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The connections between river terraces and slope deposits as paleoclimate proxies: the Guadalaviar - Turia sequence (Eastern, Iberia Chain, Spain)

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Abstract:	This study, focused on the well-exposed terrace deposits of the Guadalaviar and Turia rivers and associated slopes, provides a better understanding of the genetic connection between river-terrace sediments and slope accumulations in a setting influenced by temperate to cold (extraglacial) climates: the Sierra de Albarracín and Alfambra–Teruel depression (Iberian Chain, eastern Spain). The terrace system comprises seven levels, Qt1 to Qt7. In the two older levels (Qt2 and Qt3) lateral connections with thick stratified slope screes were observed. The lower terraces (Qt4 to Qt7) have less expressive slope deposits. New Optically Stimulated Luminescence (OSL) ages, using quartz-OSL and pIRIR 290, were obtained from these Quaternary deposits. Qt2 is dated ~310 to 270 ky (Marine Isotope Stage (MIS) 9–8); Qt3 dates from ~175 to 150 ky (MIS 6), Qt4 from ~136 to 80 ky (MIS 5e–a) and Qt5 from ~23 ky (MIS 2); Qt6 has a tufa dated to 10–4.6 ky (early–middle Holocene), while Qt7 probably records the last 4 ky (late Holocene). The thick slope deposits connected with the upper parts of the Qt2 and Qt3 terraces were generated under the cold-climate conditions of MIS 8 and MIS 6, respectively. These are the oldest dated slope deposits connected with fluvial terraces documented in the Mediterranean region, their preservation and recognition thus being of considerable significance. Chronological correlation of the glacial–interglacial cycles of the Pyrenees with the marine isotope stages conforms to the interpretation of paleo-environmental data and sedimentary controls of terrace genesis in extraglacial fluvial basins under temperate- to cold-climatic conditions.
Suggested Reviewers:	Kurt Stange, PhD kmstange@uni-bremen.de He is an expert in the subject.
	José M García Ruiz, PhD humberto@ipe.csic.es He is an expert in the subject.
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	Augusto Pérez Alberti, PhD xepalber@gmail.com
	Jeff Vandenberghe, PhD vanj@geo.vu.nl He is an expert in the subject.

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Opposed Reviewers:	
Response to Reviewers:	Tucumán, 20 december 2021 Dear Editor, Thank you very much for your considerations about our paper, please find below all asnwers to the reviewers. Sincerely yours, Dr. José Luis Peña-Monné Universidad de Zaragoza jlpena@unizar.es Complete contact address: Dr. José Luis Peña-Monné Dpto. de Geografía y Ordenación del Territorio Universidad de Zaragoza Pedro Cerbuna, 12 50009 Zaragoza (Spain) jlpena@unizar.es +34 696495028 Ref.: Ms. No. GLOPLACHA-D-21-00390R1 The connections between river terraces and slope deposits as paleoclimate proxies: the Guadalaviar - Turia sequence (Eastern, Iberia Chain, Spain) Global and Planetary Change Dear Dr. Sampietro-Vattuone, Thank you for submitting your manuscript to Global and Planetary Change. I agree that authors have done excellent work in revising the manuscript and only very minor issues remain to be solved, as noted below. This work has resulted in a very interesting manuscript. Although the reviewer has recommended to accept the manuscript, I suggest to perform a (very) minor revision because the below recommendations are difficult to implement at proof times. If possible, I also suggest the abstract more general, the very detailed numbers are less useful in this manuscript section aimed at general understanding. Please do one more careful reading of the manuscript and correct already now all potential small language issues. Such a small revision will likely result in faster publication of your manuscript. Thank you for your understanding. Liviu Matenco Editor Global and Planetary Change A: The abstract was re-written following your suggestions. All other reviewer suggestions were followed. Reviewer #1: I have read the revised version of the manuscript. I agree with the editor and think that the authors did a good work about the revision. I recommend the manuscript be accepted for publication in the journal Global and Planetary Change. There are minor errors about the English usage in the present version of the ms (for example, Lines 671, 675: some sentences lack subjects "it"??). I suggest the authors carefully check the ms to ensure the correct English usage. A: YES it is “it”, we revise the manuscript again and we were not able o find another mistake of this kind. Care should be taken in the interpretations of the temporal and spatial patterns of the calculated river incision rates (Lines 677-682), since the height of some specific terrace

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Zaragoza (Spain)
16th July, 2021

Dear Editor,

Together with this letter I enclosed the manuscript "**The connections between river terrace and slope deposits: the Guadalaviar–Turia sequence (Eastern Iberian Chain, Spain)**" to be considered for publication in Global and Planetary Change.

Sincerely yours,

Dr. José Luis Peña-Monné
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Tucumán, 20 december 2021

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Thank you very much for your considerations about our paper, please find below all asnwers to the reviewers.

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Liviu Matenco
Editor
Global and Planetary Change

A: The abstract was re-written following your suggestions. All other reviewer suggestions were followed.

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A: we introduced some considerations on the subject to relativize the estimations.

Highlights

- The fluvial terraces and connected slopes of the Guadalaviar–Turia rivers are analysed.

- A Qz-OSL and pIRIR290 chronological framework was established.

- Slope deposits-fluvial terraces linkages provide palaeoenvironmental information.

- These are the oldest slope deposits dated in the Mediterranean region.

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The connections between river terraces and slope deposits as paleoclimate proxies: the Guadalaviar - Turia sequence (Eastern, Iberia Chain, Spain)

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Abstract

This study, focused on the well-exposed terrace deposits of the Guadalaviar and Turia rivers and associated slopes, provides a better understanding of the genetic connection between river-terrace sediments and slope accumulations in a setting influenced by temperate to cold (extraglacial) climates: the Sierra de Albarracín and Alfambra–Teruel depression (Iberian Chain, eastern Spain). The terrace system comprises seven levels, Qt1 to Qt7. In the two older levels (Qt2 and Qt3) lateral connections with thick stratified slope screes were observed. The lower terraces (Qt4 to Qt7) have less expressive slope deposits. New Optically Stimulated Luminescence (OSL) ages, using quartz-OSL and $pIRIR_{290}$, were obtained from these Quaternary deposits. Qt2 is dated ~310 to 270 ky (Marine Isotope Stage (MIS) 9–8); Qt3 dates from ~175 to 150 ky (MIS 6), Qt4 from ~136 to 80 ky (MIS 5e–a) and Qt5 from ~23 ky (MIS 2); Qt6 has a tufa dated to 10–4.6 ky (early–middle Holocene), while Qt7 probably records the last 4 ky (late Holocene). The thick slope deposits connected with the upper parts of the Qt2 and Qt3 terraces were generated under the cold-climate conditions of MIS 8 and MIS 6, respectively. These are the oldest dated slope deposits connected with fluvial terraces documented in the Mediterranean region, their preservation and recognition thus being of considerable significance. Chronological correlation of the glacial–interglacial cycles of the Pyrenees with the marine isotope stages conforms to the interpretation of paleo-environmental data and sedimentary controls of terrace genesis in extraglacial fluvial basins under temperate- to cold-climatic conditions.

Keywords: Fluvial terraces, Stratified screes, Quaternary, OSL dating, glacial–interglacial cycles

1. Introduction

Geomorphological, sedimentological, and chronological studies of fluvial terrace deposits and other Quaternary sediments (e.g. pediments, alluvial fans, aeolian deposits, slopes, tufas, glacier and lake deposits, among others) provide information regarding paleoenvironmental conditions as well as palaeogeographical and landscape evolution (e.g., Bridgland, 2000; Bridgland et al., 2004; Briant et al., 2005; Antoine et al., 2007;

Bridgland and Westaway, 2008; Westaway et al., 2009; Mather et al., 2017; Cunha et al., 2017, 2019). Research on such sequences usually focuses on the terrace itself and perhaps neglects the wider geomorphological context.

In this study we have utilized detailed geomorphological mapping of the entire fluvial basin as a tool to establish the landscape evolution during the Quaternary and to promote regional correlation with nearby fluvial systems. Furthermore, sound reconstruction of paleo-environmental evolution and the establishment of evolutionary stages needs reliable (geo)chronological data (Lewis et al., 2009). With the establishment of a chronological framework, the genetic interpretation of terrace and interconnected slope deposits (cf. Starkel, 2003) allows their correlation with global climatic phases, in particular the Marine Isotopic Stages (MIS) record, and the understanding of regional-scale sedimentary controls: climate, eustasy and crustal movement resulting from tectonic and atectonic influences (Maddy et al., 2000; Vandenberghe, 2003; Martins et al., 2009; Cunha et al., 2012, 2017, Silva et al., 2017; Karampaglidis et al., 2020a).

In the Iberian Chain (eastern Spain), systematic mapping of river terraces and other Quaternary deposits has provided, since the 1970s, significant insight into regional landscape evolution (e.g., Ibáñez, 1976; Lozano, 1988; Sánchez Fabre, 1989; Gracia Prieto, 1990; Gutiérrez, 1998). The temporal ordering of these fluvial units was based on cartographic criteria, with topographical and sometimes sedimentary factors dominant. The only chronological constraints available were from sporadic palaeontological remains (Esteras and Aguirre, 1964; Moissenet, 1985) and Paleolithic artefacts (Obermaier and Breuil, 1927) from terraces in the Alfambra–Teruel depression. Later improvements in the Quaternary geochronology of the Guadalaviar River came from U/Th series and ^{14}C dating of multiple Holocene tufas levels (Peña

Monné et al., 1994; Sancho et al., 1997). Reliable ages of Holocene stratified screes were subsequently determined by ^{14}C (Peña-Monné et al., 2017) and geoarchaeological studies combined with ^{14}C dating allowed the definition of accumulation–downcutting phases during the late Holocene (Peña Monné, 2018). There has been extensive dating of Pleistocene terraces and other deposits, such as tufas and slopes dated by OSL, ESR and U/Th methods, affected by neotectonic activity around the junction of the Jiloca and Alfambra–Teruel grabens (e.g., Arlegui et al., 2004; Gutiérrez et al., 2008, 2020; Lafuente, 2011; Lafuente et al. 2011, 2014; Simón et al., 2012), while Santonja et al. (2014) and Duval et al. (2017) obtained numerical ages from the Pleistocene (Lower to Middle Paleolithic) Cuesta de la Bajada Paleolithic site located at the terrace sequence of the Alfambra River.

The main objective of this paper is to establish the Quaternary evolution of a fluvial system subjected to temperate and cold climatic episodes and lying beyond the influence of glaciation, with the aim of clarifying the relationships between fluvial and slope deposits within terrace sequences, obtaining palaeo-environmental data and further clarifying the genetic interpretation of this fluvial–colluvial system. To accomplish this, it was necessary to reappraise the terraces of the Guadalaviar–Turia system and to improve correlation with the sequence in the tributary Alfambra River. The combined catchments cover a large area of the eastern Iberian Chain. Sediment samples (sands and silts) were collected for Optically Stimulated Luminescence (OSL) dating and for laboratory sedimentological characterization. The integrated analysis of data has allowed us to propose correlation with the MIS sequence and with regional palaeo-environmental features, such as the Pyrenean glacial phases.

The Guadalaviar-Turia fluvial system offers the region of the Iberian Range with the best development of fluvial terraces and connected slopes. The study of these sequences provides interesting proxies for the paleoclimatic reconstruction of the Eastern Iberian Range.

2. Regional setting

The upper Turia catchment area is located in the eastern sector of the Iberian Chain (NE of Spain, Fig. 1a), extending over the Sierra de Albarracín (1000–1936 m a.s.l.) and Sierra de Gúdar (800–2019 m a.s.l.) (Fig. 1b). The main fluvial systems are formed by the Guadalaviar and Alfambra Rivers. After leaving the ranges, both rivers enter the Alfambra-Teruel depression (800–110 m a.s.l.) to merge near the city of Teruel to be named Turia River. From there, the river flows up to the outlet in the Mediterranean Sea, close to Valencia. The Guadalaviar basin has 959 km^2 with an annual average flow of 1.96 m^3/s (San Blas gauging station) (Sánchez Fabre et al., 2013). Its main tributaries are Fuente del Berro, Griegos, and Garganta rivers. The basin of the Alfambra River covers 1398 km^2 and has an average flow of 1.16 m^3/s at Teruel (Sánchez Fabre et al., 2013). These modest flows are a consequence of low rainfall under a continental Mediterranean climate in an intra-mountaine setting. In these relieves, rainfall ranges between 600 and 800 mm per year (800–1000 in the highest areas, with snow in winter), while in the Teruel depression it generally range between 400 and 500 mm per year (Peña Monné et al., 2002). Autumn–winter rain alternates with convective precipitation in summer, the seasonal variation gradient peaking in March–April due to snow-melt from the high areas in spring (Sánchez Fabre et al., 2013).

