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Post early Cretaceous evolution of the Cévenol fault system according to U-Pb geochronology

Oriane Parizot[1,2,*], Yves Missenard [3], Stéphane Baize[1], Christophe Matonti[2], Alexis Derycke[4], Camille Thomasset[5] and Nicolas Cathelin[6]

[1] Autorité de Radioprotection et de Sureté Nucléaire (ASNR), PSE-ENV/SCAN/BERSSIN, F-92260, Fontenay aux Roses, France
[2] Géoazur, Univ. Côte d'Azur, CNRS, Observatoire de la Côte d'Azur, IRD, Valbonne, France
[3] Université Paris-Saclay, CNRS, GEOPS, 91405, Orsay, France
[4] Centre de Recherches Pétrographiques et Géochimiques, Vandoeuvre lès Nancy, France
[5] Institut des Sciences de la Terre - Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS : UMR5275 - France
[6] Institut Terre et Environnement de Strasbourg - EOST, CNRS-UMR 7063, Université de Strasbourg, 5 Rue René Descartes, 67000 Strasbourg, France

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Abstract – The Le Teil (Rhône Valley) earthquake of magnitude 4.9 on November 11, 2019, located on the Cévennes fault system has raised many questions about how regional intraplate structures may be reactivated and how they could potentially trigger strong and shallow earthquakes. This study aims to better understand the geodynamic evolution of this major structure of France's geology over geological time. A structural study was carried out between Alès and Cruas localities, and synkinematic calcite samples were collected on fault planes and dated using the U-Pb method at LA-HR-ICPMS. Four major geodynamic episodes between 110 and 25 Ma were identified. In addition to recording tectonic events related to plate boundary geodynamics, the Cévenol Fault System appears to be a key structure in accommodating vertical motion differentials between the Massif Central, the Pyrenean domain and the South-East basin.

Keywords: Cévenol fault system / intraplate domains deformation / Le Teil earthquake / U-Pb geochronology / fault-related calcite / LA-ICPMS

Résumé – Evolution du faisceau de failles cévenoles depuis le Crétacé inférieur d'après la géochronologie U-Pb. Le séisme du Teil (Vallée du Rhône) de magnitude 4.9, le 11 novembre 2019, localisé sur le faisceau de faille des Cévennes, a suscité de nombreuses interrogations quant aux modalités de réactivation des structures intraplaques régionales. Cette étude vise à mieux comprendre l'évolution géodynamique de cette structure majeure de la géologie de la France au cours des temps géologiques. Une étude structurale a été réalisée entre Alès et Cruas et des échantillons de calcites syn-cinématiques ont ainsi été prélevés sur des plans de faille puis datés par la méthode U-Pb au LA-HR-ICPMS. Quatre épisodes géodynamiques compris entre 110 et 25 Ma sont mis en évidence. En plus d'enregistrer les événements majeurs associés à des phases géodynamiques aux limites de plaques, la Faille des Cévennes apparaît comme un élément clé dans l'accommodation des différentiels de mouvements verticaux entre le Massif Central, le domaine pyrénéen et le bassin du Sud-Est.

Mots-clés : Faille des Cévennes / déformation des domaines intraplaques / séisme du Teil / datation U-Pb / calcite de faille / LA-ICPMS

1 Introduction

The Cévenol Fault System is an NE-SW trending major geological structure in southern France, almost 400 km long from the Pyrenean domain to the Alpine foreland (Fig. 1). This structure also defines the NW edge of the South-East Basin located within the intraplate domain and is known to have been reactivated several times over geological time (Séguret and Proust, 1965; Arthaud and Mattauer, 1969; Le Pichon *et al.*, 1971; Bodeur, 1976; Parizot *et al.*, 2022). Furthermore, it came into the spotlight when the Le Teil earthquake (Mw=4.9) occurred on November 11, 2019, on the La

