Tectonic Relief Basins – Alps Workshop

May 31st 2021

Online presentations and discussions

Online Workshop

Is there anything left worth studying in the Alps? This is the question that some people may ask given the long history of geoscience research in the European Alps over the past 150 years. For providing a clear answer to this question and to discuss current and future research efforts in and around the Alps, ranging from the rift-inherited heterogeneities and their impact on Alpine collision, over the alpine metamorphic, structural deformation and exhumation histories, to passive margin and foreland basin evolution, and late Neogene – Quaternary paleoclimate and biodiversity evolution, the TRB team of ISTerre holds a 1-day online workshop with contributions from students and researchers at ISTerre and other laboratories and institutions.

Workshop organization

The objective is to provide an overview on our research activities in anad around the Alps via **15-minute presentations followed by 5 minutes** for immediate discussions. At the end of each subject session an additional 40 minutes will be for further **round table discussions**.

Zoom link:
Topic: Tectonics Relief Basins Alps Workshop
Time: May 31, 2021 09:00 AM Paris

Join Zoom Meeting
https://univ-grenoble-alpes-fr.zoom.us/j/94647984956?pwd=VjJFeFVyeXhPQTVkRmJ1U2t2VDR2Zz09

Meeting ID: 946 4798 4956
Passcode: 450982

Program:

Monday 31st of May 2021

9:00 – 9:10 Introduction

9:10 – 9:30 *Dall'Asta et al.,* Fluid circulations associated with the necking of the crust: the example of the Mont-Blanc detachment fault

9:30 – 9:50 *Kalifi, Leloup et al.,* Westward propagation of thrusts in the external Western Alps (France) reappraised from an updated chronostratigraphy of the Miocene Molasses

9:50 – 10:10 *Mercier et al*., Rediscovery of a major alpine thrust: the Helvetic Basal Decollement

10 minutes pause

10:20 – 10:40 *Bienveignant et al.,* Timing of Alpine fold and thrust belt deformation and fluid circulations constrained by in-situ U-Pb calcite dating and stable isotopic analysis

10:40 – 11:00 *Bilau et al*., Timing of Penninic Frontal Thrust inversion constrained by U-Pb calcite and (U-Th-Sm)/He hematite dating

11:00 – 11:20 *Colombie et al.*, The mid-Cretaceous paleogeography of Haute-Provence: a crucial geological record of the South-East Basin

11:20 – 12:00 Round table discussion

Lunch break

14:00 – 14:05 Introduction

14:05 – 14:25 *Carcaillet et al*., Don't blush when someone tells you your age or how the coating of a rock allows to evaluate its age of exposure

14:25 – 14:45 *Cardinal et al.*, Fluvial bedrock gorges as markers for Late-Quaternary tectonic and climatic forcing in the French Southwestern Alps

14:45 – 15:05 *Lehman et al.*, Reconstruction of the dynamics and origin of rock glaciers in an Alpine environment

10 minutes pause

15:15 – 15:35 *André et al*., A new morphotectonic and InSAR approach to study seismic hazard in Western Alps? Focus on the Rémuaz Fault

15:35 – 15:55 *Lemot et al.*, Dévoluy karstic sediments record the Neogene evolution of the Western Alps

15:55 – 16:15 *Bernet et al.*, Western Alps Mountain Building and Biodiversity

16:15 – 16:55 Round table discussion and closure of the workshop

Fluid circulations associated with the necking of the crust: the example of the Mont-Blanc detachment fault

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The external crystalline massifs of the Alps, which include the Mont-Blanc massif, are found in between the external and internal parts of the orogen. The external parts correspond to the proximal domain of the Alpine Tethys (Helvetic domain), whereas the internal part corresponds to the former distal domain of the margin (Penninic domain). Therefore, the Mont-Blanc massif is a key place for understanding the proximal-distal transition during Jurassic rifting of the Alpine Tethys.

Despite numerous seismic observations at modern passive margins, the tectono-sedimentary and fluid evolution recorded in these domains called necking zone remain poorly understood. Many questions remain concerning the thermal evolution, the origin and composition of the fluids, their link to large-scale hydrothermal systems, and the impact of element transfer on the diagenesis of syn-rift sediments.

Here we focus on the Col du Bonhomme (southern Mont-Blanc massif near Bourg St-Maurice, France), where late Triassic / early Jurassic to late Jurassic sediments preserve pre-Alpine contacts between the sediment and the basement. The syn-rift sedimentary tract is composed of Sinemurian to Pliensbachian sandstones called "Grès Singuliers", lying unconformably above the pre-rift and over an exhumed fault plane corresponding to the top basement.

Characterization of the faults and overlying sediments requires a multi-scale and multi-disciplinary approach combining field observation, petrography, sedimentology, structural geology, and geochemistry. The protolith of the fault rocks is a Variscan migmatitic gneiss. The damaged zone consists of cataclasites and the core zone is made of black gouge. The gouge is overlaid conformably by Liassic sandstones that contain reworked clasts of cataclasite. The observations that the top basement fault is cut by a Pliensbachian high-angle normal fault and Triassic clasts occur in the gouge enables to date this fault as Early Jurassic.

At the micro scale, the basement shows hydratation leading to chloritization of biotite and sericitisation of feldspaths (orthoclase and plagioclase). A strong hydration-assisted deformation with increase of deformation toward the fault core leads to the formation of cataclasites. They are composed of quartz, sericite with small remnants of orthoclase, chlorites with secondary pyrites and rutiles. The fault core is a black gouge with grain size comminuition and mineral neoformation.

Evidence for fluid flow is observed in the fault leading to the hydrothermal alteration of the basement (sericitisation of feldspath and corrosion of quartz) and the formation of syn-gouge quartz and quartz-adularia veins in the black gouge (datation using the Rb-Sr an adularia and U-Pb on calcite method is in progress) .

Based on our observations we interpret the fault observed at Col du Bonhomme as a Jurassic exhumation fault associated with the necking of the European crust during Jurassic rifting. This preliminary work shows that the fault acted as an important pathway for crustal fluids with important transfer of silica and at least K, Fe and Ti. The Col du Bonhomme area gives an opportunity to study fluid circulation and basement alteration along a rift-related detachment fault in the necking domain and therefore to understand fluid-mediated element mobility during rifting.

Westward propagation of thrusts in the external Western Alps (France) reappraised from an updated chronostratigraphy of the Miocene Molasses