Geologically (Fig. 1c), the Sierra de Albarracín comprises a higher mountainous central massif formed by Palaeozoic rocks (Ordovician and Silurian quartzites and slates) bordered by extensive erosive surfaces cut on Jurassic limestones and marls, which are the main geomorphological component of the Sierra de Albarracín (Lozano and Peña Monné, 2010). The most important is the Main Erosion Surface of the Iberian Chain, ascribed to the Middle–Late Pliocene (Peña Monné et al., 1984). During the Middle–Late Pleistocene, tectonic activity promoted the deformation of this surface and the subsidence of surrounding grabens (Simón, 1984). Regional uplift drove deep incision of the fluvial network in carbonate rocks, forming lengthy fluvio-karstic canyons. Quaternary sedimentary accumulations are rarely preserved on these settings. In addition, the lithology and its previous geological structure promote the development of large karstic poljes (Peña Monné et al., 1989, 2010a) and fields of dolines (Gutiérrez and Peña Monné, 1979a, 1979b; Sánchez Fabre et al., 2010) over carbonate rocks. These major features have a principal function in the setup of the Guadalaviar drainage basin hydrological system. Besides, there are testimonies of glacial moraines over the 1000 m a.s.l. and several stages of slopes with cold genesis (periglacial environments) from Pleistocene and Holocene (Gutiérrez and Peña Monné, 1977; Gutiérrez and Jiménez, 1993; Peña Monné et al. 2020b; Peña-Monné et al., 2017).

The Guadalaviar, Alfambra and Turia rivers run through the Alfambra–Teruel depression, a graben elongated NNE–SSW that was created by an extensional fault system during the Early to Middle Miocene and reactivated as a half-graben by later extension (Simón, 1984). The Neogene filling of this basin comprises siliciclastic, evaporitic and carbonate sedimentary rocks (Fig. 1c). Fluvial incision into the lacustrine limestones (between 50 and 200 m deep) has formed a landscape of mesas (or *muelas*) among valleys where there has been extensive Quaternary deposition. Quaternary tectonics is evidenced by the presence of active faults in the eastern margin of the Alfambra-Teruel graben and the north fault of the Jiloca graben (Concud sector). Both were studied to know the activity ages (Arlegui et al., 2004; Lafuente, 2011; Lafuente et al., 2011, 2016; Simón et al., 2012, 2016; Gutiérrez et al., 2020).

3. Materials and methods

The information presented here is derived from geomorphological, tectonic, stratigraphical, sedimentological and chronological data using a standard approach for the study of fluvial and landscape evolution (e.g. Westaway et al., 2009; Stokes et al., 2012).

3.1. Geomorphological mapping and classification of terraces and slopes

A geomorphological study of the broader region was undertaken to characterize the major fluvial morpho-stratigraphical units and to produce detailed mapping of the more relevant areas, especially those where there is a potential link between river terraces and slope accumulations; two areas in the Sierra de Albarracín and another two in the Alfambra–Teruel depression were thus selected for detailed study. Fieldwork included detailed geomorphological mapping based on topographical (1/25,000) and geological (1/50,000) base maps, but also stratigraphic logging and sedimentological characterization of fluvial and slope deposits in order to obtain data on the sedimentary processes and depositional environments they represent.

Different fluvial terrace levels were identified in the Sierra de Albarracín as well as the Teruel depression. They are composed by well-rounded gravels of Mesozoic limestones, dolomites and sandstones, and Paleozoic quartzites. The terraces were differentiated on the basis of (1) relative height, (2) lithostratigraphic and sedimentological characteristics, and (3) samples for luminescence dating. Besides, slope deposits are composed of angular clasts mainly of Jurassic limestones forming abrupt slopes (30-35º). They are stratified screes normally cemented with carbonates. They were identified according to (1) their lateral connections with its respective fluvial terraces, (2) lithostratigraphic and sedimentological characteristics, and (3) samples for luminescence dating.

The record of detailed stratigraphic profiles allows to establish the inner relationships between slopes and fluvial terraces. The general correlation of the fluvial terrace system along the valley is also established drawing of a longitudinal profile. The correlation of the fluvial terrace levels along the valley is difficult due to the wide standard deviations of the datings and the local variations of terraces heights above river bed related to subsidence and lateral expansion of the terraces. For the same reasons, the estimation of incision rates shows the same problems, then, we just propose the average rates of deepening of the valleys.

3.2. Optically stimulated luminescence dating

For OSL dating, samples were collected from sediment outcrops in the study area. The sampling strategy involved targeting units from the base to the top of each terrace aggradation, in order to determine the time range represented (e.g., Cunha et al., 2017). However, in some deposits this was not possible because the target layers of sand or silt were rare, of limited thickness or absent. Sampling tubes were hammered into previously cleaned outcrops. Immediately adjacent to each tube, a sub-sample of sediment was collected for the estimation of the average water content during burial.

OSL is an absolute dating technique that measures the time elapsed since sedimentary quartz or feldspar grains were last exposed to daylight (Duller, 2004). Exposure to daylight during sediment transport removes the latent luminescence signal from those minerals. After burial, the luminescence signal (trapped charge) starts to accumulate in the mineral grains due to ionising radiation. The annual dose of a sediment sample is related to the decay of ^{238}U, ^{232}Th and ^{40}K present in the sediment itself, to cosmic ray bombardment and to the water content of the sediment. In the laboratory, the equivalent dose (De, assumed to be the dose absorbed since the last exposure to light, i.e. the burial dose, expressed in Grays - Gy) is determined by comparing the natural luminescence signal resulting from charge trapped during burial with that trapped during a laboratory irradiation. In this study, the radionuclide concentrations were measured by high-resolution gamma spectrometry (Murray et al., 1987). These concentrations were then converted to environmental dose rates using the specified conversion factors given by Olley et al. (1996). For the calculation of the dose rate of sand-sized K-feldspar grains, an internal K content of 12.5±0.5% was assumed (Huntley and Baril, 1997). Dividing the De by the environmental dose rate (in Gy/ka) gives the luminescence age of the sediment.

Sample preparation for luminescence analyses was carried out in darkroom conditions at the Department of Earth Sciences of the University of Coimbra. Samples were wet-sieved to separate the 180–250 μm grain-size fraction, followed by HCl (10%) and H_2O_2 (10%) treatments to remove carbonates and organic matter, respectively. The K-feldspar-rich fraction was floated off using a heavy liquid solution of sodium polytungstate (ρ = 2.58 g/cm^3). The K-feldspar fraction was treated with 10% HF for 40 min to remove the outer alpha-irradiated layer and to clean the grains. After such etching, the fraction was treated with HCl (10%) to dissolve any remaining fluorides.

For OSL measurements, quartz was used as the dosimeter (quartz-OSL); alternatively, K-feldspar was used, according to the pIRIR290 protocol (Buylaert et al., 2012), which is the most up-to-date protocol for use when the quartz-OSL signal is found to be in saturation. The OSL measurements were conducted at the Nordic

Laboratory for Luminescence Dating by using automated luminescence Risø TL/OSL-20 readers, each containing a beta source calibrated for irradiation on stainless steel discs and cups. Quartz measurements were made on large (8 mm) aliquots containing several thousands of grains mounted on stainless steel discs. Small (2 mm) aliquots of K-feldspar were mounted in stainless steel cups.

Quartz dose estimates were made using a standard SAR protocol using blue-light stimulation at 125°C for 40 s with a 240°C preheat for 10 s, a 200°C cut heat and an elevated temperature (280°C) blue-light stimulated clean-out step (Murray and Wintle, 2000, 2003). The OSL signal was detected through a U-340 filter. All samples have a strong fast component. The net OSL signal was calculated from the initial 0.0–0.8 s of stimulation and an early background between 0.8 and 1.6 s.

The K-feldspar equivalent doses (De) were measured with a post-IR IRSL SAR protocol using a blue filter combination (Thomsen et al., 2008; Buylaert et al., 2012). Preheating was at 320°C for 60 s and the cut-heat 310°C for 60 s. After preheating the aliquots were IR bleached at 50°C for 200 s (IR50 signal) and subsequently stimulated again with IR at 290°C for 200 s ($pIRIR_{290}$ signal). It has been shown (Buylaert et al., 2012) that the post-IR IRSL signal measured at 290°C can give accurate results without the need to correct for signal instability. For all IR50 and $pIRIR_{290}$ calculations, the initial 2 s of the luminescence decay curve, less a background derived from the last 50 s, was used.

Grain-size analyses of the sediment samples (sands and silts) were carried out using a Coulter LS230 laser granulometer (Laboratory of Sedimentology, Earth Sciences Department – University of Coimbra), with a measurement range of 0.04 to 2000 μm.

4. Results

The integration of cartographic, topographic, stratigraphic, sedimentological and chronological information has allowed the elaboration of longitudinal topographic profiles through the area in which the Quaternary terrace levels were studied. In this way, the terraces and residual slopes of the Sierra de Albarracín could be linked with the terraces of the Teruel depression, irrespective of altitudinal changes between the two. In addition, the new chronological data support correlation with regional and global palaeo-environmental indicators.

Different numbers of river terrace levels have been recorded in previous studies (Table 1). In the Alfambra, Gutiérrez y Peña Monné (1976) mapped three terraces, at 70–80 m, 35–40 m and 15–20 m above modern river bed (a.r.b.). In the area of the Teruel–Alfambra confluence, Peña Monné (1981) also noted three terraces, albeit at higher levels: 85–90 m, 45–60 m and 20–30 m a.r.b. Moissenet (1985) recognized six levels (including the modern floodplain) in the middle section of the Alfambra River, at 110–120 m, 70 m, 40 m, 20 m, 8 m and 2–3 m a.r.b.). Sánchez Fabre (1989), Lozano et al. (1996) and Sánchez-Fabre et al. (2019) identified four terraces in the Turia system, at 70-80 m, 40-60 m, 20 m and 10-15 m a.r.b. Recently, Gutiérrez (1998) and Gutiérrez et al. (2005) have identified ten levels within the Alfambra terrace staircase, at 100 m, 75 m, 55-60 m, 50 m, 30–44 m, 32–35 m, 20–23 m, 9–15 m, 3–5 m, and 1–2 m a.r.b. This scheme, with little variations, was repeated by Santonja et al. (2014) for the lower section of the Alfambra, whereas Lafuente (2011) reported terraces at 80–90 m, 45–65 m (with possible division), 20–30 m, 15–20 m and 3–5 m a.r.b. The new observations reported here from the lower courses of the Guadalaviar, Alfambra and Turia allow to us propose a scheme similar to that of Peña Monné (1981), incorporating the splitting already indicated by that author as well as Moissenet (1985), Sánchez Fabre (1989) and

Lafuente (2011), who made more localized studies. Considering all the available information, we propose the following terrace levels (a.r.b.) (Table 1): Qt1, at 100–140 m; Qt2, at 25 m–40 m in the Sierra de Albarracín to 50–55 m a.r.b. at Teruel (Guadalaviar River) and 70–80 m a.r.b. in the Turia; Qt3, at 35–40 m a.r.b. (Guadalaviar), reaching up to 60–66 m a.r.b. in the Turia; Qt4, at 18–20 m; Qt5, at 8–10 m; Qt6, at 5–10 m a.r.b. (only present in the Guadalaviar); Qt7, at 1–3 m a.r.b., corresponding to the modern floodplain. The entire terrace system can be classified as strath terraces except the Qt4 fill terrace in the San Blas sector (Table 1). The strath terraces allow the exposure of the Jurassic limestone bedrock (Sierra de Albarracín) and the Neogene clays, limestones, and sandstones (Teruel depression) (Fig. 1c; Table 1). However, in the Qt4 fill terrace from San Blas the thickening reaches 18 m without bedrock exposure.

