1). These may be 1) individual debris flows lobes from the adjoining slopes (up to 10m, e.g. Harvey, 2002); 2) tributary junction debris cones (10^1 to 10^2 m) from adjacent gully systems (e.g. Harvey, 2002); 3) tributary junction fluvial fans (10^1 to 10^3 m across) that develop where there is a suitable slope break and accommodation space for a tributary alluvial fan to develop from a larger catchment (e.g. Hereford et al., 1996; Stokes and Mather, 2015) and 4) alluvial fans ($>10^3$ m across) which occur along mountain fronts (e.g. Leeder and Mack, 2001) and at tributary junctions (e.g. Al-Farraj and Harvey, 2005). The preservation potential for the smaller scale features ($<10^3$ m) within Quaternary river terrace records is limited due to main river reworking within the terrace record, unless they occur post abandonment of the terrace level. We thus focus here on those features most likely to be preserved within a Quaternary landscape over a catchment scale – the 'classic' alluvial fans in mountain front and tributary junction locations (Harvey, 2010).

3. Thematic contributions of alluvial fans research to Quaternary fluvial archive studies

Alluvial fans are persistent features within the Quaternary landscape across a range of climatic settings where there is juxtaposition of high sediment yield from the adjacent slope and accommodation for the material at a significant slope-break (e.g. mountain front in rift basins; margins of wide glacial valley areas). As the Quaternary alluvial fan literature is mainly located separately to Quaternary fluvial archive literature, here we will briefly highlight some thematic research approaches within the alluvial fans literature and illustrate how these studies have contributed to our understanding of fluvial archives. This is not meant as an in depth review, more as opportunity to highlight the value of these approaches to Quaternary fluvial studies.

Morphometric studies

Traditionally 'classic' alluvial fans have formed the focus of numerous studies on alluvial fan morphology in relation to catchment characteristics (e.g. Bull, 1977; Harvey, 1984a; 1997). These morphometric studies have identified the 2 most consistent relationships as

$$\text{Alluvial fan gradient} = aA^{-b}$$

$$\text{Alluvial fan area} = pA^{q}$$

where A is catchment area (km^2). The value of the exponents vary, with a normal range of -0.15 to -0.35 for b and 0.7 – 1.1 for q (Harvey, 1997) and much larger variations in the constants (a and p) reflective of variations in sediment supply rates, alluvial fan age and history (Harvey, 2010). Regression analysis of morphometric variables has proven a valuable tool in exploring and understanding the influence of external forcing conditions over Quaternary time-scales such as base level (e.g. Harvey et al., 1999a; Harvey, 2005), tectonic setting (e.g. Silva et al., 1992; and Fig. 2; Calvache et al., 1997) and river capture (e.g. Mather et al., 2000, discussed later in this paper).

Sedimentology studies

The characteristics of the catchment to a major extent determine the nature of the flow process that builds the alluvial fan and thus its sedimentology. Smaller (km scale), coarser grained debris-flow dominated alluvial fans tend to develop from the smallest, steepest catchments that have reduced ability to store slope deposits (Harvey, 1984a; Kostachuk et al., 1986). Fluvial dominated alluvial fans in contrast tend to have larger, gentler catchments with a greater propensity to accumulate higher water to sediment flows (e.g. Harvey, 1984a; Kostachuk et al., 1986), and are typically dominated by a smaller sediment calibre than debris flow fans. Additionally, particularly in arid environments, lithology will play a significant role in determining sediment calibre and availability due to weathering (e.g. Stokes and Mather, 2015). The deposits of alluvial fans are usually differentiated from main river deposits by their provenance (which is often different from the main river sediments as it is derived mainly from local slopes, e.g. Mather, 2000); sedimentology (sediments may be more poorly sorted, coarser and have more angular sediment textures e.g. Leeder and Mack, 2001; Larson et al., 2015) and architecture (generally alluvial fans tend to be dominated by more sheetform geometries, less channelized deposits e.g. Stokes and Mather, 2000; Mather and Hartley, 2005).

Coupling/connectivity studies

The degree of connectivity (or coupling) between the components of a fluvial landscape determines the down-system transmission of sediment and water and the sensitivity of that system to any environmental change. Thus, as many Quaternary fluvial studies are concerned with palaeoenvironmental change, learning to read the signatures of that change within the Quaternary fluvial archive are paramount. The concept of coupling or connectivity was initially flagged by Brunsden and Thornes (1979), but has most recently incorporated the role of alluvial fans in a ‘state of science’ review by Harvey (2012). From these discussions it is clear that alluvial fans play an important role as either a buffer or coupler (e.g. Harvey, 2010; 2012) within the fluvial landscape (Fig. 3). Alluvial fans are close to the thresholds of critical stream power (*sensu* Bull, 1979) and thus sensitive to change. Where there is excess power, incision can occur which will increase coupling between the river system and the alluvial fan. Where there is excess of sediment supply to the alluvial fan it is more likely to act as a buffer (Fig. 3). Thus, integrated river terrace and alluvial fan studies can add significant information to palaeoenvironmental reconstructions, providing potential information on upstream sediment source and flood magnitude (the terrace e.g. Stokes et al., 2012a,b; Mather and Stokes 2016) and hillslope connectivity and processes (the alluvial fan, e.g. Harvey, 2012).

Dating studies

The coarse grained nature of alluvial fan deposits, and the often long Quaternary time-scale of the landforms poses particular challenges for dating such environments. To meet these challenges innovative approaches have emerged from alluvial fan studies alongside the development of new technologies to maximise the value of the limited potential dating targets preserved within the alluvial fan archives. These innovative approaches have helped further study in other fluvial archives. Within the alluvial fan stratigraphic environment dating techniques have been applied to rarely preserved flora and fauna (e.g. radiocarbon dating of rodent middens and land snail assemblages [e.g. Meyrick and Karrow, 2007 ; de Porras et al., 2015]) and weathering and soil features (e.g. Wells et al., 1995; White et al., 1998; Pope and Wilkinson 2005; D'Arcy et al., 2015). Within the fan sequences rarely preserved carbonates have proved a useful if limited dating resource within alluvial fan settings through Electron Spin Resonance (ESR) and Uranium Series dating (e.g. Rowan et al., 2000). By far the most commonly applied approaches are exposure age techniques - Optically Stimulated Luminescence (OSL) and Cosmogenic radionuclide (CRN) dating. CRN has proved most useful in older sequences, beyond the range of OSL (e.g. Evenstar et al., 2009), but is being used for increasingly younger sequence applications as it is developed (e.g. Fuchs et al., 2015). OSL has been mainly applied to the younger part of the Quaternary (e.g. Pope and Wilkinson 2005; Robinson et al., 2005; Pope et al., 2008; Spencer and Robinson 2008). For OSL both quartz and feldspar from sand lenses are the main sampling targets. The CRN isotopes most commonly utilised are ^{10}Be, ^{26}Al and ^{21}Ne from quartz based clast lithologies (e.g. granite, sandstone), ^{36}Cl on carbonate clast lithologies and ^{3}He from pyroxenes in basaltic clast lithologies. CRN sampling typically employs 2 main approaches: 1) surface exposure dating of large individual boulders (e.g. Evenstar 2009) or profile dating (e.g. Rodés et al., 2011). CRN studies can be used to calculate the age of landform surfaces, and the rates at which erosion has affected them since their formation. A common issue is that of inheritance in both CRN and OSL. However, evolving techniques in CRN burial dating of paired cosmogenic depth profiles (^{10}Be and ^{26}Al) are becoming increasingly more sophisticated and providing more robust results over longer timescales (e.g. Rodés et al., 2014). Similarly refinement of techniques in OSL alluvial fan studies means that smaller sand lenses in coarse grained deposits can now be used for OSL (e.g. Kenworthy et al., 2014), widening its applicability to other archives. These dating studies help us better understand the evolution of alluvial fan features (e.g. Wells et al., 1995, Matmon et al 2006) that in turn can be utilised to understand rates of tectonic activity and timing of climate change (e.g. González et al., 2006, Quigley et al 2007, Evenstar et al., 2009, Jordan et al., 2014).

4. Alluvial fan-fluvial terrace integrated case study contributions to understanding Quaternary fluvial archives

Alluvial fans which interact with fluvial systems tend to occur in 3 distinct stages of landscape evolution over Quaternary and longer time-scales. These stages can be broadly grouped into i) continuous mountain front alluvial fans interacting with a non incising but laterally eroding axial fluvial system; ii) alluvial fans which transition into fluvial terraces as sedimentary basins shift from net aggradation to net incision and iii) tributary-junction alluvial fans that develop predominantly within incising river valley systems. These stages of landscape evolution can occur under a variety of both climatic and tectonic settings and time-scales. Within each of these landscape development stages the alluvial fan system may play a slightly different role depending on the relationships between main river flow and the characteristics of the tributary river systems supplying sediment and water to the main river system (Fig. 3).

Lateral interactions in a non-incising fluvial system: Basin and Range USA.
The basin and range of the USA demonstrates the interaction of river and alluvial fan systems on Quaternary time-scales and sedimentary basin spatial scales. The examples from Idaho and New Mexico (Figs. 4 and 5) provide insights into what happens where alluvial fans along mountain fronts interact with axial river systems in adjacent aggrading basins prior to the dominance of vertical incision i.e. during periods dominated by lateral erosion. They thus potentially inform on the river terrace-alluvial fan interaction during terrace building within Quaternary fluvial archives.

1) Big Lost River, Idaho
The Big Lost River of Idaho comprises a bajada of alluvial fan surfaces tributary to the axially draining Big Lost River (Fig. 4) that drains from north to south within a half-graben setting. The alluvial fans are 1-6 km long with slopes of 1° to 3°, grading down to the Big Lost River channel belt, which is 1-2 km wide (Leeder and Mack, 2001). The area is tectonically active and close (~12km) to the location of the Ms 7.3 Borah Earthquake (28th October 1983; Leeder and Mack, 2001) that developed a pronounced surface rupture still visible on satellite imagery. Around the study area (Fig. 4b), fault trenching indicates the last fault activity was about 4ka (Scott et al., 1985). The alluvial fans were mainly constructed from meltwater and sediment discharges related to the Last Glacial Maximum and were incised under Holocene climate conditions. (Leeder and Mack, 2001). The alluvial fans can be distinguished from the axial river sediments as they tend to be poorly sorted pebbles to boulders with coarse sands whereas the river sediments tend to be well sorted gravel to sands containing laterally accreting point bars and channel bars. Where the modern active axial channel does not interact with the alluvial fans (e.g. Elkhorn Fan, Fig. 4c), the alluvial fans have an asymptotic contact with the axial drainage wetlands. In direct contrast, where the alluvial fans are in contact with the active channel they are terminated by a 2-12 m high erosional scarp (Fig. 4b). This foreshortening is attributed to lateral toe cutting (*sensu* Leeder and Mack, 2001; Larson et al., 2015) by the Big Lost River. Some alluvial fans have been bevelled by some 300m of alluvial fan retreat (Leeder and Mack, 2001). Although the axial river is non-incising, lateral toe cutting effectively foreshortens the alluvial fan which in turn creates an apparent relative base-level fall for drainage on the alluvial fans. This stimulates basal incision in tributary alluvial fans that are in contact with the axial river (Fig. 4b). Where the axial river has moved away from the toe of the alluvial fans, prograding 'healing lobes' (Leeder and Mack, 2001; Fig. 4b) are visible that prograde over both fluvial sediments and previously bevelled alluvial fan sediments. This presents challenges for dating of such sequences. This style of lateral erosion is also apparent in other settings (see Leeder and Mack, 2001 and Larson et al., 2015) and is discussed further in relation to fluvial archive stratigraphy in the example below from New Mexico. The role of the alluvial fans in the landscape has varied from being totally to partially buffered (Figs. 3, 4b and 4c) during the glacial to interglacial transitions when

maximum sediment and water discharge was available. Partial buffering would be likely to occur where lateral toe cutting occurs (Fig. 4b), effecting alluvial fan foreshortening and a relative base-level drop. During the Holocene when incision has dominated the alluvial fans are behaving in a more coupled manner (Fig. 4b) due to both top down (discharge) and bottom up (toe-cutting) stimuli.

2) Rio Grande, New Mexico
The Rio Grande rift basin in New Mexico, USA (Fig. 5) comprises a series of interconnected half-grabens containing a thickness of >1km of Plio-Pleistocene fluvial deposits (both river and alluvial fan - Mack and Seager, 1990; Hawley and Hasse, 1992; Hawley et al., 1995; Connell et al., 2013). Subsidence rates average 0.03mm/yr (Leeder et al., 1996). Within this system ~90% of the land surface geomorphology is alluvial fan and ~10% axial river, although subsurface data indicate that this has varied through time (Weissmann et al., 2015). The axial system itself drains axially along the interconnecting half-graben system, to a terminal half-graben (Mack et al., 1997). As the axial fluvial system flows through its <3km wide valley into an adjacent basin the axial system may aggrade or incise depending on the relative base-level change between the grabens, leading locally to the development of incisional behaviour in the main river. Quaternary climate has also affected sediment supply and discharge changes within the Rio Grande and the tributary mountain front alluvial fans over the last 0.8 Ma (Connell et al., 2013; Mack et al., 2011) and over the last 12.4ka has produced 4 vertically closely spaced (<2m apart) river terraces (Mack et al., 2011).

Palaeomagnetic and geochronological studies of the Plio-Pleistocene sequence (Mack et al., 1993; 1998; Leeder et al., 1996) has helped document the interaction between the axial fluvial and alluvial systems (Leeder et al., 1996; Mack and Leeder, 1999; Leeder and Mack, 2001). These works demonstrate that the footwall-derived alluvial fans from the Caballo Mountains (Fig. 5c) contain significant intercalations of both axial-fluvial and alluvial fan material. In the Palomas Basin up to 3 intercalated axial fluvial 'wedges' occur (Figs. 5b and 5c). The alluvial fan deposits are terminated with scarp like ends (Fig 5b) which represent former toe cuts. The flat bases to the sediment wedges and sharp vertical terminations are interpreted as subsurface expressions of the morphological observations derived from Idaho by Leeder and Mack (2001). The observations in Idaho (Fig. 4b) indicate that where the axial river moves away from the alluvial fan 'healing wedges' can develop (Leeder and Mack, 2001) formed by younger alluvial fan lobes that gradually prograde across the axial river deposits (Fig. 5b). These observations clearly have important implications for both alluvial fan stratigraphy but also the river terrace record where such intercalations occur within a terrace. Where such sequences occur it suggests periods of lateral erosion rather than vertical downcutting. Surficial morphological expression of this foreshortening (distal alluvial fan incision and perched alluvial fan surfaces) could be misinterpreted as evidence of active downcutting by the channel. However, if preserved within a terrace, the recognition of the internal architecture and spatial distribution (Fig. 5) could assist in understanding the attributing cause (see discussion).

