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Vivien Mai Yung Sen, Yann Rolland, Pierre G Valla, Stéphane Jaillet, Olivier Bruguier, et al.. Fold-and-Thrust Belt and Early Alpine Relief Recorded by Calcite U–Pb Dating of an Uplifted Paleo-Canyon (Vercors Massif, France). *Terra Nova*, 2024, 10.1111/ter.12761 . hal-04947840

HAL Id: hal-04947840

<https://hal.science/hal-04947840v1>

Submitted on 14 Feb 2025

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RESEARCH ARTICLE OPEN ACCESS

Fold-and-Thrust Belt and Early Alpine Relief Recorded by Calcite U–Pb Dating of an Uplifted Paleo-Canyon (Vercors Massif, France)

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Received: 29 August 2024 | **Revised:** 27 November 2024 | **Accepted:** 29 November 2024

Funding: This work was supported by the Agence Nationale de la Recherche and the Université Grenoble Alpes.

Keywords: Alpine collision and tectonics | relief evolution | river networks | U–Pb calcite dating | Vercors subalpine massif (France)

ABSTRACT

The long-term evolution of orogenic drainage systems is closely related to the propagation of tectonic structures, which gives rise to the topography and hence anisotropies for river incision. This study focuses on the subalpine Vercors Massif (SW French Alps), reconstructing the geometry of an uplifted paleo-canyon and applying calcite U–Pb dating to its carbonate-rocky talus slope deposits. U–Pb ages of the blocky calcite veins range from 58 to 9 Ma, related to multiple tectonic motions along the E–W compressive fault on which the paleo-canyon was dug. U–Pb dating on calcite cement sealing the breccia porosity yields a minimum age of ca. 2 Ma for the paleo-canyon abandonment and rockfall infill. Cementation of the breccia, infilling and uplift since the late Neogene to Pliocene times highlight the reorganisation from radial to longitudinal drainage in relation to frontal Alpine tectonics and surface uplift of the western French Alps.

1 | Introduction

Mountain drainage networks adapt to geodynamic changes and relief building (Robl, Hergarten, and Prasicek 2017). Widening of orogenic prisms through the development of fold-and-thrust belts drives major changes in surface drainage through divide migration and river capture in a competition between transverse and longitudinal drainage systems (Champel et al. 2002; Ma et al. 2022). These geomorphic transient changes can be observed in evolving foreland fold-and-thrust belts (Chen et al. 2023), but evidence of past drainage reorganisations is harder to detect in mature mountainous environments because of surface erosion of the paleo-fluvial archives (Cardinal et al. 2022). Fold-and-thrust belts developed in carbonate-rich layers, such as the subalpine massifs (frontal Western Alps), have been prone to

long-term karstification. Therefore, they have a good potential for long-term preservation of geomorphic archives because of ‘karstic immunity’, that is, the relative preservation of geomorphic markers in karst areas due to groundwater flow that partially reduce surface erosion (Delannoy 1997; Audra et al. 2007). Among these geomorphic markers, carbonate-rocky talus slope deposits are widespread in the European Alps and generally attributed to Quaternary paraglacial dynamics (Sanders, Ostermann, and Kramers 2009), although they may also evidence older topographic changes. Nevertheless, the paucity of data pertaining to the long-term evolution of Alpine mountain geomorphology persists, largely due to the lack of both surface archives and adapted geochronological methods for such contexts. The advent of U–Pb calcite geochronology has been increasingly used to constrain the timescales associated with fault

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dynamics (Parizot et al. 2022; Roberts and Holdsworth 2022; Bilau et al. 2023a, 2023b; Curzi et al. 2024a, 2024b) and sediment diagenesis (Godeau et al. 2018). Furthermore, this technique has now made it possible to decipher topographic relief evolution in connection with fault activity on Neogene to Quaternary timescales (Bilau et al., 2021). Here, we focus on the frontal Alpine fold-and-thrust Vercors Massif (SE France, Figure 1A), with a unique geomorphic marker of a paleo-drainage system: a paleo-canyon located at ~2000 m on the eastern edge of the karstic Vercors Massif (Figure 1B), separating the present-day north-flowing Drac valley (~300 m) from the east-draining Bourne watershed (~1000 m). The latter drains into the Vercors Massif and cuts through the massive Mesozoic Urgonian limestone, which has been tectonically thickened and uplifted during the fold-and-thrust history (Kalifi et al. 2021; Bilau et al. 2023a). Applying U–Pb calcite dating on the paleo-canyon sediment infill, we aim to provide constraints on its abandonment associated with the late Miocene Alpine relief evolution and drainage reorganisation of the western frontal part of the Alps.