Most of the Guadalaviar drainage basin is located in the Sierra de Albarracín (Fig. 1b). This upland area marks the hydrographic boundary between the Guadalaviar and the Tajo (Tagus) and Júcar basins. The main Guadalaviar and its tributaries flow mainly in fluvio-karstic canyons deeply incised into Jurassic limestones and dolomites (Fig. 1c). As bedrock strength and structure represent a relevant control on terrace formation (e.g. Stokes et al., 2017), and this is an area of mostly resistant rocks, there are few locations with valley widening, such as in Upper Triassic marls and gypsum and Jurassic sandy-marl. Quaternary deposits preserved along the valleys are very scarce, therefore, limiting the scope for reconstructing landscape evolution. However, there are two short reaches where is possible to find terrace and slope deposits: Entrambasaguas and Gea canyon (Figs. 1b, 1c). Those reaches document an earlier wider valley with terraces, below which there has been valley entrenchement, producing a canyon (gorge).

Downstream, where the Guadalaviar reaches the Neogene softer sediments of the Alfambra-Teruel depression, the terrace system develops longitudinal continuity both upstream and downstream of the Turia River confluence. Two sections were studied along this channel: San Blas in the Guadalaviar and Villaspesa in the Turia (Figs. 1b, 1c).

The following sections will document findings on terrace levels, ages and terrace–slope linkages from two studied sections in the Sierra de Albarracín and two sections in the Teruel-Alfambra depression, taking these in upstream to downstream sequence (Fig. 1b).

4.1. Entrambasaguas

The first study locality, high in the upland area, is at the confluence between the De la Fuente del Berro and Guadalaviar rivers, where it is possible to see two very extensive outcrops. The first (Fig. 2a – section A) shows a thick slope sequence (Fig. 2b), the stratigraphy of which can be observed in the cuttings for the A-1512 road. The exposed sedimentary succession reaches 18 m in thickness (Peña Monné and Jiménez, 1993; Peña Monné et al., 2010b). In the 1980s, the upper section of the outcrop was more visible, showing a slope deposit of stratified screes (Fig. 2c) formed by >10 m of moderately sorted subangular pebbles of Middle Jurassic limestones within an abundant fine (silt) ochrous matrix, with alternations between layers cemented by carbonates and matrix-free gravel and other layers of mainly silty-sand material (Fig. 2c). The general gradient of the slope and the bedding of the associated deposits is 30–35º, declining to the west; the original head of this slope no longer exists due to erosion. At present, in this upper part of the exposure, it is possible to see (thanks to road widening) a ~1 m thick fluvial gravel (Fig. 2b) comprising well-rounded boulders of Mesozoic limestones and dolomites, Triassic sandstones and Paleozoic quartzites. These processes are mainly coming from the Guadalaviar River. Above this are fluvial silts and sands with sporadic boulders (Fig. 2b). There was no layer suitable for OSL dating in these fluvial facies.

The second studied profile at Entrambasaguas (Fig. 2a – sector B) is located around 400 m to the east of the first, on the same river side and along the same road. It has a maximum exposure thickness of 5 m (Fig. 2d). The basal part is composed of 1.1 m of well-rounded and imbricated gravels, overlain by 0.4 m of fluvial fine sand with lenses of silt, reaching 25 m a.r.b., interbedded with slope scree as in profile A. For OSL dating, the sand sample ALBAR-1 was taken from a depth of ~3 m (Fig. 2d) and yielded a $pIRIR_{290}$ age of 271±29 ky (Table 2). From its position, it corresponds with the upper part of the Qt2 terrace of the Guadalaviar (Table 3). The fluvial component is covered by an upper division of 3.5 m thick ochrous slope deposits. This has a massive base formed by sands, clays and angular pebbles, overlapped by a stratified scree extending to the top (Fig. 2d). This stratified scree has a gradient of 25–30º, declining to the SE. It is composed of angular limestone clasts, well-ordered in parallel layers following the deposit gradient, interbedded with thin levels of clayey silts. The thickness of the scree increases to the west. It is visible on both sides of the road, but the best outcrop is to the south (Fig. 2a). A sample for OSL dating (ALBAR-2) (Fig. 2f) provided an age of 310±34 ky (Table 2). The well-sorted fine sands and silts interbedded within the stratified screes are, probably, of nivo-aeolian origin. The fine materials were probably transported by wind from up slope, perhaps in connection with snow-blow.

In the valley floor at Entrambasaguas it is possible to observe a fluvial terrace 5-10 m thick, formed by carbonate tufas that lack a detrital component, belonging to the

Qt6 level (Fig. 2a, Table 1). It was dated to 10.1±0.3 ky (U/Th) and to 7.26±0.42 ky BP (^{14}C) (Table 3) (Peña Monné et al., 1994; Jiménez et al., 1996; Sancho et al., 1997).

4.2. Gea canyon

In the area between Albarracín and Gea de Albarracín, the Guadalaviar has cut the meandering Gea canyon into Jurassic limestones and dolomites (Figs. 1a, 1b). Several Quaternary deposits, from different evolutionary levels, are preserved above the height of the incised meanders. They were sedimented before the incision was produced and are located to the north of the present course of the Guadalaviar. An outstanding accumulation, attributed to Qt2 (Fig. 3a), of strongly cemented boulder gravel some 40-45 m a.r.b. is preserved. Its geometric position suggests that it followed an older, higher-level meandering course. Unfortunately, it was not possible to collect suitable samples for OSL dating.

Exposed below the Qt2 outlier and above the A-1512 road is the uppermost 6 m of a slope deposit (Fig. 3a, 3b). This has similar characteristics to the slope deposits at Entrambasaguas, being formed of ochrous sandy-clay layers with scattered angular clasts, cemented by calcium carbonate (Fig. 3c, 3d). The gravel layers represent a well-stratified scree, with a depositional slope of around 10-15º to the S. However, they contain abundant fines, in contrast to the more open-framework scree at Entrambasaguas. A sample (ALBAR-5), taken from one of the sandy layers at 4.2 m depth, was dated (Table 2) to 173±11 ky ($pIRIR_{290}$). This slope has no connection with any fluvial terrace, but its OSL age implies that it is contemporaneous with the Qt3 level.

In a lower position, close to the river and disconnected from the slope previously mentioned, another fluvial terrace is preserved at ~10 m a.r.b. (Fig. 3b). A 6 m thickness of this terrace can be observed in outcrop, showing a variable stratigraphy, with abundant layers of imbricated rounded gravel, interbedded with lenses of fine sand. Sample ALBAR-3 was taken from the topmost fluvial facies, at 1.15 m depth (Fig. 3e, 3f, 3g), and dated to 22±7 ky ($pIRIR_{290}$; Table 2). This terrace belongs to the Qt5 level (Tables 1, 3). In the uppermost part of the outcrop is 0.8 m of tufa, with fossil moulds of charophyte stems and mosses, and comprising fractured blocks (Fig. 3e, 3f and 3g).

On the other side of the valley (Fig. 3a) some 9 m of tufa is exposed. Dated to 4.63±0.14 ky BP by ^{14}C (Peña Monné et al., 1994; Sancho et al., 1997); it belongs to the Qt6 level (Tables 1, 3). The upper part of this tufa shows similar facies and topographic position to that at the top of Qt5 terrace, thus implying that the Qt6 has overlapped onto the Qt5 fluvial deposits.

4.3. San Blas

The Guadalaviar River flows through the Sierra de Albarracín in the canyon where the del Arquillo dam is located (Figs. 1a, 1b). From there it enters the Alfambra–Teruel depression, widening its valley as it flows on to the basin-fill of soft Neogene sedimentary strata. This has favoured the development of substantial terraces between San Blas and the confluence with the Alfambra, at Teruel, with the widening persisting downstream in the Turia valley (Fig. 4a). This area is ideal for study of the terraces, because the complete system is preserved. On the left side of the valley, the Qt2 and Qt4 terraces are represented at 35-40 m and 18-20 m a.r.b., respectively; close to the Alfambra confluence, it is also possible to see the Qt3 and Qt5 terraces (Fig. 4a). On the right valley-side there are no terraces due to the presence of the La Muela structural upland. However, close to the Alfambra confluence and over the eastern flank of La

Muela, cut on limestones, the Qt1, Qt2 and Qt3 levels appear at 100-140 m, 50 m, 40 m a.r.b., respectively (Fig. 4a).

Close to San Blas there is a quarry exposing the Qt4 terrace, reaching 18 m in thickness. This outcrop is described in three profiles, together covering the complete terrace exposure (Fig. 4b), although the substrate is not visible. The terrace comprises mainly gravels, with several silt–sand channel fills, most of them showing cross stratification. The coarse fluvial deposits, consisting of matrix-supported gravels, almost without imbrication, are attributed to a torrential system of braided channels. In their upper parts, the profiles show overlapping sedimentary sets of fine sands and silts (Fig. 4b) interpreted as floodplain deposits. Sample SBLAS-3 was taken from a sandy layer (Fig. 4c) at 18 m depth (5.7 m in the local outcrop), and dated to 136±20 ky ($pIRIR_{290}$). In another level of the gravel pit (Fig. 4b), at 4 m depth, sample SBLAS-1 was taken from a cross-bedded sandy channel fill (Fig. 4d). It was dated to 111±6 ky (quartz-OSL). Finally, sample SBLAS-2, from a depth of 1 m (Fig. 4e), yielded an age of 81±5 ky (quartz-OSL; Table 2).

4.4. Villaspesa

Downstream from the Guadalaviar–Alfambra confluence, the river changes its name to Turia and flows NNE–SSW along the Alfambra–Teruel depression. The landscape here is dominated by structural mesas (*muelas*) between 970 and 1100 m a.s.l. (110–140 m above the Turia floodplain). Southwards from the mesa upon which Teruel is built, the left valley-side is dominated by the Qt3 terrace level (60–65 m a.r.b.), with some isolated remnants of the Qt2 (70–80 m a.r.b.) and Qt4 (20 m a.r.b.) levels.

Muela de Morante (978 m a.s.l.), north of Villaspesa (Figs. 1a, 1b), is formed in Neogene lacustrine limestones and is bordered by a scarp ~30 m high. At its foot, marls and clays display a varied morphology that results from fluvial activity, slope dynamics and the development of badlands (Figs. 5a, 5b). The Qt3 terrace here reaches a thickness of 10–15 m, heavily cemented in its basal part by calcium carbonate to form a highly resistant conglomerate, which has probably promoted its extensive preservation. In the past, the river floodplain of the Qt3 terrace was laterally connected with slope deposits descending from the limestone scarps, allowing interbedding of sediments from the slope and from the Turia River (Figs. 5a, 5b). The slopes have been disconnected from the mesa by headwater erosion by a tributary of the Rambla de Aldehuela stream, entrenched into the Neogene clays. This has given rise to the development of a talus flat-iron landform with its triangular apexes oriented toward the cliff of the present mesa, while its distal area extends towards the terrace, connecting with it both at the surface and internally (Fig. 5b).

A gravel pit in the surface of the Qt3 terrace provides an exposure (Figs. 5c, 5d). The lower part of the section here shows alternation of massive gravels and compacted sand layers. The top of the deposit comprises gravels with lenses of fine sands. One of the latter, at 2.3 m depth, was sampled (VILLASP-1) and dated to 152±17 ky ($pIRIR_{290}$) (Fig. 5c, 5d, Table 2). Another sand sample (VILLASP-2) was taken (at 5.3 m depth) but did not produce reliable OSL results.

On the map (Fig. 5a) it is possible to identify two further slopes, one ascribed to the Pleistocene and the other Holocene. The largest, covering the foot of the mesa and Qt3 scarps, is the youngest; it is very extensive throughout the Alfambra–Teruel depression and was dated to the upper Holocene (3000–2500 yrs cal BP) by ^{14}C, supported by geoarchaeological data (Burillo et al., 1981; Peña Monné, 2018). It is probably linked climatically with the cold phase of the Iron Age. These slopes have been incised by minor streams that have formed small alluvial fans extending onto the Turia floodplain (Fig. 5a).

