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RESEARCH ARTICLE

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Early onset of Pyrenean collision (97–90 Ma) evidenced by U–Pb dating on calcite (Provence, SE France)

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Abstract

Early Late Cretaceous uplift of Provence gave rise to the Durance Isthmus. In the present study, U–Pb dating on calcite of compressional structures related to Pyrenean foreland compressional deformation in Provence shows that N-S shortening occurred coeval with emersion of the Durance Isthmus, through the development of combined top-to-the-North to NW thrusts between 97 and 90 Ma. This large-scale event, recorded from the Pyrenees to the Middle-East regions is interpreted as a far-field internal plate precursor of the Africa-Europe plates reorganization. Furthermore, the change in tectonic style and amount of shortening between Provence and Pyrenees was accommodated by sinistral reactivation of the NE–SW Cevennes and Nimes faults, acting as transform boundaries in this incipient collisional context.

KEYWORDS

Provence (SE France), Pyrenean Collision, U–Pb Calcite

1 | INTRODUCTION

In recent years, U–Pb geochronology on calcite has been increasingly used to constrain time scales associated with the dynamics of fault development (e.g., Bilau et al., 2021, 2023; Parizot et al., 2021; Roberts & Holdsworth, 2022). Such an approach provides key temporal insights in complement to the traditional approach of brittle systems, in which timing of deformation stages is only bracketed by relative stratigraphic cross-cutting relationships and thus generally suffers from large uncertainties. In this paper, we focus on the Provence region (SE France), where unravelling the successive deformation stages remains challenging due to the superimposition of several deformation stages, and reactivation of fault systems, during the Pyrenean and Alpine orogenic events. This region suffered widespread, low amplitude, large-scale deformations during Cenomanian–Turonian times and these were combined to the so-called 'Durance Isthmus'. This event, caused the Cretaceous carbonate platform to be exposed to aerial erosion and lead to the formation of bauxite (e.g., Combes, 1990; Guyonnet-Benaize et al., 2010). Based on AFT and stratigraphic cross-cutting relationships, the uplift of the Massif Central on the western side of the Cevennes Fault is attributed to the Albian-Aptian (Barbarand et al., 2001; Pagel et al., 1997; Peyaud et al., 2005). Recent studies on the eastern (Provence) side of the Cevennes Fault present younger ages (ranging between 97 and 90 Ma) based on U–Pb geochronology on calcite (Corrêa et al., 2022; Godeau et al., 2018). However, the tectonic context in which the Durance uplift occurred is still puzzling as most authors link this uplift to thermal doming during the development of rifting, like in the Pyrenean domain (e.g., Chorowlcz and Mekarnia, 1992; Balansa et al., 2022), while this event is also recognized as a compressional phase featured by the development of E-W folds throughout the Provence region (e.g., Caby, 1973; Guieu & Roussel, 1990). Later on, the region underwent repeated deformation events during further compressional phases of the Pyrenean and Alpine orogens, which complicated the structural pattern. In this paper, we focus on two areas of Provence/SW Alps to show that the application the U–Pb geochronology on calcite can be used to provide robust information on the early stages of a complex deformation history. These data are further used to discuss the tectonic context.

2 | GEOLOGICAL SETTING

The Provence fold-and-thrust belt is considered as the eastern limit of the Pyrenean orogenic system in southeastern France, between the Alps to the northeast, and the Ligurian Basin passive margin to the south (Figure 1; Dielforder et al., 2019).

Classically, the main phase of shortening in the Provence domain is named the Pyrenean-Provence compression and is attributed to the Campanian-Eocene period in relation to collisional and subduction processes occurring along the Sardinia-Corsica boundary of Eurasia (Figure 1; e.g., Balansa et al., 2022; Lacombe & Jolivet, 2005). However, the understanding of the successive deformation phases that occurred in the Provence domain is difficult due to superimposition with the same nearly E-W orientation of the Pyrenean and the Alpine shortening from the Turonian to early Oligocene and reactivations during Miocene times (Champion et al., 2000; Ford & Stahel, 1995). Based on stratigraphic constraints, two folding phases have been recognized in SE France: (1) The Pre-Senonian (Turonian) folding phase (also known as the Eoalpine) is best defined in the Dévoluy region (Flandrin, 1966; Michard et al., 2010) and (2) a second phase, known as the 'Pyrenean-Provençal' 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: e.g., Caby, 1973; Debrand-Passard et al., 1984; Siddans, 1979; Ford, 1996; Espurt et al., 2019; Balansa et al., 2022). N-S compression gave rise to E-W folds developed in SE France (Caby, 1973; Lemoine, 1972), and the distribution, age, and origin of these folds are still poorly understood. Some authors also attribute these folds and growth strata to Jurassic halokinetics (Célini et al., 2020; Michard et al., 2010; Wicker & Ford, 2021). In some areas, such as Baronnies-Diois, these folds record significant shortening mostly attributed to a main Eocene–Oligocene shortening event (>15 km, Gratier et al., 1989; Ford & Stahel, 1995).