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The fact that the western Alps Miocene foreland basin succession is poorly dated impacts directly our understanding of the deformation kinematics of that part of the external part of the Alpine belt (France). Here we propose a multidisciplinary approach aiming at building a robust tectono- stratigraphic framework of the Miocene deposits at the basin scale (northern subalpine massifs, southern Jura, Royans, Bas-Dauphiné and La Bresse basins). Sr isotopes stratigraphy combined with magnetostratigraphy and biostratigraphy enable sequence stratigraphy subdivisions S1 to S8 between the Upper Aquitanian (-21 Ma) and the Tortonian (-9 Ma) dated with a precision <0.5 Ma. These results highlight four different palaeogeographical domains during the Miocene: (i) the oriental domain with depositional sequences S1a to S3 (~21.3 to 15Ma), (ii) the median domain, in which sequences S2, S3, S4 and S5 occurred (~17.8 to 14Ma), (iii) the occidental domain with sequences S2 to S8 (~17.8 to ~9.5Ma); and (iv) the Bressan domain, in which sequences S6 to S8 are found (~ 11.5 to ~9.5Ma).
This revised chronostratigraphy was complemented with a structural and tectono-sedimentary study based on new fieldwork data and a reappraisal of regional seismic profiles, allowing to highlight five major faults zones (FZ). It appears that the oriental, median and occidental paleogeographical domains are delineated by FZ1, FZ2 and FZ3, therefore suggesting a strong interplay between tectonics and sedimentation. Evidences of syntectonic deposits and a westward migration of the depocenters impart the following deformation chronology : a Oligocene compressive phase (P1) corresponding to thrusting above FZ1 rooted east (above) Belledonne, which generated reliefs that limited the early Miocene transgression to the east; an Early- to Middle Miocene W-WNW/E-ESE-directed compressive phase (P2) involving the Belledonne massif basal thrust, which between 18.05 +/- 0.15 Ma and 12Ma successively activated the Salève thrust fault, and the FZ2 to FZ5 from east to west. P2 deeply impacted the Miocene palaeogeographical evolution by a rapid westward migration of depocenters in response to the exhumation of piggy- back basins above the growing fault zones; a last Tortonian phase (P3), less well constrained, apparently implied a significant uplift in the subalpine massifs, combined with the activation of the frontal Jura thrust.

Rediscovery of a major alpine thrust : the Helvetic Basal Decollement

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Since two centuries the European Alps are a natural laboratory to study continental lithosphere deformation during mountain building. Since the early studies, a constant question has been to evaluate the importance of vertical versus horizontal displacements in the building of reliefs. Whilst the occurrence of large thrust sheets, as initially proposed from field observations, are now well explained in the frame of plate tectonics, controversies still arise on the precise geometry, amount, and timing of major thrusting during the orogeny.

We present a new detailed 3D structural study of the cover/basement relationships in the Chamonix synclinorium in between the Mont-Blanc (MB) and Aiguilles Rouges (AR) ranges. These massifs are two of the main external basement ranges of the western Alps. The study allows deciphering the area structural history: the Mesozoic sedimentary cover has been thrust at least 10km NW above the Helvetic Basal Décollement (HBD) before to be offset by late steep thrusts during exhumation in the Miocene.

Such interpretation fundamentally diverges from the classical view of the sedimentary cover of the Chamonix synclinorium being expulsed from a former graben during a single deformation phase and implies that a major thrust phase lasting ~10 Ma has been overlooked (Fig 1). Our observations show that the HBD was a major thrust system active between ~30 and ~20 Ma, possibly until 15 Ma, with a shortening of more than 10km in the south to 20km in the north. It extends below most of the subalpine ranges and emerges in front of the Bauges and within the Chartreuse and Vercors massifs, and was rooted east of the External Cristalline Massifs (Mont-Blanc and Belledonne). During the Miocene, the HBD was cut by steep reverse faults and uplifted above the basement culmination of the External Cristalline Massifs obscuring its continuity and precluding its recognition as a major structure even if it was previously described at several localities.

Key words : Structural Geology, Alps, 3D model, thrusting

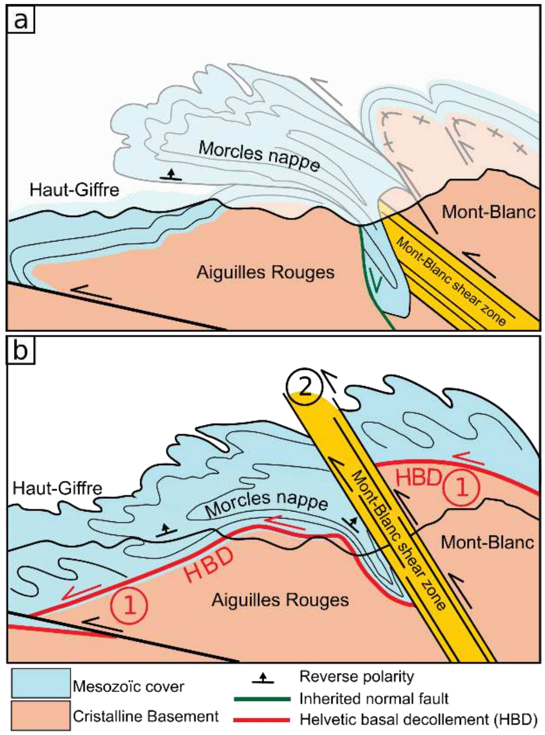

Figure 1: Contrasting models for alpine deformation of the external crystalline basement ranges and their cover, as exemplified in the AR and MB ranges. a) One-stage folding of the thick sedimentary series located within half grabens, resulting in parautochtonous folds. The folding is either linked to a reverse shear zone (case depicted) or to a tight basement fold. b) Two stages deformation model. 1- Décollement of the cover with respect to the basement (Helvetic basal Décollement). 2- Two stages model with an offset of a décollement level (1 - Helvetic basal Décollement) by a steep reverse shear zone (2 - MB shear zone).

Timing of Alpine fold and thrust belt deformation and fluid circulations constrained by in-situ U-Pb calcite dating and stable isotopic analysis

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The subalpine massifs (Vercors-Chartreuse) correspond to a fold-and-thrust belt located in the western Alps foreland. The analysis of the implementation of such a deformation system can be undertaken by the study of the major thrusts and syntectonic sediments (molasses) constituting the flexural basins within those same massifs (figure 1). Indeed, the deformation of the sedimentary cover and the erosion products (deformed pebbles) enables the record of the past tectonic activity, often under the form of striated fault planes and calcite veins. Recent analytical progress in geochronology makes now possible the use of the in-situ U-Pb method on calcite (Godeau, 2018; Bilau et al., 2021). Dating this ubiquitous mineral gives the possibility to temporally constrain the structuration of these massifs. The results of the direct dating method of those objects show an evolution in three stages of the frontal thrust system: (1) development of the Moucherotte internal thrust around 14-15 My, then (2) the propagation of the system up to the subalpine massifs fronts around 12 My, and finally (3) the multiple reactivations of the most internal thrusts between 9 and 2 My (figure 2). The precocious phase (1-2) which spreads out from 15 to 12 My enables the formation of the main accidents, propagating from east to west. Later, between 9 and 2 My, the reactivation of tectonic accidents was underlined by the apparition of a strike-slip component affecting external zones. This kinematics reminds the current seismotectonic context and can be explained by the anti-clockwise rotation of the Adriatic plate (Collombet et al., 2002). Furthermore, this article presents a redefinition of thrusts on both sides of the Isere clue. The model that is exposed here concludes on the identification of the klippe of Moucherotte and proposes a link between the thrust of St Egrève (right bank) and the thrust of Sassenage (left bank), thus rejecting the idea that the hypothetical Cluse fault (Gidon, 1995) is involved. Coupled with an in-situ isotopic analysis (SIMS) of the deformed zones, it is possible to trace the origin of the mineralising fluids of the calcites dated by the U-Pb method. The isotopic signatures obtained are compatible with a mixture of meteoric water and fluids buffered by the sedimentary cover, leaving the possibility to carry out a paleo-altimetry study of the external zones (for instance, Campani et al., 2012). Moreover, the petrographic analysis of the calcite-filled microstructures, coupled with the Physico-chemical parameters of the fluids show that only the veins with a blocky texture, whose crystallization is rapid, seem to be datable by the U-Pb method, contrary to fibrous calcites whose crystallization is slower and incremental.