5. Discussion

5.1. Chronology of the fluvial terrace system

The mapping, documentation and dating of outcrops/exposures of fluvial deposits in the Guadalaviar–Turia system has confirmed a terrace staircase with seven levels a.r.b. (Tables 1, 3; Fig. 6). Some of the terraces show considerable variations of thickness, bedrock and gradient, both locally and along the river. In the Teruel area, a soft substratum and periods of less uplift or even subsidence have produced an increased thickness of the terrace deposits. Downstream of the Guadalaviar–Alfambra confluence, the terraces, especially Qt2 and Qt3, are very thick and show an increasing elevation above the present river bed. This is perhaps related with the knickpoint generated by the change in downstream gradient at the exit from the del Arquillo canyon (Fig. 6), a location that marks an abrupt change in substrate from resistant Jurassic limestones and dolomites to Neogene marls, which are softer and, indeed, are also fractured. This change in bedrock might well explain the gradient disruption. Otherwise, the increase in the divergence between the modern Turia thalweg and related Pleistocene terraces might be related to an increase in the incision rate further downstream (Fig. 6).

The staircase comprises strath terraces in the Escorihuela–Alfambra area (Alfambra River) and in the Guadalaviar upstream from San Blas, whereas further downstream, as well as in the final reach of the Alfambra (above its confluence with the Guadalaviar) the terraces are of cut-and-fill type, especially at the Qt2, Qt3 and Qt4 levels. The Muela de Teruel area is highly complex due to the eastward gradient of the structural relief and the existence of artificial scarps that might be wrongly interpreted as terrace steps.

There are no available numerical ages for the Qt1 level, but it must be significantly older than the age provided by sample ALBAR-2 for the Qt2 terrace: 310±34 ky. The most important outcrop in the Teruel area is located on La Muela (Fig. 4a). There may be a link with the so-called "*cono de Gea*" (Gea alluvial fan; Fig. 6), which extends from the eastern end of the Jiloca graben, with a gradient of 1.0%, and is located at heights in relation to the Guadalaviar River between 140 m (Gea de Albarracín reach) and 85–90 m a.r.b. (Industrial Park area, Teruel). On the maps of Godoy et al. (1981), this level is shown as equivalent to the highest terrace of the Muela de Teruel (Qt1), as was also indicated by Moissenet (1985). The isolation of the *cono de Gea* from the scattered Guadalaviar Qt1 remnants, given the extent of local deformation in the area, makes it difficult to establish correlation, although the topographic alignment is clear in Fig. 6. Accordingly, these highest levels will remain without chronological ascription until dating by Electron Spin Resonance (ESR) or Terrestrial Cosmogenic Nuclides (TCN) is possible.

In the case of the Qt2 level, the new OSL ages obtained were 271±29 ky (ALBAR-1) in terrace deposits and 310±34 ky (ALBAR-2) in related stratified screes (Table 2). At the Cuesta de la Bajada archaeological site, several numerical ages were obtained from Alfambra terrace deposits located at 53 m a.r.b. and attributable to Qt2; the 50 m thick terrace here contains faunal remains and Early to Middle Palaeolithic industries (Santonja et al., 2014). The OSL ages were 293±24 ky to 264±20 ky. From the same levels, ESR dating provided less reliable older ages (Duval et al., 2017). Integration of our new dates with the previously published ages suggests that aggradation of Qt2 spanned ~310 to 270 ky and can be correlated with MIS 9b to MIS 8a (Fig. 7, Table 3).

The Qt3 terrace deposits are typically indurated by carbonate cement. A single OSL age, 152±17 ky (VILLASP-1), was obtained from the terrace of 60 m a.r.b. at Villaspesa, in the Turia valley (Fig. 1b, Table 2). Slope deposits in the Gea canyon (Fig. 3), from which an OSL age of 173±11 ky (ALBAR-5) was obtained (Table 2), can also be ascribed to the Qt3 level (see section 4.2), but no associated terrace deposits are preserved, due to erosion. In the area of Los Baños (Alfambra River; Fig. 1b), Arlegui et al. (2004) dated (U/Th method) two levels of tufa overlying terrace deposits at 40 m a.r.b. (Qt3), obtaining ages of 164±10 ky and 116±4 ky (Table 3); the lower dated tufa level perhaps corresponds to the topmost deposits of Qt3, but the upper dated tufa is probably contemporaneous with the Qt4 level. In addition, there are palaeontological records of *Mamuthus trogontherii* Pohlig in the terrace of the Seminario de Teruel (Esteras and Aguirre, 1964), corresponding to the Qt3 level, and Moissenet (1985) found faunal remains of that age in Alfambra terrace remnants at similar heights at Villalba Alta (Table 3). By integration of all the available chronological data and MIS correlation, the Qt3 aggradation interval can be dated as ~175 to 150 ky and correlated to MIS 6, or MIS 6d–MIS 6a (Fig. 7).

The main outcrop of Qt4 is at San Blas, where the terrace is 18–20 m thick, although its base is not seen. This thickening might be related to subsidence during the Quaternary in the Teruel area or even with the activity of the Concud fault, at the Jiloca graben margin, or the Alfambra–Teruel fault. The divergence of the terraces in this region suggests that there has been relative subsidence of the Neogene Alfambra–Teruel depression. From base to top, the obtained ages (Table 2) are 136±20 ky (SBLAS-3), 111±6 ky (SBLAS-1) and 81±5 ky (SBLAS-2), allowing correlation with substage 6a and all of MIS 5 (5e–5a) (Fig. 7, Table 3). Lafuente et al. (2011) provided a date of 114±7 ky from an Alfambra terrace deposit (Los Baños-Teruel sector) that might be related with Qt4 level. In the surface of the San Blas terrace, Obermaier and Breuil (1927) found rolled or slightly rolled Palaeolithic artefacts; they consider these to pre-date Qt4 terrace formation, belonging to the Qt3 level but probably moved downslope subsequently.

From remnants of the Qt5 terrace, Lafuente (2011) obtained an age of 22±16 ky in the Alfambra and OSL ages of 15.6±1.3 ky and 14.1±0.9 ky to the north of Teruel (Los Baños); Gutiérrez et al. (2008) recorded similar dating (15±9 ky) from Los Baños. In the Gea canyon, where the sample ALBAR-3 was collected from the topmost fluvial facies (just below tufa), the present study records an age of 22±7 ky (Table 2); thus, the Qt5 terrace corresponds with MIS 2 (Last Glacial Maximum) although its base is probably from late MIS 3 (Table 3; Fig. 7).

The Qt6 terrace has usually a thickness between 5 and 10 m, reaching exceptionally higher thickness. It is usually formed by tufa in the absence of detrital materials. It has extensive continuity in the Guadalaviar canyon and in the tributaries from the Sierra de Albarracín. It disappears downstream from San Blas, where the river enters the Alfambra–Teruel depression. The thickest tufas are located in the de la Fuente del Berro River, close to Calomarde (Fig. 1b), where there is a waterfall associated with a 27 m high tufa stack. U/Th dating has provided ages of 6.8±0.3 ky BP and 8.0+0.8/-0.7 ky BP (Peña Monné et al., 1994; Jiménez et al., 1996; Sancho et al., 1997). Other tufas at this level, and of Holocene (MIS 1) age, appear (1) at the confluence between the de la Fuente del Berro and the Guadalaviar, at Entrambasaguas (Fig. 2a), dated (U/Th) to 10.1±0.33 ky BP and (^{14}C) 7.26±0.42 ky BP (Peña Monné et al., 1994; Jiménez et al., 1996; Sancho et al., 1997) and (2) in the Gea canyon, dated (^{14}C) to

4.63±0.14 ky BP (Peña Monné et al., 1994; Sancho et al., 1997; Fig. 3a; Table 3). From integration of the available chronological data, the Qt6 aggradation interval has an age range of ~10 to 4.6 ky, correlating with much of MIS 1 (Fig. 7).

The Qt7 level is at 1–3 m a.r.b., corresponding with the modern floodplain. A sample collected from the Alfambra valley was OSL dated to 3.4±0.7 ky (Lafuente, 2011).

5.2. Connection between river terrace and slope deposits

Clastic inputs into rivers from lateral, as well as longitudinal connected sources are important, and can result in sedimentary and landform features. First, a depositional terrace can link laterally with an erosion surface, usually in situations where the valley slopes are gentle and so the lateral contributions to the river are minimal. Where slopes are more prominent, a depositional terrace can link laterally to a slope with colluvium, in which case this lateral source provides a significant volume of clastic material to the river. In a third situation a depositional terrace can link laterally with tributary alluvial fans, which can supply very large volumes of clastic materials to the river, potentially exceeding the longitudinal input. In the study area, the situation conforms with the middle of these three scenarios.

In the Mediterranean region, several studies have analysed the relationship between fluvial terrace deposits and lateral interconnected deposits of pediments, glacis or alluvial fans (Sanchez-Fabre et al., 2019); these connections have high geomorphological relevance because they provide information regarding the integrated fluvial system (the main river and tributaries). Studies of such connections between colluvial slopes and fluvial terraces are scarce, especially for records older than Late Pleistocene. Nonetheless, such studies provide paleo-environmental information of value in the interpretation of Quaternary landscape evolution in particular types of fluvial basins: those under semi-arid temperate to cold climatic conditions but outside the influence of glaciation and intense periglaciation. It is extremely rare to find this kind of relationship in stratigraphic levels as old as the Middle Pleistocene examples represented by the higher-level terraces and related slopes in the Guadalaviar–Turia valley.

The most common landforms formed under cold environments in the Sierra de Albarracín are the stratified screes. These accumulations are covering many slopes with well classified angular clasts and are characteristic results of cold processes in middle altitudes of Mediterranean mountains (Van Steijn, 2011; Pérez-Alberti and Cunha, 2016). Peña Monné and Jiménez (1993) and Peña Monné et al. (2010b) identified two groups of stratified screes in the Sierra de Albarracín. The first group, considered as "old screes", are characterized by their ochre/orange colour and considerable thickness. Usually located in high positions in relation to the modern floodplains, they are linked with the terminal aggradation phases of the Qt2 (MIS 8) and Qt3 (MIS 6) terraces. The second group comprises "recent screes" and is characterized by greyish colors, a less clayey matrix, less thickness and linkage with the Qt6 and Qt7 (MIS 1) terraces, and particularly tufa. The latter group has been studied in detail in the Calomarde canyon (Fig. 1b), where it can be related to Holocene cold phases, ranging from the early Holocene to the 'Little Ice Age' of the 16^{th}–17^{th} centuries (Peña-Monné et al., 2017).

The "older stratified screes", which reach up to 18 m thick, are typically located in the canyons of several rivers of the Iberian Chain. In the present paper, these slopes have been studied at the Entrambasaguas and Gea canyon sites. Here, the cold characteristics of these old stratified screes and the dating provided in this study fit well with the cold substages of the last part of the MIS 9 and the whole of MIS 8 (Fig. 7). In the high areas of the Sierra de Albarracín (>1200 m a.s.l.), there are deposits with such characteristics, pointing to the regional importance of cold-phase processes. An example is the Toril outcrop (Fig. 1b), where Peña-Monné et al. (2017) obtained two ^{14}C ages older than 43.5 ky B.P. In the Macizo del Tremedal (1936 m a.s.l.) there are other landforms and deposits indicative of intensely cold environments, such as the block and stream slopes described by Gutiérrez and Peña Monné (1977), as well as the morainic remains of a small glacier and of rock glaciers (Peña Monné et al., 2010b). These cold-climate records have yet to be dated, but might be related to the same stage identified at Entrambasaguas, since that (MIS 8) was the most important cold phase in the region. In the NE of the Iberian Peninsula this stage can also be related to an early phase of Pyrenean glaciation (Fig. 7), defined from a glacio-fluvial deposit of the Aragón River, dated to 263±21 ky, correlative with MIS 8 (García Ruiz et al., 2012; Fig. 7).

