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Plio-Quaternary uplift of the Iberian Chain (central–eastern Spain) from landscape evolution experiments and river profile modeling

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ABSTRACT

The Iberian Chain (central–eastern Spain) is characterized by a dome-shaped topography with poorly incised and relatively flat landscape in its interior at an elevation of ~1300 m. A recent regional tectonic event started during or after the Late Pliocene, inducing deep valley incision on the flanks of the Iberian Chain. The rate and timing of this deformation, as well as the magnitude of the uplift-induced erosion processes, still lack a quantitative validation. We used 3D (SIGNUM) and 1-D (river profile) numerical models to investigate the landscape evolution of the Iberian Chain from the Late Pliocene to the present and to study the response of topography and rivers to tectonically induced base level lowering. Our model results are supported by geological, geomorphological and geochronological data. The results of the SIGNUM experiments show that the Iberian Chain topography has experienced regional uplift since ca. 3 Ma with rates between 0.25 and 0.55 mm y^{-1}. In response to this uplift, rivers have incised at an average long-term incision rate of about 0.22 mm y^{-1} and have progressively captured drainage areas from the chain interior. To further validate the results of landscape evolution modeling, we use a 1-D river incision model to explore the incision history of several rivers draining the Iberian Chain. The results constrain the range of values of bedrock erodibility from 5.8×10^{-5} to 5.0×10^{-4} $m^{0.4}$ y^{-1} and predict long-term incision rates similar to those from the SIGNUM experiments.

1. Introduction

The topography of a mountain chain is the result of the complex interactions between tectonics (uplift) and erosion (Willett, 1999; Hovius, 2000; Willett et al., 2001). Tectonics generates topography, and surface processes redistribute rock by erosion, transport and sedimentation, resulting in loading and unloading of the crust and mantle lithosphere (e.g., Willett, 1999; Roe et al., 2006; Stolar et al., 2006; Burov and Toussaint, 2007; Cloetingh et al., 2007). A multidisciplinary approach is required for studying topography because of the complexity of the interactions among tectonics, erosion and climate that govern the development of topography in a given setting. Nevertheless, the timing and rate of uplift are usually difficult to quantify from landscape topography and from geological and geochronological data. For this reason many numerical models of landscape evolution have been developed in the last decades that facilitate our understanding of topographic responses to changing tectonic boundary conditions (Tucker and Slingerland, 1994; Braun and Sambridge, 1997; Densmore et al., 1998; Tucker et al., 2001; Carretier and Lucazeau, 2005; Hancock et al., 2011; Refice et al., 2012).

As an example of how numerical models can provide a more complete understanding of the tectonics of a mountain chain, we combine a landscape evolution model and a river longitudinal profile model to investigate the uplift history of the Iberian Chain (central–eastern Spain). The Iberian Chain is an ideal location for this type of investigation because the timing and rate of the relief generation are still debated (Gutiérrez et al., 2008; Casas-Sainz and De Vicente, 2009; Scotti et al., 2014 and references therein). The Iberian Chain is an intraplate thrust-belt originally formed during the Late Cretaceous to the Middle Miocene (Álvaro et al., 1979) and has a dome-shaped topography characterized by a poorly incised relict landscape in its interior. This old landscape, standing at a mean elevation of ~1300 m, includes one or more nearly flat Miocene–Middle Pliocene erosion surfaces (Birot, 1959; Solé Sabarís, 1979; Peña et al., 1984; Simón, 1984; Gracia-Prieto et al., 1988; Gutiérrez Elorza and Gracia, 1997). In contrast, the flanks of the Iberian Chain are deeply incised by rivers that have been capturing the drainage network of the chain interior as these rivers begin to incise the relict landscape in response to a base level change (Scotti et al., 2014 and references therein). It is generally accepted that a regional tectonic event uplifted the relict landscape and induced rivers to incise the Iberian Chain (Simón, 1984, 1989; Muñoz-Martín and De Vicente, 1998; Gutiérrez et al., 2008; Casas-Sainz and De Vicente, 2009). Geological and geomorphological evidence indicates that this uplift started at or after the Late Pliocene (Scotti et al., 2014 and

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references therein); however, the rate and timing of this deformation, as well as the magnitude of the uplift-induced erosion processes, still lack a quantitative validation.

