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Cave levels as proxies for measuring post-orogenic uplift: Evidence from cosmogenic dating of alluvium-filled caves in the French Pyrenees☆

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A B S T R A C T

The rates and chronology of valley incision in mountain ranges have been studied in various parts of the globe, but the causes of river incision are often blurred because tectonic, climatic, and sea level-related forcing signals are difficult to distinguish from one another. The Têt River limestone gorge in the Eastern Pyrenees, which displays multiple cave levels containing datable alluvial deposits, provides an opportunity for clarifying this debate. Horizontal epiphreatic passages in limestone can be used as substitutes for fluvial terraces because they correspond to former valley floors and, therefore, also record the position of former local base levels. In the Têt canyon, the passages are filled with quartz-rich sand and gravel sequences that can be dated by $^{26}Al/^{10}Be$ burial dating. The canyon has cut into a Middle Miocene pediment system—now forming a raised plateau at 1250–1500 m—and displays nine cave levels over a vertical height of 1 km. One alluvial fill sequence in a cave at +270 m above datum (i.e., the local river bed) yielded a weighted mean age of 5.14 ± 0.41 Ma; another, situated at +110 m above datum, yielded weighted mean ages of 2.23 ± 0.230 Ma and 1.20 ± 0.286 Ma. The data convert to a mean incision rate of ~52 $m \cdot Ma^{-1}$ since the beginning of the Pliocene, and involved an acceleration to 92 $m \cdot Ma^{-1}$ during the Quaternary. Pre-burial catchment denudation rates range from 35 to 7 $m \cdot Ma^{-1}$, and these also doubled during the early Quaternary. It is concluded that: (i) valley incision into the Miocene pediment has been occurring since 5, probably 10 Ma; (ii) there is no evidence of a Messinian canyon in the Villefranche gorge, strongly suggesting through various additional indicators that interference of the Messinian Salinity Crisis with the canyon incision history was minimal; (iii) valley deepening was not a steady process, and recorded periods of stability around 1–2 Ma and perhaps 6–5 Ma; and (iv) the terraced network of epiphreatic cave levels is primarily explained by tectonic uplift. It follows that the elevated erosion surfaces of the Pyrenees, such as the Miocene pediment directly situated above the canyon edge, were not shaped at high elevations, e.g., by 'altiplanation'; they formed, instead, close to base level and were uplifted in successive stages by tectonic processes. The study emphasizes the more general proposition that tectonic signals (as opposed to climatic or eustatic) in valley-incision chronologies are best singled out at locations situated among the outer ranges of mountain belts, i.e., in canyons such as the Têt, that respond immediately to base level changes relative to the adjacent foreland. In the inner ranges, fluvial incision is more likely to be affected by the interference of climatic factors (e.g., glaciers), or to be delayed by bedrock impediments to upstream-propagating knickpoints.

1. Introduction

The uplift of tectonically active orogens narrowly controls valley incision rates by rivers, which themselves are tuned to sharp climatic changes, for example those that occurred during the Quaternary (Willett et al., 2006, and references therein). However, fluvial incision rates, which have been measured by various methods in a wide range of settings (Finnegan et al., 2014), mostly provide local records of valley deepening. The causes of incision are difficult to decipher because valley incision is driven by tectonics, sea-level changes, and stream power (river discharge is a function of precipitation, and hence climate). As a result, it is often spurious to directly infer tectonic uplift rates from, for example, canyon depths unless auxiliary evidence can rule out other contributing causes to base level- and climate-related change. Here we focus on the value of cave levels as a tool in tectonic geomorphology,

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and report on a natural setting in the Pyrenees where canyon incision can be confidently used as a measure of Neogene—i.e., post-orogenic—crustal uplift of the mountain range.

The Pyrenees are generally not seen as an active orogen despite the fact that seismic activity is far from negligible (Souriau and Pauchet, 1998; Chevrot et al., 2011) and that evidence of neotectonic deformation has been reported from the core and the periphery of the mountain belt (Philip et al., 1992; Calvet, 1999; Goula et al., 1999; Ortuño et al., 2008; Lacan and Ortuño, 2012; Lacan et al., 2012). Indications that ~2 km of topographic uplift has occurred during the last 10 Ma have been documented by multiple methods including geomorphology, biochronology, paleobotany, stratigraphy and thermochronology. Part of the evidence is predicated on the existence of vestiges of an ancient erosion surface, which now occurs at elevations of 2.2–2.9 km but which formed in connection with marine base levels at much lower paleoelevations (Calvet, 1996; Calvet and Gunnell, 2008; Gunnell et al., 2009; Ortuño et al., 2013). The likely driving forces of uplift are isostatic but also thermal, the post-orogenic topographic buoyancy being caused by partial melting of the dense lithospheric root beneath the orogen (Pous et al., 1995)—particularly in the eastern Pyrenees (Gunnell et al., 2008)—or even by gravitational detachment of the lithospheric root (Vanderhaege and Grabkowiak, 2014; Chevrot et al., 2014).

This model of topographic growth has been largely based on the history of planar landforms and on the sediment record of Neogene deposits in the intermontane and foreland basins of the orogen. However, the model gains from being further tested with independent evidence from histories of valley incision. Valley incision rates in a mountain range such as the Pyrenees have been difficult to capture through fission-track and (U–Th)/He dating. Only four valley-floor Neogene exhumation ages have been published thus far, all from the Central Pyrenees (Sinclair et al., 2005; Gibson et al., 2007; Jolivet et al., 2007; Metcalf et al., 2009). They consistently indicate a middle Miocene age, i.e., 15 to ~10 Ma. This may provide an upper age bracket to valley incision, but the Pyrenean valleys clearly also have a post-Miocene history of incision, whether glacially driven or otherwise. It is possible that $^3He/^4He$ dating might contribute to a refinement of these valley incision ages, but it would likely not capture variations in incision rates between the Miocene and the present.