Another phase of slope generation with stratified screes, correlated with MIS 6 and related to the Qt3 terrace (Fig. 7), has been described in the Gea canyon (Guadalaviar River) and Villaspesa (Turia River) sites. To the south of Teruel, the wide valley of the Turia is bordered by mesas developed in Neogene limestones. In this part of the system, where river terraces are developed more extensively than in the Sierra de Albarracín, there are numerous examples of slopes linking the mesas with fluvial accumulations. The best of these is on the left side of the Turia, around Villaspesa (Fig. 1b). The best-developed terrace in this area is the Qt3 level, at 60–66 m a.r.b. The terrace is situated alongside a slope deposit that gradually increases in gradient, demonstrating that originally it was connected with the Muela de Morante (Fig. 5a, 5b). Actually, this connection survives only in a small area, whereas the rest of the slope now adopts a talus flat-iron morphology, with its apices oriented toward the east, where it formerly ascended to connect with the old cliff of the mesa (Fig. 5a). The slope deposits here are different to those described in the outcrops of the Sierra de Albarracín (dated to 173±11 ky, VILLASP-1) because they have only Neogene limestone blocks and clasts, in chaotic arrangement without stratification. These landforms can be classified as debris cones that formerly had thicker ascendant apices widening downwards to a foot that interdigitated with fluvial deposits of the Turia, dated to 152±17 ky (Fig. 5c, 5d, ALBAR-5). Similar landforms have been described in the valley of the Cinca River, southern Pyrenees (Sancho et al., 1988), and in the valley of the Henares River, close to Guadalajara (Peña-Monné et al., 2020). In both cases, talus flatirons are connected with river terraces. From their morphological and sedimentary characteristics, their formation can be attributed to cold environmental conditions with large-scale production of debris by freeze–thaw on the mesa corniches. In the Pyrenees (Gállego, Cinca, and Aragón rivers) it is possible to identify the Penultimate Glacial Maximum recorded by fluvio-glacial and glacial terraces dated between 178 ky and 140 ky, within MIS 6 (Lewis et al., 2009; García Ruiz et al., 2012; Fig. 7).

In the area of Villaspesa, it is possible to identify two other evolutionary stages of slope deposits. There is no doubt that they also had alluvial sediments as base levels during their formation, but at present there are no direct connections with fluvial terrace deposits. This is the case with the slope named "Pleistocene slope b" in Fig. 5a. Lastly, the presence of a Holocene slope related to the Iron Age cold phase was mentioned previously, corresponding with a late Holocene cold event.

Beyond Iberia, commonplace linkage between river terraces and laterally connecting deposits is seen in other regions within the Mediterranean climatic zone, where an important aspect of the environmental similarity with the study area might be relatively low levels of precipitation. Linkage between coalesced fans from multiple episodes and terrace deposits of the local ephemeral rivers represent valuable

Quaternary archives in different locations (Mather et al., 2017) and especially North Africa, as expressed in work on the Souss valley (Bhiry and Occhietti, 2004; Aït Hssaine and Bridgland, 2009; Chakir et al., 2014) and the Dadès River (Stokes et al., 2017), Morocco. Here the third of the above scenarios applies, with a dominance of lateral clastic input over longitudinal transport by the non-perenial rivers. In extensive geomorphological mapping in the Near East, in association with studies of Lower to Middle Palaeolithic occupation, French workers classified river-terrace sediments and associated glacis formed in slope deposits in the Kebir and Orontes rivers in Syria according to a standard notational scheme that bears some resemblance to that used in the present paper, designating Middle–Late Pleistocene levels (terraces and glacis alike) as QfIV to QfI, approximately equivalent to the four main Alpine glaciations (Besançon et al., 1978a, b; Copeland and Hours, 1978; Sanlaville, 1979; cf. Bridgland et al., 2012). In the Kebir, the terrace/glacis system designated QfIII, and therefore with a potential age of ~MIS 12, was later found to comprise only slope deposits that had been sculpted by erosion, including residual pinnacles perhaps comparable with the grid-iron features described in the present study region (Bridgland et al., 2008).

5.3. Estimated deepening average rates

In an area that has experienced continuous uplift, such as the study area, the amount of fluvial incision over multiple climatic long-term (glacial–interglacial) cycles can be regarded as a proxy for uplift (Maddy, 1997; Bridgland, 2000; Westaway et al., 2002). For the study area, taking into account the short distance (~150 km) to the marine base level, it is not clear if eustatic control has been significant (e.g., Schumm, 1993; Cunha et al., 2017).

It is not possible to establish the a.r.b. heights of all strath terraces of the Guadalaviar–Turia valley, especially where the deposits are of greater thickness, as at San Blas. For this reason, it is very imprecise to calculate incision rates, although it is possible to try to estimate average rates of deepening on these valleys. This estimation was made using the height of each terrace surface a.r.b. Considering the Qt2 to Qt6 terrace levels, and the probable ages of their topmost deposits, the following estimated rates can be calculated: for Qt2, 0.09 m/ky (25 m/270 ky) in the Sierra de Albarracín, 0.19 m/ky (50 m/270 ky) at Teruel, and 0.26 m/ky in the Turia River (70 m/270 ky); for Qt3, 0.25 m/ky (38 m/150 ky) to 0.42 m/ky (63 m/150 ky); for Qt4, 0.24 m/ky (19 m /80 ky); for Qt5, 0.64 m/ky (9 m/14 ky); for Qt6 as 1.63 m/ky (7.5 m/4.6 ky). These values are just estimations as the data were not taken on the same river section and terraces show height variations along the river course. However, in general terms, we can infer that the deepening rates of the studied terrace staircases have increased, at least during the last ~300 ky; the same interpretation is obtained by observation of the terrace long profiles (Fig. 6). In addition, obtained rates are similar to those obtained by other authors on neighboring rivers. The estimated incision rates of Scotti et al. (2014) for the Iberian Chain rivers is ~0.6 m/ky, and according to the river profile model of Giachetta et al. (2015) there has been a mean incision rate of 0.22 m/ky due to the regional tectonic uplift of the Iberian Chain (average uplift of 0.25 to 0.55 m/ky for the last 3 Ma). In this context, the estimates obtained for the Guadalaviar–Turia system seems coherent for an upper fluvial reach. These rates are higher than those calculated for the large Iberian rivers such as the Cinca River (Ebro basin) (0.12-0.15 m/ky) (Sancho et al., 2016) or the Ebro River (0.025 to 0.08 m/ky), for several reaches of the Lower Tagus (0.07-1 m/ky, Cunha et al., 2008; 0.13-0-5 m/ky, Martins et al., 2009), the Middle Tagus (0.05-0.2 m/ky) (Silva et al., 2017), or the Upper Tagus (0.06-0.15 m/ky)

(Karampaglidis et al., 2020b). In the Duero River and tributaries, Moreno et al. (2012), Schalter et al. (2016) and Rodríguez-Rodriguez (2020) estimate incision rates of 0.122≤0.250 m/ky (middle basin) to 0.088-0.068 m/ky (upper basin); in the lower Duero incision rates reach between 0.15 and 0.54 m/ky (Cunha et al., 2019b).

A possible explanation is that this might be a crustal adjustment in response to the acceleration of surface processes, particularly erosive ones, following the Mid-Pleistocene transition and the start of longer (100 ky) climatic cycles, with increased severity of glacial phases; the forcing influence can be described as erosional isostasy (see Bridgland and Westaway, 2008; Westaway et al., 2009).

5.4. Controls on terrace genesis

Fluvial drainage systems respond to external forcing expressed by changes in relative base level, crustal uplift rate and climate (e.g., Merritts et al., 1994; Maddy, 1997; Antoine et al., 2000; Bridgland, 2000; Westaway et al., 2002; Bridgland and Westaway, 2008; Cunha et al., 2008, 2017; Whipple et al., 2013; Stokes et al., 2017).

In the temperate latitudes of Eurasia, the normal river development during the late Cenozoic has been to form staircases of terrace deposits (except in areas of subsidence or in stable cratons; Bridgland and Westaway, 2008). These have been interpreted as formed in response to climatic forcing, which was considered to have led to cyclic incision and aggradation in synchrony with glacial–interglacial cycles, superimposed upon a background of progressive uplift (Bridgland, 1994, 2000; Maddy, 1997; Maddy et al., 2000; Bridgland and Westaway, 2008). The OSL ages of the terraces of the South Pyrenean rivers (Gállego, Cinca, Segre) show synchrony with the dating of the moraines located at their respective upstream glacial sources (Lewis et al., 2009); the estimated incision rates for these rivers (Stange et al., 2013, 2014; Lewis et al., 2017) during the Pleistocene point to climatic triggering combined with Pyrenean uplift as drivers for the aggradation–incision phases. However, the Lower Tagus terraces in Portugal, located less than ~300 km from the mouth of that river at the Atlantic margin, developed under temperate to cold climatic conditions but with a strong eustatic control, Cunha et al. (2017, 2019a) concluded that the beginning of each fluvial sedimentation episode could be correlated with the beginning of an interglacial stage (e.g., MIS 9, MIS 7, MIS 5, MIS 3 and MIS 1) and that the downcutting to new terrace levels has occurred during glacial stages (usually late within these). The study-area catchment of the Guadalaviar River occurs in a similar climatic zone to the Upper Tagus (Sierra de Albarracín), has also lacked glaciers during the Quaternary and is located ~150 km from the Mediterranean sea. The studied sedimentary levels in the Guadalaviar–Turia system record aggradation during MIS 9b to MIS 8b (Qt2), MIS 6d to 6b (Qt3), MIS 6a to MIS 5a (Qt4) and MIS 2 (Qt5). Thus Qt2, Qt3 and Qt5 result from aggradation during glacial stages, but the Qt4 and Qt6 terraces were predominantly aggraded during interglacial stages. In conclusion, cyclic incision and aggradation is not completely in synchrony with glacial–interglacial cycles for all stages, and a more precise chronological framework is needed for full understanding of the forcing mechanisms for river terrace genesis in the study area. The surroundings of Teruel have been subject to less uplift and tectonic activity, leading to altitudinal changes between areas (differential uplift) and divergence of the terraces, such deformation being documented by the Qt2 terrace at Cuesta de la Bajada. Tectonic probably influenced the subsidence and local thickening of the San Blas terraces, although we consider that it is not the main reason.

Furthermore, it is necessary to take into account the control of bedrock lithology on terrace development. The Guadalaviar–Turia system flows across a major change in bedrock lithology that has given rise to a 5 km long knickzone in the vicinity of the El Arquillo dam, separating graded profiles upstream in the hard materials of the Sierra de Albarracín (mainly Mesozoic limestones) from the soft Neogene sediments (sands, silts, clays and evaporites) of the Alfambra–Teruel tectonic depression (Figs. 1b and 6). The lithologically-controlled knickzone has exerted significant control over terrace development in Alfambra–Teruel. Although the contact between both areas is accompanied by faults derived from the Alpine tectonic, there is no evidence of activity during the Quaternary. Upstream of the Neogene basin, canyons with incised meanders and only localized remnants of Qt2 and Qt5 are found, but downstream of the El Arquillo knickzone there is full development of the Qt1–Qt5 terrace sequence. According to the reconstructed profiles (Fig. 6) the knickzone did not exist during the development of the older terraces (Qt1, Qt2). The Guadalaviar River deepened in the Neogene limestones of the Teruel depression up to reach the underlying Jurassic limestones (El Arquillo Dam sector) and the Neogene clays and gypsums (Teruel depression). After that, the knickzone started to develop between the formation of Qt3 and Qt4 terraces (Fig. 6). The major deepening in the Neogene clays favored the lateral widening and thickening of Qt4 terrace in the San Blas sector. Although we consider that lithological control on the terrace thickening is dominant, it is not possible dismiss the influence of subsidences related to the presence of gypsums and/or the vicinity to active faults. These effects are less notorious on the more recent levels (Qt5 to Qt7).

As also documented by literature (e.g., Montgomery, 2004; Cunha et al., 2005, 2019b; Martins et al., 2009, 2017; Schanz and Montgomery, 2016; Karampaglidis et al., 2020a) this is an expected result of the control of bedrock lithology on terrace genesis; terraces are thus developed where a river can flows on soft rocks and can readily widen its valley, but they are almost absent in areas where a river has cut into the hard rocks of the basement and is therefore laterally constrained.

6. Conclusions

The terraces of the Guadalaviar–Turia fluvial system include up to five Pleistocene levels and two of Holocene age. The chronology of this terrace system has been improved by the integration of new luminescence (quartz-OSL and pIRIR290) ages and previously published data. The terrace and associated slope deposits can now be summarized as follows:

- Qt1, at 85–90 m and 100–140 m a.r.b., is probably older than ~340 ky
- Qt2, at 25–40 m a.r.b. in the Sierra de Albarracín, 50–55 m a.r.b. near Teruel (Guadalaviar River) and 70–80 m a.r.b. in the Turia valley, with faunal remains and Early–Middle Palaeolithic industries, dates from ~310 to 270 ky (MIS 9–8)
- Qt3, at 35–40 m (Guadalaviar River) and up to 60–66 m a.r.b. (Turia River), comprises fluvial gravels and sands interbedded with thick stratified slope-derived screes (also with faunal remains) dates from ~175 to 150 ky (MIS 6)
- Qt4, at 18–20 m a.r.b., dates from ~135 to 80 ky (late MIS 6 and MIS 5e–a)
- Qt5, at 8–10 m a.r.b., is dated ~22 to 14 ky (MIS 2)
- Qt6, at 5–10 m a.r.b. and found only in the Guadalaviar valley, dates from 10 to 4.6 ky (Early–Middle Holocene, MIS 1)
- Qt7, at 1–3 m a.r.b. and coinciding with the modern floodplain, probably represents the last 3.5 ky (late MIS 1).