2 | Geological Setting

The Vercors fold-and-thrust belt corresponds to the propagation of the SW Alpine collisional belt, which formed during Miocene times (Figure 1; Kalifi et al. 2023; Bilau et al. 2023a and references therein). This foreland belt developed in response to E–W shortening between the European and Apulian plates (Schwartz et al. 2024), and resulted in a series of N–S trending folds and propagating east-dipping thrusts (Figure 1B; Deville 2021), although the timing for associated topographic surface uplift of the Vercors Massif has remained unconstrained. The onset of E–W shortening was accommodated by a westward-propagating thrust activity between 15 and 8 Ma (Bilau et al. 2023a), merging downwards with a crustal transpressive structure exhuming the External Crystalline Massifs (Rolland et al. 2022; Schwartz et al. 2024). This Miocene Alpine thrusting partly reactivated a former E–W compressional belt known as the ‘Pyrenean-Provence’ in SE France (Dielforder et al. 2019; Balansa et al. 2022). Several shortening phases occurred during the construction of the Pyrenean-Provence orogen, in relation to collisional and subduction processes occurring along the Sardinia-Corsica boundary of Eurasia (Lacombe and Jolivet 2005; Jourdon et al. 2014; Balansa et al. 2022; Bilau et al. 2023b). The main ‘Pyrenean-Provence’ deformation phase has been given a variable time span but is usually accepted as having occurred between the Late Cretaceous and the early late Eocene (i.e., pre-Priabonian; Caby 1973; Siddans 1979; Ford 1996; Jourdon et al. 2014; Balansa et al. 2022). However, it still lacks direct dating in the SW Alpine foreland. Recent U–Pb dating of compressional N–S deformations highlighted a Cretaceous event at 97–90 Ma (Bilau et al. 2023b), which are shown as overprinted by an Upper Cretaceous unconformity (Flandrin 1966). These structures were largely overprinted by the classical Eocene ‘Pyrenean-Provence’ faulting event largely evidenced by cross-cutting relationships of Cenozoic detrital basins (Ford and Stahel 1995). However, the age of N–S shortening is unknown in the subalpine massifs of the Western Alpine fold-and-thrust belt.

The studied ‘Vallon de l’Ours’ paleo-canyon lies on the eastern side of the Vercors Massif (Figure 1A). In a N–S cross-section

(Figure 1D), the paleo-canyon occurs along an E–W striking thrust and anticline structure formed during a N–S contractional phase (yellow star in Figure 1A–D). In WNW–ESE cross section (Figure 1B), it lies in the hanging-wall of a top-to-the-west thrust (the Moucherotte Thrust; Bilau et al. 2023a). This paleo-canyon was thus dug in a zone of combined previous top-to-the-north thrust faulting (i.e., classically referred the ‘Pyrenean-Provence’ phase) reactivated during the ‘Alpine’ (< 15 Ma) fold-and-thrust deformation, but the age of the N–S shortening remains unconstrained (Bilau et al. 2023a). Furthermore, this paleo-canyon, preserved within an Urgonian limestone bar, can be considered as a landform archive for the onset of topographic relief during the early fold-and-thrust belt structuration after 15 Ma, also constraining subsequent topographic surface uplift of the Vercors Massif (i.e., paleo-canyon abandonment). It also provides the opportunity to trace the timing of former tectonic events recorded in calcite veins cross-cutting the limestone blocks that infill the paleo-canyon.

3 | Results

3.1 | 3D Model and Infill of the Paleo-Canyon

A 3D photogrammetric model acquisition from aerial photographs allows reconstructing the geometry of the paleo-canyon, perched on the summit crest of eastern Vercors (Figure 2 and Suppl. Mat. 1–2). The Urgonian limestone is massive, with multi-metric beds dipping eastward (from 20° to about 45°). The southern flank of the canyon has a vertical E–W fracturation fabric that is aligned with the canyon (Figure 2). It shows a steeply incised morphology, with high slopes (> 70° on the northern and 90° on the southern flank). It is filled by an unsorted clast-supported conglomerate breccia with Urgonian limestone clasts of various sizes (cm–m large, Figure 2) and speleothem fragments. A rough bedding of the paleo-canyon is measured at N0°E–30°W. The preservation of the canyon is explained by the massive Urgonian limestone lithology, which makes up the N–S crest and paleo-canyon walls. Also, the carbonated and indurated matrix cement allowed the preservation of the breccia clasts despite erosion on the crest edge. We targeted both calcite veins in carbonate clasts to provide a maximum abandonment age for the paleo-canyon, as well as to record the regional tectonic history, and the breccia cement to estimate a minimum abandonment age. A total of nine calcite samples were analysed for in situ LA-ICP-MS U–Pb dating.

3.2 | Petrography of the Paleo-Canyon Breccia

The analysed thick sections of the paleo-canyon breccia are composed of Urgonian limestone clasts, calcite clasts, a reddish matrix, calcite veins mainly cross-cutting the clasts, blocky calcite cement and voids (Figure 3). The Urgonian clasts are angular and cut by numerous veins filled by blocky calcite (sample OUR23, Figure 3B,C). Some clasts are solely composed of blocky calcite (sample OUR23-3, Figure 3B), which can be attributed to reworked calcite vein clasts. Some rare calcite veins cut across the whole thick section (Figure 3A). The boundary between the matrix and the cemented porosity is smooth, and the calcite grains show a centripetal growth with some layering with the

