Morphogenetic evolution of the Têt river valley (eastern Pyrenees) using 10Be/21Ne cosmogenic burial dating

Amandine Sartégou, Pierre-Henri Blard, Regis Braucher, D.L. Bourles, Marc Calvet, Laurent Zimmermann, Bouchaib Tibari, Gabriel Hez, Yanni Gunnell, Georges Aumaitre, et al.

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A. Sartégou (1,2), P.-H. Blard (3), R. Braucher (2), D. L. Bourlès (2), M. Calvet (1), L. Zimmermann (3), B. Tibari (3), G. Hez (4), Y. Gunnell (5), G. Aumaitre (2) and K. Keddadouche (2)

(1) UMR 7194 HNHP, Perpignan ; (2) CNRS-IRD UM34 CEREGE, Aix-en-Provence ; (3) UMR 7358 CRPG, Nancy ; (4) Université de Savoie, UMR 5204 Edytem, Le-Bourget-du-Lac ; (5) Université Lumière-Lyon II, UMR 5600 EVS

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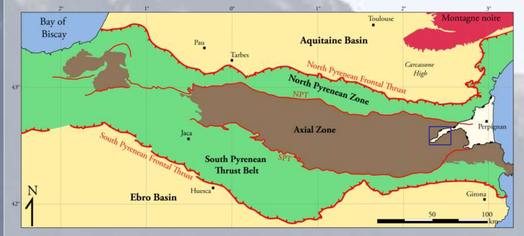
Why this study ?

The rates and chronologies of valley incision are closely modulated by the tectonic uplift of active mountain ranges and were controlled by repeated climate changes during the Quaternary (*e.g.* Molnar et England, 1990; Reiners *et al.*, 2003). The continental collision between the Iberian and Eurasian plates induced a double vergence orogen, the Pyrenees, which has been considered as a mature mountain range in spite of significant seismicity (*e.g.* Chevrot *et al.*, 2011) and evidence of neotectonics (*e.g.* Goula *et al.*, 1999). Nevertheless, recent studies indicate that the range may have never reached a steady state (Ford *et al.*, 2016). One option for resolving this controversy is to quantify the incision rates since the Miocene by reconstructing the vertical movement of geometric markers such as fluvial terraces. However, the few available ages from the Pyrenean terrace systems do not exceed the middle Pleistocene. Thus, to enlarge the time span of this dataset, we studied alluvium-filled horizontal epiphreatic passages in limestone karstic networks. Such landforms are used as substitutes of fluvial terraces because they represent former valley floors (*e.g.* Palmer, 2007; Audra *et al.*, 2013). They record the transient position of former local base levels during the process of valley deepening.

The Eastern Pyrenees: a key zone to understand the late evolution of the orogen



Paleozoic massifs | External Pyrenees: deformed Mesozoic and Cenozoic strata | Cenozoic Basins | Oligo-Miocene graben

- The Pyrenees were formed along the boundary between the Iberia and European plates and result from the Late Cretaceous–Cenozoic inversion of a Cretaceous transcurrent hyper-extended rift created during the opening of Bay of Biscay;
- After the collision or during the last phase of plate convergence, the eastern Pyrenees were affected by a period of crustal thinning related to the well-defined Oligocene–Early Miocene rifting seen in the Gulf of Lions;

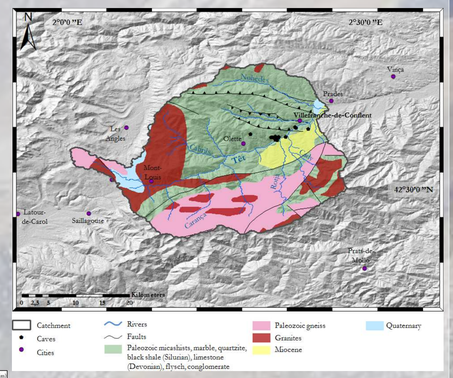
➢The Têt: river connected to the Mediterranean domain and affected by the Messinian Salinity Crisis (*e.g.* Clauzon *et al.*, 2015);