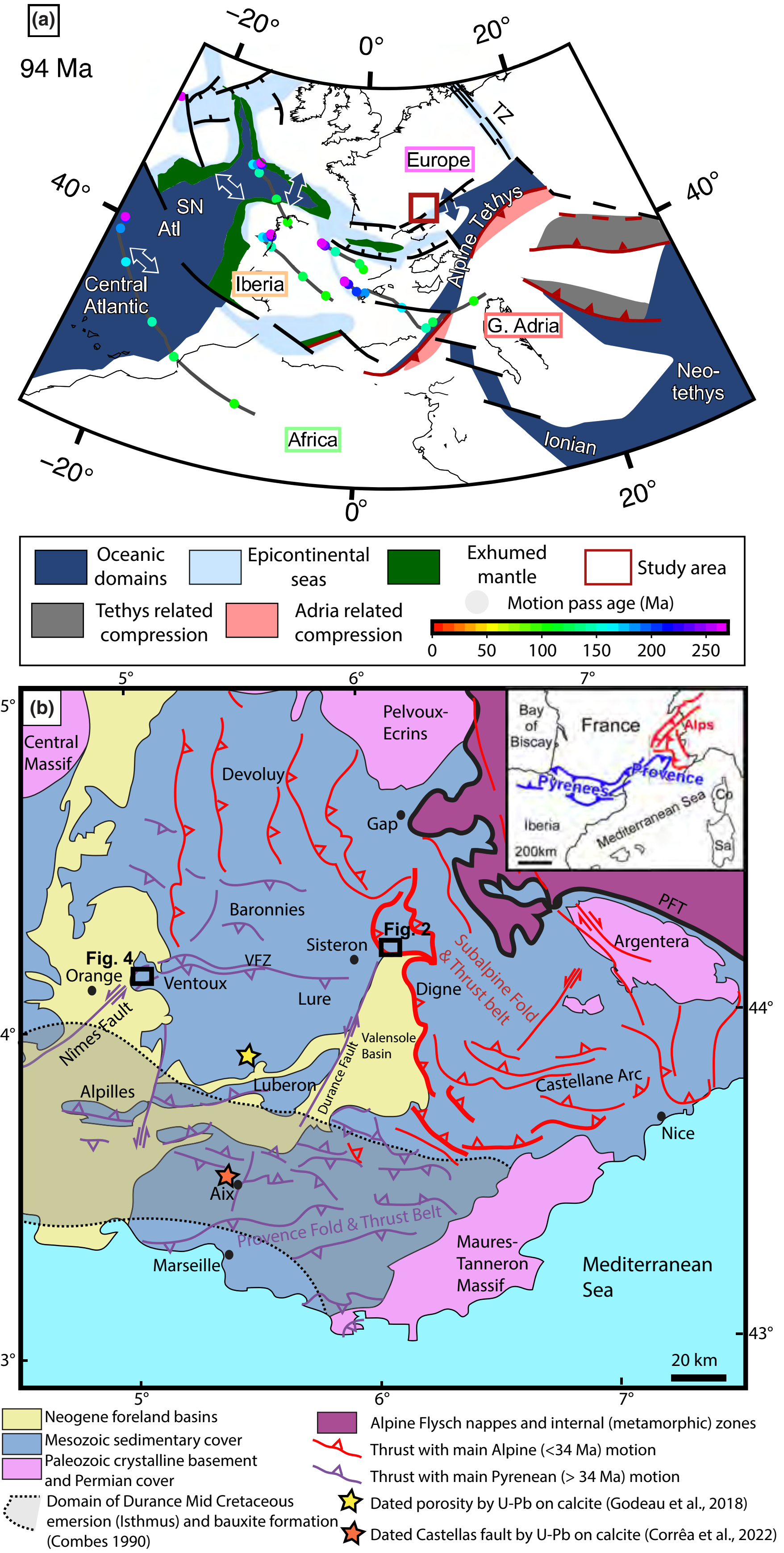
However, despite a similar suggested timing of compression, the tectonic context of the Pyrenees and of the Provence domains are distinct:

- In the Pyrenees, ongoing extension led to high-temperature (HT) metamorphism related to mantle exhumation between ~110 and 90 Ma (Clerc et al., 2015). Shortening started in Late Cretaceous and remained until Miocene times as a result of the collision between Eurasia and Iberia (e.g., Desegaulx et al., 1990).
- In Provence, rifting is bracketed in a similar Albian–Aptian time interval as in the Pyrenees by extensional fault activity (Montenat et al., 2004). However, extension was more limited, and no evidence of crystalline basement or mantle exhumation, nor HT metamorphism have been found. In addition, onset of shortening remains debated, due to superimposed stages deformations showing less amplitude than in the Pyrenees and to the absence of absolute age constraints for brittle deformation. N-S Compression is suggested since the Turonian (94–90 Ma, e.g., Masse & Philip, 1976) but is more widely evidenced since the Campanian (80 Ma, e.g., Espurt et al., 2019; Wicker & Ford, 2021; Balansa et al., 2022). Further, N-S Pyrenean compression continued until the Late Eocene. Afterwards, the opening of the West European rift was followed by the NE trending back-arc rifting of the Ligurian basin, which occurred during the Oligocene–Miocene period (e.g., Romagny et al., 2020) and Miocene E-W compression (e.g., Bilau et al., 2023). These latter tectonic events led to superimposed N-S and E-W cross-cutting extensional faults partly reactivated in compression during the Alpine orogeny since about 20 Ma (Balansa et al., 2022; Hemelsdaël et al., 2021), which makes the tectonic restauration challenging. Eurasia–Adria collision and growth of the Alps were responsible for renewed Neogene to present-day shortening and deformation mainly in western (Champion et al., 2000) and eastern (Jourdon et al., 2014) Provence. The superimposition of these late tectonic phases strongly modified the overall geometry of the Provence Chain and makes it difficult to unravel its

STATEMENT OF SIGNIFICANCE

This study shows how the application of the U–Pb dating system on calcite allows deciphering complex tectonic histories in which fault systems were affected by multiple phases of reactivations, burial etc. We show that the calcite U–Pb system has retained the memory of an early Late Cretaceous (97–90 Ma) compressional event on eastern and western sides of the Provence region, which could be related to the formation of the Durance high or Isthmus. This paper brings new insights supporting orogenic uplift in a time interval in which either convergence or rift-related processes can be involved. We provide structural evidence to interpret the most significant exhumation phase as a result of compressional deformation and not only extension as is generally proposed in the recent literature. This event, featured by NE–SW to E-W fold development and top-to-the-North or NW thrusting is interpreted as a diffuse internal plate deformation, which occurred at onset of Eurasia-Africa convergence with interplay of Iberia microplate. It is suggested that this distributed internal plate deformation event corresponded to a rearrangement of stress during plate kinematic inversion, just before a subduction zone was activated along the southern Neotethys region.

