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Tectonic and lithological controls on fluvial landscape development in central-eastern Portugal: Insights from long profile tributary stream analyses

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ABSTRACT

This study examines the long profiles of tributaries of the Tagus and Zêzere rivers in Portugal (West Iberia) in order to provide new insights into patterns, timing, and controls on drainage development during the Quaternary incision stage. The studied streams are incised into a relict culminant fluvial surface, abandoned at the beginning of the incision stage. The streams flow through a landscape with bedrock variations in lithology (mainly granites and metasediments) and faulted blocks with distinct uplift rates. The long profiles of the analyzed streams record an older transitory knickpoint/knickzone separating (1) an upstream relict graded profile, with lower steepness and higher concavity, that reflects a long period of quasi-equilibrium conditions reached after the beginning of the incision stage, and (2) a downstream rejuvenated long profile, with steeper gradient and lower concavity, particularly for the final reach, which is often convex. The rejuvenated reaches testify to the upstream propagation of several incision waves, interpreted as the response of each stream to increasing crustal uplift and prolonged periods of base-level lowering by the trunk drainages, coeval with low sea level conditions. The morphological configurations of the long profiles enabled spatial and relative temporal patterns of incisions to be quantified. The incision values of streams flowing on the Portuguese Central Range (PCR; ca. 380–150 m) are variable but generally higher than the incision values of streams flowing on the adjacent South Portugal Planation Surface (SPPS; ca. 220–110 m), corroborating differential uplift of the PCR relative to the SPPS. Owing to the fact that the relict graded profiles can be correlated with the Tagus River T1 terrace (1.1–0.9 My) present in the study area, incision rates can be estimated (1) for the streams located in the PCR, 0.38–0.15 m/ky and (2) for the streams flowing on the SPPS, 0.22–0.12 m/ky. The differential uplift inferred in the study area supports the neotectonic activity of the bordering faults, as proposed in previous studies based upon other geological evidence.

1. Introduction

The Portuguese territory, positioned along the western Atlantic border of Iberia, presents a complex geodynamic setting characterized by interplay between (i) passive margin Atlantic ridge push effects and (ii) interplate interactions related to NW-SE convergence of Eurasia and Africa (Nubia; at 4–5 mm/y; Calais et al., 2003; Nocquet and Calais, 2004; Cloetingh et al., 2005; Fernandes et al., 2007). The resulting stress field produces long wavelength vertical movements (uplift/subsidence) as well as fault movements, which together accommodate the tectonically induced finite strain. This neotectonic activity impacts on the regional landscape, acting upon an inherited morphology that has evolved through the Cenozoic (Cabral and Ribeiro, 1993; Ribeiro et al., 1996; Cloetingh et al., 2002, 2005; De Vicente et al., 2007, 2008, 2011; Cabral, 2012).

The landscape of mainland Portugal is characterized by a high average elevation, dominated by the northern Meseta (a plateau at an altitude ranging from ca. 650 to 700 m). It also presents a succession of

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~NE-SW trending mountain ranges, with altitudes of up to ca. 2000 m, and intervening topographic lows corresponding to sedimentary basins at altitudes of ca. 600 to 100 m. These regional scale topographic variations trend normal to the present-day intraplate compressional stress trajectories, having been interpreted as the result of lithospheric buckling coupled with reverse faulting (Cloetingh et al., 2002, 2005; Vegas, 2005; De Vicente et al., 2008). The morphology is largely dominated by erosional plateaus elevated to different heights. These are cut onto metasedimentary rocks and granites of the Neoproterozoic and Palaeozoic Hesperian Massif, as well as onto Mesozoic and Cenozoic sedimentary basin fill successions. Relief distribution and hypsometry (43% of the landscape area is below 200 m, 30% above 400 m, and only 0.5% above 1200 m altitude) reflects the amplitude of the vertical movements. Some 95% of the landscape areas above 400 m are located in the northern and central parts of the country. In the central region, uplift was the greatest, raising the Portuguese Central Range (PCR) to a maximum altitude of 1993 m.

A broad regional scale characterization of the Quaternary vertical movements in mainland Portugal has been tentatively performed through the use of geological and geomorphological markers. Sea level markers in modern coastal regions include a regional Pliocene wavecut platform dated as ca. 3.70–3.61 My (Diniz et al., 2016) overlain by a sedimentary unit that has the top surface (the Culminant Fluvial Surface) with a probable age of 1.8 My (Cunha et al., 2016) and some dated Pleistocene marine terraces (e.g., Ramos et al., 2012; Carvalhido et al., 2014). Inland, terrestrial land surface markers include also the Culminant Fluvial Surface (CFS) as well as fluvial terraces along major river valleys. When using the CFS as a geomorphic marker for the last ca. 1.8 My, the estimated long-term uplift rate varies from 0.05 to 0.2 mm/y, but is generally higher inland relative to coastal areas. The highest estimated uplift rates, of ca. 0.2 mm/y, relate to the NE part of Portugal and the PCR (Cunha et al., 2005, 2008, 2012, 2016; Martins et al., 2009; Cabral, 2012).

River terraces provide useful insights into the dominant forcing mechanisms for fluvial systems: tectonics, climate, and sea level. However, terrace records are often spatially and temporally fragmented and where preserved are more likely to be associated with higher order trunk river systems. Lower order tributary streams commonly lack terrace records because sediment storage space is limited and the steeper gradients result in higher stream power, which tends to promote sediment erosion and transport. Thus, the valley floors of tributary streams are often dominated by bedrock reaches or, at the very least, by a thin transitory cover of alluvial material. In such settings, the long profile of the tributary stream is often the only geomorphological information that can be used to provide insights into the long-term fluvial landscape history.