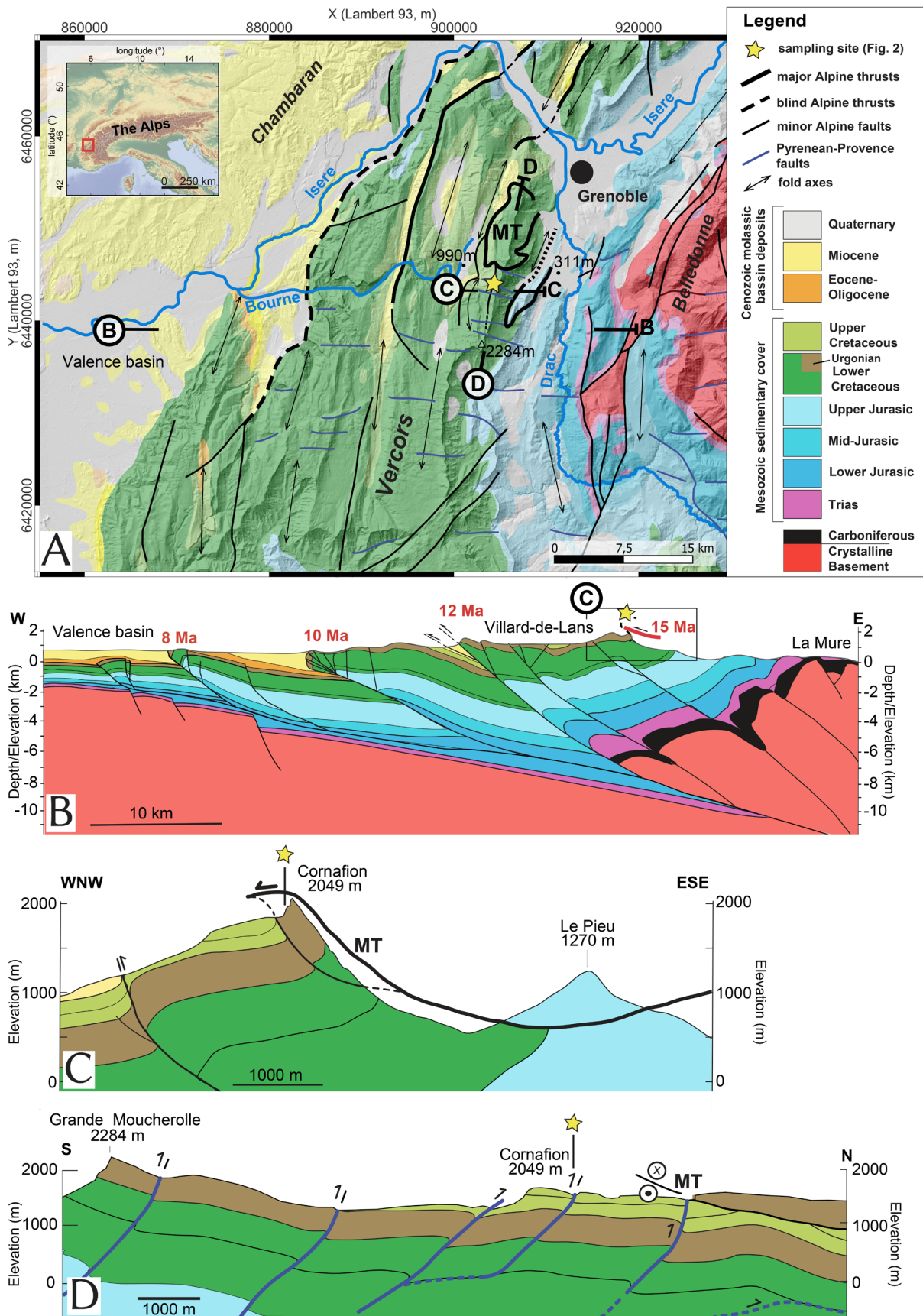


FIGURE 1 | Legend on next page.

FIGURE 1 | Geological setting of Vercors Massif in the Western Alps. (A) Geological map of the SW Alpine foreland (after Bilau et al. 2023a), with E-W (B and C) and N-S geological cross-sections (D) of the Vercors Massif (after Bilau et al. 2023a). Bold red numbers on panel B indicate the timing of thrust activity, dated by U–Pb on calcite between 15 and 8 Ma (Bilau et al. 2023a). Upper-left inset shows the location of panel A in the European Alps. The location of the study area, the paleo-canyon ‘Vallon de l’Ours’, is highlighted by the yellow star in the map and cross-sections (Bourne and Drac rivers are also indicated in blue). Note that the Vallon de l’Ours lies in the footwall of the Moucherotte thrust (MT) resulting from the 15-Ma E-W Alpine shortening phase, as featured on the E-W section (C). On the N-S section (D), the canyon is shown to merge in a top-to-the-north thrust and ramp anticline structure developed during previous N-S compression of unknown age. This N-S compression results in a ~1.5 km uplift of the southern Vercors Massif with respect to its northern part. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

