Long-term dynamic topographic support during post-orogenic crustal thinning revealed by stable isotope (δ18O) paleo-altimetry in eastern Pyrenees

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Understanding the geodynamic and Earth surface processes at the origin of post-collisional surface uplift in mountain ranges requires reconstruction of paleo-elevation. Here, we focus on the topographic evolution of the Cerdanya Basin in the eastern Pyrenees formed by post-orogenic extension during the Late Miocene. Stable isotope (δ18O) analyses of small rodent teeth and biogenic carbonates show the basin uplifted by 500 m since 6.5 Ma. These new paleoaltitudes constraints when combined with the regional geology and geophysical data reveal the anomalously high topography of the region is the result of density changes in the sublithospheric mantle associated with crustal thinning and then opening of Gulf of Lion during the Chattian-early Burdigalian.

The drivers of post-collisional topographic uplift of mountain ranges, when plate convergence has ceased, are debated. Main processes invoked include the thinning of the dense lithosphere by sublithospheric deblobbing, delamination of a sinking slab, and replacement by the lighter asthenosphere1 or isostatic rebound caused by enhanced erosion2. Where changes in plate kinematics from contraction to extension occur, post-orogenic crustal thinning should promote subsidence not uplift. The case of the eastern Pyrenean mountain belt is particularly relevant because the region recorded crustal thinning during the opening of the Mediterranean Sea (Gulf of Lion) and currently shows high topography in presence of an attenuated crustal root. This is reflected by the isostatic anomalies that reveal a non-isostatic dynamic support of the topography3. Mechanical removal of the mantle lithosphere has been proposed4,5, but details on the timing and amount of uplift are lacking to further discuss the drivers of post-orogenic surface uplift.

Collision in the Pyrenees occurred from Late Cretaceous to the Early Miocene6–8. Low-temperature thermochronological constraints from the Central Pyrenees define that exhumation, possibly enhanced by climatic changes at the Eocene-Oligocene transition9, accelerated at 37–30 Ma (>2.5 km/Myr)10,11. Paleo-elevation of the Pyrenees is estimated to 2 ± 0.5 km in the Lutetian12. This value is in agreement with other estimates of maximum 2 km in the Middle Lutetian based on flexure modelling13, although a more recent flexural study considers that this altitude might have been reached later in the Late Eocene14.

Since the Chattian-Aquitanian, back-arc extension related to slab retreat led to the opening of the Gulf of Lion15 and affected the eastern prolongation of the Pyrenees. From that period onwards, the eastern Pyrenees recorded a different tectonic evolution in comparison with the central Pyrenees. An uplift of about 1 km has been inferred from palynological constraints but its initiation at 10 Ma (Tortonian) or ca. 6 Ma (Messinian) is not resolved16. Extension in the eastern Pyrenees is documented by the 22 km-thick crust in the Roussillon Basin, east of the Têt Fault8. Despite half of the crust has been removed during extension, the topography stands well above sea level at 2 km on average (e.g. Canigou massif; Fig. 1), indicating a component of the topography is...

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Stable isotopic constraints on rodent teeth.

Rodent incisors (n = 5) and lagomorph teeth (n = 4) from the Can Villela section (Cerdanya Basin) yielded mean $\delta^{18}$O$_{POM}$ composition of 16.6 $\pm$ 0.3% and 17 $\pm$ 0.5% (Fig. 2). For the Castelnou 3 cave (n = 5) (Roussillon Basin), a mean $\delta^{18}$O$_{POM}$ value of 18.6 $\pm$ 0.3% were obtained. The charophyte oogonia (n = 8) yielded mean $\delta^{18}$O$_{ch}$ of $-7.4 \pm 0.6\%$. For the pulmonate gastropods, the clausilid shells (n = 3) and the Testacella specimens (n = 5) have mean $\delta^{18}$O$_{Ga}$ of $-2.5 \pm 0.5\%$ and $-2.2 \pm 1.4\%$ respectively (Fig. 2). To convert the $\delta^{18}$O$_{POM}$ of teeth to $\delta^{18}$O of the local water ($\delta^{18}$O$_{lw}$), we adopt the Eq. (1) of25, established from the analysis of west European living small rodents:

$$\delta^{18}\text{O}_{POM} = 1.21(\pm 0.2)\delta^{18}\text{O}_{lw} + 24.76(\pm 2.7)$$  \hspace{1cm} (1)

where $\delta^{18}$O$_{POM}$ is the $\delta^{18}$O value of the phosphate of the rodent teeth and $\delta^{18}$O$_{lw}$ is the $\delta^{18}$O isotopic composition of the local water. We deduce from Eq. (1) $\delta^{18}$O$_{lw}$ values of $-6.6 \pm 0.3\%$ and $-5.1 \pm 0.2\%$ for Can Villela and Castelnou 3 sections, respectively (Fig. 2).

The Eq. (2) of27 allows estimating summer temperature values for lake waters from the charophytes based on the $\delta^{18}$O$_{lw}$ obtained on mammal teeth:

$$\text{Temperature}_{summer} = 6.2(\pm 0.2)\delta^{18}\text{O}_{lw} - 14.5(\pm 0.2)$$  \hspace{1cm} (2)

Results and Discussion

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where $\delta^{18}O_{ch}$ is the isotopic composition of the charophytes. We infer a mean summer temperature of $19.5 \pm 2.6 ^\circ C$. Mean annual air soil temperature is calculated based on $\delta^{18}O$ of the terrestrial gastropods ($\delta^{18}O_{Ga}$) according to\(^{28}\):

$$T(\degree C) = 15.7 - 4.36(\delta^{18}O_{Ga} - \delta^{18}O_{lw}) + 0.12(\delta^{18}O_{ch} - \delta^{18}O_{lw})^2$$

(2)

It yields mean annual air temperature of $12.9 \pm 0.6 ^\circ C$ and $13.6 \pm 1.6 ^\circ C$ for the clausilids and *Testacella*, respectively. This is slightly lower than the $15.5$ to $19.8 ^\circ C$ obtained for the MAT from pollen analyses\(^{16}\).

Climate models have shown that modern atmospheric circulations in western Europe, characterized by dominant moisture source from the north Atlantic, were established during the late Miocene\(^{29}\). Thus, the modern isotope lapse rate established for the eastern Pyrenees\(^{30}\) is used to extrapolate the $\delta^{18}O_{lw}$ values to estimate a $\Delta$-elevation paleogradient between the two sites during the late Miocene. Measurements from modern small rivers yielded a gradient of $-3.76‰/km$ for the $\delta^{18}O$\(^{30}\). We infer a mean $\Delta\delta^{18}O_{lw}$ of $-1.5‰$ for the Miocene samples that corresponds to an altitude difference of $\Delta H = 396 \pm 50$ m according to the modern isotope lapse rate.

The modern difference of elevation is $910$ m between the two sites (Fig. 3). This result therefore suggests that the Cerdanya Basin uplifted by about $500$ m since $6.5$ Ma. The basin is currently at $1100$ m, we thus estimate a paleo-elevation of $600$ m consistent with altitude inferred from pollen floras\(^{16}\). The concordant results obtained based on two independent approaches emphasize the robustness and the accuracy of the calculated paleo-elevation. We derive a surface uplift rate of $0.07 \ mm/\text{a}$ since $6.5$ Ma in the range of $0.06-0.12 \ mm/\text{yr}$ obtained by\(^{16}\) for the same basin and close to uplift rates of $0.08-0.19 \ mm/\text{yr}$ obtained for the Central Pyrenees\(^{31}\). Such a rate is also close to incision rates of $0.05-0.09 \ mm/\text{yr}$ since $5$ Ma obtained in the Têt river canyon (current
eroded into the existing Mesozoic sedimentary succession or the Cerdanya Basin was synchronous with normal faulting along the oblique NNW-trending Transverse Fault system and moderate crustal thinning in the SE direction. The Cerdanya Basin was therefore exhumed before the Burdigalian (18 Ma) with up to 2 km of exhumation during late Oligocene (26–27 Ma) and likely related to normal faulting with a component of left-lateral strike-slip movement. The Conflent Basin, along the northern segment of the Têt Fault (Fig. 1) preserves remnant of a thick assemblage (~1 km) of coarse clastic sediments: the Marquixanes Formation of Aquitanian age sourced from the surrounding Variscan massifs and topped by the Lentilla alluvial series dated to the early Burdigalian based on mammal fauna. The Têt Fault therefore exhumed the Variscan basement and thinned the crust prior to the Burdigalian, like other N70°E-striking faults recognized offshore.