*Corresponding author: oriane.parizot@geoazur.unice.fr

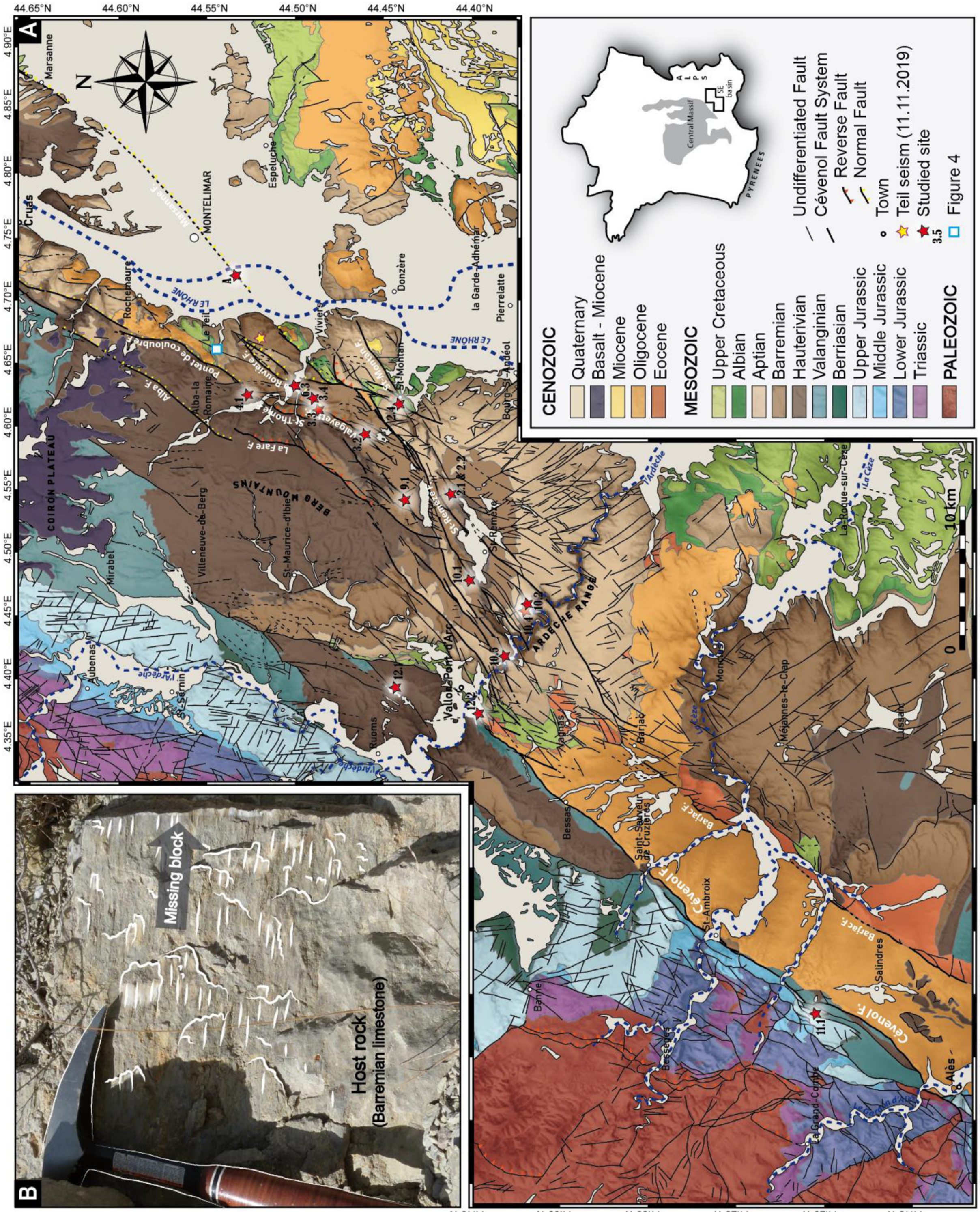

Fig. 1. A. Structural scheme of the study area and sampling outcrops (with red stars). Modified after 1:50 000 BRGM geological maps. B. Illustration of a strike-slip fault plane associated with syn-tectonic calcite observed at the site 9.1, north of St-Remèze.

Rouvière fault, a segment of the Cévenol Fault System near the city of Montélimar. This earthquake caused a surface rupture (Ritz *et al.*, 2020) (Fig. 1) and significant damages in some towns such as Le Teil, Saint-Thomé and Viviers. Even if the physical characteristics (M_w 4.9, reverse-faulting focal mechanism, epicenter on southeast-dipping La Rouvière fault) were later precisely established, the origins of this earthquake is debated (Larroque *et al.*, 2020; Burnol *et al.*, 2023).