Time-transgressive interactions in an incising system: Betics, SE Spain

Changes in, and the interplay between, tectonic and climate regime can stimulate a landscape to evolve from net aggradation to net incision (e.g. Mather, 1993; Maddy et al., 2001; Silva et al., 2008; Harvey et al., 2016). Over Quaternary time-scales drivers of these changes may be down to regional changes in factors such as stress fields as part of an evolving compressive margin (e.g. Mather and Westhead, 1993); orientations of intra-plate stress fields (e.g. Cloetingh et al., 1990) and coupled climatic change (loading/unloading effect of sediment and water during glacial/interglacial cycles) and sub-surface mantle flow (e.g. Westaway, 2001). These drivers may stimulate bottom up (river incision) or top down (sediment supply) responses within the evolving fluvial landscape (Fig. 3), and within this context it is possible for alluvial fans to transition into river terrace sequences as incision begins to dominate over aggradation. This evolution will be time-transgressive in nature with distributive basin margin systems usually the last to be affected as any resulting wave of incision stimulated by basinal incision works its way from its point of origin (base-level fall). The mechanism that drives the lowering of the base level for the sedimentary basin may vary. It may be a wave of incision related to river capture and the opening of a previously endoheric drainage basin, or may be rejuvenation caused by regional tectonic uplift. SE Spain provides a range of such examples (Harvey et al., 2014; 2016).

The modern climate for SE Spain is <300mm of rainfall pa (Machado et al., 2011) and precipitation is mainly influenced by westerly weather patterns (Capel-Molina, 1981; Benito et al., 2015). The regional Quaternary fluvial incision is well documented by a series of coarse-grained strath river terraces that typically aggraded during global glacials, especially during glacial-to-interglacial transitions (Harvey et al., 2014). During glacial stages in this region effective frost action in the mountain source areas would likely have increased sediment supply whilst greater aridity would have reduced the effectiveness of vegetational stabilization, leading to greater sediment availability. Thus although glacial periods were drier (i.e. less effective rainfall; Hodge et al., 2008), the lower frequency rainstorms that did occur would have generated more effective run-off as a result of the sparse vegetation cover, facilitating incision. Here we will examine 3 of the sedimentary basins and their associated Quaternary terrace and alluvial fan records – 1) Tabernas Basin, 2) Sorbas-Vera Basin and 3) Almería Basin (Fig. 6). The last of these examples will present new data on the sedimentological record of this transition within the terrace sequence of the Río Alías.

1) Tabernas Basin

The Tabernas Basin (Box 1, Fig. 6) contains 3 different scales of alluvial fans that co-exist with an axial river system (Fig. 7a). The Filabride alluvial fans to the north are backfilled into their catchments on a non faulted mountain front whilst to the south the Marchante alluvial fans occur along a mountain-front thrust fault to the north of the Sierra del Marchante (Fig. 7a). During the earliest stages of basin evolution, what are now preserved as terrace remnants within the landscape can be identified as former alluvial fan systems based on their sedimentology and morphology (Levels 1 and 2, >200 ka, Geach et al., 2015 and Figs. 7b and 8a) which have subsequently been dissected. In contrast, Level 3 reflects much finer deposits within the main, dissected axial system (Fig. 8c). These sediments were deposited from 41.3±2.8 ka and continued until 14± 1ka (Geach et al., 2015a,b). The calibre of sediment is due in part to the coarse material being deposited in the major tributary systems (Fig. 8b) and the main axial system becoming impeded by deformation in the SW (Harvey et al., 2003 and Fig. 7a) leading to the development of palustrine conditions (Figs. 7b and 8c). During the latest Pleistocene a wave of incision worked its way up the basin related in part to river capture and in part to tectonics (Alexander et al., 2008; Geach et al., 2015). This led to a bottom up coupling through some of the former alluvial fan systems in the lower parts of the basin (e.g. Rambla Sierra, Fig. 7a), enabling coarser material to be delivered from tributary mountain catchments to the developing axial river terrace system. The Filabres alluvial fans, in the upper basin, however, are currently unaffected by this incision and still acting as sedimentary buffers, as are the Marchante alluvial fans (Fig. 7). This affects the sediment delivery to the developing fluvial terrace sequence downstream of the well-coupled areas. Where the system is buffered by alluvial fans, only fine materials are available to the axial river (e.g. distal areas of alluvial fan systems in the east of the basin, Fig. 7a), whereas once incision and thus coupling has occurred coarser bedload becomes available.

2) Sorbas-Vera Basin

To the east of the Tabernas Basin (Box 2, Fig. 6), in the adjacent Sorbas Basin (and its continuation into the south-central part of the Vera Basin) this transition from alluvial fan to incising river systems is apparent and occurred much earlier (~1Ma according to ^{10}Be and ^{21}Al cosmogenic profile dating by Ilott, 2013 and Fig. 9) and thus much of the depositional evidence has been removed. However use of relict mountain front alluvial fan surfaces that preserve alluvial fan characteristics, together with remaining sedimentary basin deposits and the regression analysis of younger, regional Quaternary alluvial fan databases has enabled reconstruction of drainage evolution which assists in the interpretation of river terrace records (e.g. Stokes et al., 2012b). Alluvial fan characteristics could be used to semi-quantify reconstruction of original drainage relationships (Mather et al., 2000) and assess the magnitude and direction of change in drainage area routing (Fig. 9). The preserved fluvial deposits (provenance, sedimentology e.g. Mather, 1999) of adjacent Quaternary sequences could be used to confirm these findings and provide regional and drainage evolution context for what helped drive the captures in terms of localised tectonically induced base-level lowering (Stokes and Mather, 2000).

3) Almería Basin

To the south of the Tabernas-Sorbas-Vera basins, The Río Alías of the Almería Basin (Boxes 3 and 4, Fig. 6) provides evidence of both ‘top down’ and ‘bottom up’ controls on the alluvial fan to river terrace transition at the basin margins. The Río Alías is an ephemeral, transverse fluvial system (Fig. 6) containing 4-5 level terrace levels that have been correlated with those of the Río Aguas in the adjacent Sorbas Basin (Whitfield and Harvey, 2012). Initially it had been assumed that the Quaternary river terrace sequence represented a fully “fluvial” system development. However geomorphological mapping, sedimentology and provenance analysis of both the coarse and fine sediment assemblages (Maher, 2005; Whitfield and Harvey, 2012), suggests that during the earliest terrace stage (Terrace A, >300-400ka: Fig. 10 and 11) the headwaters of the catchment (Box 3, Fig. 6) formed via coalescing alluvial fans, and on exiting it’s transverse course across the Sierra Alhamilla, the Río Alías formed a tributary-junction alluvial fan extending

3-5km beyond the mountain front (Box 4, Fig. 6). 5km beyond this the system became fully entrenched and displays characteristics associated with axial river systems (dominated by channelized deposits). In the area around the village of Lucainena (Box 3, Figs. 6 and 12), there is evidence of entrenchment of the fluvial system development away from the mountain front location during the aggradation of terrace A (>300-400ka). Following the aggradation of Terrace A an incisional phase ensued prior to aggradation of the second terrace level (Terrace B, >200ka). This is likely to reflect climate driven, cold stage related incision and the development of partial to total coupling (Fig. 12). Further incision was driven by bottom up base-level changes within the upper reaches of the Rio Alias (Fig.12) leading to full coupling of the system. Terrace B displays no alluvial fan characteristics throughout the mountain front area of either basin, apparently evolving as a gravel bed river system. However, the transverse reach preserves evidence of alluvial fan burial of older terrace deposits (Terrace B sediments buried by alluvial fans of D age 21.5±3.4 ka to 10ka, based on relative stratigraphic indicators).

Recognition of the tributary-junction alluvial fans within the terrace record is challenging and requires the systematic use of sedimentology and terrace geometry. Within the Alías system both the geometry and sedimentology of the proposed 'tributary-junction' alluvial fan of terrace A was different from that represented in Terrace A deposits further downstream (Maher, 2006). The conglomerates are conformable with the underlying geology (Mather, 1991; 1993; Fig.11) and are dominated by gravels and sands with subordinate coarse units (B axis up to 15cm) and thick accumulations of sandy/silty layers (Fig. 11). Although erosive scours are preserved in places (often marking the base of a flow event deposit beginning with a coarse unit and followed by a fining up sequence), the sequence is dominated by vertical aggradation in horizontal sheets that may pinch out laterally (Fig. 11a). At an outcrop scale around 50% of the sediments in view have been deposited under tractional flow conditions (Fig. 11b) although there is significant indication of hyper-concentrated flows, suggested by the floating nature of some clasts. The tributary-junction aspect of the alluvial fan is evident from its position within the preserved morphology of the valley networks and fluvial terrace record (upstream of a junction with the Rambla de los Feos junction, Fig. 6). The only preserved remnants of Terrace A downstream of the Rambla de los Feos confluence suggest the dominance of a braided (?), gravel bed river, quite probably due to increased discharge from the tributary Rambla de los Feos (Fig, 6) and sediment load from the Alías tributary. Following an incisional event after the aggradation of alluvial fan Terrace A, the Río Alías became fully incised (and coupled) throughout its course and no indication of alluvial fan development within the terrace deposits is preserved.

Tributary junction alluvial fan interactions in an incising river system: High Atlas, Morocco

Where vertical erosion of an axial river system is occurring, this will affect the base level for any tributary alluvial fans through a 'bottom-up' base level lowering. The response of the alluvial fans to that base-level lowering will be highly dependent on climate controls which drive the 'top-down' tributary catchment sedimentation (e.g. Harvey et al., 1999; Weissmann et al., 2005 and Fig. 3). The vertical and lateral accommodation space for any building alluvial fan will determine both the geometry of the alluvial fan and its longevity. For example, where lateral toe-cutting of alluvial fans by the main river is occurring alluvial fans may be foreshortened, or where sediment input from tributary alluvial fans is sufficient, the main channel may be displaced laterally within is valley facilitating the spatial expansion of the alluvial fan area. Thus depending spatially on when sediment supply within the landscape is switched on, the alluvial fan will act as either a buffer to hillslope sediment supply to developing terrace records, or may be bypassed through complete alluvial fan trenching, in which case the system will become fully coupled (Fig. 3). The way in which the catchment is behaving at the time is very much revealed by the potential interaction (or not) of the alluvial fan and river terrace records. If combined with appropriate dating technologies this can provide a powerful tool to unlocking landscape responses.

Take as an example the Ait Said tributary-junction alluvial fan of the Dades River, High Atlas Morocco (Fig. 13). The Dades valley is dominantly undergoing incision driven in part by climate change and in part by regional tectonics (Stokes et al., 2008; Boulton et al 2014; Stokes and Mather, 2015). This incision has left behind a sequence of inset river terraces (Figs. 13a, 13b and 14a). The modern tributaries to the Dades are typically ephemeral (Fig. 15a), supply limited drainage systems. In a ~20km reach of the system, only 16% of the tributary drainages generated tributary junction alluvial fans (Stokes and Mather, 2015). These alluvial fan generating catchments are typified by higher relief, longer length, lower gradient and larger areas than the non- alluvial fan catchments (Stokes and Mather, 2015). The modern alluvial fans build during annual localised winter-spring storm events but are reset by less frequent (>10 year) large floods down the main river, leading to episodic removal of the alluvial fans and incorporation into the fluvial deposits (Stokes and Mather, 2015). Over longer (Pleistocene) time-scales, the preservation of these small alluvial fan lobes is poor, but larger, relict alluvial fans are preserved within the modern landscape (Fig. 13). These older and larger tributary-junction alluvial fans date back to periods of enhanced sediment supply from the regional slopes (glacial cold stages; Stokes and Mather, 2015). During these stages the alluvial fans acted more as buffers owing to the higher sediment availability from the slopes (Fig. 3) and no interaction of the sedimentology has been identified (to date, by the authors) in the field within the river terrace record (Figs. 13a, 13b and 14a). Despite the similarities in bedload lithology between the main river and alluvial fan deposits (both are predominantly limestone), the sedimentology is distinctly different (compare Figs. 14a and 14d). What is observable, however is the difference in sedimentology. Modern river gravels are predominantly larger, well rounded and better sorted (Fig. 14a) whereas the alluvial fan sediments in the Quaternary sections tend to be angular-sub-angular, smaller and more poorly sorted (Fig. 14d). Their style of deposition suggests debris flow and only localised normal tractional flow. The lack of intercalation of alluvial fan and fluvial sourced material clearly demonstrates the action of the tributary alluvial fans at this time as buffers within the landscape. The smaller, more angular sediment texture most probably reflects freeze-thaw operative within the catchment. Contrast that with the setting today, and the tributary alluvial fan is fully incised (Figs. 13, 14c and d, Fig. 15) and coupled with the main system (Fig. 13a and b and 15). Modern deposits in the incised section of the channel tend to be larger (Fig. 15a) which in part reflects the channelised, more efficient flow conditions within the confined trench. These modern sediments are more rounded than the Pleistocene deposits by the time they reach the terminal alluvial fan lobes (Fig 15b,c) but are still less rounded than the main river gravels evident in the terrace record (Fig. 14a). The modern catchment of the Ait Said is largely supply limited and down to bedrock. This assists in the transportation of any available sediment and may account for the most recent incision of the system (Figs 14d and 15a). Similarly, during interglacial stages when the water : sediment flow characteristics increased, incision would be likely. The episodic nature of the ‘top down’ (climate sediment control) driven incision and ‘bottom up’ (Dades River valley incision) is reflected in the inset alluvial fan terraces within the relict tributary alluvial fan and their internal sedimentology, which indicates episodic breaks in sedimentation (Fig. 14d). Modern river gravels are a mixture of these textures suggesting intermixing of the modern sediment supply. Thus in the modern context the tributary alluvial fan is acting as a coupled system driven by base-level incision (incision of the River Dades) whilst the alluvial fans appear to demonstrate periods of both hillslope buffering (cold stages) and enhanced coupling (interglacials), indicating the changing dynamics of the system (Fig. 3).

5. Discussion

Alluvial fan and river connectivity

Alluvial fans occur at a variety of spatial and temporal scales (Fig. 1) that influence the connectivity of the sediment and water transport system from the slopes to the river (Fig. 3) and wider catchment areas. Whether the alluvial fan is aggrading (buffering the channel from the slope/tributary inputs), or incised (coupling the alluvial fan catchment area and river) is important to how the fluvial landscape works (e.g. Harvey, 1996). Alluvial fan buffering traps and stores coarse sediment from mountain tributaries suppressing supply to the contemporaneously developing river terrace sequence, whereas coupling enables the linkage of sediment sources. This may be reflected in the provenance and sedimentology of river terrace deposits. This relationship can change on different spatial and temporal scales (Figs. 1 and 3). On Quaternary regional catchment scales in arid environments, if climate change led to increased sediment supply form hillslopes and to the mountain tributary alluvial fans, then buffering may occur. If, however, stream power were to increase by the generation of more effective runoff, then alluvial fan capture and incision may occur, coupling the environments by through alluvial fan trenching (e.g. Harvey, 1996). On the humid west coast of New Zealand at $<10^3$ yr time-scales alluvial fans undergo episodic, high magnitude sediment delivery and aggradation from large landslides with intervening persistent alluvial fan head trenching when sediment delivery returns to ‘normal’, although these systems tend to be in dynamic equilibrium over longer time-scales (Davies and Korup, 2006). On Recent time-scales, Fryirs et al., (2007) using work from the Hunter catchment in SE Australia demonstrate that the magnitude of the storm event affecting the catchment (the frequency of which will vary across Quaternary climate scales) also affects the nature of the fluvial connectivity within the system with alluvial fans acting as buffers under low magnitude flow conditions but coupling the system under high magnitude flow events. Within the SE Spain case study area, a 1 in 100 year flood (in 1984) did not lead to fluvial continuity between the Filabride alluvial fans and the modern river system of the Tabernas Basin (Harvey, 1984b) but the 1 in 1000 year flood (in 1973) coupled large parts of the modern alluvial fan and main river systems within the region (Mather & Stokes, 2016).