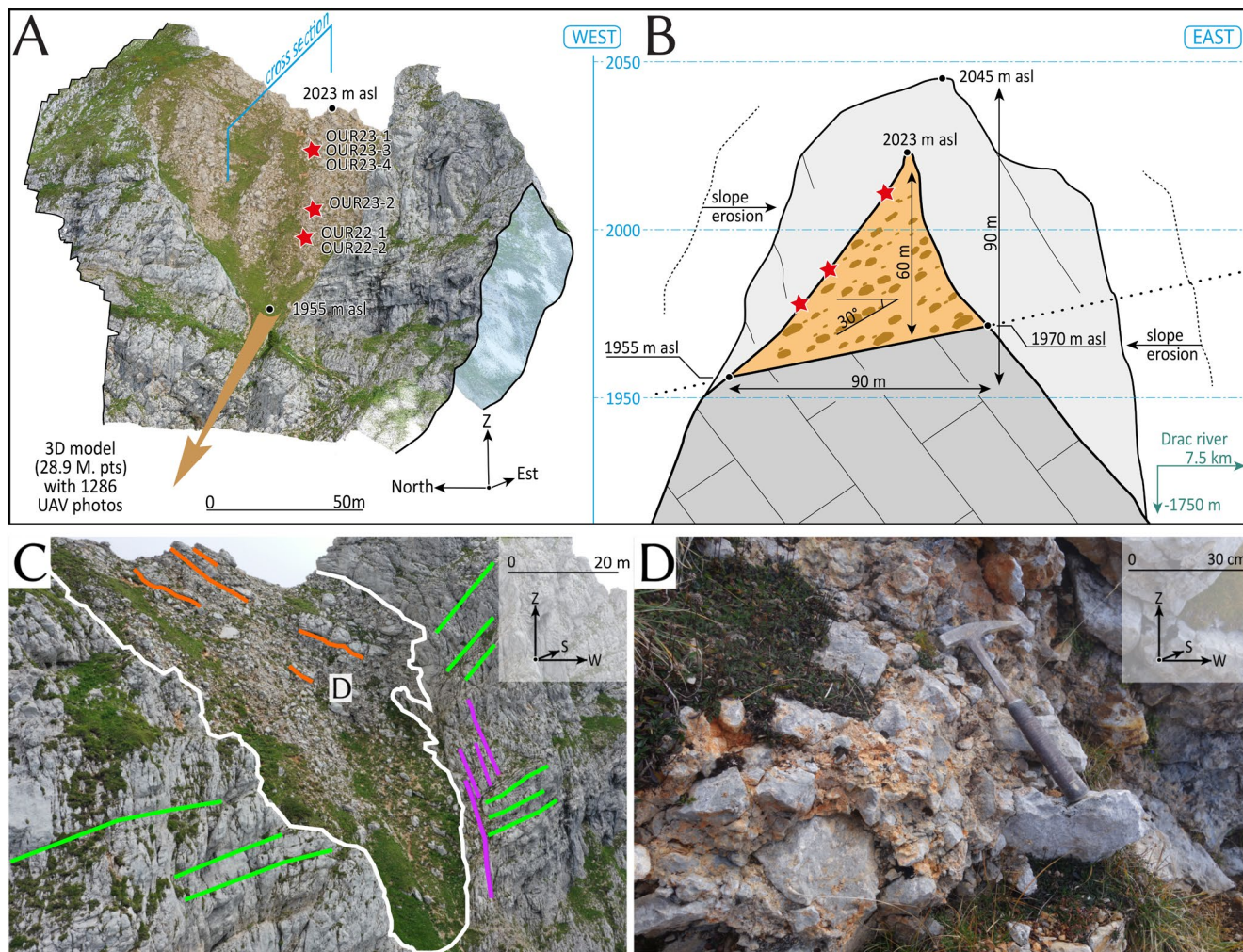


FIGURE 2 | Paleo-canyon geometry and sedimentary filling. (A) 3D frontal view of the paleo-canyon and its rocky-block sediment filling (light brown) from the meshed 3D model. The brown arrow represents the westward paleo-flow direction (see Supp. Mat. for details). The steep V-shape of the paleo-canyon is visible at the contact between the Urganian limestone (pale blue on the right) and the breccia fill (i.e., carbonate-rocky talus slope, light brown). Red stars show sample locations and names. The blue line defines the longitudinal cross-section shown in panel B. (B) East–west longitudinal cross-section of the paleo-canyon. Only 90m of the paleo-profile are preserved (northern flank of the paleo-canyon indicated as pale grey in background), showing the significant retreat of the Urganian bedrock ridge (slope erosion indicated by black arrows). The breccia fill is maximum 60-m high and shows N0°E-30°W west-dipping bedding surfaces. The location of the Drac valley to the east is indicated. (C) Drone view of the paleo-canyon. White line: Contact between the Urganian limestone and the breccia fill. Green lines: Urganian limestone bedding surfaces. Purple lines: Fracture surfaces in the Urganian limestone, parallel to the paleo-canyon longitudinal profile. Orange lines: Stratigraphic planes in the breccia fill (30° west-dipping, panel B). (D) Close view of the breccia fill (location in panel C) showing the unsorted angular Urganian clasts embedded in the reddish indurated matrix. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

matrix (Figure 3D). The calcite cement does not entirely fill the porosity, leaving rounded voids within the porosity (Figure 3D). Cathodoluminescence observations show that the Urganian clasts are luminescent whereas the matrix and the porosity are dull

(Suppl. Mat. 3). In the following, we report U–Pb ages obtained on the calcite veins, related to pre-canyon tectonic events, and on the blocky matrix porosity fill post-dating the abandonment and sediment filling of the canyon.