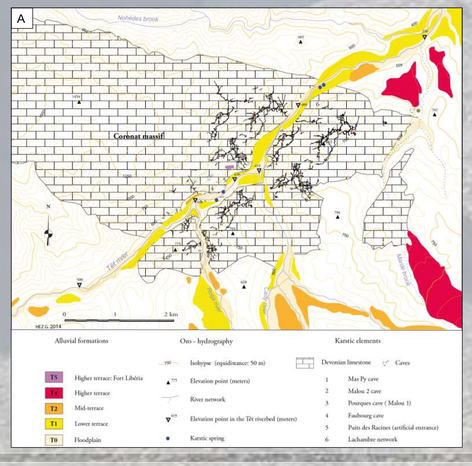
➢Sediment provenance in the investigated catchment: Paleozoic crystalline massifs (gneiss, granites) and metasediments. But also Mio-Pliocene deposits due to the Miocene extension phase;

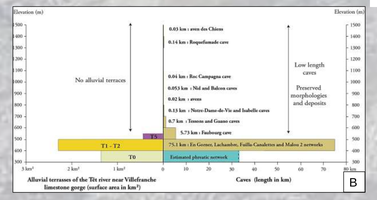
➢Poor conservation of alluvial terraces into the Villefranche-de-Conflent gorges;

➢Important karstification of Devonian limestones massifs;

Geology et tectonic structures of the Têt catchment ➔

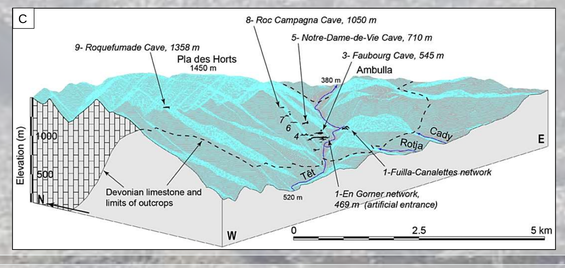






➢Eight epiphreatic levels on ~600m height;

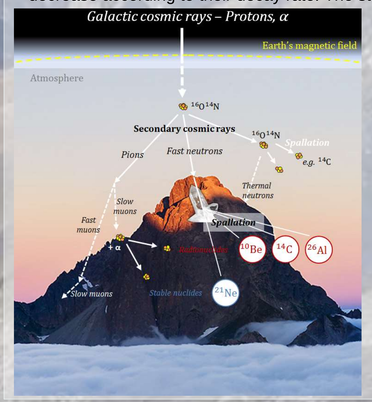
➢ One level is particularly developed, with 75 km of galleries discovered, (En Gorner, Lachambre & Fuilla – Canalettes networks), probably due to a pronounced base-level stationary phase (Audra, 1994).



← A: The Têt river valley near Villefranche – de – Conflent. Karstic networks spatial distribution in the massifs and terraces cartography (modified after Hez, 2015); B: spatial relationships between alluvial terraces and epiphreatic levels (modified after Hez, 2015); C: spatial distribution of most of the investigated caves (after Calvet *et al.*, 2015).

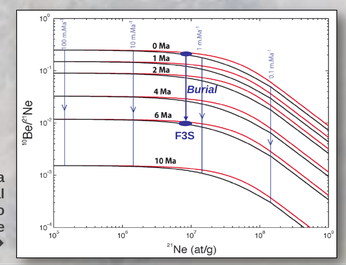
How to determine alluvium burial duration?

Terrestrial cosmogenic nuclides (TCN) are produced from nuclear reactions between cosmic ray particles and atoms constituting the Earth's crust minerals. When sediment is buried and efficiently shielded from cosmic ray flux into the cave, the concentration of TCNs in the buried minerals , for example quartz, will decrease according to their decay rate. The stable noble gases concentrations, such as ^{21}Ne, will remain constant.



← Interacting with Earth's atmosphere components, cosmic ray energetic particles induced a nuclear cascade, producing in abundance secondary particles like neutrons, which allow formation of TCN. In the lithosphere, production rates exponentially decrease with the crossed material thickness.

