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Modelling the impact of regional uplift and local tectonics on fluvial terrace preservation

W. Viveen [a,b,*], J.M. Schoorl [a], A. Veldkamp [c], R.T. van Balen [d]

[a] Soil Geography and Landscape Group, Wageningen University, P.O. Box 47, NL-6700 AA Wageningen, The Netherlands
[b] Instituto Universitario de Geologia, Edificio de Servicios Centrales de Investigacion, Campus de Elviña, University of A Coruña, 15071 A Coruña, Spain
[c] ITC Faculty of Geo-Information Science and Earth Observation, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands
[d] Faculty of Earth and Life Sciences, Vrije Universiteit Amsterdam, De Boelenlaan 1085, 1081 HV Amsterdam, The Netherlands

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A terrace formation model (TERRACE) combined with a longitudinal river profile model (FLUVER) was used to simulate fluvial terrace formation and preservation in the northwest Iberian lower Miño River basin under the influence of three tectonic conditions; namely regional vertical uplift, local basin subsidence, and localised differential uplift. The simulation results were compared against mapped terrace altitudes and deposit thicknesses. The best results were achieved by combining all three tectonic factors, indicating that specific terrace formation is a complex interplay of regional and local tectonics. The best fit regional uplift rate of 0.10 m ka^{-1} over the past 600 ka is higher than the 0.08 m ka^{-1} previously estimated for a section farther to the west, which can be attributed to an increase in tectonic uplift from the NW Iberian Atlantic margin toward the east. Local relative subsidence causes sediment accumulation in the local basin and less sedimentation in the fluvial terraces on the surrounding uplifting blocks. Different uplift rates on both sides of the valley caused preservation of unpaired terraces, which are fill terraces on one side of the valley and strath terraces on the other side. Usually, the formation of fill or strath terraces is considered to be only climate-dependent. Our results indicate that local tectonics can be important in the terrace formation and preservation. This suggests that terrace correlations in other river systems, based on deposit thicknesses only, might be over-simplified.

1. Introduction

Tectonic motions are an important factor on river terrace formation. Firstly, terrace staircases are formed as a result of regional uplift (Burbank et al., 1996; Pazzaglia and Brandon, 2001; Wegmann and Pazzaglia, 2002; Bridgland and Westaway, 2008a; Cunha et al., 2008; Claessens et al., 2009). Secondly, differential tectonic movements may cause the formation of unpaired terraces along a river (Peters and van Balen, 2007; D'Allesandro et al., 2008; Larue, 2008; Martins et al., 2009; Ramos et al., 2012) or cause differences in terrace dimensions because the river is forced to migrate in a predetermined direction (e.g., Cox, 1994; Salvany, 2004). Differential uplift may also cause differences in fluvial sediment thicknesses between terrace levels, especially if one or several of the terraces are located in areas of relative subsidence, causing a local depression in which large amounts of sediments can accumulate (Viveen et al., 2012a; Stange et al., 2013). The influence of tectonic movements on terrace formation and preservation is, however, always registered as an end result, without clear indications for the relative contributions of the different tectonic components (e.g., local, regional, and tilting). Thus, in most case studies the exact effects of tectonic motions on terrace formation remain poorly understood.

In this paper we use a forward model to simulate the effects of various tectonic processes on terrace formation and preservation in order to deduct what their individual contributions are to the observed net results. A terrace staircase from the NW Iberian lower Miño River is used as a case study because the terrace ages are well-constrained by cosmogenic ray exposure (CRE) and thermoluminescence dating (Viveen et al., 2012b) and because the influence of other external factors such as base level change and climate change on the regional terrace sequence is well understood (Viveen et al., 2013a). Lastly, an extensive data set based on field observations such as mapped terraces and terrace deposit thicknesses and on tectonic basins (Viveen et al., 2012a, b) makes it possible to compare the modelled results against real-world data.

2. Regional setting

The Miño–Sil river system is situated in the NW Iberian Peninsula (Fig. 1). Here, Precambrian and Palaeozoic rocks (predominantly gneisses, schists, and slates) dominate the subsurface lithology. They were deformed during the Variscan orogeny and intruded by granitoids.

* Corresponding author at: Soil Geography and Landscape Group, Wageningen University, P.O. Box 47, NL-6700 AA, Wageningen, The Netherlands. Tel.: +34 981 167000x2694.
E-mail address: wim.viveen@wur.nl (W. Viveen).