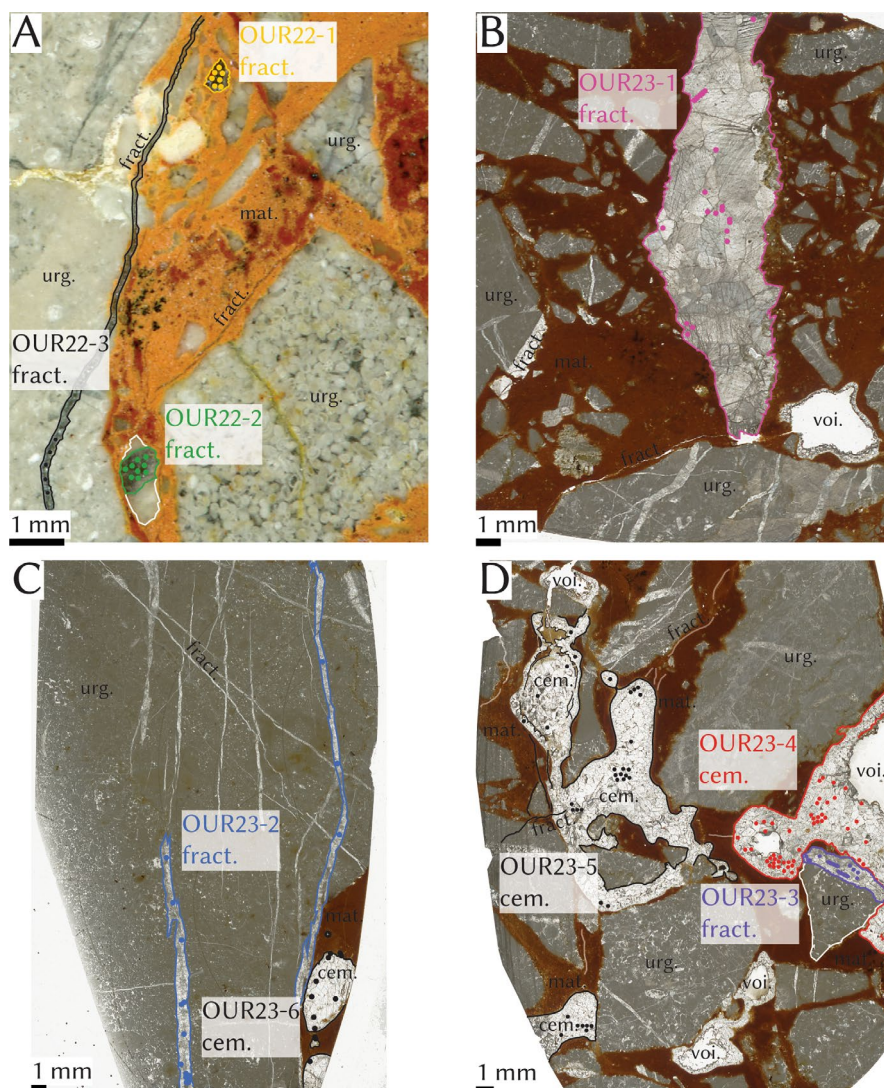


FIGURE 3 | Thick-section microscopy pictures of the paleo-canyon clasts and matrix (see Figure 2A for sample locations). The four thick sections (A, B, C and D) are composed of fractured Urganian clasts (urg.) and calcite veins (fract.) in a reddish carbonated matrix (mat.). The porosity of the matrix is partially sealed by calcite (cem.) with some remaining voids (voi.). Coloured dots indicate laser spots (size: 140 μm) for U–Pb analysis (Figures 5–6). Black dots are laser spots for U–Pb analysis which did not provide a consistent age (see Supp. Mat. 6). Each sample is associated with a specific colour, common to Figures 4 and 5. The apparent colour of the matrix in Figure 3A appears to be different from that in Figure 3B–D due to different light exposure parameters, but the matrix in all samples is similar in colour and texture. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/terms-and-conditions)]

3.3 | U–Pb Dating on Calcite Veins and Cement

Analytical details and results for calcite U–Pb dating can be found in the Supporting Information 4 and 5. On a total of nine analysed calcite sub-samples (Figure 3), six sub-samples have sufficient $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{238}\text{U}/^{206}\text{Pb}$ dispersions to compute consistent U–Pb ages with statistically acceptable errors (Figure 4). The U concentrations are significantly higher for the calcite veins in the Urganian clasts (mean [U] of 0.34–5.79 ppm) than for the calcite cement (mean [U] of 0.17 ppm). Five consistent U–Pb ages are obtained from calcite veins in Urganian clasts, ranging from 58.4 ± 1.5 Ma to 8.7 ± 3.4 Ma, and one U–Pb age of 3.2 ± 1.5 Ma for the calcite cement within the porosity.

