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Peneplanation and lithosphere dynamics in the Pyrenees

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ABSTRACT

The morphology of the Pyrenees is characterized by the presence of high-elevation, low-relief surfaces. The origin of these Lower-Miocene surfaces is still debated. Two major interpretations have been proposed, both assuming that these surfaces are remnants of a single composite planation surface. The first interpretation proposes that this surface corresponds to a peneplain developed near sea level before the Late Miocene, subsequently uplifted and dissected. The present-day Pyrenees is therefore supposed to rise from the Late Miocene. In the second interpretation, the rise of the efficient base level of the chain induced the progressive inhibition of erosion and the smoothing of the relief before the Late Miocene, resulting in a highly elevated peneplain. According to this latter interpretation, the high elevation of the low-relief surfaces does not equate to post-orogenic uplift. We test these two interpretations by investigating, among other considerations, the relation between the elevation of the planation surface remnants and the deep structure of the chain. We find that (1) the isostatic compensation of the dissected Pyrenean planation surface by crustal thickening and (2) the absence of thinning of the lithosphere mantle below the chain favors the second interpretation.

1. Introduction

Moving plate tectonics and deep mantle dynamics create uplift and subsidence of the Earth's surface, whereas Earth's surface processes, namely erosion, transport and sedimentation, tend to counteract these positive and negative vertical movements. Uplift (or subsidence) has two origins: isostasy that is controlled by the difference between crustal and mantle densities, and dynamic topography that is controlled by mantle dynamics (e.g., Molnar and Houseman, 2013). Wavelength and elevation changes for local isostasy are respectively of several tens to hundreds kilometers and up to several kilometers, whereas for dynamic topography they are typically of several hundred to thousand kilometers, and several hundred meters up to one kilometer, respectively (e.g., Braun, 2010). Whether or not surface uplift equates to rock uplift depends on whether or not erosion is active (England and Molnar, 1990). As surface uplift is controlled by crust

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and/or mantle dynamics, the resulting elevation change must be considered in terms of mean elevation at a minimum area of a thousand of square kilometers (e.g., England and Molnar, 1990). In a general way, crustal thickening causes surface uplift. The growth of a mountain belt by crustal thickening requires a rate of erosion much lower than the rate of rock uplift. When increasing erosion rate tends to equate to rock uplift rate, a dynamic equilibrium occurs once the mountain belt has risen. Crustal thinning will result in surface lowering that can be partially compensated for by sedimentation and/or by concomitant thinning of the lithospheric mantle. Extreme thinning of the continental lithosphere inevitably causes surface lowering below sea level. Only thinning of the lithospheric mantle and its concomitant replacement by less dense asthenospheric mantle can produce surface uplift when crustal thickness is kept constant. So, any attempt to determine the evolution of the topography requires investigating both Earth's surface and deep processes at the origin of the relief (e.g., Casas-Sainz and de Vicente, 2009; Molnar et al., 2015). The Pyrenees is an emblematic example: how the topography of the belt has changed over time and what were the deep processes involved is highly debated.

The Pyrenees are classically described as an intracontinental orogen that results from the inversion of a continental rift during the convergence between Eurasia and Africa (Choukroune et al., 1990; Muñoz, 1992). Beyond the considerable debate that is currently concerned with the width of this rift that developed during the Cretaceous and resulted in mantle exhumation (Jammes et al., 2009; Lagabrielle and Bodinier, 2008), no doubt exists that crustal thickening was at the origin of the Pyrenees uplift during Eocene and Oligocene times. Indeed, the Moho beneath the central Pyrenees reaches a depth of about 50 km (Chevrot et al., 2014; Choukroune et al., 1990).

The "Pyrenees" geographic and geomorphologic labels differ from the Pyrenean orogen ("tectonic" Pyrenees). The Pyrenean orogen extends from the Cantabric Range in north-western Spain to the west, to Provence in south-eastern France to the east. The initial chain was about 1000 km in length, whereas the geomorphologic Pyrenees are only 400 km in length. The disappearance of the Pyrenean orogen below the Mediterranean is due to the tectonic collapse of the former during considerable Oligocene to Aquitanian crustal and lithospheric thinning in the Gulf of Lion margin and subsequent oceanic accretion in the NW Mediterranean (Séranne et al., 1995). This event succeeds the continental rifting that developed in Western Europe from the Oligocene. It also affected the easternmost part of the geomorphologic Pyrenees. We refer hereafter the geomorphologic Pyrenees to the Pyrenees.

2. The high-elevation, low-relief erosional surfaces in the Pyrenees

The most striking feature of the Pyrenean morphology is the occurrence at high elevation of low-relief erosional surfaces, which are considered as remnants of a single composite planation surface recently dissected (Babault et al., 2005; Calvet, 1996; de Sitter, 1952; Kleinsmiede, 1960; Zandvliet, 1960). This planation surface erodes the Pyrenean tectonic structures and is locally overlapped by Upper Miocene continental deposits in the Val d'Aran and Cerdanya, providing an upper limit age for its development (Cabrera et al., 1988; Roca, 1996; Ortuño et al., 2008, 2013; de Sitter, 1953). The high-elevation, low-relief surfaces form smooth reliefs paradoxically situated at crest zones up to ~2800 m asl in the Axial Zone of the Pyrenees (Fig. 1). They occur irrespective of lithology, mainly granitic rocks and micaschists. Typically, the slope along these surfaces does not exceed 20°. Depending on their altitude in the chain, they are more or less disrupted by glacial erosion. Within the high-elevation, low-relief surfaces, glacial erosion produces excavation surfaces, easily identifiable by their concave-up geometry, their steep slopes and their marked roughness. To reconstruct the Pyrenean planation surface, we analyzed and mapped several remnants of this surface and we used literature data to compile a regional map (Babault et al., 2005; Calvet, 1996; Kleinsmiede, 1960; Ortuño et al., 2008; Zandvliet, 1960). Then we used an automatic method of landform classification called TPI (Topographic Position Index; Jenness et al., 2013; Weiss, 2001) to map these remnants across the Axial Zone of the Pyrenees.

The Weiss method uses digital elevation models to measure the difference between the elevation of each cell and the mean elevation with a variable radius of calculation. The variation of the radius, the TPI type and the slope permit to distinguish different landforms in the landscape. We use 25-m resolution DEMs from the French, the Spanish and the Andorran Geographical Institutes, allowing us to detect areas down to 500 m^2. TPI type, TPI radius and slope were determined from surfaces previously mapped by field investigations. We have developed the methodology. It will be the subject of another publication. The applied methodology results in a limit between the remnants of the planation surface and glacial landforms more consistent and regular than using traditional interpretative mapping (Fig. 1). We then verify on the field the existence of the surfaces identified by the Weiss method, which were not previously mapped.

Fig. 2a shows the pervasive occurrence of the remnants of the Pyrenean planation surface in the Axial Zone. Hypothesizing that these surfaces are the remnants of a single paleosurface of planation, we tentatively restore this latter by interpolating the neighboring remnants (Fig. 2b). The resulting surface is gently undulating with a mean elevation of about 2400 m. Local relief does not exceed 300 m (Fig. 2c). This surface can therefore be described as a high peneplain (Davis, 1899; King, 1953). Note that the mean elevation of the restored planation surface is some hundred meters higher than the mean elevation of the present-day topography.

3. Moho depth and deep structure in the Pyrenees

The first works on the Moho depth below the Pyrenees (Choukroune and ECORS Team, 1989; Daignières et al., 1982; ECORS Pyrenees team, 1988; Roure et al., 1989; Souriau and Granet, 1995; Vacher and Souriau, 2001)