FIGURE 1 (a) Paleogeographic map during Cenomanian (94 Ma) (Angrand & Mouthereau, 2021). The location of the study area is highlighted by the red box. (b) Sketch geological map of SE France showing the repartition of Pyrenean and Alpine thrusts in the Provence–SW Alps domain and the Cretaceous Durance Isthmus (uplift) in grayscale, adapted from Balansa et al. (2022). Boxed areas correspond to Figures 2 and 4. PFT, penninic frontal thrust; VFZ, ventoux-lure fault. The Star indicates where U–Pb on calcite dating was applied to limestone porosity by Godeau et al. (2018) and to calcite cementation related to Castellas fault activity (Corrêa et al., 2022).



complete geological history (Balansa et al., 2022). Additionally, halokinetic processes are thought to have had a significant influence on the structural evolution of Provence (Célini et al., 2020).

This study is focused in two areas: the western Provence domain (Dentelles) and the western termination of the Alpine domain (at the transition with the eastern Provence domain at Authon, Figure 1), in which compressional deformation is classically interpreted as mostly Cenozoic in age. Here, we use U–Pb geochronology on calcite to provide absolute time constraints on the oldest compressional deformation phase.

3 | RESULTS

3.1 | "Authon" study site

The studied structure lies in the hanging-wall of the Valavoire thrust, which in turn developed in the footwall of the main Digne nappe in Eastern Provence (Gidon, 1997; Célini et al., 2020; Figures 1 and 2). This nappe is detached along Triassic evaporites, and is thought to reactivate diapiric structures that developed during Jurassic extensional tectonics (Célini et al., 2020).

Field relationships highlight a south-dipping (~40°) top-to-the-North ϕ1 thrust that has been crosscut by the ϕ2 Digne–Valavoire thrust, which corresponds to the main thrust transporting the so-called Digne Nappe. The ϕ1 thrust footwall is affected by a South-dipping schistosity consistent with top-to-the-North kinematics (~E-W trending S0/S1 intersection; Figure 2g,i). The thrust contact and secondary faults connecting to it (corresponding to the thrust 'Damage Zone') are characterized by cataclasites exhibiting mm-to m-scale blocks in a calcite matrix (Figure 2e). Thin-section features and ages are shown in Figure 3. Details off the U–Pb on calcite dating method are provided in Supporting information S1 and U–Pb analyses are available in Supporting information S2. Cataclasite calcite filling is composed of centimetre size "dusty" calcite with highly marked twins (Figure 3a and Supporting information S3). In cathodoluminescence, this calcite is fairly luminescent and homogeneous but is highlighted by shining "nuggets" inclusions (e.g., Seydoux-Guillaume et al., 2012). The U–Pb spots were placed on two zones of the same calcite crystal. U–Pb dates on calcite from the fault cataclasite gave an age of 95.2 ± 3.1 Ma. The significance of the high MSWD value (6.5) is discussed in Supporting information S3 in sight of elemental mapping, microscopic and cathodoluminescence images.

3.2 | "Dentelles de Montmirail" study site

The "Dentelles" site belongs to a fold belt located at the western end of Provence region, close to the connection between the Nimes Fault and the Ventoux–Lure range (Figures 1 and 4). The Pyrenean–Provence tectonic phase and the activity of diapirs has been studied by several authors (e.g., Casagrande et al., 1989; Emre & Truc, 1978; Lapparent, 1940). These studies show that the main diapiric activity took place between the Eocene and the Pliocene, and that the evaporites reached the surface during or soon before Oligocene. The Suzette diapir crosscuts a pristine fold and trust structure formed during the Mesozoic (likely in the Lower to Late Cretaceous; Brasseur, 1962), and it is overprinted by the late Alpine Miocene folding.

The sub-horizontal N60°E folds are cross-cut by metre-large NW-SE vertical veins filled with coarse cm-large calcite fibres (Figure 4e). Veins orientations are consistent with a N-S to NW-SE shortening, and with the development of the N60°E fold. U–Pb dating undertaken on calcite from the NNW–SSE vertical veins cross-cutting the ENE-WSW folds returns an age of 90.6 ± 6.5 Ma (MSWD: 2.0, Figure 5). In this sample, calcite fibres are observed testifying of a crystallization rate higher than the fracture opening rate and interpreted as the limit between crack-seal-slip and crack-seal textures by Roberts and Holdsworth (2022). This petrological observation suggests that cementation occurred soon after fracturing, included in the uncertainty of the U–Pb age (e.g., Bilau et al., 2023; Corrêa et al., 2022). The dated calcite corresponds to a late stage of the vein opening (Figure 5c) still compatible with the main fibres orientation. Thus, this age is interpreted as the age of calcite crystallization in relationship to vein opening, and is considered as a minimum age for the NE–SW folding.

In summary, we obtained U–Pb dates on calcite veins and cataclasite cement associated to tectonic structures related to a N-S to NW-SE shortening phase. The obtained ages between 97 and 90 Ma may be interpreted as the earliest "Pyrenean" shortening stage occurring along two inherited fault trends on both sides of the Provence region. A top-to-the-North thrust preserved in the hanging-wall of the Valavoire and Digne thrust-sheets yields an age of 95.2 ± 3.1 Ma, while in Dentelles area, NNW–SSE vertical veins associated with ENE-WSW folds yields an age of 90.6 ± 6.5 Ma. In both areas, it is suggested that the thrusts are rooted in Triassic evaporites (Célini et al., 2020; Roure & Howell, 2022) and both developed in a top-to-the-North kinematic context with the influence of the inherited Durance and Nimes fault trends. It is thus likely that compressive deformation nucleated in weak zones corresponding to the diapiric structures (Figure 6), although the final emplacement of the diapirs is more probably Oligocene.

4 | TIME CONSTRAINTS FOR EARLY PYRENEAN COMPRESSION IN RELATION TO AFRICA–EUROPE CONVERGENCE INITIATION

Paleomagnetic constraints show that plate convergence between Africa, Iberia, and Europe began in the Late Cretaceous at the end of the Santonian (86–84 Ma; Figure 6; e.g., Rosenbaum et al., 2002; Macchiavelli et al., 2017), with a convergence motion of 6 mm year^{-1} throughout the Late Cretaceous period.