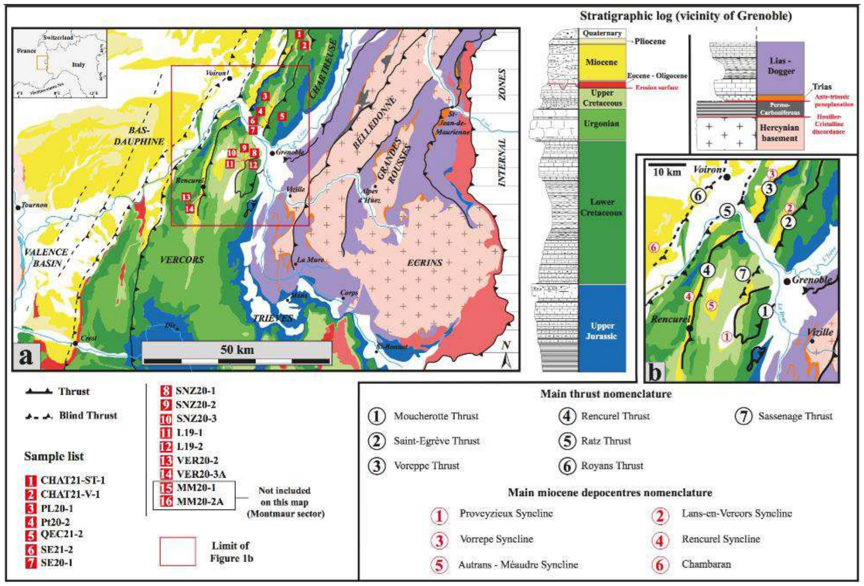

Figure 1 : (a) Geological map (Kalifi, 2020, simplified) and stratigraphic log of the Grenoble area (Joseph Fourier University document, modified and not to scale). (b) Location and nomenclature of the main Tertiary thrusts and depocentres (Kalifi, 2020, modified).

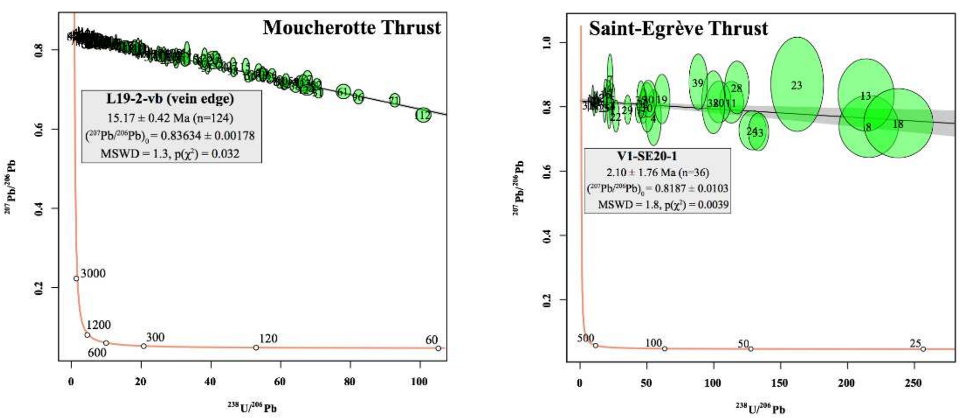

Figure 2 : Example of two ages obtained by the application of the U-Pb method on calcite. The measurements were carried out with the LA-ICPMS (Element-XR coupled to a NWR193 laser) at CEREGE in Aix-en-Provence.

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Timing of Penninic Frontal Thrust inversion constrained by U-Pb calcite and (U-Th-Sm)/He hematite dating

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In the last decade, important improvements in dating methods have been made and make it possible to go into the details of fault gouge formation and evolution. Common minerals like calcite and hematite can now bring detailed information on timing of fault development and fluid-rock interaction. We applied those novel techniques to a tectonically well constrains alpine context, though still lacking key chronological constrains. The targeted fault zone is the Penninic Frontal Thrust (PFT) of SW Alps, which is a major tectonic boundary that juxtaposed the metamorphic internal Alps over the unmetamorphosed external Alps, primarily as a thrust during the Oligocene (*Simon-Labric et al., 2009*). The PFT was later reactivated as an extensional detachment in the Mio-Pliocene, though the age of this reactivation remained unconstrained. *Sue and Tricart (2003)* showed that ongoing extensional seismic activity along the PFT, corresponding to the High-Durance Fault System (HDFS), is characterized at the surface, by an extensional fault network, Fig. 1.

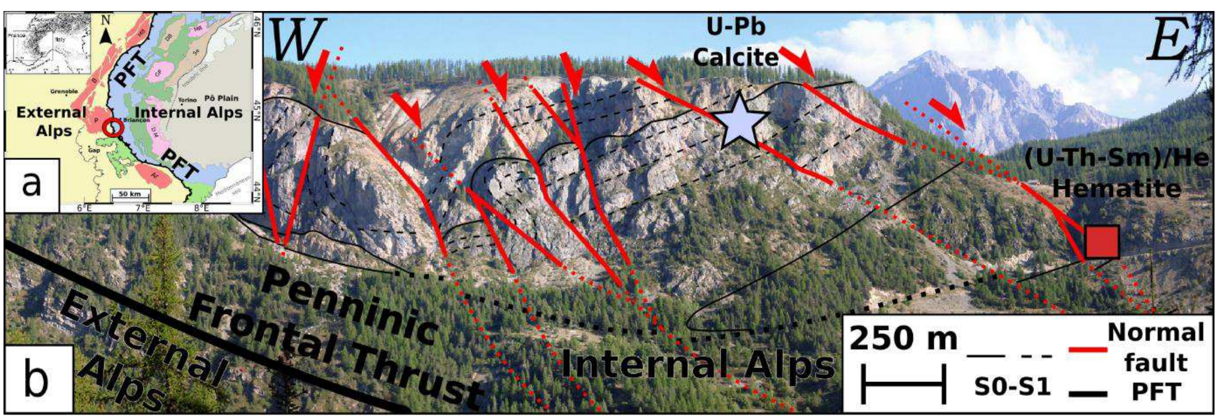


***Fig. 1.** (a) Geological map of the Western Alps. (b) Geological interpretation of the Fournel Valley cross-section with normal faults of the HDFS. Calcite and hematite sampling site are respectively grey star and red square.*

In this context, the HDFS corresponds to extensional reactivation of the PFT as a consequence of Pelvoux external crystalline massif exhumation.
In this study, we coupled field tectonic, in-situ calcite U-Pb and hematite (U-Th-Sm)/He dating to stable and isotope analysis to infer the HDFS activation age and to investigate the related fluid circulations.

Isotopic signature ($\delta^{13}C$ and $\delta^{18}O$) of compressional veins, en-echelon extensional veins and cataclasite fault gouge have been determined (*Bilau et al., 2021*).
This study allows pinpointing the evolution of deformation and fluid-rock interaction in the PFT footwall during its progressive extensional exhumation. The older U-Pb ages obtained on the cement of the gouge fault range between 2.4 to 5.9 Ma, Fig. 2.