Laterally eroding river systems and mountain front alluvial fan interactions

The work in the Basin and Range by Leeder and Mack (2001) emphasises the potential bearing of lateral erosion (no vertical incision) on river terrace and alluvial fan interactions. The impact is highly dependent on the ability of the axial river to remove the sediment and the relative sediment and water discharge being produced from the adjacent alluvial fan systems. This balance may alter due to changes in the alluvial fan catchments or the axial river. The Idaho alluvial fans presented above reflect this type of process – and are dominated by a top down catchment control on the balance of erosion and deposition within the alluvial fan system (the axial system is not incising). This toe cutting is formed by lateral erosion rather than vertical incision and base-level change in the main river, but can mimic these effects by for-shortening the alluvial fan and improving coupling within the system. Recent studies (Giles et al., 2016) suggest that this is most likely to occur on the upstream side of tributary alluvial fans, such that this may this be the most likely route for future coupling within these systems (as can be observed in the Dades example of Fig. 3). Tectonic tilting of the axial river can also effect lateral erosion, which can lead to channel avulsions in the axial river which then toe-cut the alluvial fans (as in the USA examples). This kind of forcing is likely to be more spatially and temporally variable as it is dependent on localised fault movement along segments (Leeder and Mack, 2001). Alternatively fault propagation can also account for such patterns of lateral toe cutting where it causes the axial river to pass through a new transfer cross-over zone (e.g. Green Canyon and Apache canyon, Figs. 5c and 5d, Leeder et al., 1996; Mack and Leeder, 1999). Thus identification of these intercalated alluvial fan and fluvial sequences within a terrace unit may potentially inform on climate change or tectonic activity and care with interpretation combined with careful observation of the spatial nature of these features needs to be applied when interpreting fluvial archives that show such features.

Vertically eroding (valley constrained) river systems and tributary-junction alluvial fan interactions

In incising landscapes the transition of alluvial fans to river terrace records may be time-transgressive within a fluvial terrace unit, as illustrated in the case of the Río Alías. The nature of the relationship will change as the main fluvial system continues to incise (Fig. 3). The role of the tributary-junction alluvial fans within the fluvial landscape is thus spatially and temporally dynamic and will to a large extent be governed by the sediment and water discharge of the main river and also the timing of tributary and main river flow activity. This will either lead to alluvial fan construction (the 'build') or removal (the 'reset') by erosion of the main river in a 'build and reset' cycle (Stokes and Mather, 2015). These may be reflected in the spatial variation of thickness of terrace records (e.g. Merritts et al., 1994) or spatial variations in channel pattern recorded within the individual sedimentary architecture of the terrace units. For example work by Harvey (2007) has shown that more persistent braided sedimentation typically occurs downstream of tributary-junction alluvial fans and debris cones and that the sediment in these reaches may be coarser and more angular (where systems are coupled). Additionally where periods of tributary alluvial fan expansion are facilitated by high sediment discharge, these may form a constriction for subsequent main river flood events. These latter flood events, and their timing, may be independent of climate conditions at their point of deposition. They may, for example, reflect an entirely different climate regime in very large axial river systems, or those draining across large altitudinal ranges. This provides opportunity for tributary alluvial fans to ‘build’ before being ‘reset’ by larger magnitude, main river floods (Stokes and Mather, 2015). Where these mixed load higher magnitude flood events encounter tributary-junction alluvial fans the morphological constructions they create are capable of impounding the flood waters in temporary or longer lived palustrine to lacustrine environments (e.g. Harvey et al., 2003; Blumentritt et al., 2009). Alternatively the tributary alluvial fans may create spatial opportunity for the accumulation of flood slack water deposits (Fig. 15d). Similar, fine-grained deposits within Quaternary terrace and alluvial fan archives have formed the focus of mixed interpretations with significant ramifications for the interpretation of Quaternary landscapes. For example in the Mojave River, USA such deposits have been interpreted both as representing former lake levels and flood slack water deposits (see discussions in Reheis and Redwine, 2008). There is thus clear need to better understand and recognise the nature of interaction between alluvial fan and adjacent fully ‘fluvial’ environments.

Impact of sustained river incision on alluvial fan interactions

Other considerations that should be taken into account when considering the existing alluvial fan and river terrace literature is the nature of any base-level change. Within river systems affected by river capture, for example, this can be exceptionally rapid in Quaternary terms (for example the Río Aguas in SE Spain was captured ~70ka leading to a local base-level drop of 90m almost instantaneously on a Quaternary time-scale, Mather et al., 2002; Stokes et al., 2002; Harvey et al., 2014; Harvey et al., 2016). Even in mechanically hard bedrock such changes can lead to rapid vertical readjustments of fluvial systems (Antón et al., 2015). The impact of this incision on any tributary alluvial fans will be highly dependent on the valley and terrace width. For example, if a tributary alluvial fan is feeding onto a wide river terrace so that it remains unconnected with the main river, then the alluvial fan may not recognise the base-level fall at all. Unlike the most commonly reported river system scenarios, base-level fall affecting alluvial fans is not necessarily associated with incision and may in fact lead to alluvial system progradation. The response is based on the balance between sediment flux to the alluvial fan (top down controls) and the gradient of the exposed foreshore (in the case of sea-level or lake-level related base-level drops; e.g. Harvey et al., 1999a,b; Harvey, 2005). In the case of tributary alluvial fans feeding into a main river this base-level drop will be much sharper morphologically due to the vertical incising nature of the main river. Thus where alluvial fans are partially connected to the fluvial system (Fig. 3) incision in the distal areas of the alluvial fan will occur at the vertical drop created by the incision and will likely lead to a localised increase in relative stream power and thus headcut development, increasing connectivity between alluvial fan and river environments. This may lead to through alluvial fan trenching and the development of truncated alluvial fan surfaces (e.g. Fig. 13b) or, in situations of high sediment input from tributary alluvial fans, progradation may occur but will be spatially limited by the valley (both active river and river terrace) morphological characteristics.

6. Conclusions

Alluvial fans provide extremely useful perspectives on Quaternary fluvial landscapes and their evolution. Traditionally, river terrace studies tend to have been carried out in isolation from alluvial fan studies, however it is apparent that recognition of the occurrence of alluvial fan sedimentation within the river terrace stratigraphic record can be mutually beneficial. Whilst alluvial fans may pose some problems (e.g. burying river terrace surfaces, or posing potential dating issues) their benefits greatly outweigh their disadvantages. Careful use of the sedimentology, stratigraphy and morphology of alluvial fan archives can help better understand the landscape context which can assist in terms of understanding where to date and what has been dated and improve understanding of apparently conflicting evidence (e.g. a lack of adjacent slope sediments within river terrace records at times of high sediment production from the valley slopes may in fact represent a period when the alluvial fan was aggrading and acting predominantly as a sediment buffer within the landscape). Thus a better integrated use of alluvial fan and river terrace studies can improve understanding of the source to sink nature of sediment at catchment spatial scales. The new conceptual model focuses on the dynamic role of alluvial fans under changing environmental conditions within a fluvial landscape context, utilising commonality between the limited number of published studies currently scattered across the geomorphological and geological literature, together with some new data presented here. At times of high sediment yield the alluvial fan will act as a buffer between the river and slope environment, preventing slope material from entering the fluvial terrace archive. Alternatively during periods of low slope sediment supply to the alluvial fan, coupling with the river environment will be enhanced. The intensity of buffering or coupling will be dependent on the relative importance of the spatial controls (top down and bottom up) affecting the alluvial fan environment. The model simplistically summarises the complex dynamic role of alluvial fans in the transfer and storage of sediment between local slopes and the main river channel and provides simple language to describe that complex interplay (e.g. totally buffered, top down, high sediment yield system). Identifying these often subtle relationships within fluvial archives will assist in maximising value to interpretations of the older Quaternary fluvial landscape. These older Quaternary field investigations can then in turn better inform landscape evolution modelling to assist in exploring the longer-term Quaternary impact of external controls such as climate change in a pre-human landscape context to advance our understanding of the response of Pleistocene and older landscapes to palaeoenvironmental change.

References

Alexander, R.W., Calvo-Cases, A., Arnau-Roalen, E., Mather, A.E., Lazaro- Suau, R., 2008. Erosion and stabilisation sequences in relation to base-level changes in the El Cautivo badlands, SE Spain. Geomorphology 100, 83-90.

Antón, L., Mather, A.E., Stokes, M., Munoz-Martin, A., De Vicente, G., 2015. Exceptional river gorge formation from unexceptional floods. Nature Communications 6, 7963, doi:10.1038/ncomms8963

Benito, G., Macklin, M.G., Zielhofer, C., Jones, A.F., Machado, M.J., 2015. Holocene flooding and climate change in the Mediterranean. Catena 130, 13-33.

Blumentritt, D.J., Wright, H.E.Jr., Stefanova, V. 2009. Formation and early history of Lakes Pepin and St. Croix of the upper Mississippi River. Journal of Paleolimnology 41, 545-562.

Boulton, S.J., Stokes, M., Mather, A.E., 2014. Transient fluvial incision as an indicator of active faulting and Plio-Quaternary uplift of the Moroccan High Atlas. Tectonophysics 633, 16-33.

Bridgland, D., Maddy, D., Bates, M., 2004. River terrace sequences: templates for Quaternary geochronology and marine–terrestrial correlation. Journal of Quaternary Science 19, 203-218.

Bridgland, D.R., Westaway, R., 2014. Quaternary fluvial archives and landscape evolution: a global synthesis. Proceedings of the Geologists' Association 125, 600-629.

Brunsden, D., Thornes, J.B., 1979. Landscape Sensitivity and Change. Transactions of the Institute of British Geographers 4, 463-484.

Bull, W.B., 1977. The alluvial fan environment. Progress in Physical Geography 1, 222–270.

Bull, W.B., 1979. Threshold of critical power in streams. Geological Society of America Bulletin 90, 453–464.

Busschers, F.S., Kasse, C., van Balen, R.T., Vandenberghe, J., Cohen, K.M., Weerts, H.J.T., Wallinga, J., Johns, C., Cleveringa, P., Bunnik, F.P.M., 2007. Late Pleistocene evolution of the Rhine-Meuse system in the Southern North Sea basin: imprints of climate change, sea-level oscillation and glacio-isostacy. Quaternary Science Reviews 26, 3216-3248.

Calvache, M.L., Viseras, C., Fernández, J., 1997. Controls on fan development - evidence from fan morphometry and sedimentology; Sierra Nevada, SE Spain. Geomorphology 21, 69–84.

Capel-Molina, J.J., 1981. Los Climas de España, Oikos-Tau, Barcelona, 429 pp.

Cloetingh, S., Gradstein, F.M., Kooi, H., Grant, A.C., Kaminski, M.,1990. Plate reorganisation: a cause of rapid late Neogene subsidence and sedimentation around the North Atlantic. Journal of the Geological Society, London 147, 495-506.

Connell, S.D., Smith, G.A., Geissman, J.W., McIntosh, W.C., 2013. Climatic controls on nonmarine depositional sequences in the Albuquerque Basin, Rio Grande rift, north-central New Mexico. In: Hudson, M.R., Grauch, V.J.S., (eds.), New Perspectives on Rio Grande Rift Basins: From Tectonics to Groundwater. Geological Society of America Special Paper 494, pp. 383–425.

D'Arcy, M., Boluda, D.C.R., Whittaker, A.C., Carpineti, A. 2015. Dating alluvial fan surfaces in Owens Valley, California, using weathering fractures in boulders. Earth Surface Processes and Landforms 40, 487-501

Davies, T.R.H., Korup, O., 2007. Persistent alluvial fanhead trenching resulting from large, infrequent sediment inputs. Earth Surface Processes and Landforms 32. 725-742.

De Porras, M.E., Maldonada, A., Zamora-Allendes, A. Latorre, C. 2015. Calibrating the pollen signal in modern rodent middens from northern Chile to improve the interpretation of the late Quaternary midden record. Quaternary Research 84, 301-311

Evenstar, L.A., Hartley, A.J., Stuart, F.M., Mather, A.E., Rice, C.M., Ching, G. 2009. Multiphase development of the Atacama Planation Surface recorded by cosmogenic ^{3}He exposure ages: Implications for uplift and Cenozoic climate change in western South America. Geology 37, 27-30.

Florsheim, J.L., 2004. Side-valley tributary fans in high-energy river floodplain environments: Sediment sources and depositional processes, Navarro River basin, California. Geological Society of America Bulletin 116, 923-927.

Fryirs, K.A., Brierley, G.J., Preston, N.J., Spencer, J., 2007. Catchment-scale (dis)connectivity in sediment flux in the upper Hunter catchment, New South Wales, Australia. Geomorphology 84, 297-316.

Fuchs, M., Reverman, R., Owen, L.A., Frankel, K.L. 2015. Reconstructing the timing of flash floods using 10Be surface exposure dating at Leidy Creek alluvial fan and valley, White Mountains, California–Nevada, USA. Quaternary Research 83, 178-186.

Garzantia, E., Andòa, S., Padoana, M., Vezzolia, G., El Kammarb, A., 2015. The modern Nile sediment system: Processes and products. Quaternary Science Reviews 130, 9-56.

Geach, M.R., Viveen, W., Mather, A.E., Telfer, M.W., Fletcher, W.J., Stokes, M., Peyron, O., 2015a. An integrated field and numerical modeling study of controls on Late Quaternary fluvial landscape development (Tabernas, southeast Spain). Earth Surface Processes and Landforms 40, 1907-1926.

Geach, M.R., Thomsen, K.J., Buylaert, J-P., Murray, A.S., Mather, A.E., Telfer, M.W., Stokes, M., 2015b. Single-grain and multi-grain OSL dating of river terrace sediments in the Tabernas Basin, SE Spain Quaternary Geochronology 30, 213-218.

Giles, P.T., Whitehouse, B.M. and Karymbalis, E. 2016. Interactions between alluvial fans and axial rivers in the Yukon, Canada and Alaska, USA. In: Ventra, D., Clarke, L. E. (eds) Geology and Geomorphology of Alluvial and Fluvial Fans: Terrestrial and Planetary Perspectives. Geological Society, London, Special Publications, 440, http://doi.org/10.1144/SP440.3

Gómez-Villar, A., Álvarez-Martínez, J., García-Ruiz, J.M., 2006. Factors influencing the presence or absence of tributary-junction fans in the Iberian Range, Spain. Geomorphology 81, 252–264

González, G., Dunai, T., Carrizo, D., Allmendinger, R. 2006. Young displacements on the Atacama Fault System, northern Chile from field observations and cosmogenic 21Ne concentrations. Tectonics 25 doi:10.1029/2005TC001846

Harvey, A.M., 1984a. Aggradation and dissection sequences on Spanish alluvial fans: influence on morphological development. Catena 11, 289-304

Harvey, A.M., 1984b. Geomorphological response to an extreme flood: A case from southeast Spain. Earth Surface Processes and Landforms 9, 267-279.