In this study we use fluvial drainage analysis, namely river long profiles and slope-drainage area analyses to characterize the Quaternary uplift evolution in a study area located in the PCR and its adjacent South Portugal Planation Surface (SPPS), where relatively high uplift rates and significant differential vertical movements between fault-bounded crustal blocks have been documented.

For this we used a section of the Tagus River that flows across the SPPS adjacent to the SE piedmont of the PCR, and the related drainage network, including one major tributary (the Zêzere River) that flows through the PCR (Figs. 1 and 2). The Tagus River was chosen because of its size (longest river in Iberia, with a length of 1040 km and the third largest drainage area, of 81,000 km^2), thus assuring a relatively fast response to external forcing mechanisms and providing a relatively stable regional base level, and because of its location in the regional morphotectonic framework. The targeted tributaries are located in the main relief of the PCR. Their long profiles and knickpoints are used to identify differential uplift between uplifted blocks and local fault interactions as components of the regional long-term uplift rate.

Three main objectives are considered: (i) to estimate the magnitude of fluvial incision post-dating a generalized steady phase on landscape evolution and consequently formation of a graded longitudinal profile on drainage; (ii) to use the fluvial incision as a proxy for uplift; (iii) to analyze the stream profiles and drainage basins to calculate the normalized steepness index k_{sn} (Wobus et al., 2006), which is considered a sensitive parameter to tectonics, in order to detect differential uplift between crustal blocks and to infer neotectonic activity of bordering faults.

2. Geological and morphotectonic setting

The drainage network of the study region flows mostly on the Iberian Hesperian Massif, consisting predominantly of slates and metagreywackes of Neoproterozoic to Cambrian age intensely folded by the Variscan Orogeny. Ordovician to Devonian quartzites and slates occur at the core of synclines exposed along narrow bands trending NW-SE, following the regional Variscan fabric. Also outcropping are some pre- and late to post-orogenic granite intrusions (Fig. 2). From the end of the Variscan Orogeny in the late Carboniferous and continuing to the early Cenozoic, the basement was eroded to a broad planation surface (the Iberian Meseta), above which the Ordovician quartzites and slates form elongated 'Appalachian' style resistant reliefs, but also occurring scattered inselbergs in granite areas (Cunha, 1992; Cunha and Pena dos Reis, 1995; Dinis et al., 2008).

During the Cenozoic, this broad planation surface was deformed into topographic highs (pop-ups) and lows (pop-downs; these constituting sedimentary basins) as a result of the Alpine interplate compression (Ribeiro, 1984; Ribeiro et al., 1990; De Vicente et al., 2007, 2011; Pais et al., 2012). The Alpine compression generated the NE-SW trending PCR, corresponding to a complex pop-up structure bounded by major NE–SW reverse faults, though slightly asymmetric, with one major fault (Seia-Lousã fault, SLf) on the NW side and deformation distributed across several faults on the SE side (including the Sobreira Formosa fault, SFf; e.g., Ribeiro et al., 1990; Sequeira et al., 1997; Figs. 2 and 3).

Tectonically controlled piedmont depressions occur on the SE side of the PCR, namely the Sarzedas and the Ródão-Idanha a Nova-Moraleja (Fig. 2), displacing the SPPS (Ribeiro, 1942; Cunha, 1987, 1992; Dias and Cabral, 1989; Vegas, 2006). These are bounded to the NW by the Sobreira Formosa and Rapoula faults (SFf and Rapf) and by the Ponsul fault (Pf), respectively (Fig. 2), corresponding to subbasins of the wider Lower Tagus Cenozoic basin. The sedimentary infill of this basin consists predominantly of alluvial fan gravelly sandstones (probably Eocene) and fluvial sands and silts (Miocene), overlain by coarser lithoclastic (slates and metagreywackes clasts) alluvial fan deposits attributed to the latest Miocene and Zanclean. These coarser deposits have been correlated to the main phases of mountain building (Cunha, 1992, 1996), thus indicating that major uplifting of the PCR occurred in the upper Neogene. The uppermost sedimentary unit, represented by the siliciclastic Falagueira Formation, has been considered of Piacenzian to Gelasian in age (3.65 to 1.8 My) and interpreted to record the capture of an Iberian endorheic drainage (Madrid Cenozoic basin) by a westward-draining Atlantic fluvial drainage (Lower Tagus basin) (Cunha, 1992, 1996; Cunha et al., 1993, 2005, 2008, 2012; Pérez-González, 1994; Pais et al., 2012).

The study area partially covers the southwestern part of the PCR and the adjacent SPPS, across which the Tagus River flows in an entrenched valley. In this area, the Falagueira Formation is generally 10–20 m thick, always at the top of interfluves, associated with the coeval relict Culminant Fluvial Surface (expressed as a very large paleovalley) preserved in remote areas away from the modern Tagus channel, and in minor sheltered areas of the PCR (Fig. 3). The geomorphic and sedimentary characteristics indicate that the ancestral Tagus River flowed on a laterally extensive low gradient alluvial plain. This period of the drainage history marks the final stage of sedimentary infilling in the Lower Tagus basin prior to the onset of the fluvial incision stage, which probably began just after the Gelasian (1.8 My; Cunha et al., 2012, 2016; Rosina et al., 2014).