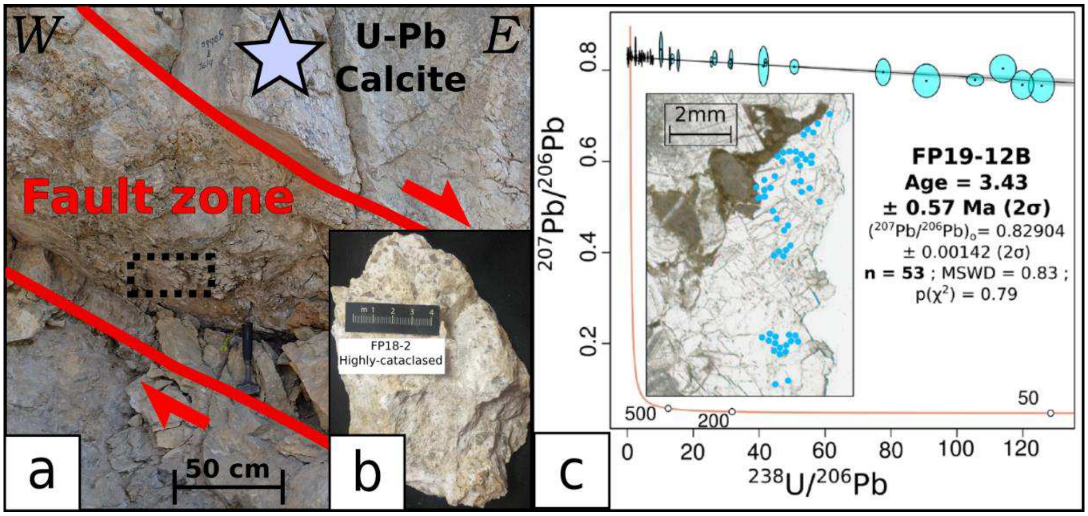
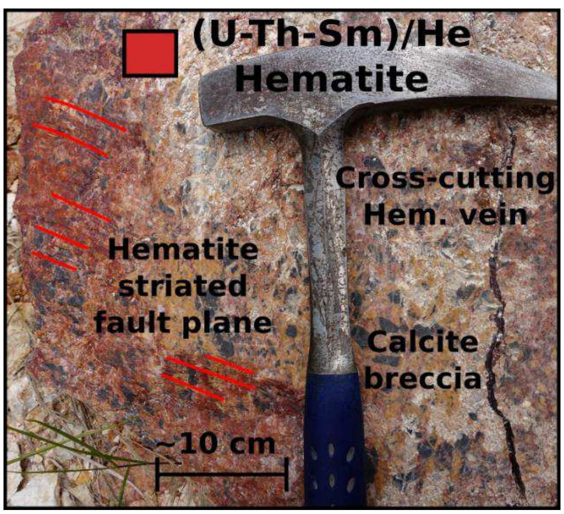


Fig. 2. *(a) Outcrop of the Tournoux scarp. (b) FP18-2 Sampled polyphased calcite cataclasite. (c) Tera-Wasserburg plot dating the latest calcite generation in the sample.*



Taking into consideration uplift rate, comparison to currently seismicity depth and calcite brittle/ductile transition temperature, calcite crystallization may have occurred between 5 and 2 km. The hematite cross-cutting calcite, Fig. 3, appears at shallower levels in the latest stages of the fault displacement at 3-1 km depth. A transition in the nature of fluids, controlling the redox state, can be highlighted here. This transition occurs between the calcite and hematite forming events at 2-3 km depth, which is probably related to a significant influx of meteoric fluids into the drainage of the fault system.

Fig. 3. *Outcrop of the Pousterle path, evidence of crystallization chronology between calcite and hematite.*

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The mid-Cretaceous paleogeography of Haute-Provence: a crucial geological record of the South-East Basin

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Located at the Pyrenees-Alps linking zone, the Southeast Basin is a key area to better understand the role of the structural inheritance in the formation of the SW Alps fold and thrust belt / foreland basin. In the mid-Cretaceous (i.e. Albo-Cenomanian), the extension-compression transition is marked by the formation of the "Durancian uplift" in Haute-Provence, and by the sedimentary record of a major disruption of the carbon cycle (i.e. Mid-Cenomanian Event). Recently, the very detailed sedimentological and stratigraphical analyses and correlation of 5 Cenomanian sections show important variations of facies and thickness, which imply a significant tectonic control on sedimentation that might be due to halokinetic motions or subsidence. Each section belongs to different paleoblocks bounded by Jurassic and Cretaceous normal faults of N-S orientation. The differential vertical motions of these paleoblocks suggest a west-to-east spatiotemporal migration of deformation over an interval of only 2 Ma during the early Cenomanian. This migration might be related to to the Alpine convergence and more specifically to the north-directed thrusting that shortens the South Provence Basin (south of the "Durancian uplift").
The main objective of this proposal will be to precise the Haute-Provence pre-alpine paleogeography by characterizing and dating the Albo-Cenomanian tectonic and paleoenvironmental events. It will combine very detailed sedimentological and stratigraphic analysis of sections and boreholes with thorough structural analysis. Notably, U/Pb dating on calcite-mineralized faults will enable to identify active fault systems. All these results will be integrated for subsidence analysis and structural restorations. This multi-method approach aims at delivering paleogeographic reconstructions of unprecedented accuracy (i.e. 100 kyrs) that are essential to precise the nature, geometry, kinematic (either extensional or compressional) for the poorly documented Albo-Cenomanian of Haute-Provence. Replaced in its geodynamic context, this crucial geological record may provide new keys to assess the still disputed Pyrenean-Alpine linking zone at the transition between the Alpine divergence and convergence.

Don't blush when someone tells you your age or how the coating of a rock allows to evaluate its age of exposure

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Rockfalls and rock avalanches are active processes in mountain areas as, for example, in the Mont Blanc massif. Massif rockfalls frequency has strongly increased over the last century and especially the last 30 years, likely due to permafrost degradation driven by the climate change.
In order to understand, at a longer timescale, the relationship between rockfall frequency and climate dynamics in the Mont Blanc massif (MBM), we use 72 Terrestrial Cosmogenic Nuclide (TCN) dating of rockfall scars to identify periods of high rockfall intensity. The chronological framework has been compared with glacial and climate proxies to verify the hypothesis that rockfalls were more frequent during warm periods.
However, this technique is extremely time-consuming, costly and not very eco-friendly!
We thus explored a new method to evaluate the exposure age of scarps from the spectrocolorimetric analyses of rock surfaces. In the MBM, the light grey colour of fresh granite surfaces turns orange when it is long exposed to weathering. In order to study a colour/age relationship, reflectance spectroscopy was performed on surface samples, compared with TCN dating to obtain a relationship between scar exposure ages and colour of the rockwalls.
The GReen- Infrared GRanite Index (GRIGRI), a normalized difference between the granite 770 nm and 530 nm reflectance values, was developed. The GRIGRI value of a weathered granite surface has a close relationship with its exposure age (R2 = 0.85). The reflectance spectra of 9 samples without TCN ages were used to calculate their GRIGRI value to assess the colour-based ages, that were plausible according to rock wall morphology and the TCN exposure ages of the surrounding surfaces. We thus propose a new method of surface dating for the rock walls of the MBM using reflectance spectroscopy.