4 | Discussion

4.1 | Paleo-Canyon History

The overall narrow shape of the paleo-canyon, with high and subvertical flanks and a steep westward profile, is consistent with the geometry of a rapidly incising river canyon (Schaller et al. 2005; Cardinal et al. 2021), suggesting that the initial canyon morphology was well preserved since its abandonment. The paleo-canyon was formed along a vertical E–W fault corridor (Figures 1–2). This E–W anisotropy led to subsequent incision perpendicular to the N–S axis of the subalpine Vercors Massif once the early topographic relief was set up along the fold-and-thrust belt. In addition, the flow axis is aligned with the

present-day Bourne river downstream (Figure 1A), suggesting that the modern Bourne river-flow direction is possibly inherited from an earlier incision along the E-W ‘Vallon de l’Ours’ Pyrenean-Provence fault. The presence of speleothem clasts in the breccia fill suggests that the paleo-canyon drained also underground karst water. By linearly extending the paleo-thalweg profile upstream, we propose a maximum upstream length of 1–4 km, corresponding to a paleo-watershed head with an eastern interfluvium a few kilometres to the east. This paleo-canyon and reconstructed catchment imply the presence of a topographic relief above the base level to promote incision. The reconstructed height of the paleo-canyon is about 100 m (Figure 2B), but the total canyon incision may have been several hundreds of metres or higher given that only remnants of the paleo-canyon flanks and of the breccia fill have been preserved from subsequent slope erosion.

Field and petrological observations show that the paleo-canyon filling was controlled by local rockfalls. The Urganian clasts originated from the steep flanks and fall in the paleo-thalweg with a 30° equilibrium proximal slope of the breccia talus (Figure 2; Sanders, Ostermann, and Kramers 2009). Neither alluvial nor allochthonous deposits were found in the paleo-canyon fill, suggesting rapid abandonment of the paleo-canyon. Such an abandonment can be explained by a drainage-network change in the upstream watershed, either by surface river or underground capture. The secondary porosity filling, highlighted by crystallisation of calcite cement with blocky texture, is incomplete, with residual voids within the breccia (Figure 3D). Furthermore, this cementation was likely progressive, as calcite cement layers are sometimes interbedded with matrix-rich calcite layers (Figure 3D), suggesting that the late-stage cementation was achieved by gradual flow percolation of meteoric water through the permeable breccia fill. Although the largest calcite veins cut only the Urganian clasts and are related to tectonic events predating the canyon filling, some calcite veins cut both the Urganian clasts and the matrix (Figure 3A), and sometimes, the calcite cement (Figure 3D), suggesting that some slight post-deposition deformation and fracturation may have affected the breccia elements, either by tectonic deformation or gravitational decompression.

4.2 | Tectonic Significance of New Calcite U–Pb Ages

We obtained 5 U–Pb ages from calcite veins cutting Urganian clasts, predating the paleo-canyon abandonment and ranging from 58.4 ± 1.5 Ma to 8.7 ± 3.4 Ma (Figures 4–5). These correspond to different tectonic phases identified in the W-Alps, that we suggest have imprinted in the ‘Vallon de l’Ours’ E–W striking fault. As highlighted in cross-sections (Figure 1), the paleo-canyon incised within an E–W fault corresponding to a former top-to-the-North thrust, which allowed the differential uplift of the southern part of the Vercors Massif (Figure 1D). The obtained ages cannot be directly linked to individual faults but represent tectonic events along the E–W corridor, as the paleo-canyon infill is composed of monogenic Urganian blocks originating from the canyon walls. Further work will be necessary to relate the obtained ages with Alpine fault kinematics. Sample OUR22-2 age (58.4 ± 1.5 Ma) may correspond to the onset of

the Pyrenean-Provence deformation, proposed from the Late Cretaceous to the Palaeocene (Dielforder et al. 2019). Sample OUR23-1 age (41.6 ± 0.4 Ma) marks the early N–S Alpine deformation phase documented along the eastern boundary of the Pelvoux Massif (Dumont et al. 2012; Lanari et al. 2014). The similar U–Pb ages at ~ 16.5 Ma (OUR23-2 and OUR23-3, Figure 4) indicate the onset of the fold-and-thrust belt deformation in the eastern Vercors Massif, related to the activation of the Moucherotte Thrust (M.T. in Figure 1, recorded at ~ 15 Ma; Bilau et al. 2023a). Despite larger uncertainties, the OUR22-1 age (8.7 ± 3.4 Ma) can be correlated to the end of the fold-and-thrust belt development, with the out-of-sequence reactivation of the Moucherotte thrust at ca. 9 Ma (Bilau et al. 2023a), in relation to the activation of the westernmost Vercors frontal thrust (Figure 1A).