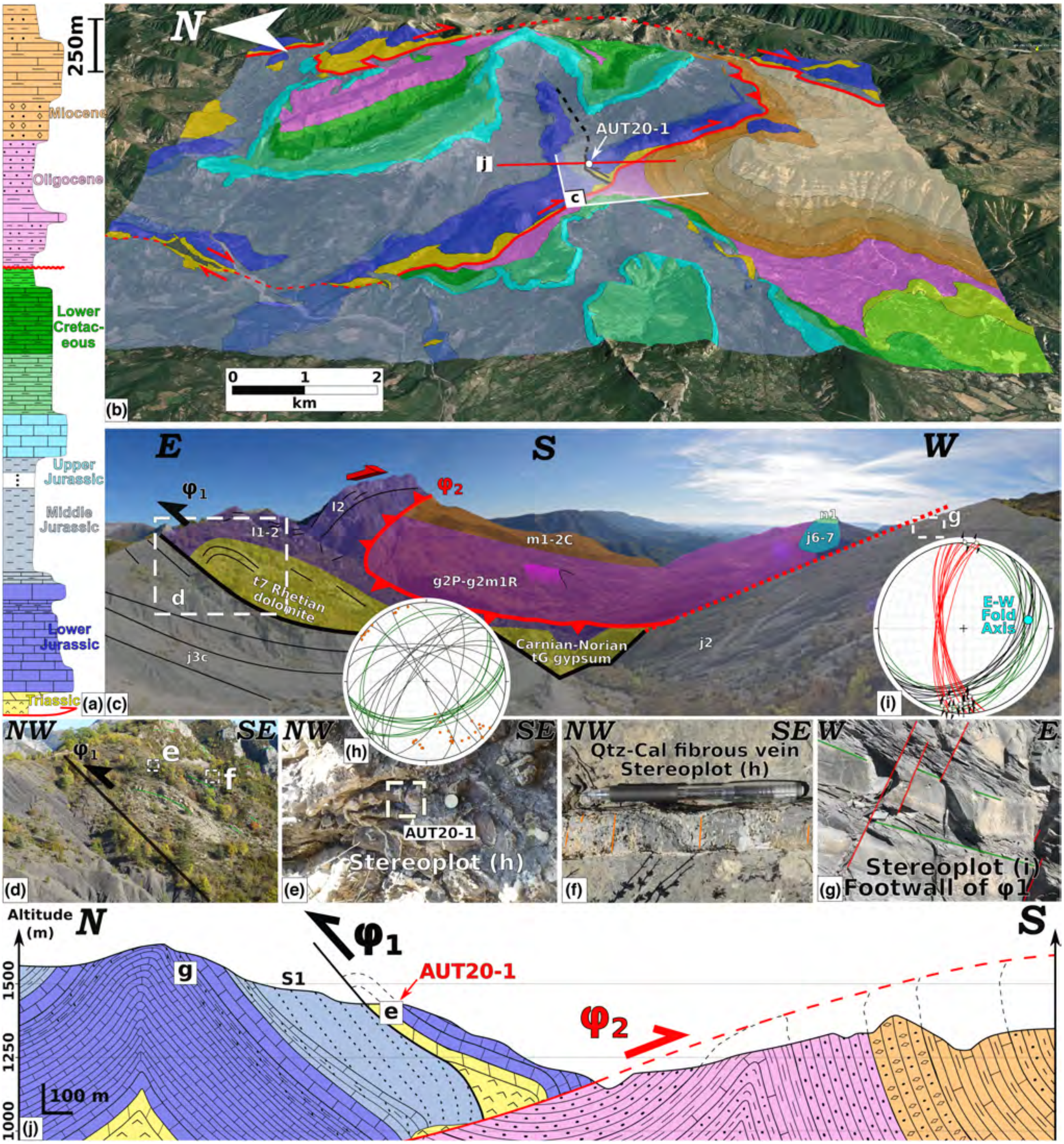


FIGURE 2 Geological context of the Authon Thrust sample (Eastern Provence). (a) Stratigraphic log of the Authon area, ϕ1 and 2 refer to the Authon and Valavoire thrusts, respectively. Triassic gypsum (decollement level) and Rhetian dolomites (stratigraphic unit where fault cataclasite has been sampled) are in yellow. (b) Geological sketch map wrapped in a DEM and GoogleEarth image of the Authon area (location on Figure 1). Top-to-the-North Authon Thrust (ϕ1) is shown in black, while top-to-the-South Valavoire thrust (ϕ2) is shown in red. (c) Field panorama with the structural relationships of the two thrusts. (d) Close view on ϕ1 thrust with location of sampling site 'e' and measurements of 'f' veins. Green lines indicate bedding. (e) Close view of the ϕ1 hanging-wall unit and of the sampled AUT20-1 fault cataclasite. (f) Quartz-calcite centimetre-scale fibrous vein with measured orientation in 'h'. (g) ϕ1 associated footwall cleavage in Jurassic marl-limestones, consistent with a top-to-the-North motion of ϕ1. Red, blue and green lines highlight joints, schistosity and bedding, respectively. (h) Schmidt stereogram (in lower hemisphere) at location 'e' and 'f'. Triassic dolostone bedding (green) $n=11$, quartz-calcite veins (grey) $n=17$ and fibres (orange) $n=35$. (i) Schmidt stereogram (in lower hemisphere) of footwall deformation associated with ϕ1 at location 'g'; colours refer to structures shown in (g). Strike-slip fault (red) $n=16$, striae (arrows) $n=14$, bedding (green) $n=7$, schistosity (blue) $n=9$. (j) Geological cross-section showing the relationships between the two main thrusts: top-to-the-North ϕ1 thrust rooted in Triassic evaporites (gypsum) with a widespread penetrative schistosity S1 in the footwall (black dotted line, g); top-to-the-South ϕ2 (Digne-Valavoire) thrust truncating the ϕ1 structure and transporting the Mesozoic series over the autochthonous Cenozoic series (Oligocene and Miocene molasse).