Fluvial bedrock gorges as markers for Late-Quaternary tectonic and climatic forcing in the French Southwestern Alps

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**ASTER Team: Georges Aumaître, Didier L. Bourlès, Karim Keddadouche*

We measured in situ-produced ^{36}Cl concentrations along the fluvially-polished bedrock walls of the Pérouré and Bévéra river gorges, which are located in the external SW French Alps. Both catchments lie beyond the previously glaciated domain during the last glacial periods, which makes them suitable to quantify fluvial incision dynamics in a non-glacial environment. Our cosmic-ray exposure (CRE) dating results provide a mean incision rate of 0.6-0.7 mm/yr over the last 20 ka. Compared to CRE dating data obtained from previous studies in neighboring catchments, we highlight three different incision dynamics for bedrock gorges in SW Alps: (i) Group A with slow and steady incision rates (0.5 mm/yr over the last ca. 30 ka), comparable to long-term denudation and rock-uplift rates in the area, suggesting tectonic forcing for incision in non-glaciated zones; (ii) Group B showing high incision rates (≈2 mm/yr) during the paraglacial period after the Last Glacial Maximum (LGM, ca. 20 ka), possibly related to an increase in sediment yield and water runoff following glacier retreat; (iii) Group C with high (≈5 mm/yr) and recent (post-10 ka) incision rates that reflect fluvial rejuvenation of glaciated catchments.

Figure 1: Location of the Pérouré (1) and the Bévéra (2) gorges from this study and previously dated sites from the literature: (3) Vésubie (Saillard et al., 2014); (4) Salso Moreno; (5) Isola; (6) Saint Sauveur; (7) Lower Tinée (Rolland et al., 2017); (8) Esteron (Petit et al., 2019); (9) Clue de Barles (Cardinal et al., 2021) in the Southwestern Alps. The grey area shows the Last Glacial Maximum (LGM) glacier extent (modified from Brisset et al., 2015). Note that the glaciated/non-glaciated specification refers to the glaciation of the highest part of river catchments during the LGM, and not for the sampling site itself.

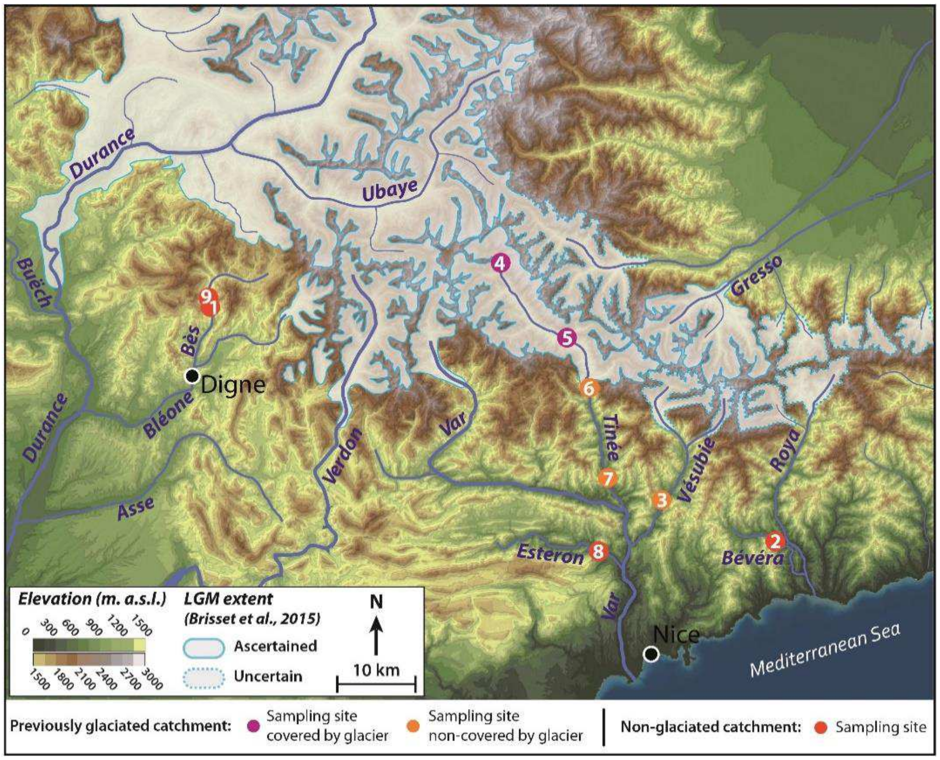
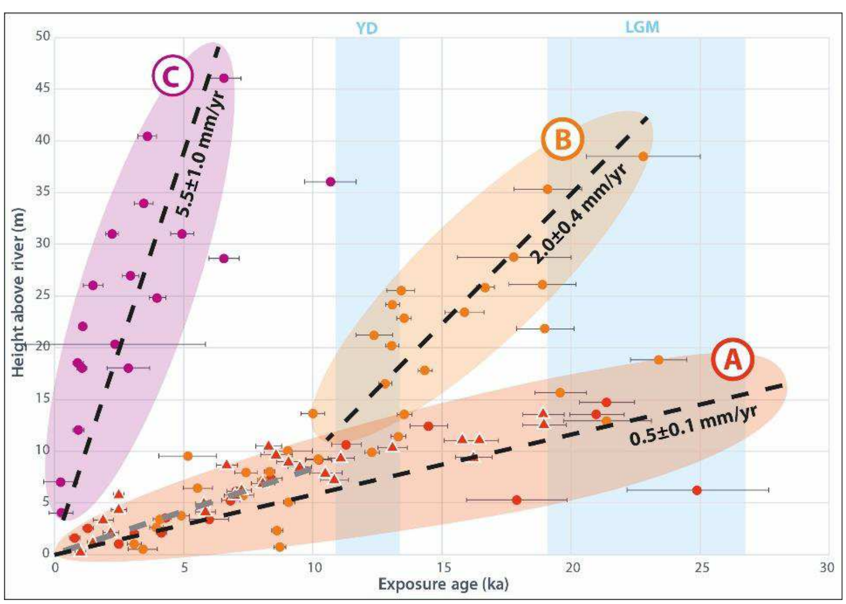


Figure 2. Comparison of CRE ages obtained from this study (triangles) and previous one (circles; Rolland et al., 2017; Saillard et al., 2014; Petit et al., 2019; Cardinal et al., 2021). The colours of the points are in reference to figure 1. From this plot, we can highlight three groups of gorges (A, B and C) with corresponding mean incision rates significantly increasing according to their altitude and location with regard to the LGM extension boundary (see figure 1). The uncertainty values correspond to the standard deviation to each of the mean incision regression. Glacial periods are chronologically represented by light blue columns: LGM (Last Glacial Maximum): ca. 26.5-19 ka (Clark et al., 2009); YD (Younger Dryas): ca. 13-11 ka (Hinderer, 2001; Heiri et al., 2014).



Reconstruction of the dynamics and origin of rock glaciers in an Alpine environment

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Rock glaciers are one of the most frequent cryospheric landform in mid-latitude mountain ranges. They influence the evolution of alpine environments on short (years to decades) and long (centuries to millennia) time scales. Representing visible expressions of mountain permafrost [1] and important water reserves in the form of ground ice [2], rock glaciers are seen as increasingly important in the evolution of geomorphology and hydrology of mountain systems in the context of climate change and deglaciation [3, 4]. On longer time scales, rock glaciers transport boulders produced by the erosion of the headwall upstream and downstream and therefore participate in shaping mountain slopes [5]. Despite their importance, the dynamics and origin of rock glaciers are poorly understood.

In this study, we propose to address two questions:

1) How does the dynamics of rock glaciers change over time?

2) What is the origin of rock glaciers and what is their influence on the evolution of alpine environments?

These two questions require an evaluation of the surface velocity field of rock glaciers by relating short and long-time scales. To adress these questions, we combine methods including remote sensing, geochronology and numerical modelling of rock glacier dynamics [6] and apply this approach to the rock glacier complex of the Vallon de la Route in the Massif du Combeynot (French alps).