4.3 | Chronology of the Paleo-Canyon Evolution

The ‘Vallon de l’Ours’ paleo-canyon abandonment and filling time should have occurred between around 9 and 2 Ma, bracketed by the U–Pb ages of (1) the youngest Urganian clast vein (OUR22-1: 8.1 ± 3.4 Ma), and (2) the breccia porosity (OUR23-4, 3.2 ± 1.5 Ma). Urganian fracture-filling calcite veins do not necessarily predate the incision phase but can be contemporaneous with the widespread E–W strike-slip tectonics and brittle deformation of the Urganian limestone, leading to fracture calcite crystallisation. Based on our new and literature constraints, the thrust activations are estimated at: 16.5–15.5 Ma for the Moucherotte thrust (Eastern Vercors Massif), around 12 Ma for median Vercors thrusts, and finally around 10–8 Ma for the frontal thrusts, in conjunction with the reactivation of the Moucherotte thrust (Bilau et al. 2023a). By ca. 15 Ma, the marine molasse sedimentation had already shifted to the western frontal Vercors, with the median and eastern parts of the massif already above sea level (Kalifi et al. 2023). Thus, the topographic relief was created in relation to shortening tectonics between 15 and 8 Ma, allowing river incision. The incision of the paleo-canyon should have initiated at this time, driven by tectonic uplift and relief development. The subsequent abandonment and breccia filling of the paleo-canyon occurred in the 9–2 Ma timespan, according to our U–Pb dating. This resulted from a major reorganisation of frontal Alpine rivers during the upper Miocene, in agreement with observations in the Devoluy massif southwards (after 11.5 ± 1 Ma; Lemot et al. 2023). This regional drainage reorganisation followed the tectonic uplift of the sub-alpine massifs, changing from an overall radial drainage pattern, compatible with the E–W paleo-canyon paleo-flow, to the formation of a longitudinal drainage divide so-called the ‘Sillon alpin’, between the External Crystalline Massifs and the sub-alpine Massifs (Figure 1A; Lemot et al. 2023). We propose that the late-Neogene abandonment of the ‘Vallon de l’Ours’ paleo-canyon is linked to the incision and enlargement of this N–S axis drainage divide, which lead to the progressive westward capture of the paleo-watershed at the eastern edge of the Vercors Massif.

5 | Conclusions

We assessed the local tectonic and geomorphic histories from an uplifted paleo-canyon in the Vercors Massif. U–Pb ages of calcite veins from Urganian clasts are representative of the multiphase