Here we explore how a numerical landscape evolution model can be used to estimate time and space variation in uplift rate and how it can improve the knowledge on the recent deformation history of an area like the Iberian Chain, where quantitative constraints are poor or missing. At the scale of a mountain range, tectonic processes operate on time scales equivalent to 10^6 y, whereas the response time of landscape to tectonic or climatic perturbations ranges from 10^4 to 10^6 y (Whipple, 2001; Wegmann et al., 2007). Therefore, the spatial scale of the Iberian Chain (~300 km^2) and the temporal scale at which the processes of interest (uplift and river incision) operate necessitate the use of numerical experiments to simulate the development of topography and hydrography following regional uplift. The ultimate goal of our experiments is to model the Plio-Quaternary evolution of the Iberian Chain, characterizing the rates and pattern of uplift and erosion that have produced the main features of the present topography. For this purpose we have designed a two-step experiment. In the first step we use a landscape evolution model called SIGNUM (Refice et al., 2012), which has been successfully used to investigate the feedbacks between uplift and erosion in active tectonic settings and the reorganization of drainage network at the orogen scale (e.g. Capolongo et al., 2011; Giachetta et al., 2014). SIGNUM is suitable to simulate the transient response of a synthetic topography representing the Iberian Chain to a tectonic perturbation over 10^6 year time scale. We ran several numerical models starting with different initial topographies and applied different magnitudes and patterns of uplift rate until we obtained the synthetic topography that best fits the present Iberian Chain. In the second step, we numerically modeled the present day river longitudinal profiles extracted from digital topography to test the time duration of the landscape evolution models, the pattern of uplift, and the stream power parameters that predict the best-fit topography. To test the reliability of the river profile modeling, we also performed a sensitivity analysis to compare the stream power law parameters predicting the best-fit river profiles with those obtained by previous works. The second step of our experiments focuses on the stream longitudinal profiles because among geomorphological systems, rivers are the most sensitive to variations in boundary conditions including tectonics, climate, base level, and lithology.

2. Geological and geomorphological settings

The present-day topography of the Iberian Chain, an intraplate double vergent thrust belt, is characterized by low relief surfaces standing at an average elevation of ~1300 m (Fig. 1a). These features have been interpreted as a unique one, the so-called Main Planation Surface of the Iberian Chain (Birot, 1959; Solé Sabarís, 1979; Peña et al., 1984; Simón, 1984), or as two distinct nested surfaces (S2 and S3; Gracia-Prieto et al., 1988; Gutiérrez Elorza and Gracia, 1997). The ages of these flat or gently undulated surfaces are from the Miocene to the Late Pliocene according to their morphological correlation with the lacustrine and fluvial deposits of intermontane basins (Gracia-Prieto et al., 1988; Casas-Sainz and De Vicente, 2009) (Fig. 1b). An older erosion surface, the Intra-Miocene Erosion Surface (Peña et al., 1984), or S1 (Gutiérrez Elorza and Gracia, 1997) developed on Mesozoic rocks and is observed on the higher peaks at an elevation of 1700–2000 m. Small ranges, like the Castilian and Aragonian branches and the Maestrazgo Mts. (Fig. 1b), stand a few hundreds of meters above the Main Planation Surface and are interpreted as relics of ancient ridges (Peña et al., 1984; Gutiérrez Elorza and Gracia, 1997). The formation of the high-standing planation surfaces has been linked to two major plate tectonics events occurred in the geological history of the Iberian plate: the collision between Africa and Europe and the opening of the Valencia Through in the western Mediterranean (Casas-Sainz and De Vicente, 2009; Scotti et al., 2014).

