Global and Planetary Change 101 (2013) 97–112

Contents lists available at SciVerse ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Terrace staircase development in the Southern Pyrenees Foreland: Inferences from ^{10}Be terrace exposure ages at the Segre River

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ARTICLE INFO

Article history:
Received 29 June 2012
Accepted 14 December 2012
Available online 23 December 2012

Keywords:
geomorphology
quaternary geology
sedimentology
river terraces
exposure dating
cosmogenic nuclides
Ebro Basin
Pyrenees
Segre River

ABSTRACT

The fluvial network of the Southern Pyrenees is an example of transverse drainage systems in young (alpine) mountain belts and it features well preserved fluvial terrace records. Some of the major Southern Pyrenees tributary rivers have been studied previously and have some age controls on their fluvial terrace levels. We extend these records to one of the largest streams in the Southern Pyrenees, the Segre River.

In this paper, we present new GIS data, field observations and exposure ages obtained from *in situ* produced terrestrial cosmogenic nuclides (^{10}Be). The focus of this paper is set to unravel the relative impact of climatic controls on the formation of the Segre terrace staircase in the Southern Pyrenees foreland (Ebro Basin).

The Pleistocene terrace staircase of the Segre River is built up by seven major terrace levels, which range from 112 to 3 m above the present-day active channel. The prominent upper and middle terraces TQ1, TQ2, TQ3 and TQ4 have been sampled for ^{10}Be exposure dating. Exposure ages have been calculated using Monte Carlo parameter simulations. Additionally, we applied a Profile Rejuvenation method accounting for variable ^{10}Be inheritance in the samples, and which yielded comparable results. The Monte Carlo results show Middle to Late Pleistocene exposure ages for TQ1: 202 ka (MIS 7), TQ2: 139 ka (MIS 6), TQ3: 100 ka (MIS 5), and TQ4: 62 ka (MIS 4), involving denudation rates of 3–8 mm ka^{-1}. The results indicate that the abandonment of Segre paleo-floodplains and the change from aggradation to predominant incision is related with Middle to Late Pleistocene cold-warm climate transitions (or early stages of interglacial periods). Major floodplain aggradation appears to be linked with intense deglaciation at the end of MIS 8, MIS 6, and MIS 4. The exposure of terrace TQ3 (MIS 5) indicates that terrace formation might also occur during relatively warm isotope stages with sufficient climate instability.

On a regional scale, the staircase morphology at the Segre River shows similarities with adjacent fluvial systems in the Southern Pyrenees. In addition, previously published chronologies for these systems are consistent with the timing of aggradation and terrace abandonment. Both, staircase morphology and chronology point to regionally synchronous phases of floodplain aggradation and river incision, which seem to be triggered by climate variability and Pleistocene glaciations in the Pyrenees since the Mid Pleistocene Climatic Revolution.

1. Introduction

The formation of river terrace staircases is commonly attributed to changing climatic conditions in combination with tectonic uplift (e.g. Bridgland, 2000; Houtgast and Van Balen, 2000; Veldkamp and Tebbens, 2001; Westaway, 2002; Vandenberghe, 2003; Peters and Van Balen, 2007; Carcaillet et al., 2009). Climate can affect rivers through variability in vegetation cover, and precipitation, which control the amount of discharge and sediment supply within a drainage system (Bridgland, 2000; Vandenberghe, 2002). Those climatic boundary conditions determine channel morphology and the development of drainage pattern (e.g. Kasse et al., 1995; Vandenberghe, 2003), and particularly whether floodplain aggradation or vertical incision is favoured along a river course. The general consensus is that the repetition of Pleistocene glacial-interglacial cycles caused an alternation of aggradation and incision (i.e. Bull, 1990; Bridgland and Westaway, 2008; Gibbard and Lewin, 2009), which, probably in combination with tectonic uplift (Westaway, 2002), led to the formation of river terrace staircases, a type of morphology which is known from rivers worldwide (Bridgland and Westaway, 2008).