Related slope deposits, connected with the middle and upper parts of the Qt2 and Qt3 terraces, were generated under the cold-climate conditions of MIS 8 and 6, respectively. These are the oldest dated slope deposits connected with fluvial terraces documented in the Mediterranean region, so their preservation and is of international significance.

A good chronological correlation with the glacial–interglacial cycles of the Pyrenees and with the marine oxygen isotope record has been achieved, supporting an improved interpretation of paleo-environmental data and sedimentary controls on terrace genesis in extra-glacial fluvial systems under temperate to cold climatic conditions. Estimated incision rates vary from 0.09–0.26 m/ky (Qt2) to 1.63 m/ky (Qt6), which indicates that regional uplift, which progressively increased during the analyzed period, has also playing an important role in the terrace genesis.

The study area includes a knickzone, directly related to bedrock hardness, corresponding with the transition between the upstream catchment of incised canyons formed on harder basement rocks and the lower valley formed on the less resistant Neogene sediments. The starting of the knickzone development is related to the development of the Qt3 and Qt4 terraces.

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Tables

References			Altitude m a.r.b.									
Peña-Monné (1991)				85-90	45-60				20-30			
Moissenet (1985)			110-120	70	40				20	8	2-3	
Sánchez-Fabre (1989) Lozano et al. (1997) Sánchez-Fabre et al. (2019)				70-80	40-60				20	10-15		
Gutiérrez (1989) Gutiérrez et al. (2005)			100	75	55-60	50	30-44	32-35	20-23	9-15	3-5	1-2
Lafuente (2011)			80-90		45-65				20-30	15-20	3-5	
This paper	Guadalaviar R.	(Sierra de Albarracín)		25-40	35-40				18-20	8-10	5-10	1-3
	Guadalaviar R.	(Teruel depression)	100-140	50-55	60-66							
	Turia River			70-80								
Terrace levels			Qt1	Qt2	Qt3				Qt4	Qt5	Qt6	Qt7

Table 1. Terrace levels of the Guadalaviar-Turia fluvial system according to diffrent authors together with this paper proposal.

Quartz-OSL

Sample (Lab)	Code	Site	Terrace type	Bedrock	Depth (cm)	Age (kyr)	Dose (Gy)	(n)	Dose rate (Gy/ kyr)	w.c. %
12 22 19	SBLAS-1	San Blas	Strath	Fill	400	111 ± 6	117 ± 3	23	1.06 ± 0.05	5
12 22 20	SBLAS-2	San Blas	Strath	Fill	100	81 ± 5	112 ± 4	26	1.37 ± 0.06	5

$pIRIR_{290}$

Sample (Lab)	Code	Site	Terrace type	Bedrock	Depth (cm)	Age (kyr)	Dose (Gy)	(n)	Dose rate (Gy/kyr)	w.c. %
12 22 21	SBLAS-3	San Blas	Fill	Neogene detritic	1800	136 ± 20	414 ± 59	6	3.03 ± 0.10	19
12 22 22	VILLASP-1	Villaspesa	Strath	Neogene limestone	230	152 ± 17	725 ± 77	6	4.78 ± 0.18	7
12 22 25	ALBAR-1	Entrambasaguas	Strath	Jurasic limestone	300	271 ± 29	749 ± 47	3	2.77 ± 0.24	7
12 22 26	ALBAR-2	Entrambasaguas	Strath	Jurasic limestone	175	310 ± 34	842 ± 86	3	2.72 ± 0.09	15
12 22 27	ALBAR-3	Gea	Strath	Jurasic limestone	150	22 ± 7	82 ± 27	3	3.68 ± 0.14	7
12 22 29	ALBAR-5	Gea	Strath	Jurasic limestone	425	173 ± 11	430 ± 20	15	2.49 ± 0.09	9

Table 2. Burial depths, equivalent doses, water contents used for dose-rate calculations and luminescence ages obtained from sediment samples from the study area. All ages were obtained by using quartz-OSL and the post IRIR290 protocol (K-feldspar). n – number of measured and accepted aliquots.

Terrace level	above river bed (m)	Ages (ky) Terraces	Slopes	MIS	Published data with chronological significance
Qt1	85-90* to 100-140**				-
Qt2	25-40* to 70-80**	271 ± 29 ALBAR-1	310 ± 34 ALBAR-2	9-8	Fauna and Early-Middle Paleolithic industries at Cuesta de la Bajada: 264 ± 22 to 293 ± 24 ky (OSL; Santonja et al., 2014) and quite older and less reliable ESR ages (Duval et al., 2017)
Qt3	35-40* to 60-66**	152 ± 17 VILLASP-1	173 ± 11 ALBAR-5	6	Los Baños tufa (Arlegui et al., 2004) Older than 164 ± 10 ky and 116 ± 4 ky (U/Th) Gutiérrez et al. (2008) 250 ± 32 ky (OSL Gutiérrez et al. (2020) 228.4 ± 11.4 ky (ESR) *Parelephas trogontherii* (Riss) (Esteras and Aguirre, 1964) Fauna correlated to Riss (Moissenet, 1985)
Qt4	18-20	136 ± 20 SBLAS-3 111 ± 6 SBLAS-1 81 ± 5 SBLAS-2		5e-a	Rounded Paleolithic artifacts found at the terrace surface (Obermaier and Breuil, 1927)
Qt5	8-10	22 ± 7 ALBAR-3		2	
Qt6	5-10			1	10.1 ± 0.3 to 6.8 ± 0.3 ky (U/Th) 7.26 ± 0.42 ky cal (^{14}C) to 4.63 ± 0.14 ky (U/Th) (Peña Monné et al., 1996; Sancho et al., 1997)
Qt7	1-3			1	3.4 ± 0.7 ky (OSL; Lafuente, 2011)

Table 3. Staircase terrace system of the Guadalaviar-Turia rivers, with the height above riverbed and chronology obtained in this study. Previously published data with chronological significance are also listed.

Figures

Fig. 1. (a) General location map (b) Digital Terrain Model of the study area, showing the relief, main rivers and localities. The sites from where sediment samples were collected for OSL dating (red stars) or were previously obtained chronological data (blue stars) are also indicated. The inset shows the location of the study area in the Iberian Peninsula; (c) simplified geological scheme of the Guadalaviar/Turia basin showing the location analyzed spots.

Fig. 2. Confluence area between the Guadalaviar and de la Fuente del Berro rivers, at Entrambasaguas (Sierra de Albarracín). a) Geomorphological scheme, with lithological information and representation of the Quaternary deposits, indication of the A and B sectors, location of the stratigraphic logs and places sampled for OSL dating. 1 -Jurassic limestones, dolostones and marls; 2- Quaternary deposit; 3 - Qt2 terrace; 4 - Holocene tufa (Qt6); 5 – floodplain; 6 – slope; 7 - stratigraphic log and samples location; b) Geological section of the A sector; c) Photograph of the stratified scree (1986); d) Stratigraphic log of the B sector; e) Collecting the OSL sample ALBAR-1 from sands at the Qt2 terrace top deposits; f) Collecting the OSL sample ALBAR-2 from a sand level in the stratified scree.

Fig. 3. Sector with incised meanders in the Gea Canyon; a) Geomorphological scheme, with lithological information and representation of the Quaternary deposits, but also location of the stratigraphic logs and places sampled for OSL dating. 1 -Jurassic limestones, dolostones and marls; 2 - Qt2 terrace; 3 - Qt5 terrace;4 - Qt6 (Holocene tufas); 5 - main river channel and floodplain; 6 – slopes; 7 - stratigraphic logs and

location of OSL samples; b) Geological section with location of the studied stratigraphic logs; c) Upper part of the slope, showing stratified screes and location of the OSL sample ALBAR-5; d) Stratigraphic log of the slope upper part, with location of the OSL sample ALBAR-5; e) Stratigraphic log of the Qt5 terrace fluvial deposits, that are covered by a tufa; location of the OSL sample ALBAR-3; f) and g) View of the slope lower part, with location of the layer where the OSL sample ALBAR-3 was collected.

Fig. 4. San Blas sector. a) Geomorphological map showing the Guadalaviar River terraces, between San Blas and the confluence with the Alfambra River and beginning of the Turia River. 1 – Neogene limestones; 2 – Neogene siliciclastics; 3 – structural slopes; 4 - Qt1; 5- Qt2; 6: Qt3; 7 - Qt4; 8 - Qt5; 9 - floodplain (Qt7); 10 - Holocene alluvial fans; 11 - Holocene slopes; 12 - terrace scarps; 13 - fluvial network; 14 - badlands. 15 infilled valleys; 16 - urban area; 17 – roads; 18 - OSL samples; b) Panoramic view of the Qt4 terrace, at San Blas; location of the three OSL samples; c) Lower part of the exposure, showing the OSL sample SBLAS-3; d) Middle part of the exposure, showing the OSL sample SBLAS-1; e) Upper part of the exposure, showing the OSL sample SBLAS-2.

Fig. 5. Villaspesa sector. a) Geomorphological map showing the Turia River terraces. 1 – Neogene limestones; 2 – Neogene siliciclastics; 3 – structural slopes; 4 - Qt3; 5 - Qt4; 6- Pleistocene slopes; 7 - Pleistocene slopes b; 8 - Holocene slopes; 9 - Holocene infills; 10 - Holocene alluvial fans; 11 - Floodplain (Qt7) and main rivers; 12 - terrace scarps; 13 - fluvial network; 14 – badlands; 15 - infilled valleys; 16 - urban area; 17 - roads; 18 - OSL samples; b) Geological section (AB in Fig. 5a), showing the several geomorphic

units; c) location of the OSL sample VILLASP-1; d) Composed stratigraphic log, showing the stratigraphic position of the OSL sample.

Fig. 6. Longitudinal profile of the modern Guadalaviar and Turia rivers (flood plain - Qt7 and river bed), between Entrambasaguas (Sierra de Albarracín) and Villaspesa. The longitudinal profiles reconstructed for the Qt1 to Qt6 terrace levels, based on the local remains and age of their associated sedimentary deposits, are also presented. A relevant knickzone can be identified between El Arquillo dam and San Blas, makes the transition from the upstream reach on hard Mesozoic rocks (only with local remains of Qt2 and Qt5) to low reach running on the Neogene deposits that promoted terrace development downstream.

Fig. 7. Relationship between the obtained OSL ages, from the studied terrace and slope deposits, with the glacial stages established in the Pyrenees (Lewis et al., 2009; García-Ruiz et al., 2012) and with the Marine Isotopic Stages and substages (adapted from Railsback et al., 2015).