Here we undertake an analysis of valley incision in the Pyrenees based on the vertical displacement of geomorphological markers in the landscape. Work using the treads of fluvial strath terraces has not produced any records going further back than the late Middle Pleistocene (e.g., Calvet et al., 2011), and these usually document distal river reaches in the foothills of the Aquitaine or Ebro basins rather than upper valley reaches within the mountain belt. Where limestone outcrops occur, however, the potential for recording stages of incision is enhanced by the possibility of dating quartz-rich, allochthonous alluvial deposits trapped in karstic cavities. Suitable candidates include epiphreatic cave passages that are episodically flooded and that occur, therefore, between the vadose zone above and the phreatic zone below them. The sediment dating relies on inventories of ^{26}Al and ^{10}Be, two terrestrial cosmogenic nuclides with different half-lives (Granger and Muzikar, 2001).

Alluvium-filled cave passages exposed in limestone canyon walls can be treated as strath terraces, and vertical cave sequences can likewise be analyzed in the same way as flights of alluvial terraces. Galleries in the limestone function as bedrock channels and ensure the transfer of water through the karst. Their altitude is dictated by the local base level provided at the time by the adjacent valley floor (Palmer, 1987; Audra, 1994; Palmer and Audra, 2004; Audra and Palmer, 2011, 2013; Gabrovšek et al., 2014). Multi-level systems of galleries of this kind can potentially occur over altitudinal differences of ~1 km or more.

Thus far, fewer than 10 sites have been studied globally using this approach (Granger et al., 1997, 2001; Stock et al., 2004, 2005a, 2005b; Häuselmann and Granger, 2005; Häuselmann, 2007; Häuselmann et al., 2007, in press; Hobléa et al., 2011; Wagner et al., 2010, 2011; Liu et al., 2013; Tassy et al., 2013). No such study exists in the Pyrenees, even though the karst-related features of several deep karst systems have been well studied by speleologists and geomorphologists in the Arbas Massif (Bakalowicz, 1988), the Pierre Saint-Martin system (Maire, 1990; Quinif and Maire, 1998), and the Arbailles Massif (Vanara, 2000). Here we deal with the Têt River catchment in the eastern Pyrenees and focus on a segment where the river, which flows to the Mediterranean Sea, has cut a canyon into the Devonian limestone outcrops of a Paleozoic syncline near Villefranche-de-Conflent (Figs. 1, 2, 3). We show how the history of valley incision has been recorded by underground landforms and deposits, and how the data in this setting provide direct clues about the magnitude and chronology of topographic uplift of the Pyrenees during the late Neogene. The data also emphasize the negligible contribution to fluvial incision from the abrupt sea-level fall that was caused by the Messinian Salinity Crisis (MSC).

2. Geological and geomorphological setting

2.1. The Pyrenees: an early Cenozoic orogen but a late Cenozoic mountain range

The Pyrenees formed as a result of collision between Europe and the Iberian microplate during and after the Late Cretaceous. The Axial Zone consists of Paleozoic basement—mainly granite, orthogneiss and metasediment—in the eastern part of the range, and an envelope of sedimentary rocks such as Silurian and Carboniferous shale and Devonian limestone. Collision-related deformation in the central and western Pyrenees ceased ca. 20–25 Ma, when tectonic activity resulting from the convergence between Africa and Europe transferred from the Pyrenees to the Betic Cordillera (Vergés et al., 2002). However, by 30–28 Ma, the eastern Pyrenees were already undergoing NW–SE crustal extension, initially related to the opening of the Western Mediterranean back-arc basin due to eastward rollback of the Tethyan trench (currently situated beneath Italy) (Durand et al., 1999). During the Neogene, extensional tectonics formed the Roussillon, Conflent and Cerdagne basins, a population of half-grabens all currently connected to one another by the Têt valley (Fig. 1). At the end of the Oligocene and during the middle Miocene, a well-dated erosion surface beveled parts of the Pyrenean structures, with vestiges of it and a younger generation of partial pediments best preserved in the eastern (Birot, 1937; Calvet, 1996; Calvet and Gunnell, 2008; Gunnell et al., 2008, 2009) and central parts of the range (Ortuño et al., 2008, 2013). The older erosion surface forms low-relief topography on range summits. The younger population of Miocene pediments is notched into the older, residual topography, with a maximum relief of a few hundred meters between the two generations of planar land surface. Extensional and transtensional faulting and uplift of these erosion surfaces occurred in several stages during the last 10 Ma and define the first-order landscape features of the eastern Pyrenees (Calvet, 1996; Calvet and Gunnell, 2008; Gunnell et al., 2008, 2009; Ortuño et al., 2008, 2013).

2.2. The Conflent Basin

The Conflent is a half-graben bounded by a bold fault scarp on its southern margin (Figs. 2, 4A). Whether they cross-cut gneiss and granite or softer schist outcrops, the triangular faceted spurs along the scarp face appear indistinguishably fresh and the relief of these tectonic landforms increases westward along the mountain front (Calvet, 1999). At the northern margin, the Madrès Massif forms comparatively gentle topography tilting southward toward the Conflent depocenter. The Hercynian limestone syncline of interest is located at Villefranche, and is cross-cut by an erosion surface known as the Pla des Horts, on Mt. Coronat. This surface has been tilted to the SE and extends at elevations ranging between 1450 and 1250 m. It is a specimen of the population of