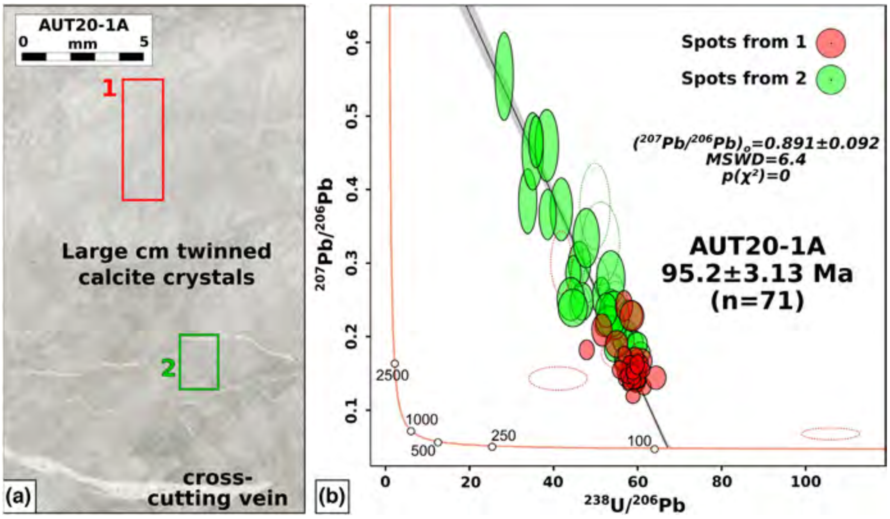


FIGURE 3 Petrological, geochemical and age relationships in the dated Authon (Eastern Provence/SW Alps) sample. (a) Thin-section picture of sample AUT20-1A with the analysed zones. (b) Tera-Wasserburg plot, spots in red are from zone 1 and green spots are from zone 2. On all the analyses a cut-off is applied on the ^{207}Pb content (see Supporting informations S1 and S2). The points whose measured ^{207}Pb content is lower than 3 times the baseline are eliminated (dotted circles).

In the Pyrenean domain, the geological evidence of Africa–Iberia–Europe convergence onset is determined by major changes in all sedimentary basins during the Santonian (Andrieu et al., 2021; Martín-Chivelet et al., 2019). This is also illustrated close to the study area by the Devoluy Cretaceous unconformity, with late Early Cretaceous extensional structures overprinted by early Late Cretaceous WSW-ENE trending folds in a basin floor setting (Michard et al., 2010). Similarly, rift inversion in northern Europe (Figure 6), witnesses a main phase of inversion occurring during end Santonian to Campanian times (e.g., Dielforder et al., 2019). This timing also agrees with the establishment of subduction along Neotethys Ocean boundaries. Early stages of subduction of Neotethys Ocean are constrained by shear zone activity at 97–80 Ma in the Eo-alpine orogenic wedge (e.g., Montemagni et al., 2023), eclogite facies metamorphism in the Sesia-Lanzo zone dated at ca. 85–65 Ma (e.g., Cenki-Tok et al., 2011; Inger et al., 1996; Rubatto et al., 1999). Consequently, the tectonic event recorded by the activation of N-directed thrusts and transpressional deformation at 97–90 Ma on East, West and South (Corrêa et al., 2022) parts of Provence region agree with the older range of ages attributed to Africa–Eurasia convergence. Revised stratigraphy of Iberia highlights a similar ~90 Ma compressional phase, featured by long wavelength folds during the Coniacian (Andrieu et al., 2021) at a similar time as shear zone development in the Eastern Alps (97–80 Ma; Montemagni et al., 2023) and as obductions in the Middle East (e.g., Rioux et al., 2016; Rolland et al., 2020). This early Pyrenean phase could thus be regarded as a precursor phase of internal plate deformation, which occurred before the initiation of a well-defined subduction zone at the plate's interface.

5 | EARLY PYRENEAN COMPRESSION AND DURANCE ISTHMUS

The formation of the ‘Provence High’ or ‘Durance Isthmus’ (e.g., Guendon et al., 1983; Figure 1) in the early Late Cretaceous is a puzzling geological question. As the Early Cretaceous rift is well-known and is shown to have significantly structured the region (see a review in Célini et al., 2023), most authors have attributed the formation of the isthmus to a regional thermal anomaly related to this rifting phase. However, emersion appears unrelated to specific extensional structures (horsts or tilted blocks), and is related to a regional doming without any volcanism. Based on new ages obtained in the present paper, it is possible that such structural configuration is more in agreement with a compressional phase occurring shortly after the rifting phase. This early Pyrenean compressional phase may also be emphasized by marine regression highlighted by the development of bauxites formed in emerged portions of the Durance Isthmus (Figure 6b). The emersion phase is constrained by relative stratigraphic relationships between the eroded Barremian sedimentary series preserved below the bauxites, which constitute a maximum age (125.0–129.4 Ma), and the Cenomanian transgression (100.5–93.9 Ma). Previously obtained U–Pb ages of calcite cements within the Urgonian platform limestones of the same region (Figure 1) range between 96.7 ± 4.9 Ma and 90.5 ± 1.6 Ma (Godeau et al., 2018). These ages correspond to the major phase of calcite cementation in the porosity, suggested by the latter authors to occur at the regional scale following an extensive subaerial exposure. This uplift and emersion have been attributed to the initiation of E-W folds (e.g., Masse & Philip, 1976), but are more recently regarded as related to Cretaceous rifting (e.g., Balansa et al., 2022 and references therein). Thus, their relationship with Pyrenean shortening is questioned, according to the description of extensional tectonics dated to the Santonian preceding the beginning of the main Pyrenean compression phase (e.g., Guyonnet-Benaize et al., 2010). However, U–Pb dating of calcite in this paper shows that emersion and shortening can be coeval. Our study and that of Godeau et al. (2018) converge to propose that emersion combined to N-S shortening occurred mostly between 97 and 90 Ma. This compressional phase shortly post-dates the Lower Cretaceous rifting phase, thus, more dating has to be done to more precisely constrain the onset of the early Pyrenean compressional deformation and its influence for emersion and Bauxite formation. Timing of this later