Based on U-Pb calcite geochronological data, a recent study highlighted multiple periods of activity of the La Rouvière fault by analyzing samples from a core drilled through the structure (Gébelin *et al.*, 2024). The aim of our study is to improve our understanding of the activity of the Cévenol Fault System in its entirety – *i.e.*, considering all map-scale structures belonging to the system – over geological time and thus establish a precise geodynamic agenda for this intraplate structure. Was it active at times other than those already highlighted in previous studies? Was the Cévenol Fault System active continuously over time or only during major geodynamic episodes? When did the change from an Oligocene extensional structure to a contractional one (Le Teil earthquake) occur? To answer these questions, the segments of the Cévenol Fault System between Cruas to the NE and Alès to the SW (Fig. 1) were studied by combining structural geology and geochronology. Analysis of the fault planes and their associated syn-kinematic calcites dating by U-Pb laser ablation – high resolution – inductively coupled plasma – mass spectrometry (LA-HR-ICPMS), allows to reconstruct the periods of activity of the Cévenol Fault System, periods which are then contextualized in a geodynamic framework at regional scale.

2 Geological context

The Cévenol Fault System is inherited from the Variscan orogeny (Séguret and Proust, 1965; Arthaud and Matte, 1975; Blès *et al.*, 1989). During the Triassic to Middle Jurassic, Southern France subsequently underwent an extensional episode resulting from the rifting of the Tethys Ocean (Lemoine, 1982; Dercourt *et al.*, 1986; Bonijoly *et al.*, 1996; Frizon de Lamotte *et al.*, 2011). This leads to an extensional reactivation of the SE-dipping Cévenol Fault System (Séguret and Proust, 1965; Roure *et al.*, 1992). Previously published U-Pb ages obtained on single-phase synkinematic calcites in the southern part of the Cévenol Fault System (Languedoc region, Fig. 1) revealed mid-Cretaceous (approx. $\asymp$ 100 Ma) activity on the latter, although no other geological evidence could validate them (Parizot *et al.*, 2022). During Eocene times, the sinistral motion of the whole Cévenol Fault System during the convergence of the Iberian and Eurasian plates thought to be related to the formation of the Pyrenean orogen (Séguret and Proust, 1965; Arthaud and Mattauer, 1969; Bodeur, 1976; Parizot *et al.*, 2022). From the Priabonian to the Aquitanian, the south-eastward retreat of the Tethys Ocean slab into the Mediterranean domain subsequently leads to the rifting of the Gulf of Lion, as well as an extensional episode in the eastern part of southern France (Séguret and Proust, 1965; Le Pichon *et al.*, 1971; Séranne, 1999; Oudet *et al.*, 2010; Jolivet *et al.*, 2020; Séranne *et al.*, 2021). This geodynamic event induces a new extensional reactivation of the Cévenol Fault System, resulting in the formation of NE-SW-trending basins along the structure (*e.g.*, the Montoulieu and Alès basins) (Le Pichon *et al.*, 1971; Séranne, 1999; Sanchis and Séranne, 2000). Since Neogene times, the geodynamic history associated with the Cévenol Fault System activity seems to be more controversial. Guerin's work (1973) highlights a dextral motion at the end of the Miocene, interpreted as a consequence of the Alpine phase. However, according to Bergerat (1987), this structure has been reactivated with a similar kinematics but earlier, during the Aquitanian, and is associated with a resumption of convergent movement of the African and Eurasian plates.

The study area (Fig. 1A) can be divided into two domains: (A) In the northern part, between Cruas and Vallon-Pont-d'Arc, the Cévenol Fault System is characterized by multiple parallel regional NE-SW faults extending over a width of almost 10 km. These include the Alba-la-Romaine and La Fare faults on the NW edge of the system and the St-Remèze and St-Montan faults to the SE. The Cévenol Fault System cuts across sedimentary formations of mainly Lower Cretaceous age. It is also possible to observe Oligocene-age deposits along some structures, as it is the case for the Pontet de Couloubre fault, north of Le Teil city. (B) Further south, between Vallon-Pont-d'Arc and Alès, the Cévenol Fault System cuts series of Jurassic to Lower Cretaceous age and consists in a single structure (Fig. 1A). Its activity during the Oligocene extension is recorded by the syn-rift filling of the NE-SW-trending Alès basin (Sanchis and Séranne, 2000).