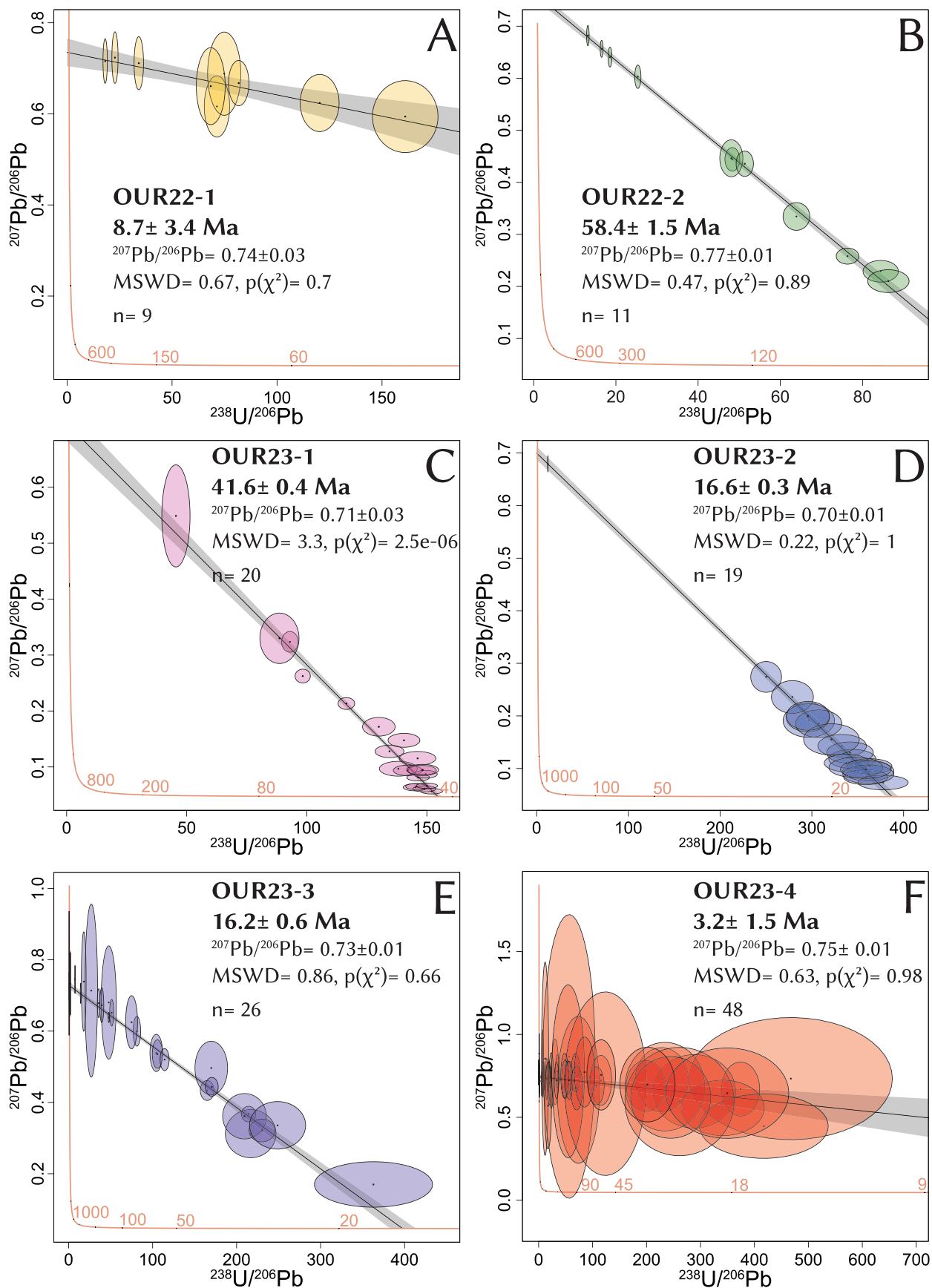


FIGURE 4 | Tera-Wasserburg plots of the pale-canyon samples with calcite U–Pb data (A, B, C, D, E and F). The ellipses represent the 2σ internal errors on individual spot measurements. U–Pb ages and statistics were computed using IsoplotR (Vermeesch 2018). Each sample is associated with a specific colour, common to Figures 3 and 5 (See Supporting Information 5 for details). [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

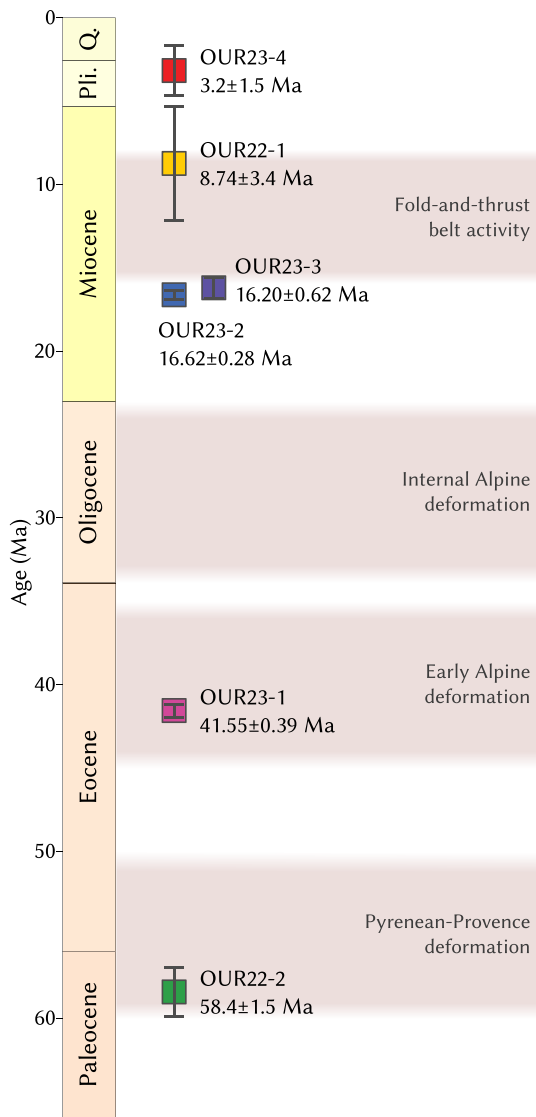


FIGURE 5 | Temporal framework with newly obtained U–Pb ages together with the main geodynamic periods synthesised from the literature for the study area (Dumont et al. 2012; Bilau et al. 2023a, 2023b). Reported uncertainties on U–Pb ages are 2σ errors. Each sample is associated with a specific colour, common to Figures 3 and 4. See text for discussion. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

tectonic evolution of the western Alps, from around 58 to 9 Ma, revealing that the E–W fault corridor hosting the paleo-canyon underwent several tectonic reactivations during the major Pyrenean-Provence (Early Cenozoic) and Alpine (< 16 Ma) deformation phases. U–Pb dating on calcite cement sealing the breccia porosity suggests a paleo-canyon abandonment and rockfall infill during the Late Neogene (9–2 Ma), showing that such breccia deposits can be preserved over long term in karstic mountains. Finally, our results allow for the first time to pinpoint the transition from a radial to a longitudinal drainage in the frontal western Alps.

Acknowledgements

This work was supported by the LabEx OSUG-2022 (Univ. Grenoble Alps) and the ANR-PIA Program (ANR-18-MPGA-0006). The authors thank J.J. Delannoy and P. Audra who did pioneer field investigations

in the karstic Vercors Massif, and J.L. Chabod who first described the paleo-canyon. We also thank C. Honiat for discussions in the field, and P. Nuriel for cathodoluminescence access (Univ. Geneva). We thank the associate editor and two anonymous reviewers for constructive reviews and suggestions.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data will be made available upon request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.