Harvey, A.M., 1996. The role of alluvial fans in the mountain fluvial systems of southeast Spain: Implications of climate change. Earth Surface Processes and Landforms 21, 543–553.

Harvey, A.M., 1997. The role of alluvial fans in arid zone fluvial systems. In: Thomas, D.S.G. (Ed.), Arid Zone Geomorphology: Process, Form and Change in Drylands. Wiley, Chichester, pp. 231–259.

Harvey, A.M., 2002. Effective timescales of coupling within fluvial systems. Geomorphology 44, 175–201.

Harvey, A.M., 2005. Differential effects of base-level, tectonic setting and climatic change on Quaternary alluvial fans in the northern Great basin, Nevada, USA. In: Harvey, A.M., Mather, A.E., Stokes, M., (Eds.), Alluvial Fans: Geomorphology, Sedimentology, Dynamics. Geological Society of London, Special Publications vol. 251, pp. 117-131.

Harvey AM. 2007. Differential recovery from the effects of a 100-year storm: significance of long-term hillslope-channel coupling; Howgill Fells, northwest England. Geomorphology 84:192–208.

Harvey, A.M., 2010. Local buffers to the sediment cascade: debris cones and alluvial fans. In: Burt, T.P., Allison, R.J., (eds.), Sediment Cascades: An Integrated Approach. Wiley-Blackwell, Chichester, pp. 153-180.

Harvey, A.M., 2012. The coupling status of alluvial fans and debris cones: a review and synthesis. Earth Surface Processes and Landforms 37, 64-76.

Harvey, A.M., Renwick, W.H., 1987. Holocene alluvial fan and terrace formation in the Bowland Fells, Northwest England. Earth Surface Processes and Landforms 12, 249–257.

Harvey, A.M., Wigand, P.E., Wells, S.G., 1999a. Response of alluvial fan systems to the late Pleistocene to Holocene climatic transition: contrasts between the margins of pluvial Lakes Lahontan and Mojave, Nevada and California, USA. Catena 36, 255–281.

Harvey, A.M., Silva, P.G., Mather, A.E., Goy, J.L., Stokes, M., Zazo, C., 1999b. The impact of Quaternary sea-level and climatic change on coastal alluvial fans in the Cabo de Gata ranges, southeast Spain. Geomorphology 28, 1–22.

Harvey, A.M., Foster, G.C., Hannam, J., Mather, A.E. 2003. The Tabernas alluvial fan and lake system, southeast Spain: applications of mineral magnetic and pedogenic iron oxide analyses towards clarifying the Quaternary sediment sequences. Geomorphology 50, 151-171.

Harvey, A.M., Mather, A.E., Stokes, M., 2005. Alluvial fans: geomorphology, sedimentology, dynamics - introduction. A review of alluvial-fan research In: Harvey, A.M., Mather, A.E., Stokes, M., (Eds.), Alluvial Fans: Geomorphology, Sedimentology, Dynamics. Geological Society of London, Special Publications vol. 251, pp. 1-7.

Harvey, A.M., Whitfield, E., Stokes, M., Mather, A.E., 2014. The Late Neogene to Quaternary Drainage Evolution of the Uplifted Neogene Sedimentary Basins of Almería, Betic Chain. In: Gutiérrez, F., Gutiérrez, M., (eds.) Landscapes and Landforms of Spain. Springer, pp 37-61.

Harvey, A.M., Stokes, M., Whitfield, E., Mather, A.E., 2016. Spatial characteristics of the Pliocene to modern alluvial fan successions in the uplifted sedimentary basins of Almería, SE Spain: review and regional synthesis. In: Ventra, D., Clarke, L. E. (eds) Geology and Geomorphology of Alluvial and Fluvial Fans: Terrestrial and Planetary Perspectives. Geological Society, London, Special Publications, 440, http://doi.org/10.1144/SP440.5

Hawley, J.W., Haase, C.S., 1992. Hydrogeologic framework of the northern Albuquerque Basin: New Mexico Bureau of Mines and Mineral Resources, Open-File Report OF-387, 74 p.

Hawley, J.W., Haase, C.S., Lozinsky, R.P., 1995, An underground view of the Albuquerque Basin, New Mexico. In: Ortega-Klett, C.T., (ed.), Proceedings of the 39th Annual New Mexico Water Conference, New Mexico Water Resource Research Institute Report 290, pp. 37-55.

Hereford, R., Thompson, K.S., Burke, K.J., Fairley, H.C. 1996. Tributary debris fans and the late Holocene alluvial chronology of the Colorado River, eastern Grand canyon, Arizona. Geological Society of America Bulletin 108, 3-19.

Hodge, E.J., Richards, D.A., Smart, P.L., Andreo, B., Hoffmann, D.L., Mattey, D.P., González-Ramón, A., 2008. Effective precipitation in southern Spain (266 to 46 ka) based on a speleothem stable carbon isotope record. Quaternary Research 69, 447-457.

Ilott, S., 2013. Cosmogenic dating of fluvial terraces in the Sorbas Basin, SE Spain. Unpublished PhD Thesis, Plymouth University, UK

Jordon, T.E., Kirk-Lawlor, N.E., Blanco, N., Rech, J,A,, Casentino, N.J. 2014. Landscape modification in response to repeated onset of hyperarid paleoclimate states since 14 Ma, Atacama Desert, Chile. GSA Bulletin 126, 1016-1046

Kenworthy, M.K., Rittenour, T.M., Pierce, J.L., Sutfin, N.A., Sharp, W.D. 2014. Luminescence dating without sand lenses: An application of OSL to coarse-grained alluvial fan deposits of the Lost River Range, Idaho, USA. Quaternary Geochronology 23, 9-25

Kostaschuk, R.A., MacDonald, G.M., Putnam, P.E., 1986. Depositional processes and alluvial fan-drainage basin morphometric relationships near Banff, Alberta, Canada. Earth Surface Processes and Landforms 11, 471-484.

Larson, P.H., Dorn, R.I., Faulkner, D.J., Friend, D.A., 2015. Toe-cut terraces: A review and proposed criteria to differentiate from traditional fluvial terraces. Progress in Physical Geography 39, 417-439.

Leeder, M.R., Mack, G.H., 2001. Lateral erosion ('toe-cutting') of alluvial fans by axial rivers: implications for basin analysis and architecture. Journal of the Geological Society, London 158, 885–893.

Leeder, M.R., Mack, G.H., Salyards, S.L., 1996. Axial-transverse interactions in half-graben sedimentary models: Plio-Pleistocene Palomas basin, southern Rio Grande rift, New Mexico, USA. Basin Research 12, 225-241.

Leopold, L.B., Wolman, M.G., Miller, J.P., 1964. Fluvial Processes in Geomorphology. Freeman, San Francisco. 522 pp.

Machado, M.J., Benito, G., Barriendo, M., Rodrigo, F.S., 2011. 500 years of rainfall variability and extreme hydrological events in Southeastern Spain drylands. Journal of Arid Environments 75, 1244-1253.

Mack, G.H., Seager, W.R., 1990. Tectonic control on facies distribution of the Camp Rice and Palomas Formations (Pliocene-Pleistocene) in the southern Rio Grande rift. Geological Society of America Bulletin 102, 45-53.

Mack, G.H., Leeder, M.R., 1999. Climatic and tectonic controls on alluvial fan and axial-fluvial sedimentation in the Plio-Pleistocene Palomas half graben, southern Rio Grande rift. Journal of Sedimentary Research 69, 635-652.

Mack, G.H., Salyards, S.L., James, W.C., 1993. Magnetostratigraphy of the Plio-Pleistocene Camp Rice and Palomas Formations in the Rio Grande rift of southern New Mexico. American Journal of Science 293, 49-77.

Mack, G.H., Salyards, S.L., McIntosh, W.C., Leeder, M.R., 1998. Reversal magnetostratigraphy and radioisotope geochronology of the Plio-Pleistocene Camp Rice and Palomas Formations, southern Rio Grande rift. In: Las Cruces County II. New Mexico Geological Society Guidebooks, 229-236.

Mack, G.H., Love, D.W., Seager, W.R., 1997. Spillover models for axial rivers in regions of continental extension: the Rio Mimbres and Rio Grande in the southern Rio Grande rift, USA. Sedimentology 44, 637-652.

Mack, G.H., Leeder, M.R., Perez-Arlucea, M., Durr, M., 2011. Tectonic and climatic controls on Holocene channel migration, incision and terrace formation by the Rio Grande in the Palomas half graben, southern Rio Grande rift, USA. Sedimentology 58, 1065-1086.

Macklin, M.G., Lewin, J., 2008, Alluvial responses to the changing Earth system. Earth Surface Processes and Landforms 33, 1374–1395.

Maddy, D., Bridgland, D., Westaway, R., 2001. Uplift-driven valley incision and climate-controlled river terrace development in the Thames Valley, UK. Quaternary International 79, 23-36.

Maher, E., 2005. The Quaternary evolution of the Rio Alias southeast Spain, with emphasis on sediment provenance. Unpublished PhD thesis, University of Liverpool.

Mather AE. 1991. Cenozoic drainage evolution of the Sorbas Basin SE Spain. Unpublished PhD Thesis, University of Liverpool.

Mather, A.E., 1993. Basin inversion: some consequences for drainage evolution and alluvial architecture. Sedimentology 40, 1069–1089.

Mather, A.E. 1999. Alluvial Fans: a case study from the Sorbas Basin, southeast Spain. In: Jones, A.P., Tucker, M.E. and Hart, J.K. (eds) The description and analysis of Quaternary stratigraphic sections. Technical Guide 7. Quaternary Research Association. 77-110.

Mather, A.E., 2000. Impact of headwater river capture on alluvial system development. Journal of the Geological Society, London 157, 957–966.

Mather, A.E., Westhead, K. 1993. Plio/Quaternary strain of the Sorbas Basin, SE Spain: evidence from soft sediment deformation structures. Quaternary Proceedings 3, 57-65.

Mather, A.E. & Stokes, M. 2016. Extracting palaeoflood data from coarse-grained Pleistocene river terrace archives: an example from SE Spain. Earth Surface Processes and Landforms. DOI: 10.1002/esp.4001

Mather, A.E., Hartley, A.J., 2005. Flow events on a hyper-arid alluvial fan: Quebrada Tambores, Salar de Atacama, northern Chile. In: Harvey, A.M., Mather, A.E., Stokes, M., (Eds.), Alluvial Fans: Geomorphology, Sedimentology, Dynamics. Geological Society of London, Special Publications vol. 251, pp. 9-24.

Mather, A.E., Harvey, A.M., Stokes, M., 2000. Quantifying long-term catchment changes of alluvial fan systems. Geological Society of America Bulletin 112, 1825-1833.

Mather, A.E., Stokes, M., Griffiths, J.S., 2002. Quaternary landscape evolution: A framework for understanding contemporary erosion, southeast Spain. Land Degradation and Development 13, 89-109.

Matmon, A., Nichols, K., Finkel, R. 2006. Isotopic insights into smoothening of abandoned fan surfaces, Southern California. Quaternary Research 66, 109-118.

Merritts, D.J., Vincent, K.R., Wohl, E.E., 1994. Long river profiles, tectonism, and eustasy: A guide to interpreting fluvial terraces. Journal of Geophysical Research 99, B7 14031-14050.

Meyrick, R.A., Karrow, P.F. 2007. Three detailed, radiocarbon-dated, Holocene tufa and alluvial fan mollusc successions from southern Ontario: The first in northeastern North America. Palaeogeography Palaeoclimatology Palaeoecology 243, 250-271

Piégay, H., Kondolf, G.M., Minear, J.T., Vaudor, L., 2015. Trends in publications in fluvial geomorphology over two decades: A truly new era in the discipline owing to recent technological revolution? Geomorphology 248, 489-500.

Pope, R., Wilkinson, K., Skourtsos, E., Triantaphyllou, M., Ferrier, G. 2008. Clarifying stages of alluvial fan evolution along the Sfakian piedmont, southern Crete: New evidence from analysis of post0incisive soild and OSL dating. Geomorphology 94, 206-225.

Pope, R., Wilkinson, K. 2005. Reconciling the roles of climate and tectonics in Late Quaternary fan development on the Spartan piedmont, Greece. In: Harvey, A.M., Mather, A.E., Stokes, M., (Eds.), Alluvial Fans: Geomorphology, Sedimentology, Dynamics. Geological Society of London, Special Publications vol. 251, pp. 133-152.

Quigley, M.C., Sandiford, M., Cupper, M.L. 2007. Distinguishing tectonic fromclimatic controls on range-front sedimentation. Basin Research 19, 491-505

Rachocki, A.H., Church, M., 1990. Alluvial Fans: A Field Approach. Wiley, Chichester. 161 pp.

Reheis, M.C., Redwine, J.L., 2008. Lake Manix shorelines and Afton Canyon terraces: Implications for incision of Afton Canyon. Geological Society of America Special Papers 439, p. 227-259.

Robinson, R.A.J., Spencer, J.Q.G., Strecker, M.R., Richter, A., Alonso, R.A. 2005. Luminescence dating of alluvial fans in intramontane basins of NW Argentina. In: Harvey, A.M., Mather, A.E., Stokes, M., (Eds.), Alluvial Fans: Geomorphology, Sedimentology, Dynamics. Geological Society of London, Special Publications vol. 251, pp. 153-168.

Rodés, A., Pallàs, R., Braucher, R., Moreno, X., Masana, E., Bouriés, D.L. 2011. Effect of density uncertainties in cosmogenic 10Be depth-profiles: Dating a cemented Pleistocene alluvial fan (Carboneras Fault, SE Iberia). Quaternary Geochronology 6, 186-194

Rodés, A., Pallàs, R., Ortuño, M., Garcia-Melendez, E., Masana, E. 2014. Combining surface exposure dating and burial dating from paired cosmogenic depth profiles. Example of El Límite alluvial fan in Huércal-Overa basin (SE Iberia). Quaternary Geochronology 19, 127-134

Rowan, J.S., Black, S., Macklin, M.G., Tabner, B.J., Dore, J. 2000. Quaternary environmental change in Cyrenaica evidenced by U-Th, ESR and OSL dating of coastal alluvial fan sequences. Libyan Studies 31, 5-16.

Scott, W.E., Pierce, K.L., Hait, M.H.Jr., 1985. Quaternary tectonic setting of the 1983 Borah Peak earthquake, central Idaho. Bulletin of the Seismological Society of America 106, 1212-1228.

Silva, P.G., Harvey, A.M., Zazo, C., Goy, J.L., 1992. Geomorphology, depositional style and morphometric relationships of Quaternary alluvial fans in the Guadalentin depression (Murcia, southeast Spain). Zeitschrift für Geomorphologie 36, 325-341.

Silva, P.G., Bardají, T., Calmel-Avila, M., Goy, J.L., Zazo, C. 2008. Transition from alluvial to fluvial systems in the Guadalentín Depression (SE Spain) during the Holocene: Lorca fan versus Guadalentín River. Geomorphology 100, 140-153.

Spencer, J.Q.G., Robinson, R.A.J. 2008. Dating intramontane alluvial deposits from NW Argentina using luminescence techniques: Problems and potential. Geomorphology 93, 144-155.