Remote sensing methods such as image correlation allow to reconstruct the displacement field of the rock glacier on modern time scales. Over longer periods (10^3 to 10^4 years), we used cosmogenic terrestrial nuclides (TCN) dating. By applying this methodology to boulder surfaces at different positions along the central flow line of the rock glacier, from the headwall to its terminus, we will be able to convert the exposure ages into surface displacement. The use of numerical modelling of rock glaciers [6] will allow us to relate the surface kinematics at different time scales. It will then be possible to discuss the age; the origin of rock glaciers and how topo-climatic and geomorphological processes control their evolution in Alpine environment.

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A new morphotectonic and InSAR approach to study seismic hazard in Western Alps? Focus on the Rémuaz Fault

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The small tectonic strain rates in the Western Alps make the identification of active structures difficult as well as the characterization and the quantification of the processes at the origin of the seismicity.

However, the millenary action of the deformation can be observed by the formation of cumulate morphologies, often associated with the reactivation of inherited geological structures. This action is translated by the creation of pluri meter-scale scarps that affect polished surfaces and superficial deposits. The integration of the strain processes over several seismic cycles is the key to get a representative signal that can be quantified. Recent improvements in drone photogrammetry and lidar imagery have allowed to produce DEM with a sub-metric resolution and to see through the vegetation, which is necessary for precise identification and cartography of faults in the Alpine environment.

On the other hand, InSAR time series processing of the whole SAR Sentinel-1 archive, with an acquisition every 6 days, allows recovering the ground deformation at a large-scale across the western Alpine arc, with a resolution of a few mm/year. The processing requires adjustment as snow, vegetation, abrupt relief, and strong atmospheric heterogeneities in the Alps make the deformation extraction particularly challenging. A first study led by M. Mathey during her Ph.D. using data in ascending geometry allowed testing improvements of the NSBAS processing chain to adapt it to this challenging environment. As a result, we obtained a very interesting velocity map along the satellite line of sight (LOS) across the Western Alps that allowed us to study :

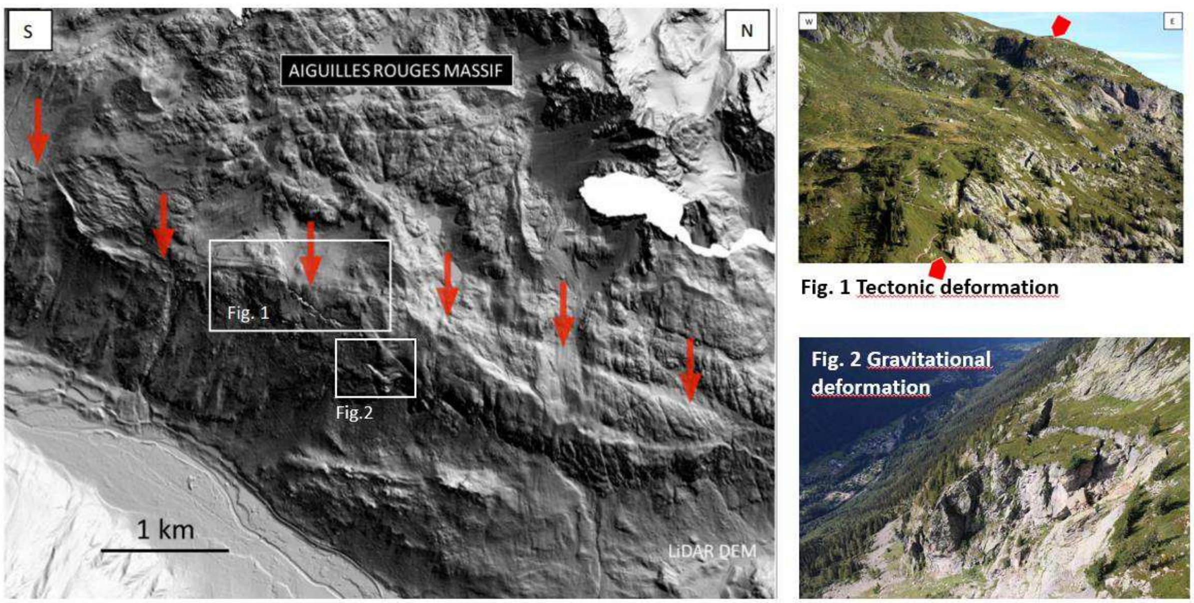
(1) Spatial heterogeneity of uplift pattern in the western European Alps (Mathey Ph.D.)

(2) Gravitational deformation DSGSD (deep-seated gravitational slope deformation) that we're mapped along numerous mountain flanks, with velocities between 3 to 20 mm/year.

For structure that show a morphologic signature of deformation it is often difficult to separate tectonic from gravitational structure therefore the processing the whole data archive on a descending track geometry is necessary to associate both ascending and descending LOS velocity maps to obtain maps of vertical and E-W velocities. The extension of the time series until 2020 should also allow a better separation of the displacement signal from the atmospheric noise and hopefully allow to measure of interseismic deformation around active faults of the western alps.

In this context, we propose an original and multidisciplinary approach that allows analyzing the state of the deformation at the regional and local scale. Morphotectonic analysis coupled with InSAR interferometry has the advantage to combine local data that integrate the cumulate deformation over thousands of years with present-day data that cover all the range continuously.

A first interesting feature to study is the Rémuaz fault, associated with the Vallorcine seismic swarm, north of Chamonix. Notable earthquakes are the 1905 Argentiere EQ (Mw=5.3), 2005 Vallorcine EQ (Mw=4.4), or the very recent 23/06/2020 EQ (Mw=3.8).



Situated between Vallorcine and Chamonix the Rémuaz fault goes through the Aiguille Rouge massif with a linear fault scarp of more than 8 km that affects glacial polished surfaces and superficial deposits.

This case study sums up well the problematics of this study as gravitational rupture has been observed all along the slope. Activity and relation between the fault and the gravitational structure are unknown and still to be studied but could potentially lead to an added hazard in case of an earthquake on the Rémuaz fault.

Dévoluy karstic sediments record the Neogene evolution of the Western Alps

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The Neogene is a critical period for the Alpine orogeny with the uplift of the external crystalline massifs [2, 4, 14], thrust propagation to the foreland [3, 9, 11], and drainage network reorganization [8]. To constrain the causes and the timing of those changes, accurate geomorphic and sedimentological archives are required. However, uplifted areas are subject to erosion which results in range-scale averaged records in peripheral basins, while local histories are less likely to be preserved. Moreover, extensive glacial cover during the Quaternary erased most of the geomorphic markers. For those reasons, the genesis of modern landscape's main features, as major valleys and drainage networks, is still poorly understood.

In my master thesis, I explored the use of karstic archives to constrain past geodynamic conditions. Cave evolution reflects a combination of internal (lithology, structural features) and external (climate, soil, sediment input, water table level, uplift) factors [1, 7]. I studied three cavities of the Obiou peak in this work, located in the Dévoluy massif (western French Alps, Fig. 1A). I focused on fossil networks disconnected from the present-day drainage network and outside of the Quaternary icefields to investigate old karstic morphologies and sedimentary archives. Sub-horizontal development and large speleothems (Fig. 1C-D) indicate speleogenesis under a warm environment with a low-elevation base level, which most probably predates the uplift of subalpine massifs. The Dévoluy massif appears at present as a "butte-témoin" separated from the crystalline massifs by the Drac valley with local relief of around 2 km (Fig. 1B). The occurrence of allochthonous sedimentary material, as well rounded boulders with crystalline lithology (Fig. 1E-F-G) or quartz-rich sand are indicators for cave infilling before the carving of Drac valley.

