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Dynamics of Mediterranean late Quaternary fluvial activity: An example from the River Ebro (north Iberian Peninsula)

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ABSTRACT

Late Pleistocene and Holocene fluvial evolution of the upper River Ebro (Miranda basin, north Spain) is analysed using geomorphological, sedimentological, and optical dating techniques. Maximum regional crustal uplift of 0.98 m/ka approximately helped preserve a suite of terraces in the Miranda basin: 5 river terraces (T1–5) were identified and their formation attributed to MIS 6 (T_1), MIS 5d (T_2), MIS 4 (T_3), MIS 2 (T_4), MIS 1 (T_5). Alluvium deposited in terraces T_1, T_2, T_3, and T_4 is well-sorted, clast-supported gravels; whereas the T_5 deposit is exclusively composed of silt. Gravels were deposited during cold and dry periods when reduced vegetation cover on hillslopes increased sediment supply to the trunk river. Silt was deposited in overbank settings under warmer and wetter climate conditions when vegetation cover stabilised hillslopes and restricted sediment supply. It also resulted in lower peak discharge and reduced flow velocities over vegetated floodplains. The chronological sequence of terraces indicates that incision occurred during climatic transitions. We conclude that the upper River Ebro responded to fluctuations in sediment supply and discharge controlled by late Quaternary climate cycles.

1. Introduction

Streams that undergo changes in the discharge to sediment-load balance are prone to recurrent phases of incision and aggradation. Alluvial terraces are one of the main features generated by the combination of these processes. Terrace formation is controlled by autogenic factors (e.g., size of accommodation space, sediment availability, meander migration) and by allogenic factors (e.g., climate, tectonic activity, base-level change, land cover and land use changes). Generally, formation and preservation of multilevel terrace systems is thought to be caused by a combination of tectonic uplift and Quaternary climatic cycles (e.g., Bridgland and Westaway, 2014).

Climate plays a major role in terrace formation by introducing changes in temperature (Vandenberghe, 2008; Stange et al., 2013; Scherler et al., 2015) and humidity (Stevaux, 2000; Thomas et al., 2001; Bekaddour et al., 2014; Hennekam et al., 2014). Variations in these parameters can alter the vegetation cover, hillslope (erosional) processes, discharge, and sediment supply, triggering periods of aggradation or incision (Bridgland, 2000; Vandenberghe and Maddy, 2001; Macklin et al., 2012). These ideas led to the formulation of numerous fluvial evolution models (Knox, 1972; Vandenberghe, 1995, 2015; Bridgland, 2000; Maddy et al., 2001). However, relationships between fluvial behaviour and climate-driven changes can be nonlinear owing to intrinsic dynamics and interlinked processes (Womack and Schumm, 1977; Bull, 1990), leading to a delayed and/or unclear fluvial response to such an external trigger (Blum and Törnqvist, 2000; Daniels, 2008).

Nevertheless, it is suggested that climatic fluctuations alone cannot explain the formation of river terraces and that epeirogenic uplift is necessary for developing and preserving terrace staircases (Bridgland, 2000). Redistribution of material after continental denudation might trigger isostatic crust adjustments (uplift), which induces fluvial incision by lowering relative base level (Bridgland and Westaway, 2008, 2014). Thus river terraces are probably formed as a response of the combined effect of uplift and climate-driven processes.

An increasing number of publications have allowed a better understanding of fluvial response during the Quaternary in the Iberian Peninsula (Cunha et al., 2005, 2008, 2012; Thorndycraft and Benito, 2005, 2006; Santisteban and Schulte, 2007; Martins et al., 2010; Ramos et al., 2012). For the Ebro basin, studies focusing on the tributaries of the River Ebro with their headwaters in the Pyrenees (Benito et al., 1998, 2010; Sancho et al., 2003; Peña et al., 2004a, 2004b; Lewis et al., 2009; Stange et al., 2013) and in the Iberian range (Macklin et al., 1994; Macklin and Passmore, 1995; Fuller et al., 1998; Peña et al., 2004c; Whitfield et al., 2013) provide a chronological framework for

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fluvial sequences that enables the linkage of fluvial processes with Quaternary climatic oscillations. However, for the main River Ebro so far only Luzón et al. (2008, 2012) and Gil et al. (2013) have provided chronological data. The main aim of these investigations was to analyse sediment preservation in relation to gypsum karstification, thus not elucidating the factor(s) controlling the longer-term fluvial evolution of the River Ebro. Better spatial and temporal control of the fluvial archives is required to gain further insight into the dynamics of the main River Ebro and enable correlations between the fluvial evolution of tributaries and the main trunk stream.

This paper presents sedimentological and chronological data of the River Ebro Quaternary terrace sequence in the northwestern highlands of the upper Ebro catchment. Fluvial dynamics in this upper catchment with its more humid setting is less impacted by peak meltwater discharges compared to the Pyrenean tributaries. We discuss the impact of external versus internal forcing on fluvial evolution for the River Ebro and present the palaeohydrological context during which the terrace sequence was developed. Results show that the River Ebro and its tributaries have responded in a similar way during the Quaternary.