The change in the ratio of the concentration of two different TCNs in the same sample, as long as one is a radionuclide, depends on burial duration, denudation rate, and depth. Usually, the $^{26}Al/^{10}Be$ ratio is suitable in quartz minerals, over the 0,20 – 5,5 Ma time interval (Granger et Muzikar, 2001).
Given that $^{26}Al/^{10}Be$ cosmogenic burial dating in this setting was limited to the last ~5 Ma (Calvet *et al.*, 2015), here we used the cosmogenic $^{10}Be/^{21}Ne$ method (*e.g.* Balco & Shuster, 2009; McPhilipps *et al.*, 2016) in order to restore a more complete chronology of valley incision.

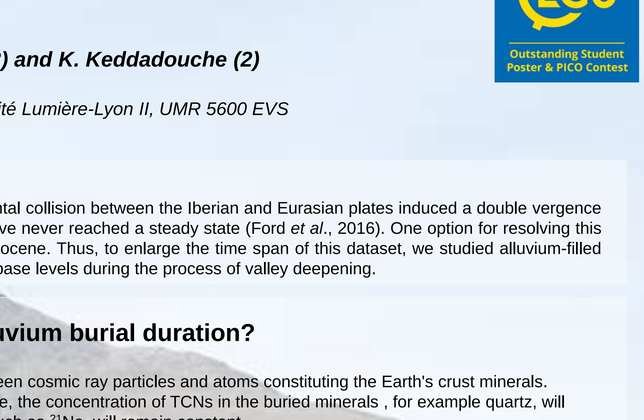


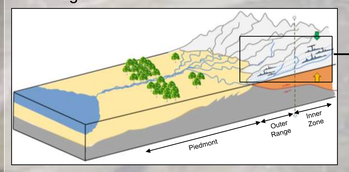
$^{10}Be/^{21}Ne$ *vs* ^{21}Ne plot. Example with a Faubourg cave sample whose burial duration is 6,0 ± 1,1 Ma. We can also determinate a paleo denudation rate of 2 m/Ma ➔

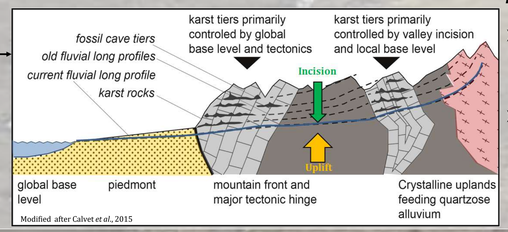
Evolution of the Têt canyon since Burdigalian

Incision record

- Continuous record of incision, but in successive stages since Burdigalian;
- Quartz from Faubourg cave record the same burial duration using both $^{26}Al/^{10}Be$ and $^{10}Be/^{21}Ne$ methods. But quartz from the low elevation karstic networks indicate a more complex history. In other context the classical interpretation is a complex burial history, but in karstic networks we could interpret this difference as sediments reworking between two connected levels or mixtures due to i) a stagnation phase, ii) base-level fluctuations. This phase could be linked with the Messinian Salinity Crisis (*e.g.* Clauzon *et al.*, 2015) and the weak tectonic activity of the zone since this epoch (Delcaillau *et al.*, 2004);
- Our results are consistent with previous works based on pollens and mammalians records (*e.g.* Agustí *et al.*, 2006, Suc & Fauquette, 2012);
- Pre-burial catchment derived denudation rates are low. Cosmogenic ^{21}Ne concentrations revealed an initial paleo denudation rate of ~0,3 m/Ma. This potentially indicate a planar poorly-incised surface 16 Ma ago. No acceleration during the Quaternary is recorded in this valley;
- The Pla des Horts plateau (+ 900 – 1100 m) seems to be Burdigalian in age.



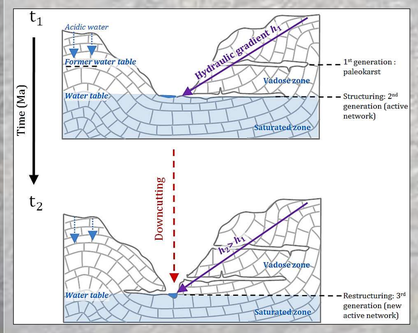




Is it possible to record uplift evolution ?