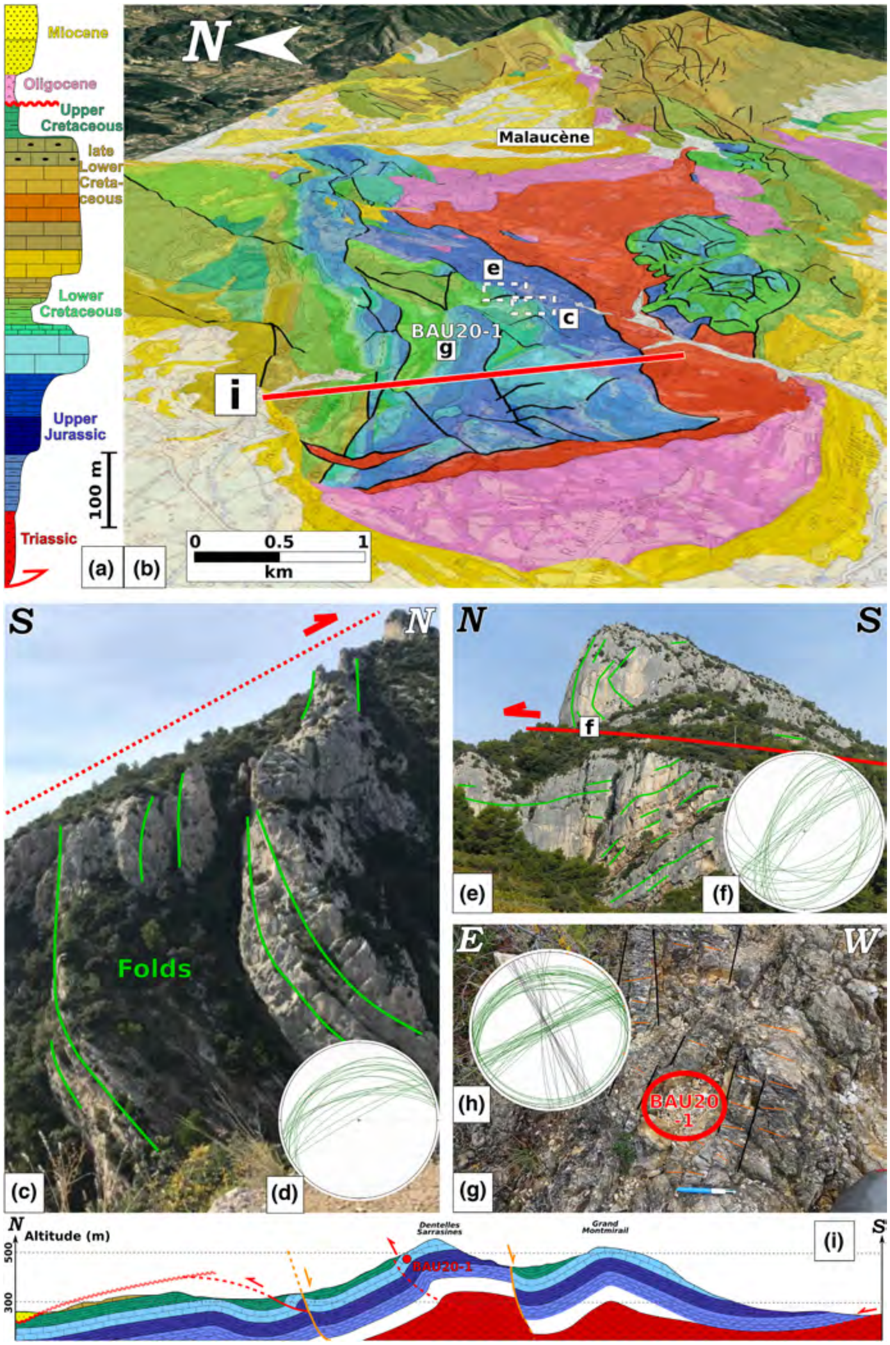


FIGURE 4 Geological context of the dated Dentelles (Western Provence) sample. (a) Stratigraphic log of the area. (b) Geological sketch map draped on a DEM and GoogleEarth image of the Dentelles area (see location on Figure 1; view towards ENE). (c) Westward view of the southern massif (Grand Montmirail) showing large-scale folding in the footwall of a top-to-the-North thrust. Green lines underline bedding and red dotted ones highlight the former location of the (now eroded) thrust. (d) Schmidt stereogram (in lower hemisphere) with Jurassic bedding in green. (e) Eastward view of Tithonian limestones in the hanging-wall of the top-to-the-North thrust (same as 'c'), with a possible thrust ramp in red. The Jurassic bedding (underlined in green) is truncated by the N-directed thrust (red). (f) Schmidt stereogram (in lower hemisphere) with Jurassic bedding in green. (g) Close view of the vein sample BAU20-1. The veins cross-cut the NE–SW antiform fold structure. (h) Schmidt stereogram (in lower hemisphere) with Jurassic bedding (green), calcite veins (grey) and fibres (orange). The veins are sub-vertical and their orientation is consistent with E-NE striking folds shown by bedding orientations. (i) Interpretative cross-section located in 'a', showing a basal truncation by Triassic evaporites, corresponding to the emplacement of the diapir. The normal faults crosscut and thus postdate some fold structures. They are probably associated with the Oligocene emplacement of the Suzette diapir in an extensional context, and are overprinted by further shortening (Miocene). Note that the Mesozoic series is locally folded to vertical above the main top-to-the North thrust, rooted on the Triassic evaporites. Structural data from the rest of the massif are displayed in Supporting information S4 and put in relation with deeper fault features interpreted from Roure and Howell (2022) seismic profile (see Supporting information S5).