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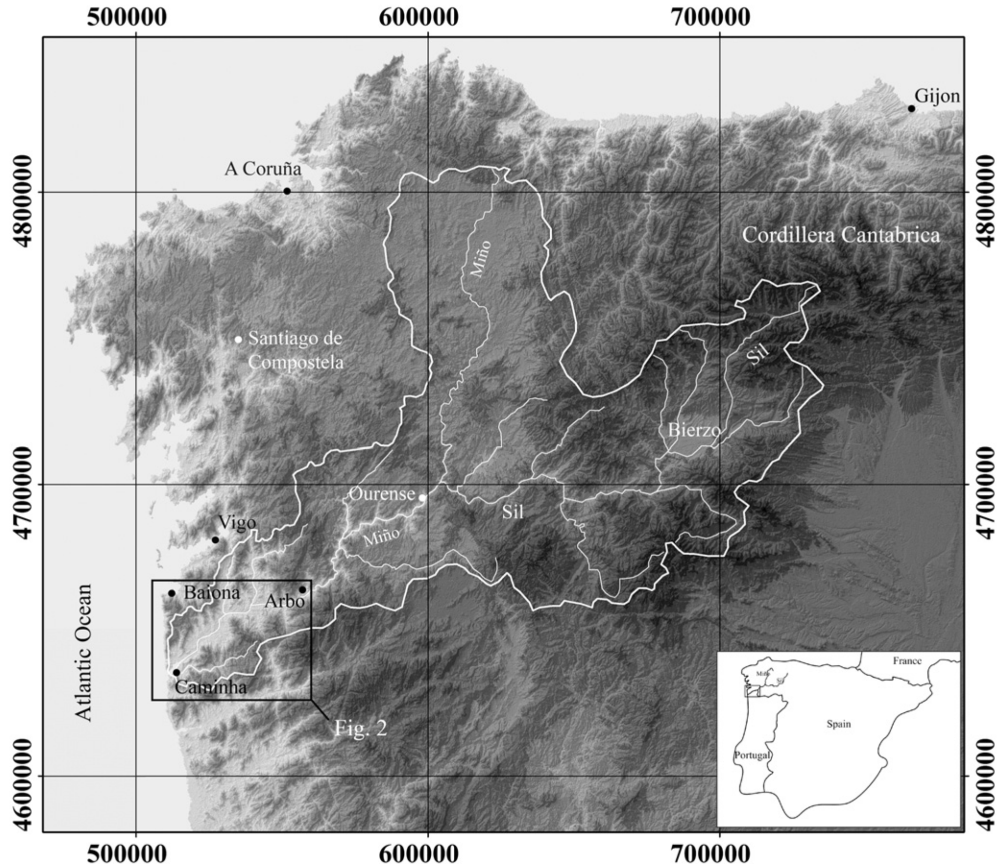

Fig. 1. Overview of the Miño–Sil catchment and location of the lower Miño River valley. Adapted from Viveen et al. (2012b).

During this deformation phase, left lateral NNE–SSW to ENE–WSW and right lateral NNW–SSE to NW–SE strike-slip faulting occurred (Ribeiro, 1990). These faults were reactivated in several tectonic phases during the Mesozoic and Cenozoic (Pinheiro et al., 1996; De Vicente and Vegas, 2009; Anton et al., 2010). A final phase of reactivation started with the collision of the Eurasian and Iberian plates during the Eocene (Pyrenean–Cantabrian orogeny). The N–S to NE–SW-directed compression reactivated the older left lateral NNE–SSW strike-slip faults and the right lateral NW–SE transpressional strike-slip faults (Vegas et al., 2004; Cloetingh et al., 2005; De Vicente and Vegas, 2009). Thrust and normal faulting have also been reported for this period (Cabral, 1995; Pinheiro et al., 1996; Martin-Gonzalez, 2009). Associated with the reactivation of the strike-slip faults is the formation of various small tectonic basins in the area during the Oligocene–middle Tortonian (De Vicente et al., 2011; Martin-Gonzalez and Heredia, 2011). This tectonic activity persists until the present day as demonstrated by earthquakes with low to moderate intensities (Lopez-Fernandez, 2008). The tectonic motions affect the river morphology, as evidenced by knickpoints in river profiles when they flow across faults, sharply incised valleys, and asymmetric drainage networks that point toward local block tilt (Viveen et al., 2012a). Evidence of faulted river terraces has been reported for the lower Miño River (Viveen et al., 2012a) and for its middle reach (Perez-Alberti et al., 2013). Regional, vertical uplift is also evident from an extensive, well-developed terrace staircase in the lower Miño River, which will be further discussed in the next section.

3. Study area

The area studied in this paper is situated in the lower reach of the Miño–Sil River system, which drains an area of 16,993 km^2 in the NW Iberian Peninsula (Fig. 1). The Miño has a mean discharge of 419.8 $m^3\ s^{-1}$ where it flows into the Atlantic Ocean (Rio-Barja and Rodriguez-Lestegas, 1992). The river has a total length of 375 km and a graded, concave profile (Viveen et al., 2013a). It starts in the Cordillera Cantabrica, after which it flows westward toward the Iberian Atlantic margin. In the upper and middle reaches, the Sil runs through a series of narrow bedrock gorges, which are alternating with a number of small, tectonic sedimentary basins such as the Bierzo basin (Fig. 1). The lowermost 80 km of the Miño River form the natural border between Portugal in the south and the Spanish region of Galicia in the north (Fig. 2). Here, the Miño is a mixed alluvial–bedrock river. The Miño–Sil river system is structurally controlled and frequently changes direction when it crosses structural lineaments. This is clearly visible in the lowermost reach, where frequent changes from an E–W flow direction to a N–S flow direction occur (Viveen et al., 2013a). Studies on faulted terraces in the lower Miño terrace record revealed steeply dipping normal faults with a maximum of 14 m of accumulative vertical offset, although strike-slip faulting cannot be excluded (Viveen et al., 2012a). Associated with the large N–S trending faults, but also with E–W to ESE–WNW and NW–SE faults, are a number of small tectonic basins (Viveen et al., 2012a): a total of 9 rhomboid-shaped basins with sizes <5 km^2 were mapped (Viveen et al., 2013b). These basins are filled in with over 20 m of sediments, mainly quartzite and quartz clasts, and underlain by thick banks of kaolinite clay (Viveen et al., 2012a).

Up to 11 well-developed terrace levels and a floodplain level are present in the lower Miño region. The typical spacing between terrace steps is 5 to 10 m (Viveen et al., 2013a,b). The thickness of the terrace deposits attains locally to 8 m, and the sediments are always composed of rounded to well-rounded quartz and quartzite clasts in a sandy to clayey matrix. The matrix is usually clast-supported. Multiple, shallow channel belts within the terraces indicate that Miño was a braided river at the time of terrace deposition. In the youngest terrace level a