This rifting phase ended in the Burdigalian as indicated by a regional erosional surface recognized in the Gulf of Lion on which the transgressive shallow-marine post-rift Burdigalian series were deposited. This places an additional elevation constraint near sea-level in the Chattian–Early Burdigalian. The mapping of the Burdigalian erosional surface offshore of the Gulf of Lion reveals subaerial erosion occurred on a crust that was moderately to extremely thinned in the SE direction (30°<h<5 km; stretching factor 1.4<β<9). The elevation of the Gulf of Lion rifted margin was therefore anomalously high and flat in the late Oligocene–Early Burdigalian. In the eastern Pyrenees, the present-day crustal thickness below the Têt Fault ranges between 30 and 40 km. It is thicker below the Cerdanya Basin and thinner below the Conflent Basin, and is only 22 km in the Roussillon Basin. Geophysical data therefore indicate that crustal thinning in the eastern Pyrenees and in the Gulf of Lion did not lead to the subsidence predicted by the McKenzie’s model, otherwise the whole region would have been buried several km below sea-level. Pre-break-up surface uplift that does not fit the subsidence effect of thinning the crust (McKenzie stretching model) is documented on many rifted margins. This requires processes leading to density reduction like serpentinitization of the exhumed mantle, mantle phase transitions to lighter mineral phases and the trapping of melt in the rising asthenosphere before breakup are required. We infer that similar processes did occur in the eastern Pyrenees and the Gulf of Lion in order to keep the region close to sea level.

Following the early Burdigalian, however, the Gulf of Lion recorded a rapid post-rift subsidence coeval with oceanic spreading in the Ligurian–Provençal Basin and rotation of Sardinia occurred between 20.5 and 15 Ma. The paleo-elevation constraints obtained in this work show that after the onset of oceanic spreading in the Gulf of Lion, the eastern Pyrenees continued to be uplifted. Differential vertical movements between the Gulf of Lion and the eastern Pyrenees likely triggered normal faulting that led to the development of the Cerdanya Basin during the Tortonian (12–9 Ma). The Late Miocene reactivation of the Têt Fault as a right-lateral strike-slip fault was contemporaneous with the deposition of 400–800 m of non-marine sediments in the Cerdanya Basin. In the Roussillon Basin, a maximum of 800–900 m of post-Messinian sediments is preserved. The formation of the Cerdanya Basin was synchronous with normal faulting along the oblique NNW-trending Transverse Fault system in the Sierras Transversales, volcanism in Empordà (10–9 Ma) and Selva (7–2 Ma) region, North-East Catalonia. Magmatism continued with the Olot (Garrotxa) volcanic system (0.7–0.11 Ma), an intraplate alkaline basaltic volcanism with close affinities to the volcanic system of the French Massif Central and Calatrava, Central Spain.