Figure1

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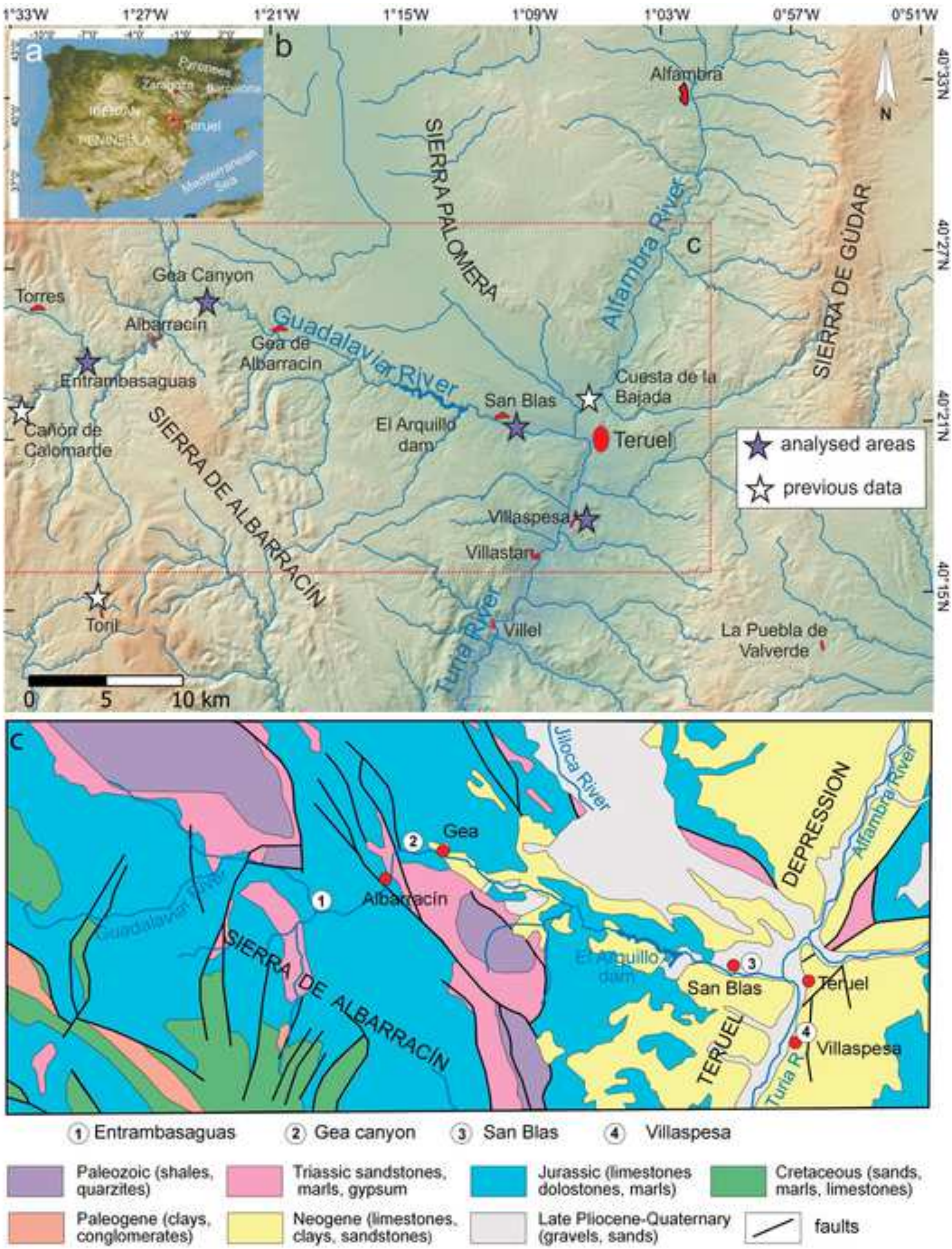

Figure2

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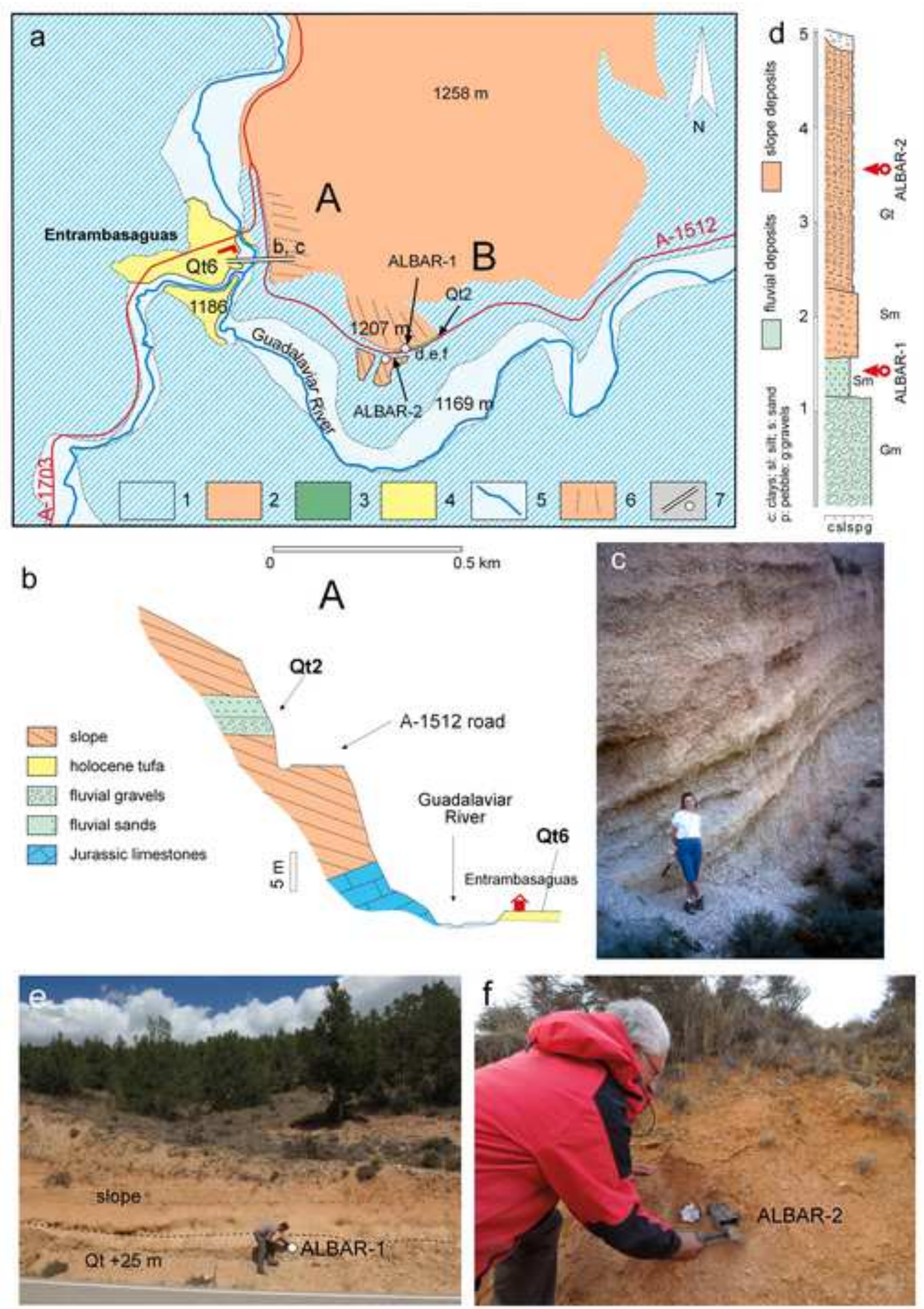

Figure3

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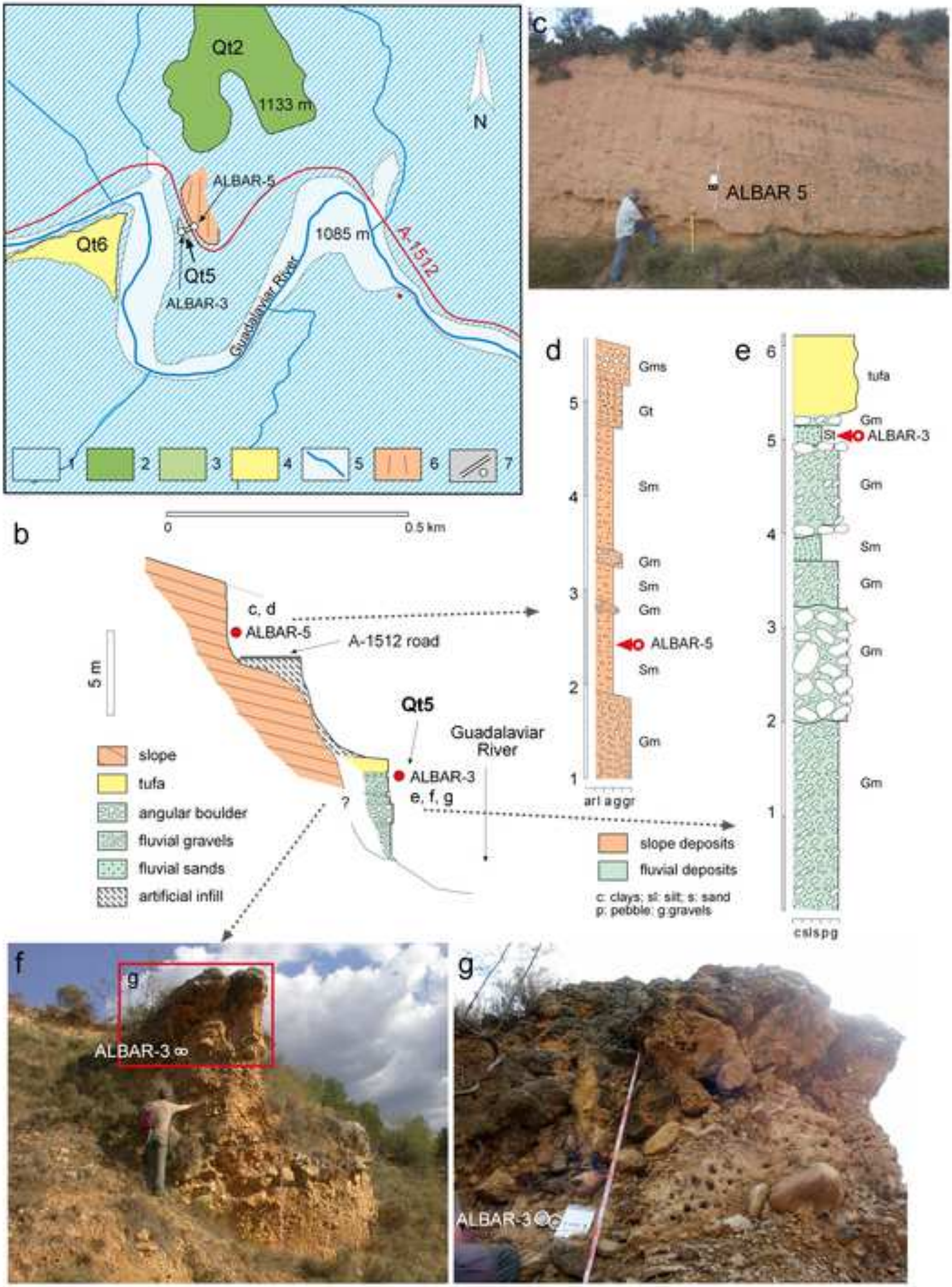

Figure4

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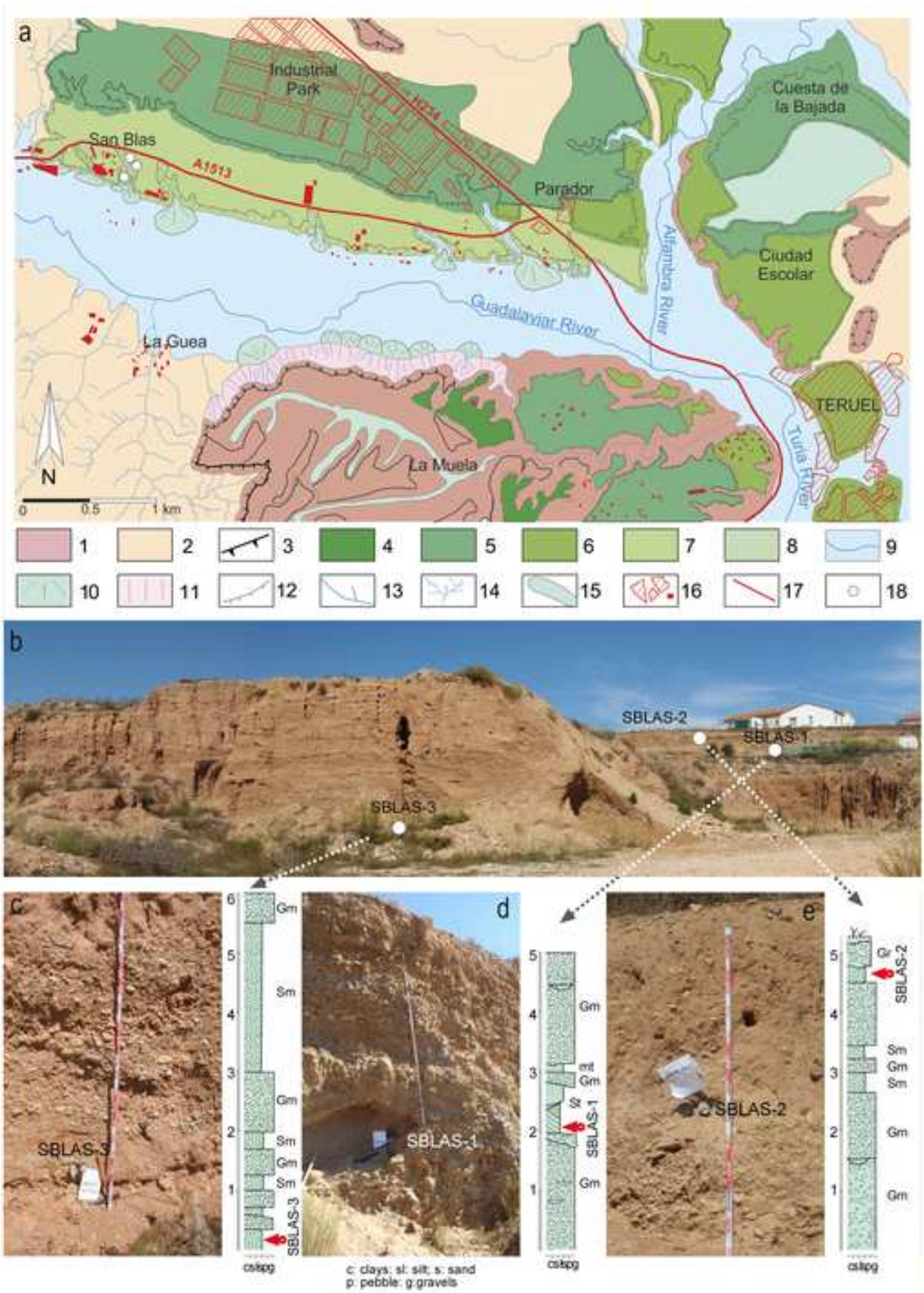