3 Methods

The outcrops considered in this study were selected according to their location: only those located along regional scale faults were selected in order to restrict the study to the intraplate major structures. The calcite dating on these objects thus provides insights on the age of the activity of these regional faults, therefore allowing for interpreting in the light of the existing regional geodynamic framework. Sampled outcrops correspond to sedimentary deposits (limestone or marly-limestone) of ages ranging from Berriasian (145 Ma) to Aptian (117 Ma). A set of decametric fault planes was measured during the structural study of the area and 70 single-phase synkinematic calcites associated with these fault planes were sampled for petrographic observations and U-Pb dating (Fig. 1B). Petrographic observation was conducted using a binocular, as well as optical and cathodoluminescence (CL) microscopy. CL observations were carried out on an Olympus BX41 microscope coupled to a Cathodyne coldcathode catholuminescence (NewTec, Nîmes, France) operating at 12−13 kV and 200−250 μA, and a Qicam Fast 1394 digital camera (TELEDYNE QIMAGING, Surrey, Canada). These petrographic observations both allow us to validate the single-phase nature of the calcite samples and to determine preferential ablation zones by excluding potentially altered/contaminated areas.

Calcite samples were dated by U-Pb geochronology using a HR-ICP-MS Element XR from Thermo Scientific coupled to a Laser Ablation system (LA) ArF 193 nm from Teledyne Photon Machines at the Paris-Saclay University, following standard methods described elsewhere (Brigaud *et al.*, 2020; Parizot, 2021; Blaise *et al.*, 2022). Among the 70 calcite samples, 23 U-Pb ages were obtained, equivalent to a success rate of around 1/3. Details of these syn-faulting calcite samples and methods can be found in the Supplementary Information.

Sample nomenclature refers to the name of the sampling site. Their name includes the prefix "TEIL23-", then the referent site number shown in Figure 1, and finally the suffix "#XX" corresponding to the sample number assigned to it at the time of sampling. Only the calcite "MAR23-U01", which was not sampled at the same time as the others, does not have this designation. It is a striated fault related calcite sampled on the site "A", SW of Montélimar (Fig. 1A).