The timing and the external controls of fluvial response to changing climatic and tectonic environments are difficult to assess and their quantification is often complicated by delayed and non-linear feedback mechanisms ("complex response", i.e. Schumm and Parker, 1973; Vandenberghe, 1995; Vandenberghe and Maddy, 2001; Cheetham et al., 2010). In order to unravel the formation of terrace staircases and its external controls, it therefore requires precise timing of terrace formation (floodplain aggradation), their abandonment and subsequent dissection (vertical incision). Maddy et al. (2001) proposed a

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http://dx.doi.org/10.1016/j.gloplacha.2012.12.007

renewed climate-driven fluvial terrace development model to explain river behaviour (phases of incision and aggradation) in response to Pleistocene glacial-interglacial climate cycles. Glacials and interglacials are seen as relatively stable phases with reduced river activity (nival discharge regime during glacials; precipitation driven discharge and single-channel river morphology during interglacials; Kasse et al., 1995; Maddy et al., 2001; Vandenberghe, 2008). This raises the question, when precisely aggradation of floodplains (preserved as terraces) and vertical fluvial incision (preserved as terrace scarps) take place.

During the last decades, many studies have been carried out on terrace formation and fluvial response to external forcing (e.g. Büdel, 1977; Bull, 1990; Kasse et al., 1995; Vandenberghe, 1995; Maddy et al., 2001; Bridgland and Westaway, 2008). It is generally accepted, that the key to unravel fluvial landscape evolution and terrace staircase formation is to understand the impact of unstable periods during climatic transitions (Vandenberghe, 2008) and to assess the (non-linear) response mechanisms of rivers to changes in climate, base-level and tectonics (i.e. Schumm, 1993; Maddy et al., 2001; Van Huissteden and Kasse, 2001; Gibbard and Lewin, 2009; Cheetham et al., 2010). It can be expected that particularly towards the termination of glacial cycles (cold–warm transition) aggradation of fluvial deposits is favoured as climate warming triggers glacier melt and significantly increases (peak) discharges and sediment supply. In their (climate-driven) model Maddy et al. (2001) distinguish two episodes of vertical incision, a phase of major down cutting at glacial–interglacial transitions and a second minor incision phase during warm-cold transitions. Respective the long-term incision by a river, tectonic uplift has been invoked to be an important external control on river entrenchment (Maddy et al. 2000; Westaway, 2002). In order to assess the impact of the various controls (climate, tectonics, and also base-level) and their consequences for terrace staircase formation, it is essential to have knowledge about the on-site morphology, local and regional tectonic settings, and to obtain age controls on the exposure of single terrace levels. In this paper we present new morphological observations and exposure ages of the lower Segre River terraces, obtained from *in situ* produced terrestrial cosmogenic nuclides (TCN), in order to assess the timing of aggradation and incision in the Ebro foreland basin and to understand its relation to Quaternary climate variability and potential neo-tectonics and base-level effects.

1.1. Regional settings

Thanks to the excellent preservation conditions in the long-term semiarid Ebro Basin (Fig. 1) and a well-established glacial chronology of the Pyrenees, the fluvial terrace staircases of allochthonous Southern Pyrenees streams are well suited to study the fluvial landscape morphology and process-based relationships between Quaternary climate variability (Pyrenees glaciations), tectonics and structural controls. The Ebro foreland basin underwent a long period of endorheic drainage before the basin opened and connected to the Mediterranean Sea, presumably