In the Late Cretaceous, the collision of Iberia with Africa and Europe generated the main mountain ranges at the eastern plate boundary: the Pyrenees (northern Spain), the Iberian Chain (central–eastern Spain) and the Central System (central Spain) (Álvaro et al., 1979; Muñoz, 1992; Teixell, 1998; Casas-Sainz and Faccenna, 2001; Vergés et al., 2002; De Vicente et al., 2007). The Iberian Chain results from the inversion of normal faults that initiated during Mesozoic extension of the Iberian Basin (Álvaro et al., 1979; Guimerà et al., 2004) and were subsequently inverted to accommodate Cenozoic intraplate shortening (Casas-Sainz and Faccenna, 2001). Conversely, the Castilian (Rodríguez-Pascua and De Vicente, 1998) and Aragonian (Ferreiro et al., 1991; Calvo Hernández, 1993; Cortés-Gracia and Casas-Sainz, 1996; Casas-Sainz et al., 1998) branches show a strike-slip component along NW–SE structures with basement-induced positive flower structures (Wilcox et al., 1973; Scotti et al., 2014).

The western margin of the Iberian Chain ends against the Central System, a double-vergence intraplate belt, elongated NE–SW and resulting from thick-skinned Tertiary compression involving metamorphic–granitic Variscan basement (De Vicente et al., 2007). The linkage between these ranges is affected by several NW–SE dextral strike-slip faults.

The formation of the Pyrenees, Central System and Iberian Chain produced topography that allowed for the development of large compressive basins containing shallow perennial lakes (Calvo et al., 1993; Wright et al., 1997; Casas-Sainz and De Vicente, 2009): the Duero Basin to the NW, the Ebro Basin to the N, the Guadiana Basin to the S, and the Madrid (High Tagus) Basin to the SW (Fig. 1b). The filling of these large endorheic basins started in the Eocene, generating thick continuous succession characterized by lacustrine and alluvial *facies* (Calvo et al., 1993; Calvo, 2004). Contemporaneously, the uplift of the Central System separated the Duero and Madrid (High Tagus) basins (Calvo, 2004). At local scale, small-size internally drained basins (hereafter referred as intermontane basins) developed in the Iberian Chain interior and were filled by similar but discontinuous continental deposits (Calvo, 2004). The origin of these basins is controversial, being related to either compressional episodes or extensional structures that can be correlated with NE–SW extensional structure along the Mediterranean coast and related to the Neogene opening of the Valencia Trough (Guimerà and Alvaro, 1990; Roca and Guimerà, 1992; Vegas, 1992; Cortés-Gracia and Casas-Sainz, 2000).

From the Late Oligocene to the Early Miocene, the large-size basins were characterized by a very discontinuous sedimentation pattern, indicating a varied tectonic activity (Calvo et al., 1993; Calvo, 2004; Casas-Sainz and De Vicente, 2009). Extensional faulting affected the Mediterranean side of the Iberian Chain (the Maestrazgo Mts.) from the Late Miocene to Pleistocene times (Simón et al., 2013). The intermontane basins remained distinct lacustrine areas until the Late Miocene, when sedimentation became widespread, overlapping the sedimentary thresholds (Armenteros et al., 1989; Alonso-Zarza and Calvo, 2000). This phenomenon is recorded by the lacustrine carbonates of the Páramo Formation (Late Miocene–Early Pliocene), the last record of endorheism before the progressive capture of the internally drained basins since the Pliocene (Gutiérrez et al., 2008). A general asymmetric dome-like uplift of the Iberian Chain started in the Late Pliocene (Gutiérrez Elorza and Gracia, 1997; Scotti et al., 2014 and references therein). In the Pliocene–Quaternary, extensional tectonics generated new depressions (Gallocanta, Munabrega, and Jiloca depressions), while others such as the Calatayud and Teruel depressions were reactivated (Cortés-Gracia and Casas-Sainz, 2000; Gracia et al., 2003; Rubio and Simon, 2007; Gutiérrez et al., 2008).

The transition from internally drained basins to an exorheic drainage network, mainly driven by capture of the Ebro, Tagus, Jalon and Turia rivers, led to the incision of the ancient landforms and sedimentation of coarser deposits in the marginal areas of the Iberian Chain (Martín-Serrano, 1991; Gutiérrez et al., 1996; Gutiérrez Elorza and Gracia, 1997; Casas-Sainz and Cortés-Gracia, 2002). The uplift drove