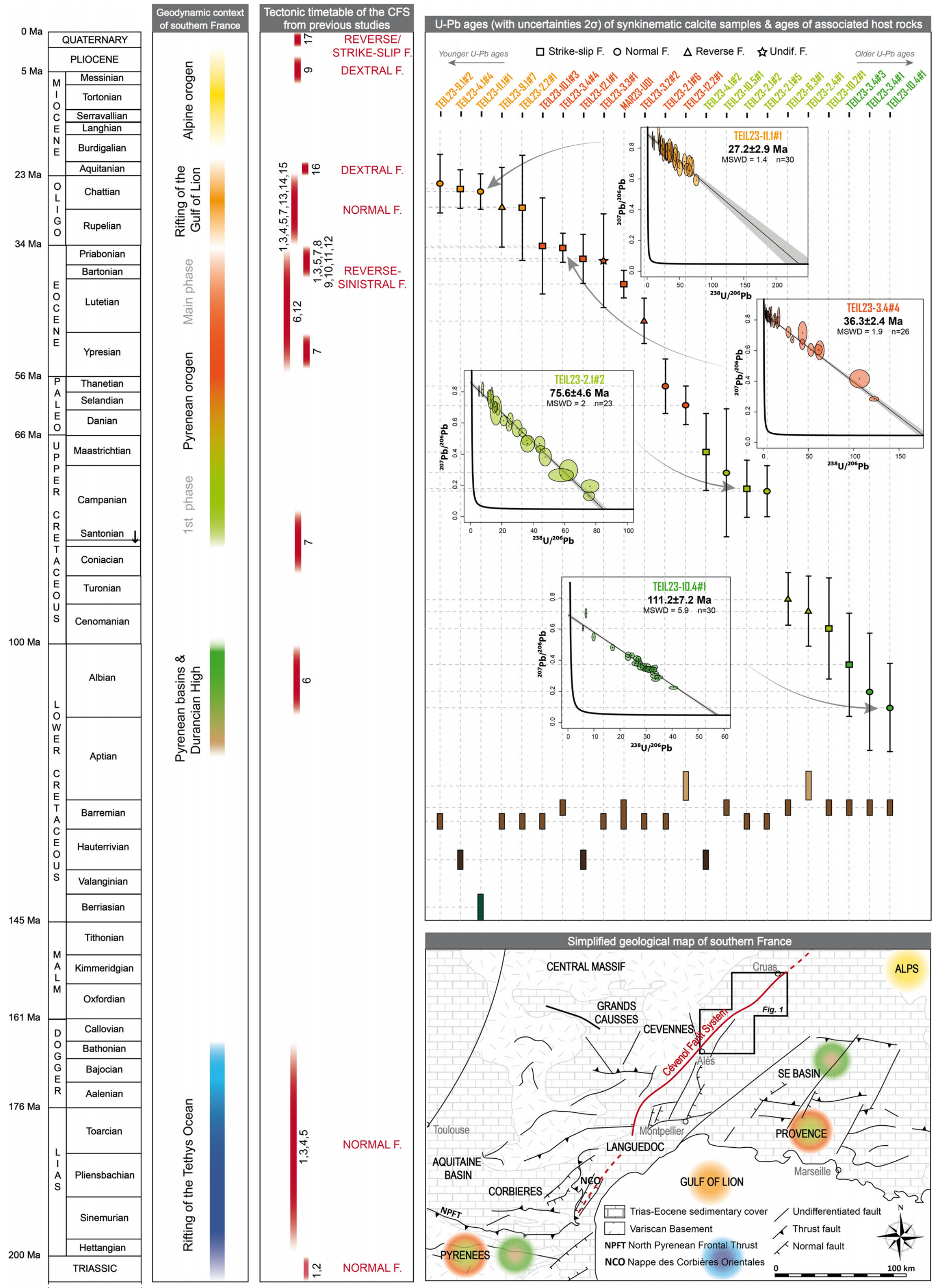

Fig. 2. Geodynamic history of southern France since Triassic period in relation to the Cévenol Fault System activities determined from previous studies. U-Pb geochronology results (U-Pb ages and their propagated uncertainty (2 σ)) and the age of the host rock associated with the synkinematic calcites samples are also visible on the Figure. 1: Blès *et al.*, 1989, 2: Curnelle and Dubois (1986), 3: Séguret and Proust (1965), 4: Roure *et al.*, 1992, 5: Hemelsdaël et al. (2021), 6: Parizot *et al.*, 2022, 7 : Gébelin et al. (2024), 8: Arthaud and Mattauer (1969), 9: Guérin (1973), 10: Bodeur (1976), 11: Bergerat (1982), 12: Séranne et al. (2021), 13: Le Pichon et al. (1971), 14: Séranne et al. (1999), 15: Sanchis and Séranne (2000), 16: Bergerat (1987), 17 : Lacassin (1998), Baize and Ritz (2022), Cathelin (2024), Thomasset-Laurent (2025).

Inferred principal stress orientations were reconstructed from fault-slip data with WinTensor© software (Delvaux and Sperner, 2003) using the right dihedral inversion method (Angelier and Mechler, 1977). However and as previously introduced, the Cévenol Fault System is a polyphase structure within which local variations in the stress field may complicate the interpretation of global stress tensors (Parizot, 2021). In this context, data inversion was carried out for each dated fault planes, in individual stereograms, to avoid any over-interpretation of the structural data – the mechanisms behind the reactivation of these structures being out of the scope of this study. Finally, as the bedding is generally sub-horizontal at the sites studied, it should be noted that the structural data were not back-tilted during analysis.

4 Results

The set of U-Pb ages obtained on the fault related calcites corresponds to an age range between *c*. 111 and 25 Ma (Fig. 2). Based on the results, four U-Pb age groups could be distinguished.

The first one involves synkinematic calcites with a mid-Cretaceous (Albian-Cenomanian) age: TEIL23-10.4#1: 111.2 ± 7.2 Ma, TEIL23-3.4#1: 108.6 ± 9.5 Ma, TEIL23-3.4#3: 104.2 ± 8.4 Ma, TEIL23-10.2#1: 98.3 ± 8.2 Ma, TEIL23-2.4#1: 95.5 ± 5.7 Ma, TEIL23-6.3#1: 93.5 ± 4.3 Ma (Fig. 2). The characteristics and Tera-Wasserburg graphs of each sample are detailed in the Supplementary Information. These U-Pb ages are associated with normal, reverse or strike-slip fault planes (Fig. 3). Due to their heterogeneity, it is thus not possible to use these data in order to determine a stress field at the scale of the Cévenol Fault System. However, near Le Teil town, at the location of a regional NE-SW fault, marls and limestones of Upper Aptian age outcrop (Figs. 1 and 4). Variations in the thickness of this sedimentary series on either side of normal fault planes support an extensional syn-depositional fault activity which could be related to the one identified in the same area by Thomasset *et al.* (2024) during the Barremian. According to the orientation of these structures, the deformation would be the result of an overall E-W directed extension. Furthermore, we can note that the most recent faults of this first phase have an inverse kinematics, suggesting either a possible change in stress field during the Cenomanian or local variations in the stress field.