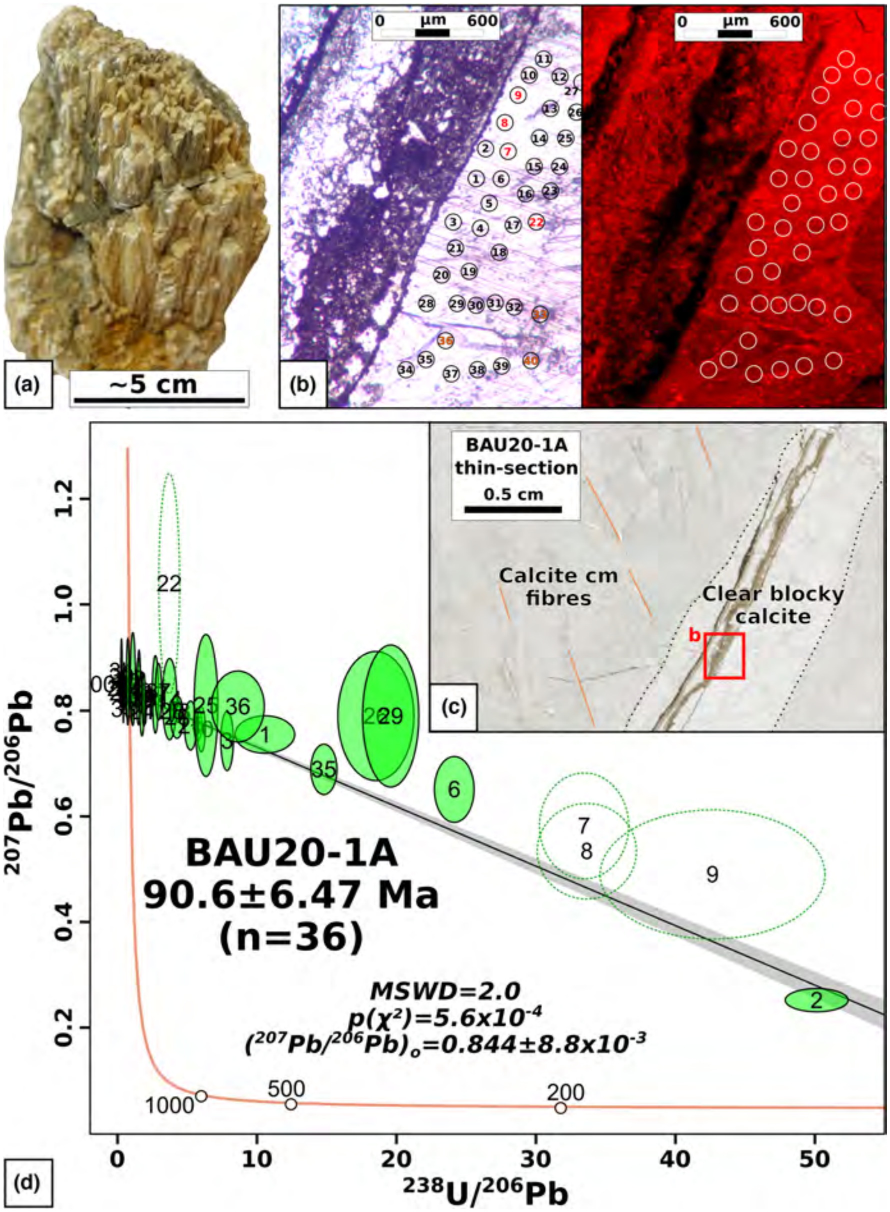


FIGURE 5 Petrological, geochemical and age relationships in the dated Dentelles (Western Provence) sample BAU20-1. (a) Sample BAU20-1 exhibits centimetre-scale calcite fibres, highlighted by orange lines in 'c'. (b) Zoom of the dated zone, Plain polarized and cathodoluminescence images, with LA-ICP-MS spots and corresponding analyse numbers (displayed in Supporting information S2). (c) Thin-section with calcite fibres underlined in orange and dated domain (b). (d) Tera-Wasserburg plot. Dotted ellipses correspond to discarded measurements.

process might be diachronous at regional scale, maybe starting earlier in the Massif Central, to the West of CF (Albian, maximum age of 115 ± 3 Ma; Marchand et al., 2021), than in Provence. Here, the time bracket for emersion appears shorter (97–90 Ma) than the stratigraphic constraints suggest (Barremian-Turonian, i.e. 130–90 Ma), as already pointed by previous authors (e.g., Combes, 1990). Here, we suggest that the Durance Isthmus uplift mostly occurred in a compressional, and not a rifting, context. We propose that marine regression is forced by shortening highlighted by North-directed faulting and ENE-WSW folding, and was triggered by sinistral strike-slip motion along the Nîmes Fault as suggested by Ford and Stahel, (1995), (Figure 6). The continuous activity of this fault system, partly associated with the CF, is highlighted by numerous U–Pb dates on calcite, which indicate activity from the Late Cretaceous to the Late Eocene (Parizot et al., 2022). As shown by the style of deformation, thrusting occurred in relationship to basement-cover decoupling in a tin-skin mode. The propagation of thrusts occurred in distal 'internal plate' positions to the North of Provence like in the Devoluy Range (Flandrin, 1966). The end of this shortening phase is suggested by cross-cutting normal faults in the Santonian (Guyonnet-Benaize et al., 2010). We suggest that these extensional faults resulted (1) from a rapid ending of compression in Provence once subduction had been initiated along plate boundaries, (2) from a steady and slow diapiric amplification of folds following the shortening phase, which lasted until the Oligocene (e.g., Espurt et al., 2019), (3) or from local extension within a globally compressive context (Tavani et al., 2015).