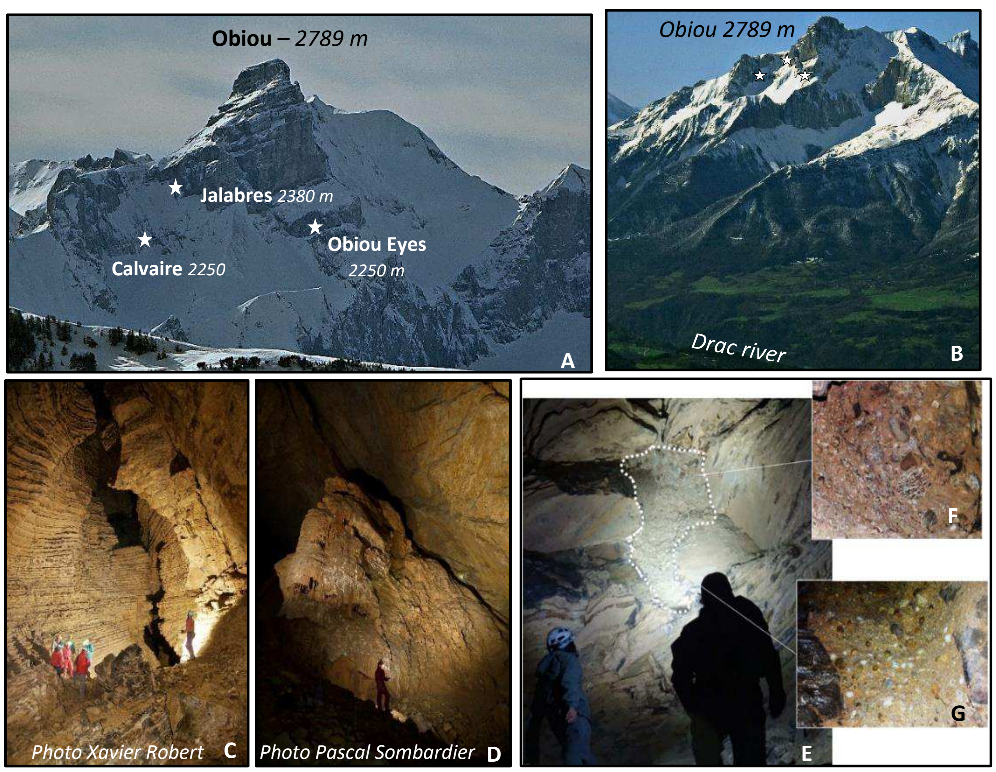

FIGURE 1: Morphology of the Obiou perched karstic system. A: Investigated caves with identified allochthonous sediment infills. B: North slopes of Obiou peak, Drac River is located 1.6 km below the caves. C: Sub-horizontal paleo-meander in Jalabres cave. D: 60-m high gallery in Jalabres cave with massive stalagmite attesting from past warm conditions (see cavist on background for scale). E-F-G: Sand deposits and crystalline cobbles preserved as an infill sediment pocket in Jalabres cave.

I applied a multi-method approach on the cave sedimentary material to (1) estimate the sediment burial age ($^{26}Al/^{21}Ne/^{10}Be$, in progress), (2) determine their provenance (cobbles petrography and detrital AFT), and (3) provide some paleo-environmental constraints (palynology). Cobbles petrography (Fig. 2A) does not include autochthonous Senonian limestone but mainly consists of granite (52%) and medium to high-grade metamorphic rocks similar to lithological units of nearby Pelvoux massif [6]. It also strongly differs from Oligocene molasse deposits from the Dévoluy [10] or internal Alpine units. Preliminary $^{21}Ne/^{10}Be$ results give an age estimate of 10±2 Ma for sediment burial in the cave, providing some time constraints for the uplift of Dévoluy and incision of Drac valley. Detrital AFT ages in both boulders and sandy sediments show a unimodal distribution that peaks at ca. 18 Ma. The lag time of 8 Ma is similar to what is measured in the same age foreland-basin sediments [5]. It also excludes any contribution from the internal zones, as AFT ages are older in this domain [12]. Track length (TL) measurements allowed modeling the cooling history (Fig. 2B) for the drained Pelvoux sediments, with an apparent acceleration of cooling between ca. 15 and 10 Ma. Paleoclimatic conditions were warm, but pollen assemblage covers both subtropical and boreal flora and suggests high relief at proximity, consistent with the uplift of the Pelvoux massif during Miocene times. Lagunar dinoflagellates indicate a coastal/low-elevation environment during Tortonian, which allows reconsidering the local paleogeography. It also gives a paleoaltimerty constraint involving an average uplift rate of 200 m/Ma for the Dévoluy massif. As the cavities are located 500 m under Obiou peak, the Miocene relief in the Dévoluy massif was already significant.

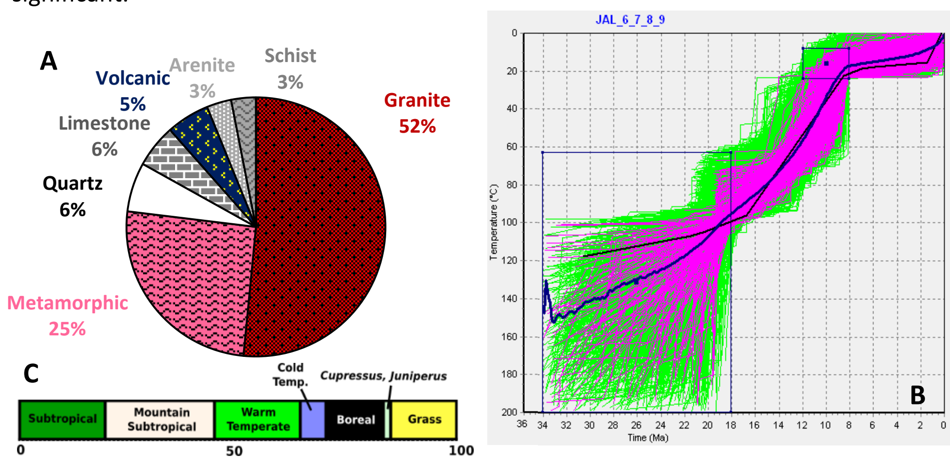

FIGURE 2: Results. A: Cobbles petrography for the Jalabres cave deposit. B: Inverse thermal history (*HeFTy*) for Jalabres sediments (AFT and TL data), acceptable paths in light green, good-fitting in pink, mean path bold. C: palynomorphs assemblage grouped by required climatic conditions, from pollen analysis in Obiou Eyes cave.