Figure5

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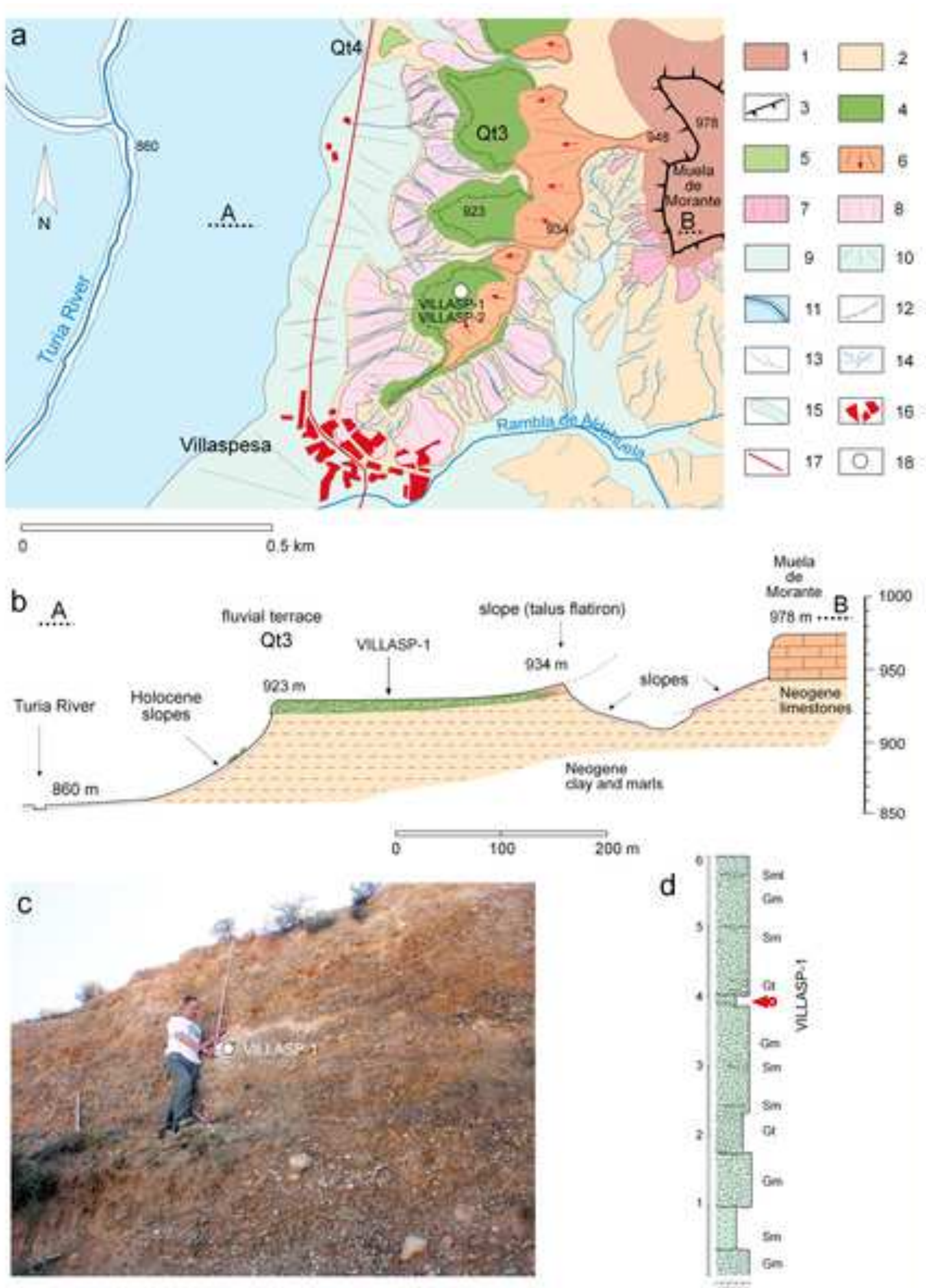


Figure6

Click here to access/download;Figure;Fig 6_R1.jpg

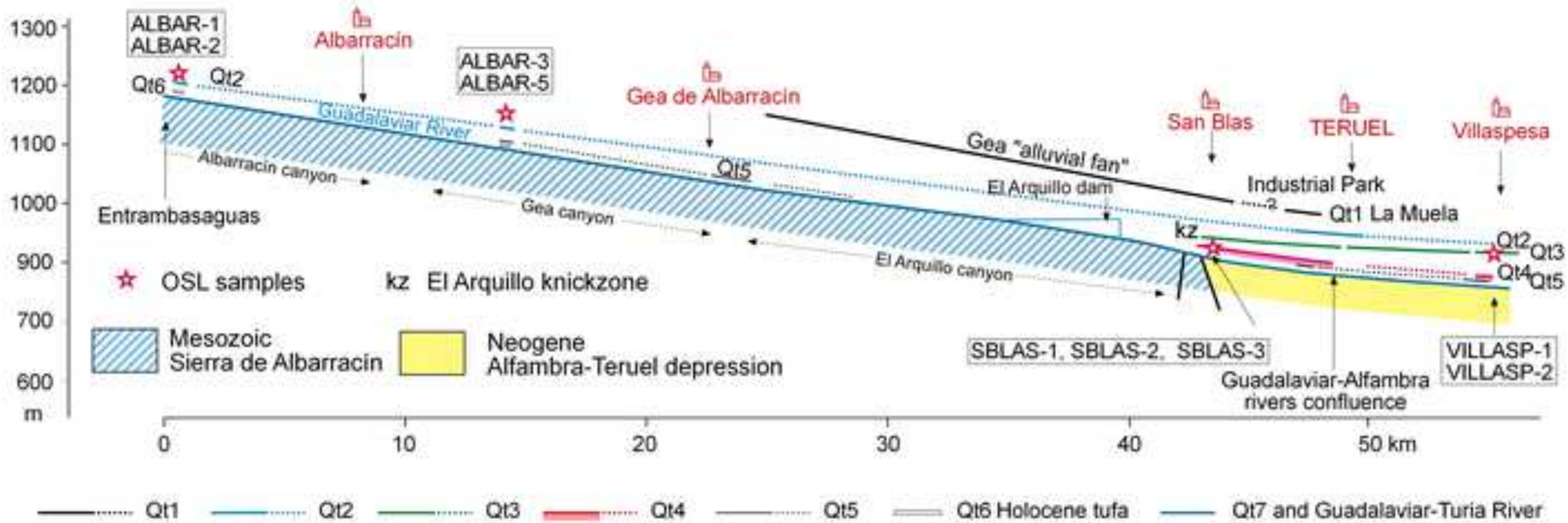
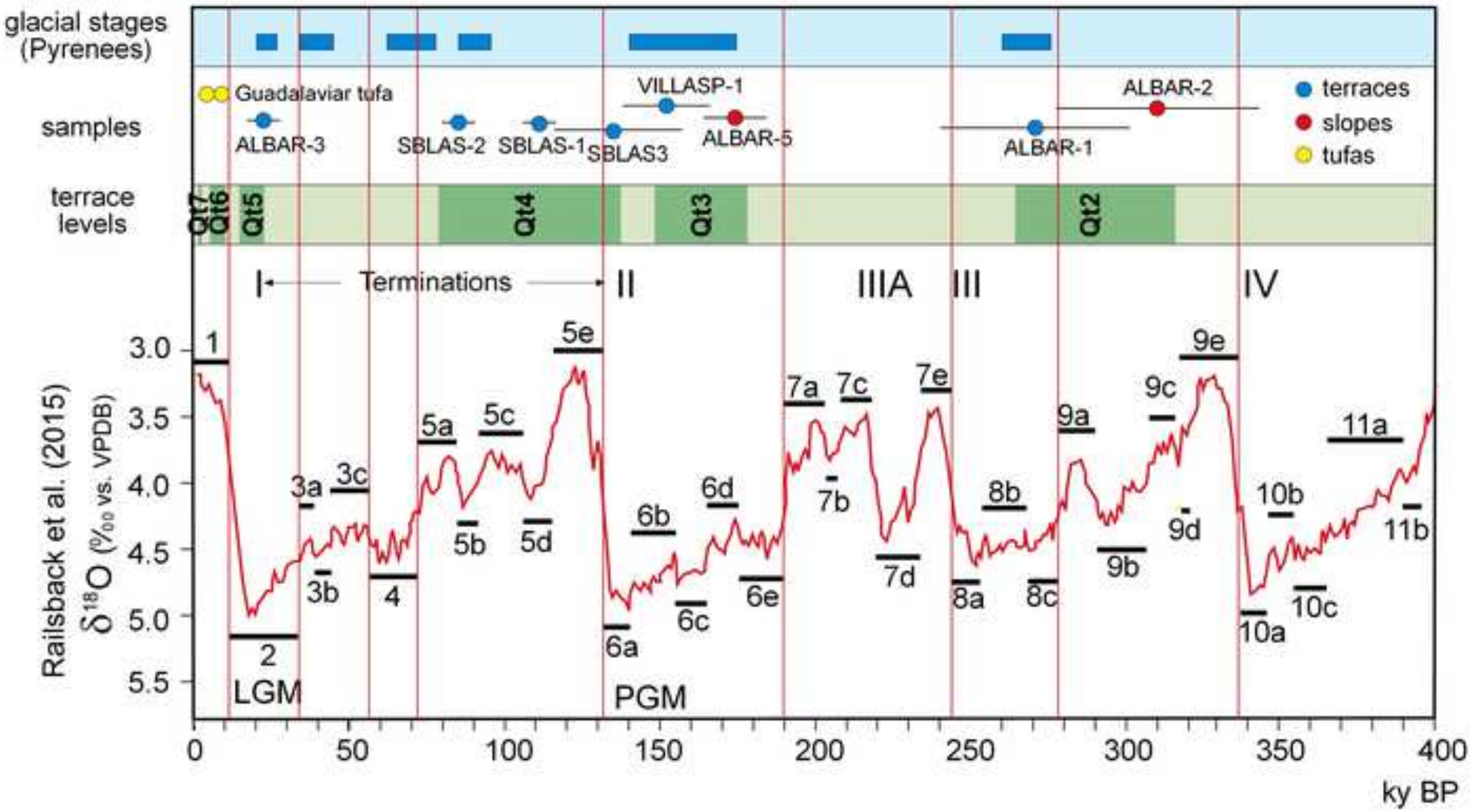


Figure7

Click here to access/download;Figure;Fig 7 v2.jpg



Zaragoza
16th July, 2021

Dear Editor,

On behalf the authors I declare we DO NOT HAVE any kind of conflict of interests.

Sincerely yours,

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