Because late Miocene normal faulting occurred when the Cerdanya Basin was at elevation, the Tortonian–Messinian extension appears to be a consequence rather than a cause of the regional uplift. The post-Messinian uplift of 500 m resolved from this study therefore represents a fraction of the long-term regional uplift that initiated in the Aquitanian–Late Burdigalian (20 Ma) when the eastern Pyrenees were close to sea-level (Fig. 4). This result reveals that the short-lived (5 Myr) initial back-arc rifting event was the main driver of the dynamic support of the topography. Because the region was close to sea-level in the late Oligocene–early Miocene then uplifted in the Late Miocene, a post-orogenic piedmont sedimentation could hardly be maintained, thus precluding the preservation of pre-Late Miocene planation surface. Other factors such as flexural uplift in the...
footwall of the Transverse Fault system or erosional unloading during the Late Miocene may have played a role, but altogether are not the drivers of the topographic evolution of the eastern Pyrenees.

Conclusion
Paleo-elevation constraints resolved from stable isotopic analyses indicates that the Cerdanya Basin, one of the main valleys of eastern Pyrenees, was at 600 m above sea level during the Messinian, 500 m below its current elevation. Because most of the relief was established at this time, we argue for a moderate late Miocene uplift of the summit planation surface of 500 m. Tectonic-stratigraphic relationships further indicate the pre-6.5 Ma topography was built on an older landscape inherited from the Chattian-early Burdigalian rifting episode that gave birth to opening of the Gulf of Lion. The non-isostatic processes required to support the current topography are therefore the consequence of a short-lived but major geodynamic event at the origin of both crustal thinning and density changes in the mantle. These new paleo-elevation constraints together with other geological data in the region suggest the uplift was a long-term process initiated in the Late Burdigalian in response to pre-breakup uplift in the Gulf of Lion. Following oceanic spreading of the Gulf of Lion and the rotation of Sardinia, the Tortonian extension associated with transcurrent deformation and volcanism was responsible for the last stage of topographic growth of the eastern Pyrenees.

Method
Paleoaltitude and paleotemperature reconstructions. The method relies on the comparison of the stable isotope signature of Late Miocene mammal teeth preserved in two basins at the eastern termination of the Pyrenean range: the Roussillon Basin that remained at low elevation since the Miocene and the Cerdanya basin which current elevation ranges between 1000 and 1200 m. The basic principle of isotopic paleoelevation reconstruction lies on the direct dependency of the $\delta^{18}O$ and $\delta D$ of rain with elevation, following the Rayleigh distillation behavior. Paleo-elevation can thus be quantified from the analysis of mineralization that precipitate from meteoric waters. A classical approach consists of analyzing nodule soils or roots carbonates in sedimentary
basins, clay minerals from fault zones or authigenic minerals mineralized at different elevation\(^1\). However, such material is rarely preserved syn-orogenic deposits and paleoelevation are thus often difficult to reconstruct. In this work, we adopt an approach combining mammal remains (rodent and lagomorph teeth) with biogenic carbonates. Small mammals are homeothermic animals living in small areas so the \(\delta^{18}O\) of their biominerals reflects both the life-long \(\delta^{18}O\) composition of their body water\(^4\) and the surface water of their living area \(\delta^{18}O\)\(^2\). From the local \(\delta^{18}O\), the \(\delta^{18}O\) analyses of non-homeothermic biogenic carbonates allow constraining paleotemperatures\(^6\). One of main challenge when reconstructing paleoelevation is to carefully take into account climatic parameters changes through time\(^4\). To minimize this impact we have compared the \(\delta^{18}O\) of rodent teeth of two sites, one that remained at low elevation and one that was potentially uplifted. We derive a paleo-\(\Delta\delta^{18}O\)\(_W\) that could be converted to \(\Delta\delta^{18}O\)\(_E\)\(^2\). Geochemical results are provided in Supplementary Dataset 1. Fossils were sampled from two contemporaneous deposits located in the eastern Pyrenees. First, we analyzed rodent incisors of the Castelnou 3 cave (\(n = 5\)) located in the Roussillon Plain at low elevation (\(~200\) m), which preserved sediments deposited near the shoreline and attributed to the late Miocene (\(~6.5\) Ma) by biostratigraphic approach\(^3\) (Fig. 1). We also sampled fossils from late Miocene alluvial to lacustrine deposits of the Can Villeva section of the Cerdanya extensional Basin\(^4\) (Fig. 1). These deposits have been attributed by magnetostratigraphy and biostratigraphy to Chron C3An.2n or C3An.2n, i.e. 6.5 or 6.1 Ma\(^6\). Teeth from the species Prolagus michauxi (Lagomorpha) (\(n = 4\)) and undetermined rodent incisors (\(n = 5\)) were analyzed (Fig. 2). This outcrop also yielded charophyte oogonia (freshwater green algae) of the species Lychnanthamnus barbatus (\(n = 8\)). Oogonia are the female reproductive organs and they are preserved as small calcitic spheres biomineralized in small lakes or ponds during the warmer weeks. Their \(\delta^{18}O\) allow constraining summer freshwater temperatures\(^6\),\(^8\). We also analyzed gastropods from the family Clausilidae (\(n = 3\)), which are small terrestrial gastropods frequently observed around the Mediterranean Sea. We also obtained land snails from the genus Testacella (\(n = 5\)), corresponding to small slugs living in soils with a reduced shell located at the posterior end of their bodies. Description of the sampling sites and photographs of the samples analyzed in this work are provided in Supplementary Dataset 2.