Stokes, M., Mather, A.E., 2000. Response of Plio-Pleistocene alluvial systems to tectonically induced base-level changes, Vera Basin, SE Spain. Journal of the Geological Society, London 157, 303–316.

Stokes, M., Mather, A.E., 2015. Controls on modern tributary-junction alluvial fan occurrence and morphology: High Atlas Mountains, Morocco. Geomorphology 248, 344-362.

Stokes, M., Mather, A.E., Harvey, A.M., 2002. Quantification of river capture induced base-level changes and landscape development, Sorbas Basin, SE Spain. In: Jones S.J., Frostick, L.E., (eds.) Sediment Flux to Basins: Causes, Controls, Consequences. Geological Society of London Special Publication 191, 23-35.

Stokes, M., Cunha, P.P., Martins, A.A., 2012a. Techniques for analysing Late Cenozoic river terrace sequences' Geomorphology 165, 1-6.

Stokes, M., Griffiths, J.S., Mather, A., 2012b. Palaeoflood estimates of Pleistocene coarse grained river terrace landforms (Río Almanzora, SE Spain). Geomorphology 149, 11-26.

Stokes, M., Mather, A.E., Belfoul, A., Farik, F., 2008. Active and passive tectonic controls for transverse drainage and river gorge development in a collisional mountain belt (Dades Gorges, High Atlas Mountains, Morocco). Geomorphology 102, 2–20.

Thorndycraft, V., Benito, G., Gregory, K.J., 2008. Fluvial geomorphology: A perspective on current status and methods. Geomorphology 98, 2-12.

Veldkamp, A., Schrool, J., Viveen, W., In review. Predicting reach-specific properties of fluvial terraces to guide fieldwork. A case study for the Late Quaternary Allier river (France) with the FLUVER2 model. Earth Surface Processes and Landforms.

Ventra, D., Clarke, L. E. 2016. (eds) Geology and Geomorphology of Alluvial and Fluvial Fans: Terrestrial and Planetary Perspectives. Geological Society, London, Special Publications, 440

Wang, H., Harvey, A.M., Xie, S., Kuang, M., Chen, Z. 2008. Tributary-junction fans of China's Yngtze Three-Gorges valley: Morphological implications. Geomorphology 100, 131-139.

Weissmann GS, Bennett GL, Lansdale AL. 2005. Factors controlling sequence development on Quaternary fluvial fans, San Joaquin Basin, California, USA. In Alluvial Fans: Geomorphology, Sedimentology, Dynamics, Harvey AM, Mather AE, Stokes M (eds). Geological Society:London; Special Publication 251: 169–186.

Weissmann, G.S., Hartley, A.J., Scuderi, L.A., Nichols, G.J., Owen, A., Wright, S., Felicia, A.L., Holland, F., Anaya, F.M.L., 2015. Fluvial geomorphic elements in modern sedimentary basins and their potential preservation in the rock record: A review. Geomorphology 250, 187-219.

Wells, S.G., McFadden, L.D., Poths, J., Olinger, C.T. 1995. Cosmogenic 3He surface-exposure dating of stone pavements: Implications for landscape evolution in deserts. Geology 23, 613-616.

Westaway, R., 2001. Flow in the lower continental crust as a mechanism for the Quaternary uplift of the Rhenish Massif, north-west Europe. In: Maddy, D., Macklin, M.,Woodward, J. (Eds.), River Basin Sediment Systems: Archives of Environmental Change. Balkema, Rotterdam, pp. 87-167.

Wheaton, J.M., Fryirs, K.A., Brierley, G., Bangen, S.G., Bouwes, N., O'Brien, G. 2015. Geomorphic mapping and taxonomy of fluvial landforms. Geomorphology 248, 273-295.

Whitfield, E., Harvey, A.M., 2012. Interaction between the controls on fluvial system development: tectonics, climate, base level and river capture – Rio Alias, Southeast Spain. Earth Surface Processes and Landforms 37, 1387-1397.

Figures

Fig. 1 The spatial and temporal scales typical of typical slope processes and landforms that commonly interact with river terrace records.

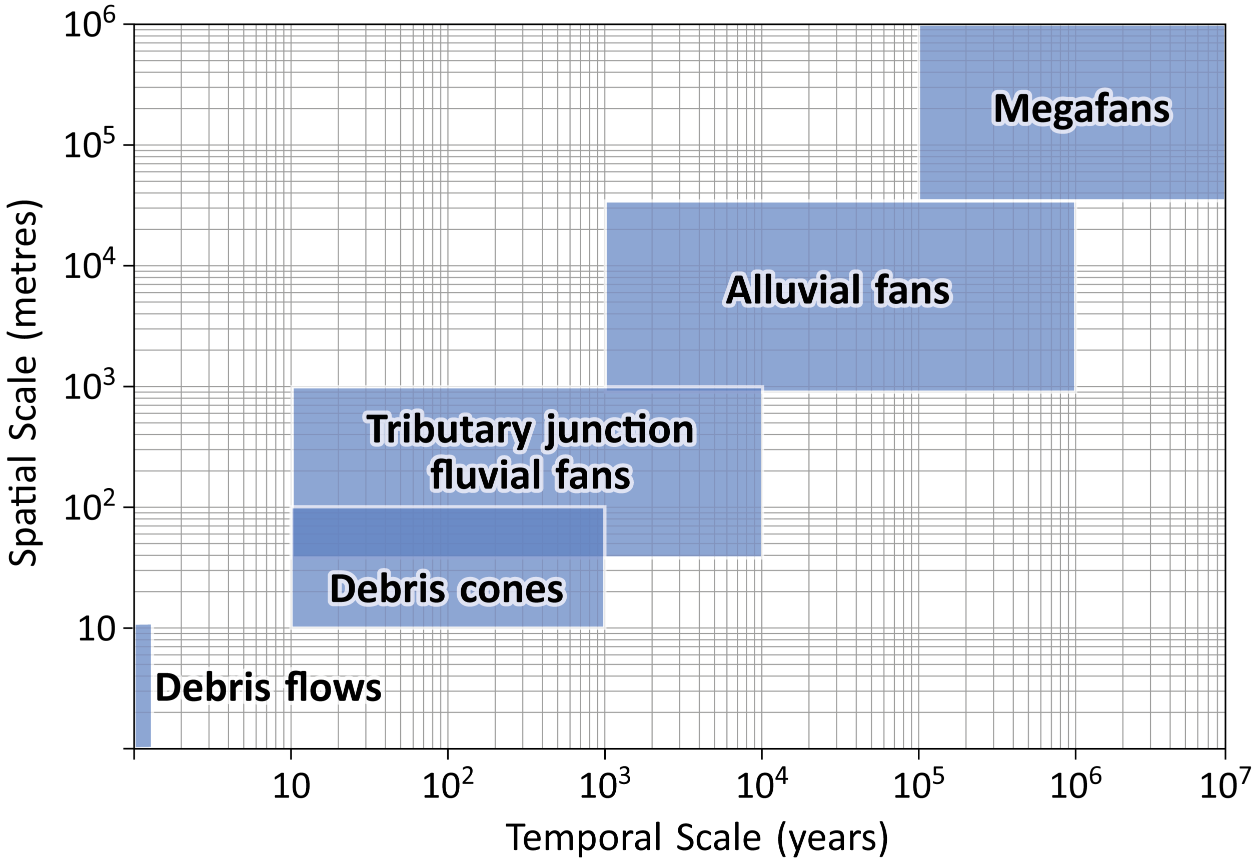


Fig. 2. An example from Silva et al., (1992) of Quaternary alluvial fan development from 5 different mountain front settings in SE Spain. 4 main alluvial fan types were identified from morphometric analysis of the alluvial fans and analysis of the regression residuals. This analysis identified that 3 regional depositional phases along 5 mountain front faults have produced 4 main morphological alluvial fan types which reflect the interaction of local source area lithology, local and regional tectonics and regional climate.

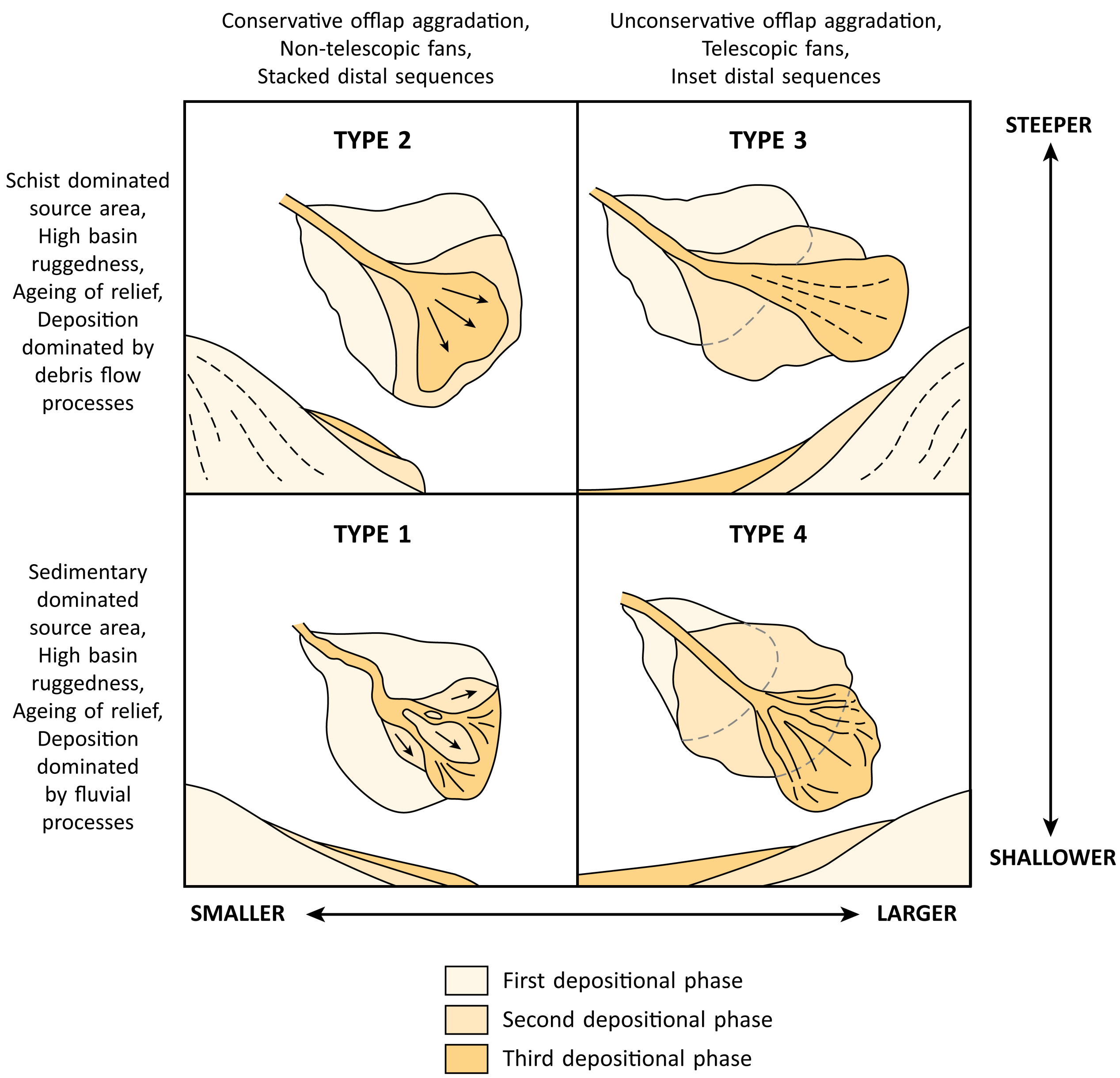


Fig.3. A conceptual model, taken from a summary of the published literature and new data used within this article, to describe behaviour of a simple alluvial fan in a tributary setting adjacent to a main river under different spatial controls (top down versus bottom up) and varying sediment supplies to the alluvial fan. The axes of the model demonstrate the key drivers which may act as top down controls on sediment and water discharge to the alluvial fan (most commonly climate driven) and bottom up base-level lowering (main river behaviour) which most commonly would be main river incision, although foreshortening of alluvial fans through main river lateral toe-cutting can have similar effects. The horizontal axis represents the direction of change in sediment supply to the alluvial fan in the form of increasing sediment supply, which ultimately can lead to the alluvial fan displacing and buffering the river from slope processes or facilitating incision in cases of sediment supply reduction. Generally within this kind of setting enhanced coupling is encouraged by main river incision (or lateral toe cutting) and also by reduction in sediment supply that promotes trenching on the alluvial fan. In the case of toe cutting the connection is most likely to be made on the upstream side of the main river flow direction.

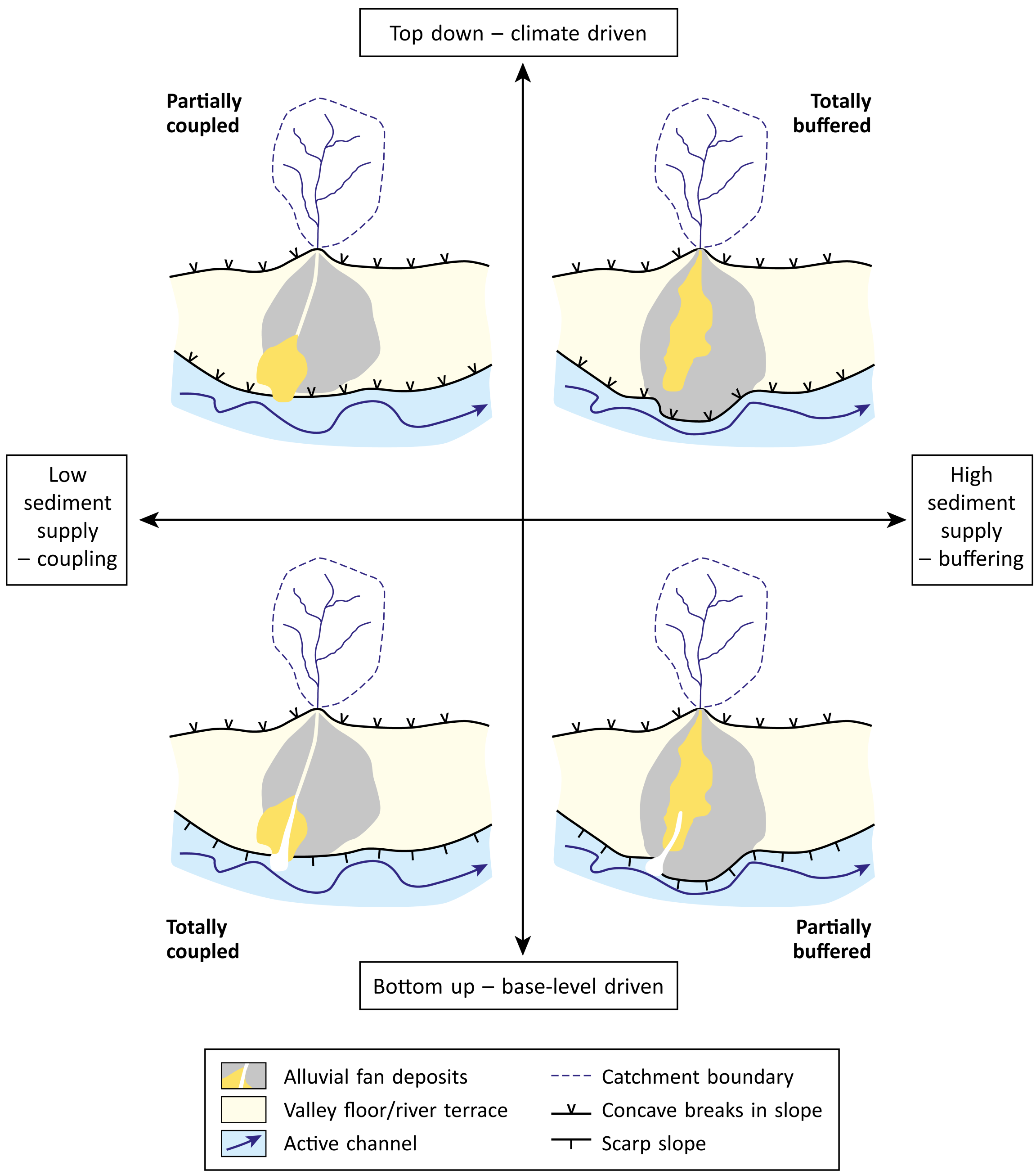


Fig. 4. USA, Idaho case study (a) location; (b) examples of mountain front alluvial fans tributary to the Lost Big River. Lateral toe-cutting is evident (TC) in the morphology of the alluvial fans, including in older Quaternary surfaces (shaded). The arrow indicates the location of distal incision associated with lateral toe-cutting – the meander scars are still visible in the scarp. Between the older, toe-cut surfaces ‘healing lobes’ and ‘healing wedges’ (after Leeder and Mack, 2001) can be observed where the alluvial fan is prograding out from the toe-cut once the main axial river has migrated away, in areas where sediment supply is sustained from the alluvial fan. Bold lines indicate the location of a Holocene (normal) fault. (c) Elkhorn alluvial fan which shows a clear lack of any toe-cutting as the main river has moved away from the base of the alluvial fan. Catchment area and alluvial fan highlighted. Images courtesy of Google Earth Professional 2016.