- Using cave levels to reconstruct uplift records is only relevant in the mountain front, where karstic networks are connected to the regional base level (Calvet *et al.*, 2015);
- For the Conflent zone, it appears difficult to directly link incision and uplift because of the direct Mediterranean Sea connection. Thus, the eustatic variations may play a significant role in the process of incision, although our recording resolution does not allow to fermly assert it.

How to quantify incision with karstic networks?



← Due to valley deepening, various generations of horizontal conduits are generated, the more recent networks forming below previous generations

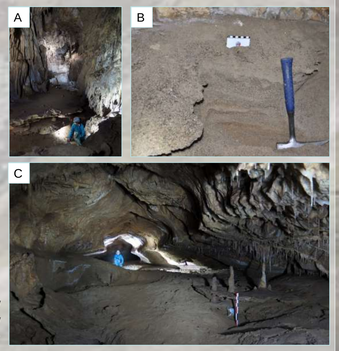
➢Network formation is very fast (10-40 ka), but morphologies and deposits are conserved for millions years;

➢Epiphreatic galleries indicate water-table proximity: they represent former valley floors;

➢Staged karstic system record the transient position of former local base levels during the process of valley deepening, as fluvial terraces;

➢We have dated alluvium which are trapped and preserved into horizontal passages.

A: Sand and gravels on the En Gorner network; B: sandy deposits of the Lachambre network; C: Porte de Fer gallery (En Gorner). Ph. G. Hez →



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Sources: Agustí *et al.* (2006). The Messinian terrestrial record in the Pyrenees: The case of Can Vilella (Cerdanya Basin). *P³*; Audra (1994). Karsts alpins. Genèse de grands réseaux souterrains. Exemple : le Tennengebirge (Autriche), l'île de Crémieu, la Chartreuse et le Vercors (France). *Karstologia Mémoire n°5*; Audra & Palmer (2013). The vertical dimension of karst: controls of vertical cave pattern. *In Treatise on Geomorphology (6) – Karst Geomorphology*; Balco & Shuster (2009). $^{26}Al-^{10}Be-^{21}Ne$ burial dating. *EPSL*; Calvet et al., (2015). Cave levels as proxies for measuring post-orogenic uplift: Evidence from cosmogenic dating of alluvium-filled caves in the French Pyrenees. *Geomorphology*; Clauzon *et al.*(2015). The Roussillon Basin (S. France): A case-study to distinguish local and regional events between 6 ad 3 Ma. *Marine & Petroleum Geology*; Chevrot *et al.*(2011). A preliminary catalog of moment tensors for the Pyrenees. *Tectonophysics*; Delcaillau *et al.* (2004). The northern segment of the Têt Fault (Pyrenees-Orientales): Neogene evolution and geomorphic implications. *Bull. Soc. Geol. Fr.*; Ford *et al.* (2016). Retro-wedge foreland basin evolution along the ECORS line, eastern Pyrenees, France. *J. of the Geol. Society*; Goula *et al.* (1999). Present and recent stress regime in the eastern part of the Pyrenees. *Tectonophysics*; Granger & Muzikar (2001). Dating sediment burial with in situ-produced cosmogenic nuclides: theory, techniques, and limitations. *EPSL*; Hez (2015). Un remarquable enregistreur de l'incision de la vallée de la Têt. Le karst étagé des gorges de Villefranche – de – Conflent, Pyrénées – Orientales, France.; McPhillips *et al.* (2016). Dating the incision of the Yantze River gorge at the First Bend using three-nuclide burial ages. *Geophysical Research Letters*. ; Molnar & England (1990). Late Cenozoic uplift of mountain ranges and global climate change: chicken or egg ? *Nature*; Palmer (2007). Cave geology; Reiners *et al.*, (2003). Coupled spatial variations in precipitation and long-term erosion rates across the Washington Cascades. *Nature*; Suc & Fauquette (2012). The use of pollen as a tool to estimate palaeoaltitude of mountains: The eastern Pyrenees in the Late Neogene, a case study. *P³*.

Sight of the Vignole cirque since Puymorens pass (Ariège) –Cécile Mahé