Uncertainties are provided both for paleoelevation and paleotemperature estimations. For paleoelevation values, we took into account the standard deviation of the \(\delta^{18}O\)POA values obtained from the analysis of the rodent teeth and the uncertainty related to the modern isotope lapse rate\(^5\). Concerning the paleotemperature values, we consider the standard deviation of the mean of all \(\delta^{18}O\) values for a given species.

**Geochemical analyses.** Mammal teeth stable isotope analyses were performed at the Biogéosciences Laboratory of the University of Burgundy (Dijon, France). The teeth were ultrasonically cleaned and residual sediment was removed with a Dremel\(^\circledR\) tool. The teeth were crushed into powder in an agate mortar and pestle, and aliquots of powderedapatite (1 mg) were dissolved in nitric acid and chemically converted to Ag\(_3\)PO\(_4\) using the method described by\(^5\). Oxygen isotope ratios were measured on CO using a High Temperature Pyrolysis Analyzer (Elementar Pyrocube) connected online to an Elementar Isoprime mass spectrometer. All \(\delta^{18}O\) values are reported in per mil relative to V-SMOW (Vienna Standard Mean Ocean Water) by attributing a value of 21.7‰ to NBS120c\(^5\) to NBS120c\(^5\). Precision is \(\pm 0.3\)‰\(\leq \pm 2\sigma\) were monitored by multiple analyses of Ag\(_3\)PO\(_4\) from NBS120c.

Charophyte oogonia and gastropods were measured at the Institut des Sciences de la Terre de Paris (ISTeP, Sorbonne University, Paris, France). Each oogonium was observed and crushed under a binocular glass to prevent any recrystallization or sedimentary filling. Gastropod shell preservation was tested by X-Ray diffraction. Each individual carbonate powder sample (80 \(\mu\)g) was reacted with a 100% anhydric orthophosphoric acid at 70°C in a Kiel IV carbonate device. Stable isotope analyses were performed on a DELTA V mass spectrometer. Isotope values are reported in conventional delta (\(\delta\)) notation relative to the Vienna Pee Dee Belemnite (VPDB) standard. We used an internal standard (marble) calibrated to the international standard NBS-19. Precision is \(\pm 0.1\)‰ for \(\delta^{18}O\). Geochemical results are provided in Supplementary Dataset 1.

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Author contributions
D.H. and F.M. conducted the research and wrote the manuscript. D.H., F.M. and L.S. interpreted the geochemical analyses. M.F. provided and identified the samples of the Cerdanya Basin.

Competing interests
The authors declare no competing interests.

Additional information
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