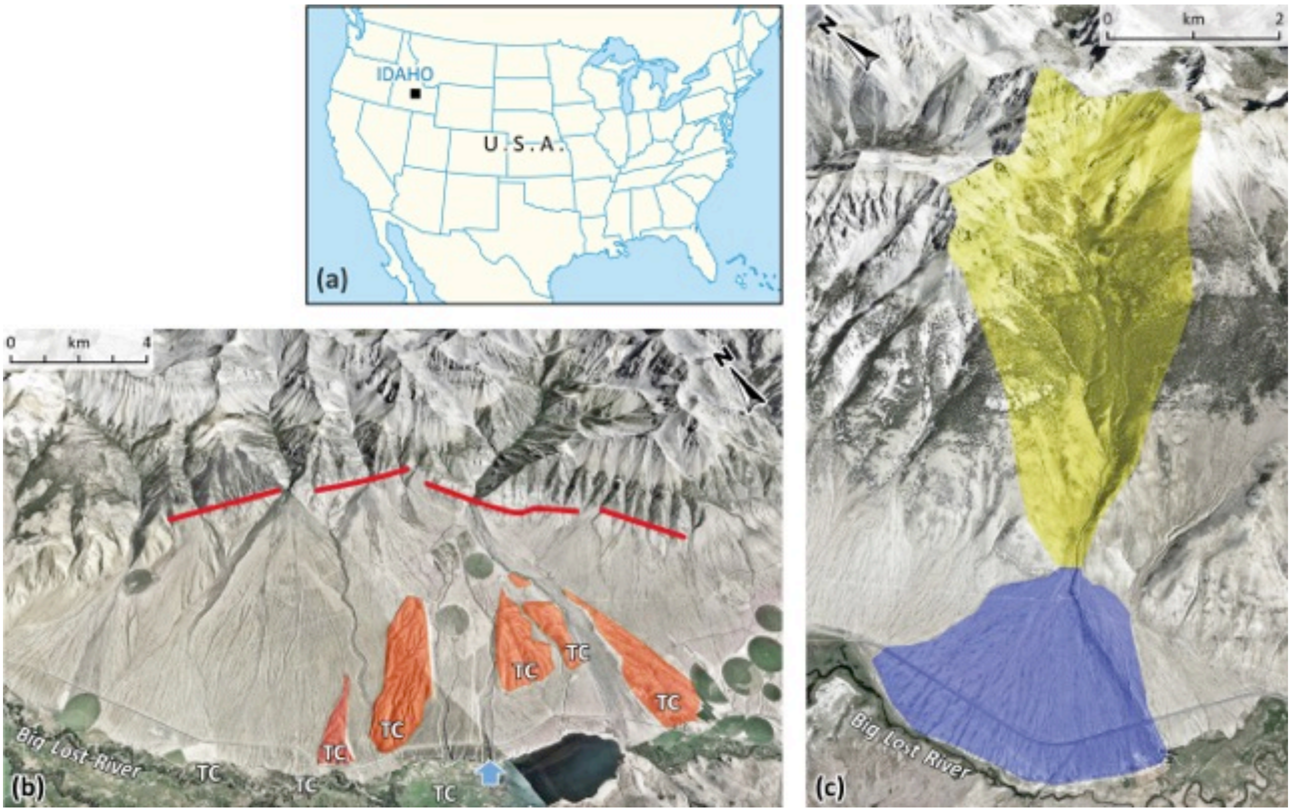


Fig. 5. Examples of the impact of lateral toe-cutting on Quaternary alluvial fan and fluvial archive stratigraphy in New Mexico. Diagrams modified from Leeder and Mack (2001). (a) General location (b) Stratigraphy through the fluvial archives based on field observations from the Palomas Basin. Note presence of toe-cut scarps and prograding alluvial fan 'healing wedge' stratigraphy. (c) distribution of intercalated river and alluvial fan deposits along the Palomas Basin in section and in planform (d). Note location of section X to X' along a transfer fault – see discussion as to significance of this.

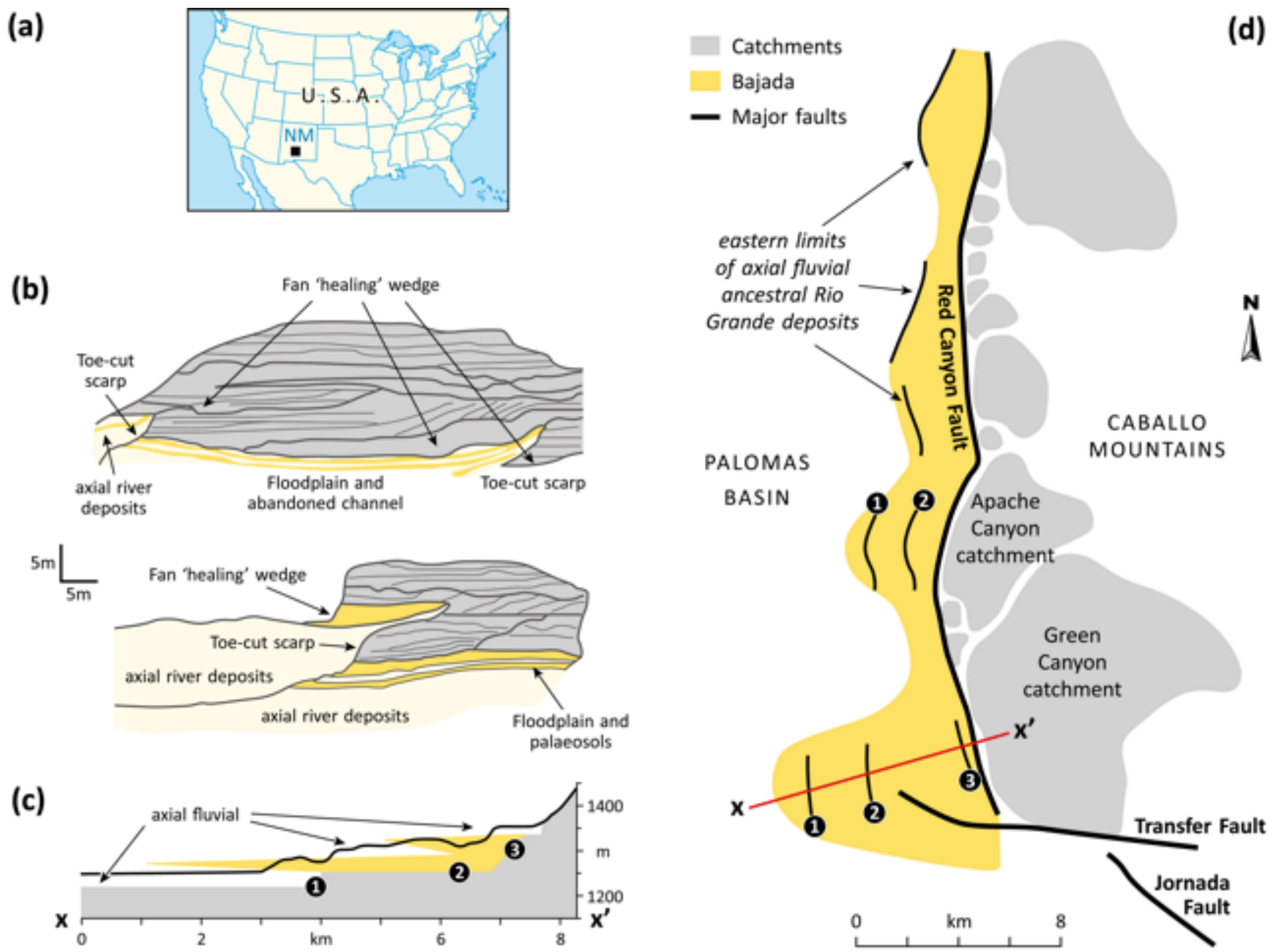


Fig. 6. Location map for SE Spain case studies. Figs. 7 and 8 (Box 1); Fig. 9 (Box 2); Figs 10 and 12 (Box 3) and Fig. 11 (Box 4). Inset image courtesy of Google Earth Professional 2016.

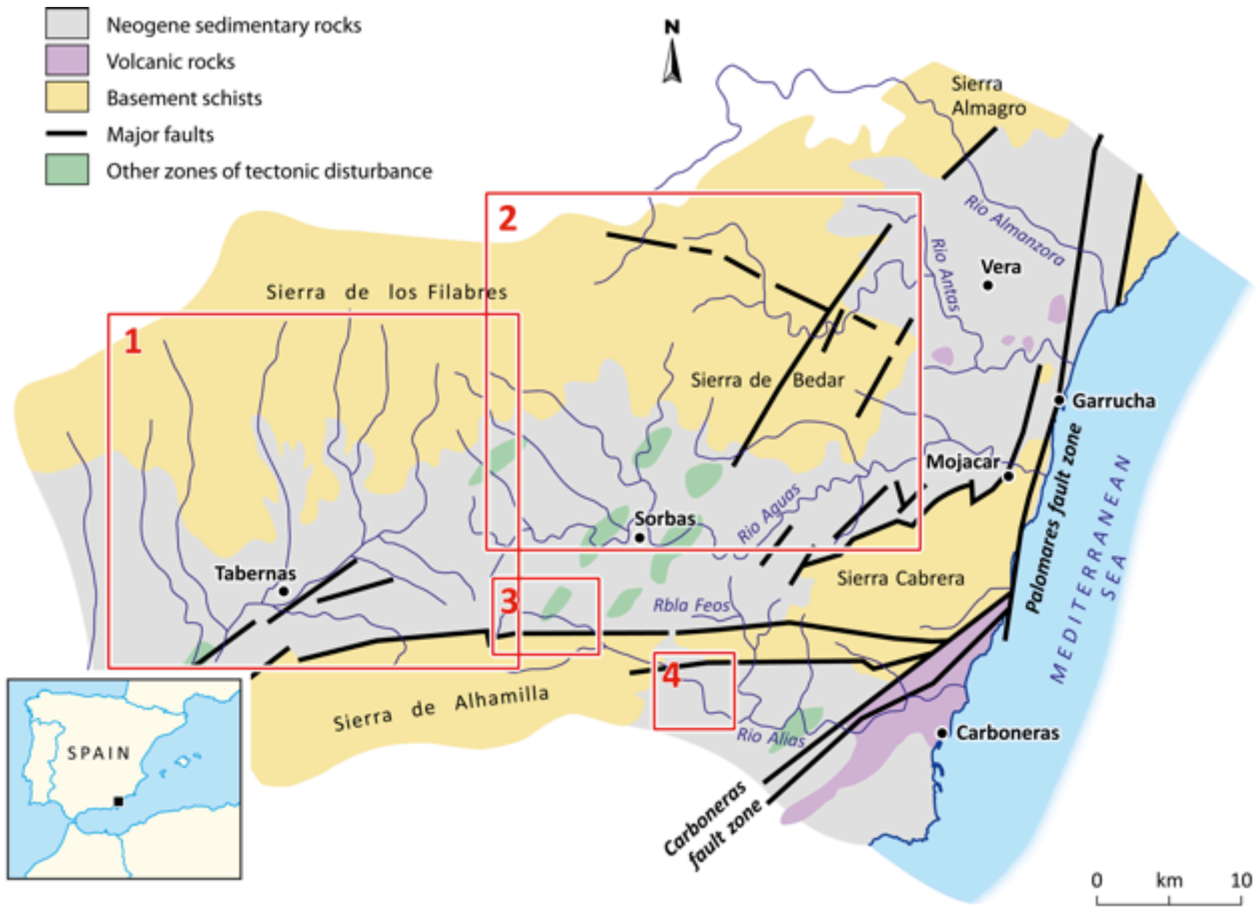


Fig. 7. Alluvial fan and related geomorphology from the Tabernas Basin (Box 1, Fig. 6). (a) plan view showing coupled west of basin and buffered east of basin. (b) relationship between buffering alluvial fans and incised terrace sequence from the west of the basin. Modified from Harvey et al., 2014. L1-L4 refer to the levels of Geach et al., (2015).