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Western Alps Mountain Building and Biodiversity

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The Western European Alps are a collisional mountain belt that emerged since continent-continent collision started during the late Eocene. Surface uplift caused by tectonic convergence and crustal thickening is one of the most remarkable effects of mountain building which has a direct impact on the local and regional climate and the biosphere. For understanding how biomes are formed and maintained, why species migrate, evolve, or get extinct, one needs to understand the geological evolution of the Earth's surface in general, and the formation of mountain belts and sedimentary basins in particular (e.g. Antonelli et al., 2018; Rahbek et al., 2019). Since Humboldt's seminal work in the dawn of the 19th century, it is known that mountain belts host a larger biodiversity than lowlands, but the mechanisms remain elusive. A range of propositions have been invoked to explain the evolution of species through adaptation and radiation, most of them focusing on the climatic conditions, as defined by the latitudinal and altitudinal gradients. However, few acknowledge that geology sets the scene for biodiversification processes: for example, the role of rock types (e.g. silicate vs. carbonate rocks), as exposed at the surface as a result of mountain building, erosion, relief, and exhumation influence soil types upon which a variety of plant types may grow and which animals can live from these plants and so on (Rahbek et al., 2019a, b). Tectonic activity, by increasing habitat heterogeneity and remodelling dispersal routes, also stimulates diversification (e.g. Silvestro et al., 2018; Badgley et al., 2017).

Studying the links and feedbacks between mountain building, climate and biodiversity is a new hot topic in Earth Sciences, reflected by the increasing number of publications on this subject and the recent book published by Hoorn et al. (2018), as well as a collection of review articles which foresee such relationships (Antonelli et al. 2018; Rahbek et al., 2019a, 2019b, Perrigo et al., 2019). Yet, the key to untangle those remains elusive.

The Western Alps are an excellent location for this type of interdisciplinary research as this mountain belt has been extensively studied over the past decades at ISTerre, in terms of topographic evolution, tectonic deformation and exhumation (e.g. Dumont et al., 2012; Fauquette et al., 2015; Glotzbach et al., 2011; Beucher et al., 2012; Bernet, 2013), just to mention a few. For example, a rich bedrock fission-track dataset exists (e.g. Hermann et al., 2013), which can be combined with data obtained from modern river and ancient foreland basin sediment deposits (Fig. 1 A-C), for reconstructing a detailed sediment provenance and exhumation history of the external crystalline massifs. Combined with reconstructions of past physiography since Miocene times, this dataset would serve as a primordial database for understanding the biogeographical evolution, as documented by researchers from partner laboratory LECA (S. Lavergne, F. Boucher). Given the present-day relief of the Western Alps in the Isère drainage, ranging from about 210 m at Grenoble to 2977 m of the Grand Pic de Belledonne in the Belledonne massif, and to 4102 m of the Barre des Ecrins in the Ecrins-Pelvoux massif, the whole range of Alpine vegetation zones (sub-Mediterranean or foothills (~200-700 m), montane (~700-1500 m), subalpine 1500-2100 m, Alpine (~2100-

2800 m), and snow zone (>2800 m)) are present (Fig. 1D). Furthermore, the Joseph Fourier research station of the Université Grenoble Alpes and CNRS botanical garden at the Col de Lautaret, within the study area, provides the foundation for integrating geological, ecological and biological research.

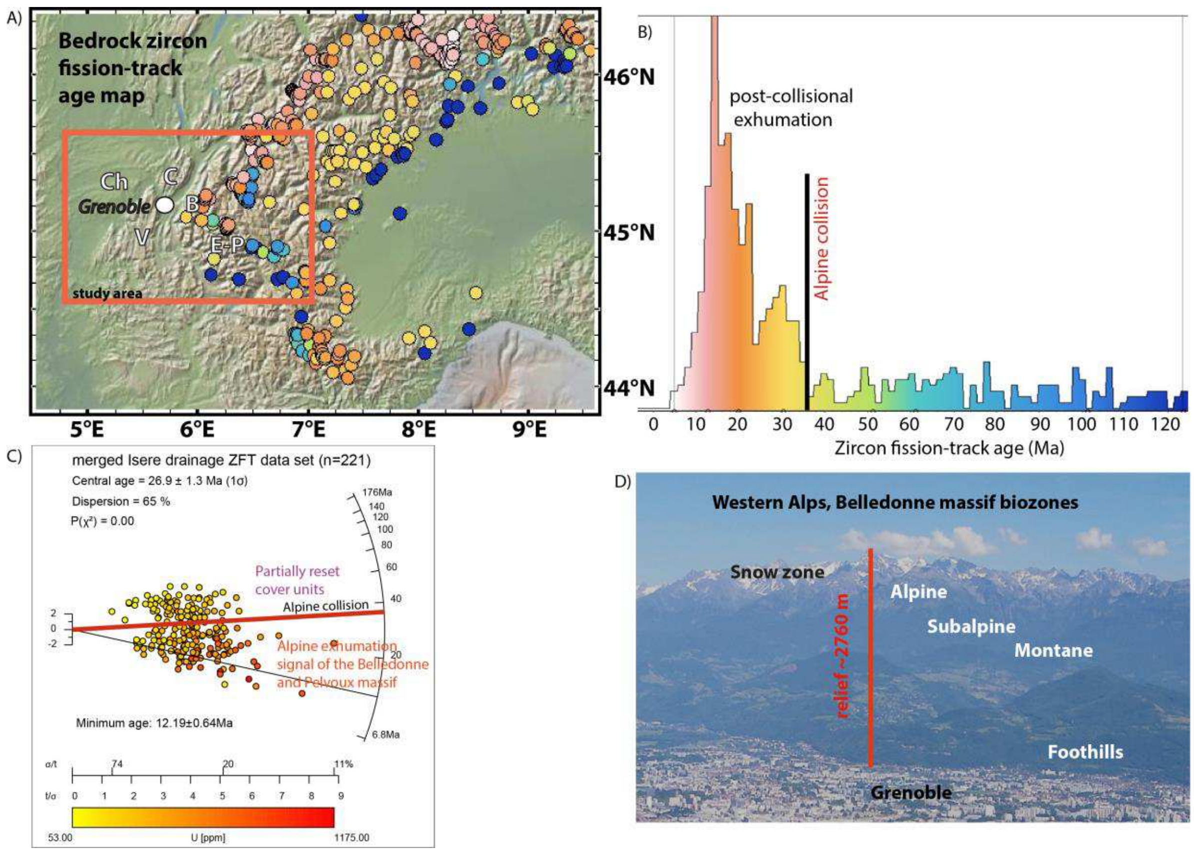

Fig. 1 Example of existing thermochronological data. A) Bedrock zircon fission-track (ZFT) data map of the Western Alps. Note the general trend of older to younger ZFT ages from east to west. The proposed study area is shown as a red square. V = Vercors, C = Chartreuse, B = Belledonne, E-P = Pelvoux, Ch = Chambaran. B) Age scale and colour code of the ZFT ages in A). C) Radial plot of modern river sand ZFT data from the Isère River drainage (data from Bernet, 2013). D) Alpine vegetation zones: foothills (~200-700 m), montane (~700-1500 m), subalpine (1500-2100 m), Alpine (~2100-2800 m), and snow zone (>2800 m).

The primary objective of this pilot study is to evaluate how the erosion dynamics and the transient physiography of the Western Alps driven by tectonic deformation and climatically controlled surface processes have evolved since the middle Miocene. In this respect, we want to trace the long-term exhumation of the external crystalline Belledonne and Ecrins-Pelvoux massifs caused by the erosional removal of the Penninic thrust sheet and the Mesozoic sedimentary cover. Of importance will be to see when did the first crystalline rocks (i.e. granite and gneiss) appear in the fluvial deposits of the paleo-Isere drainage system and the foreland basin, and which cooling/exhumation history they record. The secondary objective is to trace how biodiversity has evolved from pollen assemblages and the paleobotanic record preserved in fine-grain fluvial deposits of the foreland basin remnants, and consequently try to understand how the changes in physiography and geodynamics have impacted biodiversity within the study area of the Western Alps.