6 | CONCLUSION

This study shows that the application of the U–Pb dating system on calcite allows deciphering complex tectonic histories in which fault systems were affected by multiple phases of reactivations, burial etc. From the above example, we show that the calcite U–Pb

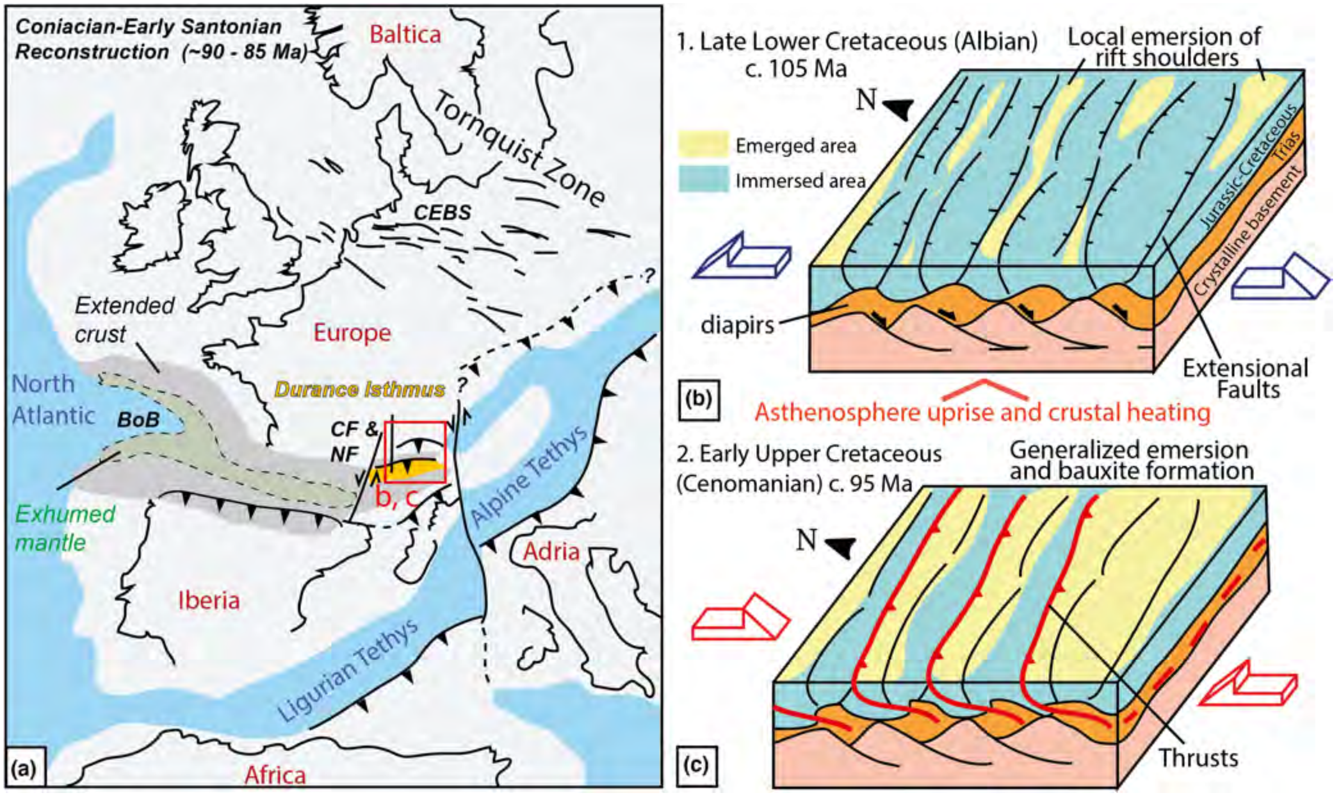


FIGURE 6 (a) Coniacian-Early Santonian (~90–85 Ma) general geodynamic sketch of Western Europe and Mediterranean regions in the context of the Early Pyrenean compressional phase. Compression that occurred in the Provence domain led to a generalized internal plate compressional context, and likely to uplift amplification in the Durance Isthmus. The difference in tectonic style between the Provence and Pyrenean domains is explained by differential accommodation of internal plate shortening along the Cevennes and Nimes sinistral faults (CF and NF; Parizot et al., 2022). Position of continents and structural domains are after Dielforder et al. (2019), modified. CEBS, Central European Basin System (black lines are major faults). Green and dark grey areas indicate zones of exhumed mantle rocks and extended continental crust, respectively, in the Pyrenean realm and Bay of Biscay (BoB). Light grey and blue areas indicate continental and oceanic domains, respectively. In northern Iberia, along the southern rim of the Pyrenean Rift, long wavelength folding occurred during the Coniacian (~90 Ma, Andrieu et al., 2021). In northern Europe, the Tornquist zone is part of the Palaeozoic suture between Baltica and Europe. The Tornquist zone and CEBS have subsequently been intensely reactivated during the Early Pyrenean compressional phase at ~81–69 Ma (e.g., Fischer et al., 2012). (b) Sketch bloc diagram of Provence at Albian times. Graben structures are formed in relation to diapiric activity in a general extensional context. Rift shoulders are locally emerged leading to initiation of bauxite formation. (c) Sketch bloc diagram of Provence Sketch bloc diagram of Provence at Cenomanian times. E-W Thrusts are formed and nucleate at diapirs as weak spots in a thin-skin tectonic mode. This generalized compressional context occurring in a context of previously hot and buoyant crust led to widespread emersion and bauxite formation.

system has kept the memory of an early Late Cretaceous (97–90 Ma) compressional event. This shortening event coincided with the time of Eurasia-Africa convergence initiation and early Alpine metamorphism, and shortly predated the onset of subduction in the western Mediterranean domain. It is thus suggested that this distributed internal plate deformation event accommodated convergence before a subduction zone was activated along the southern Neotethys region. This shortening episode occurred in the Provence region while the Pyrenean domain was still undergoing a rifting phase followed by compression. We propose that this discrepancy may be explained by the activity of the Cévennes and Nimes faults, acting between 97 and 90 Ma as major transform boundaries between the Pyrenean and Provence domains. The main result and outcome of this study is that the U–Pb system in calcite retains memory of ages related to some precursor deformation phases. Ages can be preserved despite significant and multiphase further deformation along or nearby the same structures. This leads to some confidence in using this new dating tool in studies dealing with brittle deformation, where mostly relative ages have been used in the past.

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DATA AVAILABILITY STATEMENT

The data that support the findings will be available in [U/Pb dating of Provence deformation] at [https://edytem.osug.fr/-morphodynamiques-] following an embargo from the date of publication to allow for commercialization of research findings.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Data S1.

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