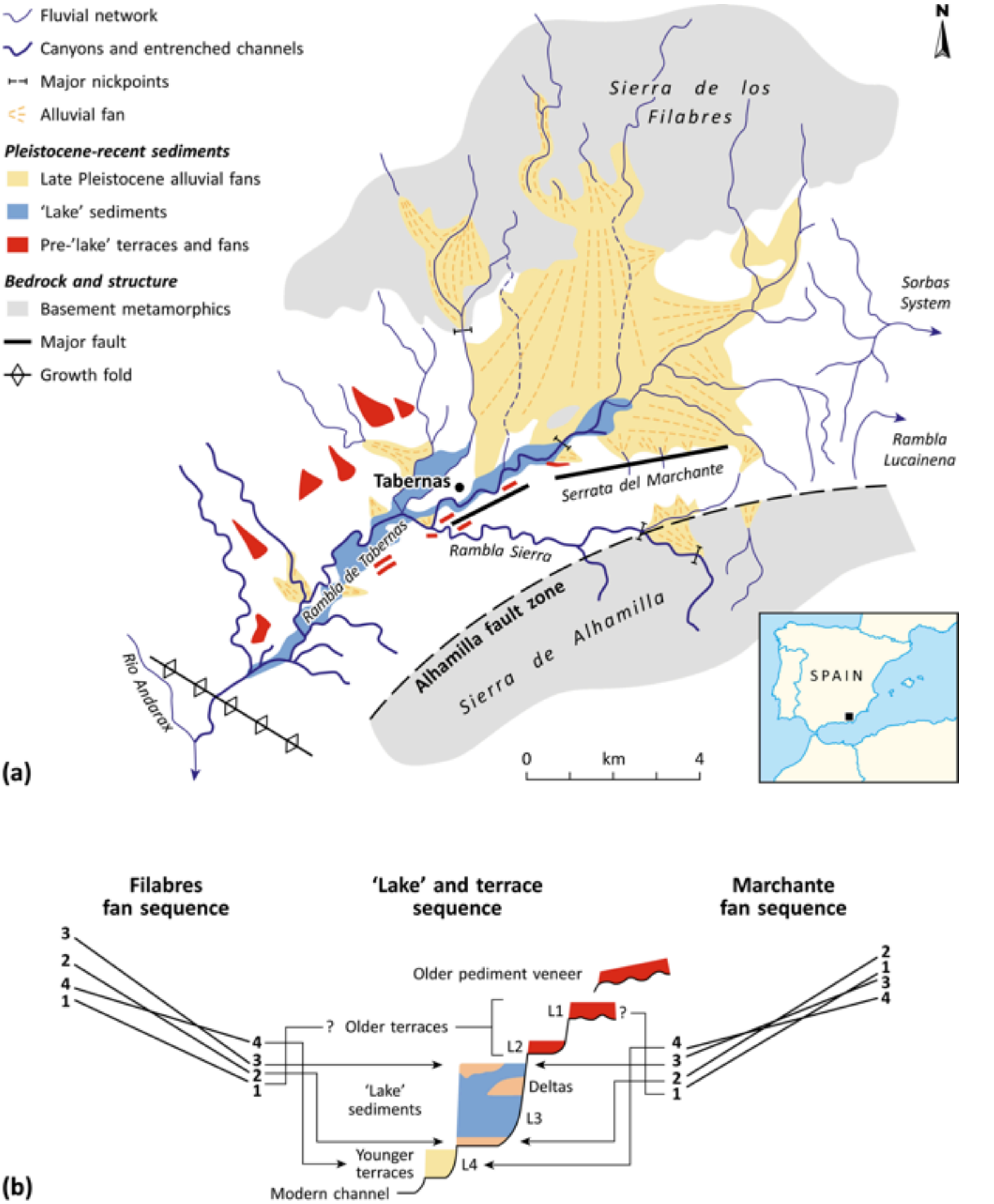


Fig. 8. Field images from Tabernas. (a) Level 2 alluvial fan deposits displaying evidence of tractional flow and sheetform geometries suggesting unconfined flows (section oblique to flow which is to the left). (b) Level 3 coarse terrace deposits from Rambla Sierra (Fig. 7a) lying unconformably on Neogene basin deposits within the Rambla Sierra (southwest portion of the Tabernas Basin) which at this time is buffered by an alluvial fan at its mouth from the more central basin locations. Dashed line indicates base of terrace. (c) palustrine – lacustrine sediments of Level 3 in the basin centre. Note the lack of fine sediments. Dashed line picks out erosive channel within the Level 3 sediments. The coarsest material observed in the section is medium to coarse sand. Note person in foreground for scale.

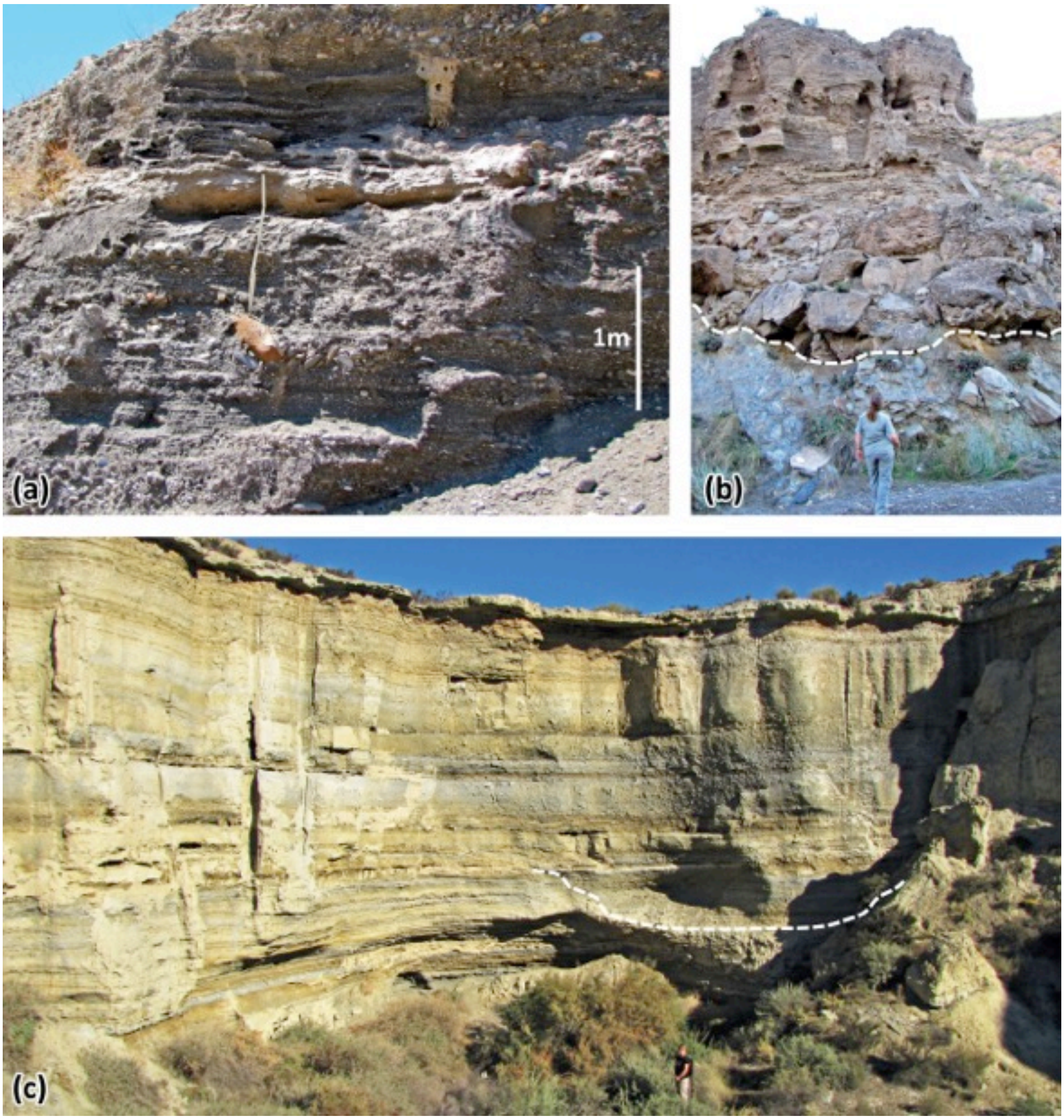
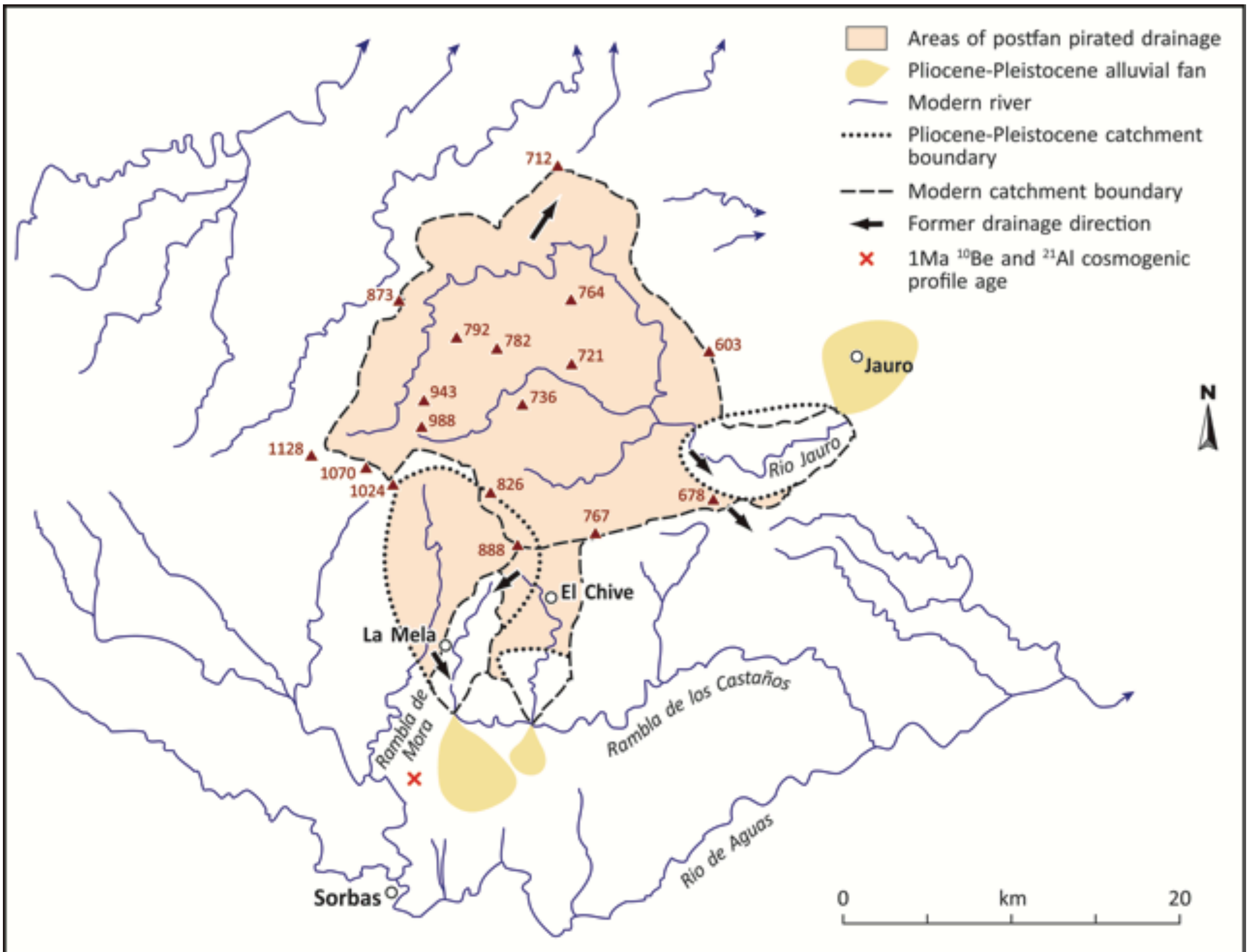


Fig. 9. Catchment changes in the Sorbas-Vera basin (Box 2, Fig 6) modified from Mather et al. (2000). Dashed lines indicate the early Quaternary catchments which have been reconstructed using a knowledge of the provenance of the preserved Quaternary alluvial fan deposits combined with the predicted catchment area characteristics based on alluvial fan area and gradient regressions on a regional database of Quaternary alluvial fans. The table shows the predicted versus modern values based on the dataset.



Fan	F	G	A Predicted	A SE ±1	A SE ±2	A Modern	B Predicted	B SE ±1	B SE ±2	B Modern
La Mela	6.8	0.031	21.8	11.4	5.9	4.25	609	398	261	320
El Chive	1.3	0.035	2.6	7.9	15.2	12	271	412	630	498
Jauro	5.8	0.020	12	22.9	43.8	123	460	701	1071	800

Notes: F – fan area (km^2); G – fan gradient; A – catchment area (km^2); SE – standard error; B – basin relief (m)

Fig. 10. Long-profiles for the terrace sequences in the Lucainena headwater tributaries and the Rambla de Lucainena (Box 3, Fig. 6). Terrace A >300-400 ka; Terrace B > 200 ka; Terrace C>78 ka; Terrace D 32.5±3.4 ka to 10ka; from Whitfield and Harvey (2012).

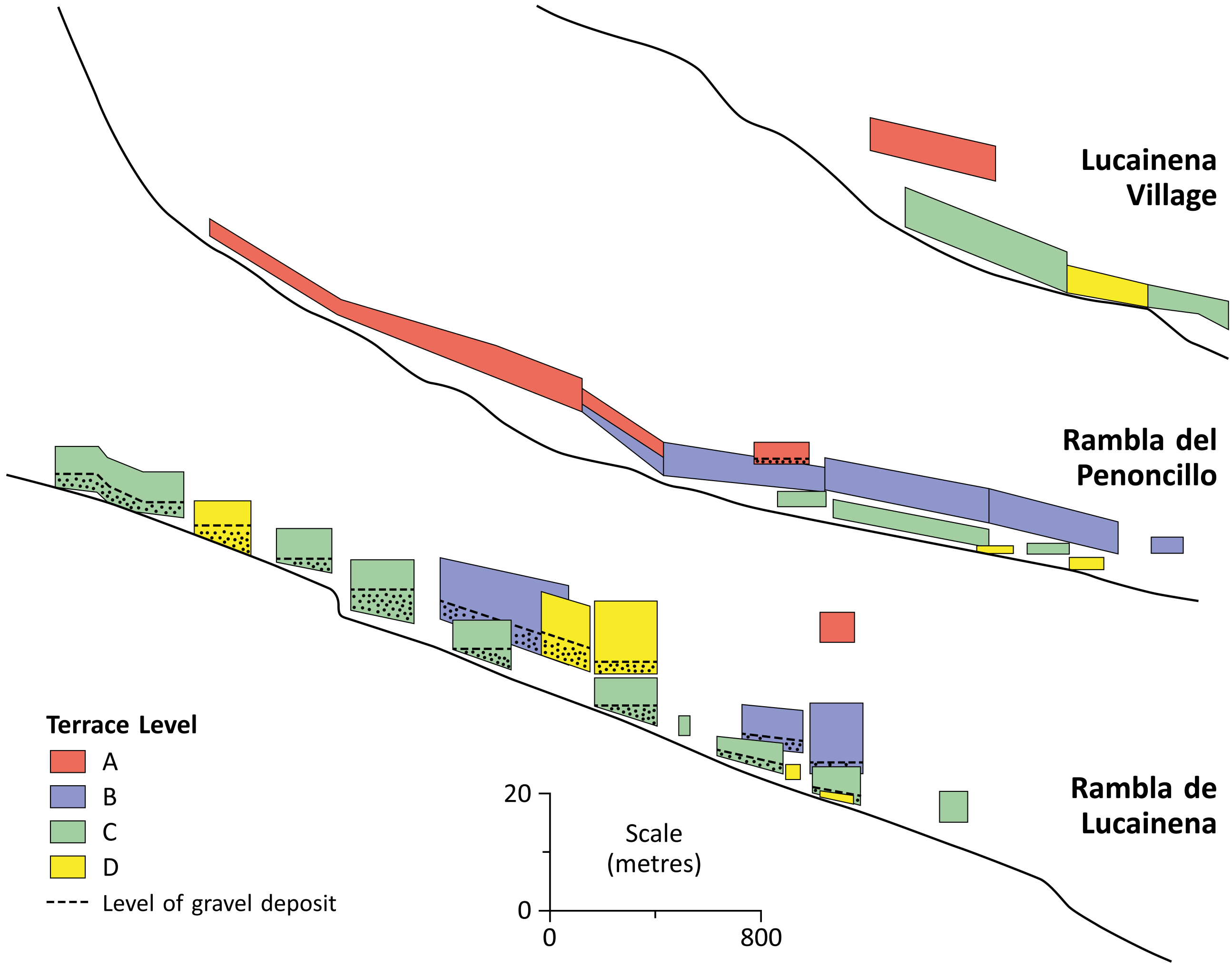


Fig. 11. Field images from Box 4 (Fig. 6) of the tributary-junction alluvial fan (Río Alías) within terrace A before the Rambla de los Feos tributary junction. (a) alluvial fan terrace A gravels (above dashed white line) conformably overlying the Polopos Formation at Collado de Polopillos. Note the unconfined, sheetform geometries of the Terrace A deposits. (b) Terrace A imbricated gravels indicating flow to the south/southeast. There is no evidence of channelisation or confinement of flow. Note also floating clasts within a finer gravel sand matrix indicating hyper-concentrated flow.