2. Regional setting

The River Ebro basin is the largest river basin in the Iberian Peninsula with a catchment area of 85,000 km^2. The river has its headwaters in the Cantabrian Range (north Spain) and flows southeastward until it discharges into the Mediterranean Sea (Ebro Delta); 185 km away from its source, the River Ebro flows into the Miranda basin (Fig. 1). The Miranda basin is part of the Cenozoic Pyrenean Cordillera, which was uplifted during the early Oligocene and created a continental sedimentary basin in the area around Miranda de Ebro. The post-alpine tectonic evolution of the basin is characterised by the development of a NW-SE trending joint system that could be the result of revealing continuous convergence between Iberia and Europe (Merino et al., 1996) or constant isostatic uplift in response to excavation of the Ebro foreland basin after an exhorreic system established around 12 to 7.5 Ma ago (García-Castellanos and Larrasoaña, 2015).

The Miranda basin is confined by the uplifted central axis of the Miranda-Treviño syncline to the north, the Sobrón anticline to the west, and the thrust of the Sierra Cantabria–Obarenes Mountains to the east and south (Fig. 1). The River Ebro enters the Miranda basin through the Sobrón anticline, flows for 25 km approximately following the WNW-ESE–trending Miranda-Treviño synclinal structure and opens toward the Ebro foreland basin, cutting through the Sierra Cantabria–Obarenes thrust. The mountainous margins of the Miranda basin (Sobrón anticline, Sierra Cantabria–Obarenes Mountains) are composed of Cretaceous limestones, marls, and sandstones. The Cenozoic basin is filled by continental conglomerates passing laterally into sandstones and lacustrine limestones toward the depocenter of the basin. Overlying the Tertiary succession, the River Ebro has deposited a sequence of fluvial sediments during the Quaternary (Aranegui, 1927; Gonzalo Moreno, 1981; Figs. 1 and 2). Until now, no chronometric information for the fluvial beds has been available.

3. Material and methods

3.1. Geomorphology

Fluvial terraces within the Miranda basin were mapped using aerial photographs (scale 1:18,000), orthophotos (scales 1:50,000, 1:25,000, 1:10,000, and 1:5000), and geological maps (IGME, scale 1:50,000). This information was supplemented by data collected during field work. Elevation data was obtained from topographic maps published by the regional governments of Castilla y León and País Vasco (scales 1:10,000 and 1:5000). Area, width, and length of terraces as well as valley cross and longitudinal profiles were determined using QGIS and 5-m cell size, LiDAR-derived DEMs published by IGN (Instituto Geográfico Nacional).

3.2. Sedimentology

Logging, sampling, and identification of sedimentary units were carried out on 12 natural exposures and quarry faces. Fluvial sediment was characterised following procedures outlined by Cailleux and Tricart (1963), including clast lithology, size, roundness, and flatness. Fluvial environments were identified by characterizing lithofacies and architectural elements (Miall, 1996). Additionally, sand samples were collected for grain-size determination through dry-sieving. These were

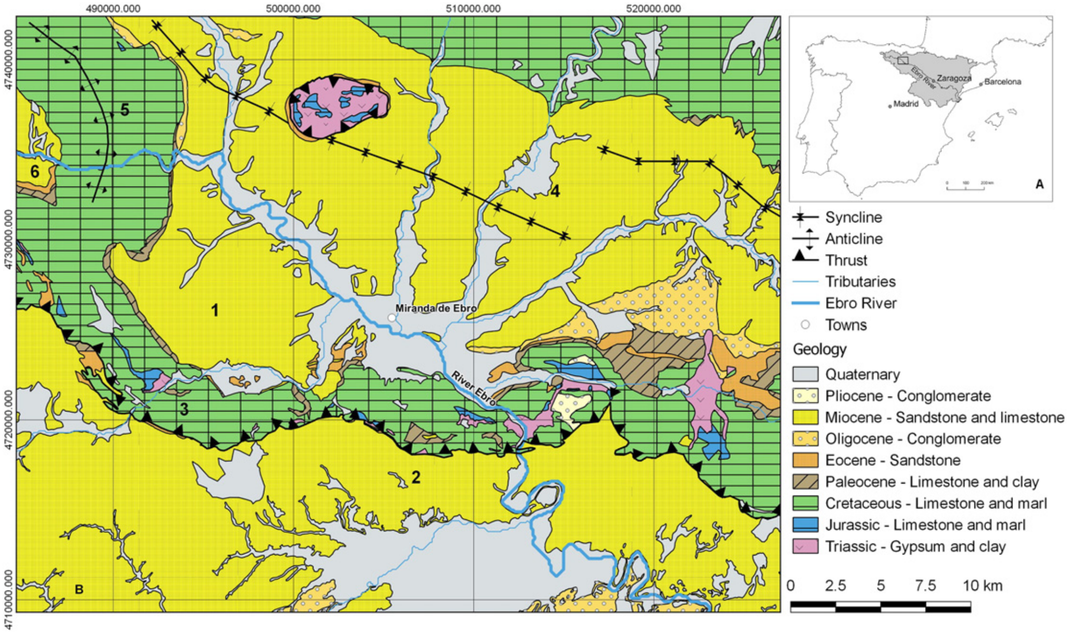

Fig. 1. (A) Location of the study area within the catchment of the Ebro River (grey zone), situated in the northern Iberian Peninsula. (B) Geological map of the Miranda basin: 1) Miranda basin; 2) Ebro foreland basin; 3) Obarenes-Sª Cantabria thrust; 4) Miranda syncline (uplifted central axis); 5) Sobrón anticline; 6) Tobalina valley.