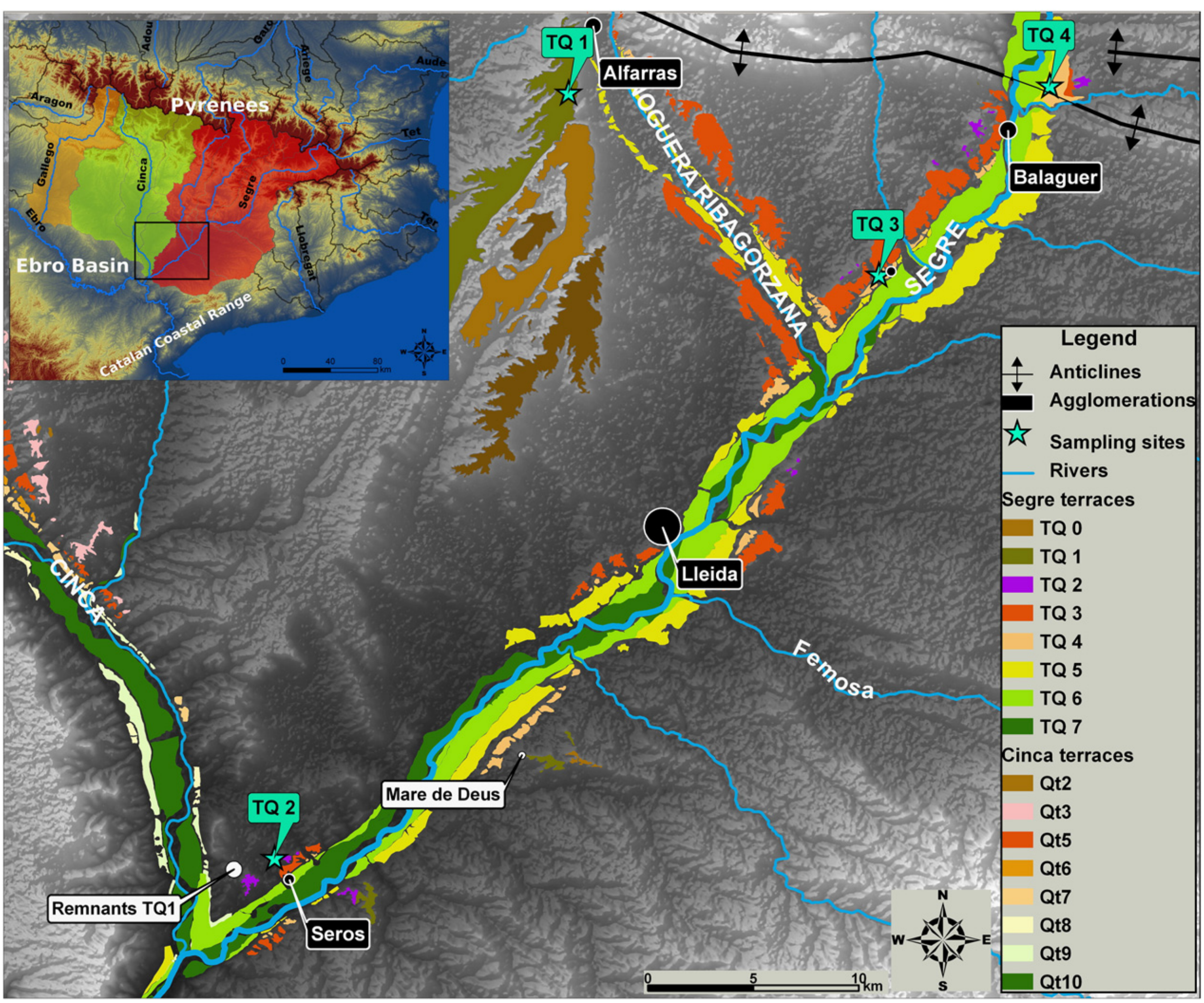

Fig. 1. Overview of the Study area and the foreland records of terrace remnants at the rivers Segre, Noguera Ribagorzana (Peña, 1983) and Cinca (Lewis et al., 2009) including main agglomerations and location of the sampling sites. Inset, left: A simplified map of regional topographic units and the extent of major river catchments in the Southern Pyrenees (Gállego River in orange, Cinca River in green, and Segre River in red).