Fig. 12. River capture acting as a bottom up coupling mechanism for the alluvial fan and river system in the headwaters of the Rambla Lucainena and Rambla del Penoncillo (Box 3, Fig. 6), and demonstrating the time transgressive nature in the landscape from east to west.

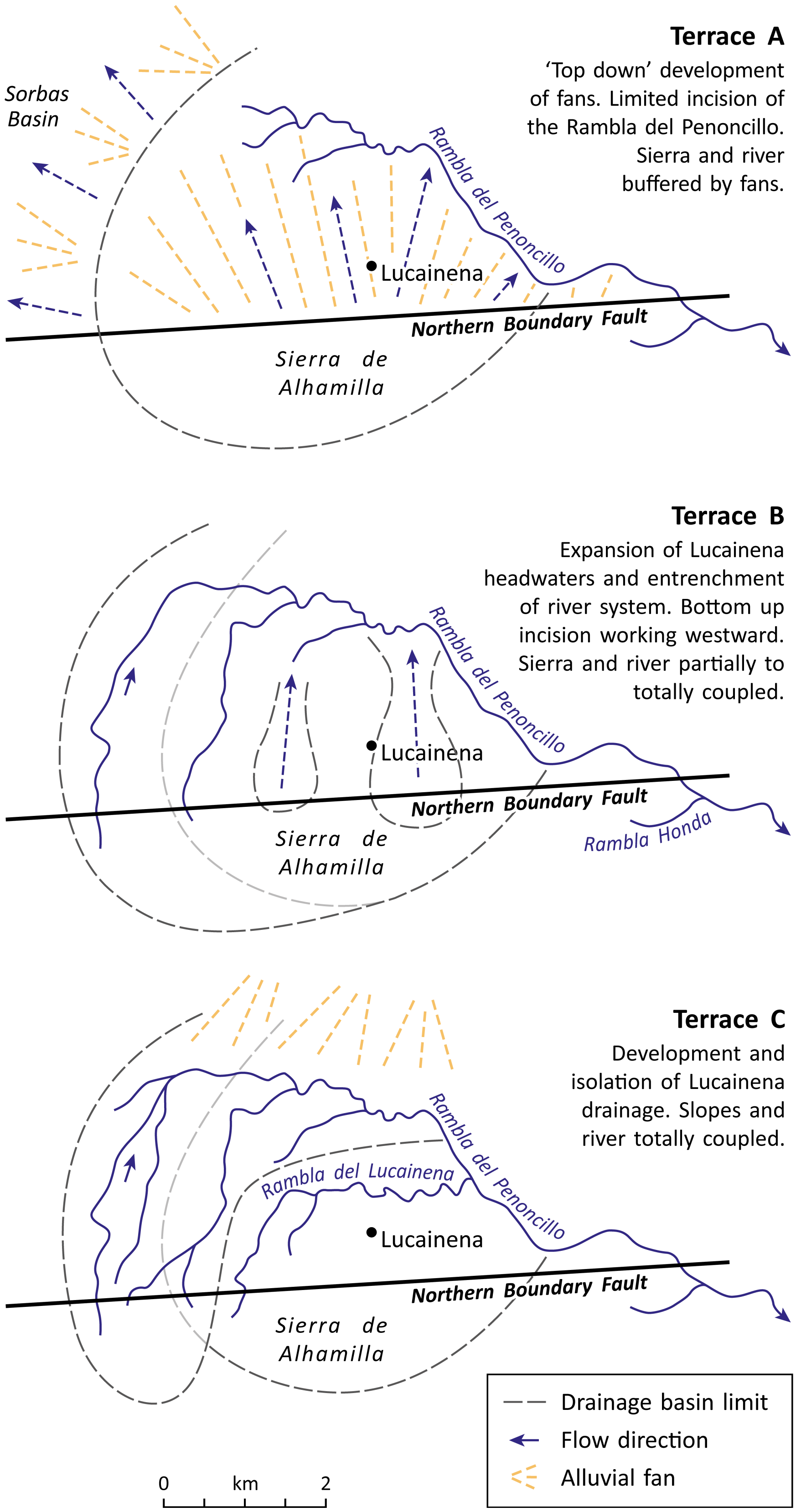


Fig. 13. (a) Location of the Ait Said tributary alluvial fan (QF1) in the River Dades Catchment. (a) relationship of alluvial fan and river terrace deposits. Darker area of image is the Holocene flood plain of the River Dades. Images courtesy of Google Earth Professional 2016. (b) field image of the tributary alluvial fan and terraces. Note steepness of alluvial fan surface (6°) compared to modern river. X – X' indicates position of cross-section, blue arrows indicate line of trench through alluvial fan. (c) cross-profile though the alluvial fan showing insipient incision and alluvial fan head trench (RHS) and (d) modern alluvial fan trench profile and relict alluvial fan surface (QF1) taken up the mid-fan line. Field survey undertaken using a Trupulse$_{TM}$ 360° laser range finder.

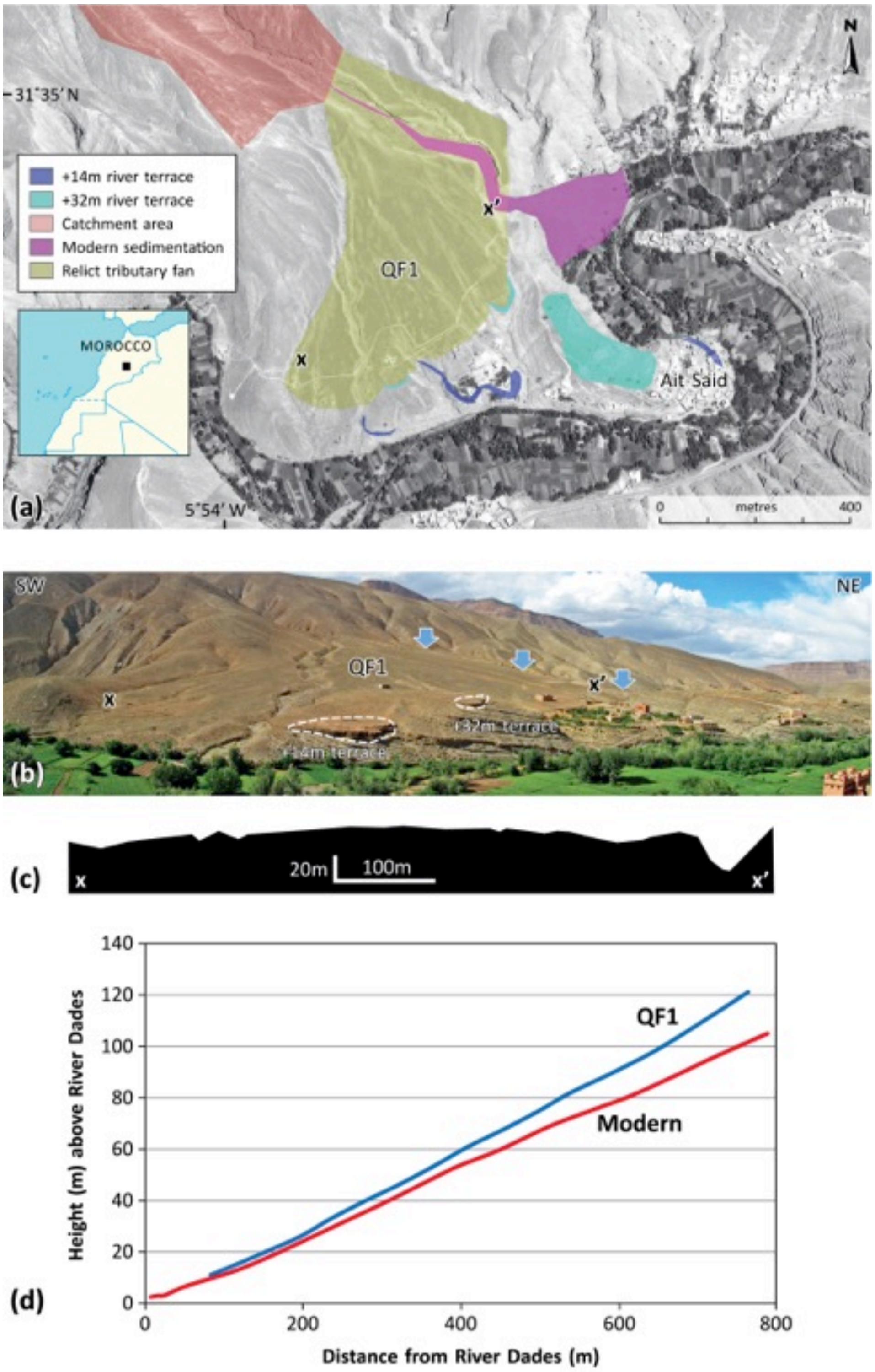


Fig. 14. Field images from the Dades study area of the Quaternary landform and associated sediments. (a) river terrace level at Ait Said (base 32m above modern river level). Note well rounded cobbles and clast supported nature of the deposits. Provenance is the same as the tributary junction alluvial fan (predominantly limestone). (b) Pleistocene alluvial fan surface (QF1) looking up alluvial fan to apex. Note lack of meso-micro relief. (c) view looking down alluvial fan trench from QF1 apex. Note inset levels in the alluvial fan (QF2, 3 and 4). Approximately 20m thickness of sediments are locally present although basement geology is evident (arrowed). (d) Note laterally unconfined nature of flows and indication of episodic deposition during alluvial fan building (palaesol arrowed). Inset shows detail of sedimentology – poorly sorted angular to subangular limestone fragments suggestive of debris flow deposition. Person circled for scale.

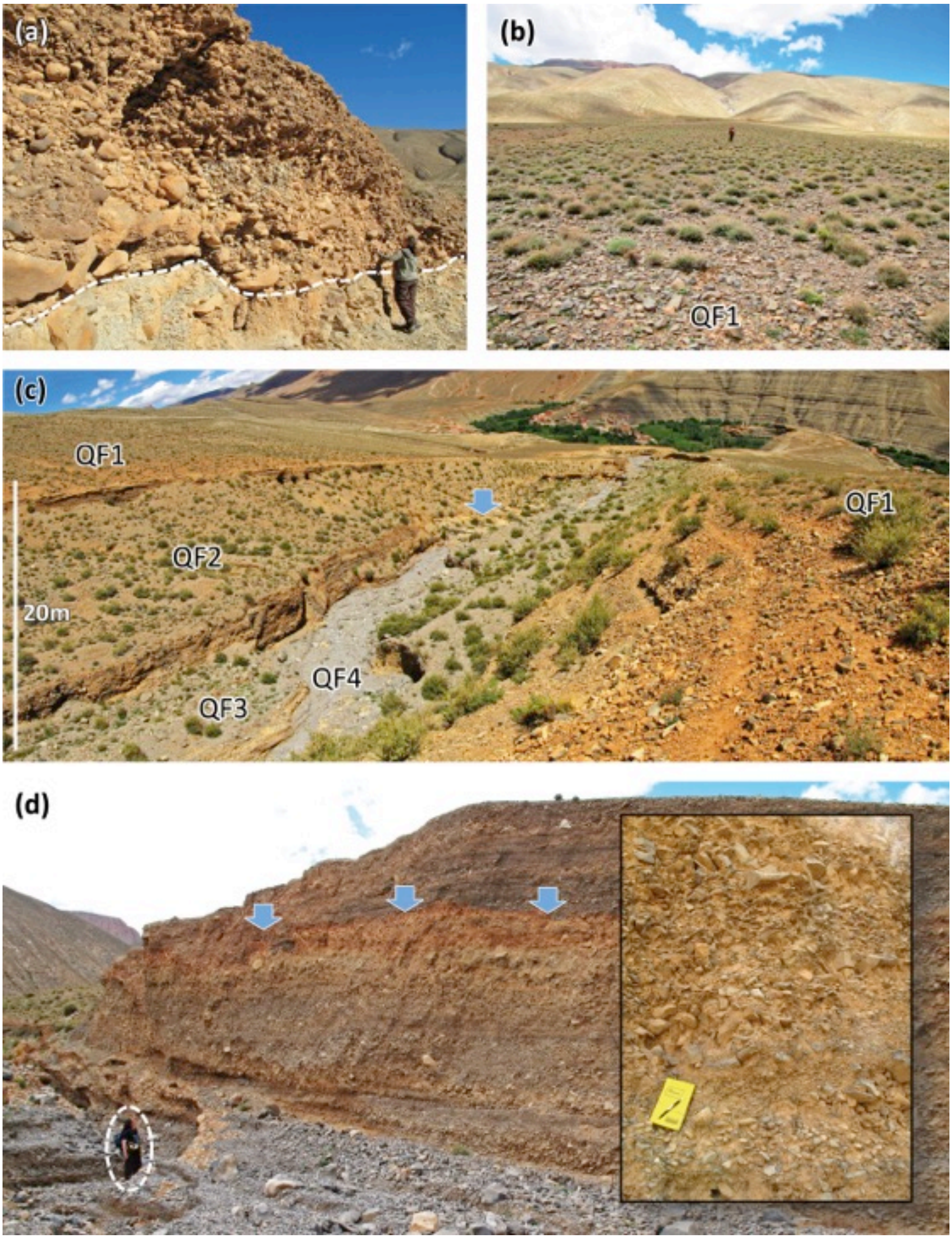


Fig. 15. Field images of modern flow processes (a) cohesionless debris flows in the upper part of the Ait Said alluvial fan trench – note size of material; (b) cohesionless debris flows on the depositional modern alluvial fan lobe (seen in c). Different colours reflect insitu weathering of older lobe (darker colour) over-ridden by more modern flow lobes. (c) modern depositional alluvial fan lobe toeing out into the River Dades (visible on the RHS of image). The system today is totally to partially coupled depending on the timing of the ‘build and reset’ cycle operating within the recent record (see Stokes and Mather, 2015 for fuller discussion). (d) localised slack water deposits from Holocene Dades River floods comprising sand and silt grade material as horizontal laminations (top half of section) and climbing ripples (lower half of section) trapped upstream of a tributary alluvial fan constriction.