The second U-Pb age group was identified from 6 fault-related calcites dating a tectonic episode from the Campanian to the Paleocene. These are: TEIL23-2.1#5: 76.0 ± 4.1 Ma, TEIL23-2.1 # 2: 75.6 ± 4.7 Ma, TEIL23-10.5 # 1: 73.0 ± 10.4 Ma, TEIL23-4.1 # 2: 69.6 ± 6.3 Ma, TEIL23-12.2#1: 62.0 ± 3.1 Ma, TEIL23-2.1#6: 58.9 ± 4.4 Ma (Fig. 2). All these dated samples are related to normal faulting, except TEIL23-2.1#2 and TEIL23-4.1#2 associated to strike-slip faulting (Fig. 3). They demonstrate that an extensional event caused the reactivation of the Cévenol Fault System as a normal (or transtensive) system during Campanian-Paleocene times.

Given the similarity of the data and their uncertainty range, the boundary between the 3rd and 4th age groups is not straightforward. Six fault related calcites produced an Eocene U-Pb age (Lutetian-Priabonian) : TEIL23-3.2#2: 48.2 ± 3.7 Ma, MAR23-U01: 42.2 ± 2.2 Ma, TEIL23-3.3# 1: 38.4 ± 7.6 Ma, TEIL23-12.1 # 1: 38.1 ± 4.0 Ma, TEIL23-3.4#4: 36.3 ± 2.4 Ma, TEIL23-10.1#3: 36.0 ± 7.8 Ma (Fig. 2). Structural data show an activation (or reactivation) of at least three sinistral strike-slip fault planes (≈ NE-SW oriented) and one reverse fault plane oriented NW-SE. The inversion of these fault-slip indicates a compressional episode along the Cévenol Fault System associated with a maximum principal stress σ_1 oriented ≈ NNE-SSW (Fig. 3). Such a stress orientation is compatible with the overall sinistral reactivation of the Cevenol Fault System during the Middle – Upper Eocene (Lutetian-Priabonian).

Furthermore, five other fault related calcites are dated to the Oligocene (Chattian, Fig. 2) : TEIL23-2.2#1: 29.8 ± 8.2 Ma, TEIL23-9.1#7: 29.7 ± 6.5 Ma, TEIL23-11.1#1: 27.2 ± 2.9 Ma, TEIL23-4.1#4: 26.8 ± 3.2 Ma, TEIL23-9.1#2: 25.9 ± 4.8 Ma (Fig. 2). Among them, the uncertainty of the first two shows that they could be associated with the previous group (the "Eocene" group) as well as the Oligocene one. We therefore refer to the structural data of the three youngest calcites to discuss the orientation of the stresses. These calcites come from strike-slip (TEIL23-4.1#4) and normal (TEIL23-11.1#1 and TEIL23-9.1#2) fault planes, highlighting normal (or transtensive) activity of the Cévenol Fault System during the Upper Oligocene, associated with a ~ NNW-SSE-trending σ_3 (Fig. 3).

5 Discussion

The various activities of the Cévenol Fault System revealed in this study and in previous works, based on the study of map-scale faults belonging to a hundreds kms long structure can be placed in a broader geodynamic context, at the southern France scale (Fig. 2). Overall it seems that the Cévenol Fault System records continuous deformation from the mid-Cretaceous to the Upper Oligocene, without clear evidence for tectonic quiescence.

Indeed, the U-Pb and structural results indicate a first activity of the Cévenol Fault System during mid-Cretaceous times. This activity has also been identified in the southern part of the system (Parizot *et al.*, 2022) suggesting a displacement along its entire length (Fig. 5). Furthermore, field data indicate that this event is compatible with the extensional activity of the Cévenol Fault System already underlined during lower Cretaceous times (Thomasset *et al.*, 2024). During the Albian, the geodynamic context of France was associated with the development of the Pyrenean basins at the present location of the orogen (Choukroune and Mattauer, 1978; Lagabrielle *et al.*, 2010; Mencos *et al.*, 2015). This period is also characterized by the exhumation of some areas such as the Massif Central and the Durancian High leading in particular to the formation of bauxite in Provence (Masse and Philip, 1976; Combes, 1990; Séranne *et al.*, 2002; Guyonnet-Benaize *et al.*, 2010; Godeau *et al.*, 2018; Barbarand *et al.*, 2020). The Cévenol Fault System then appears to bound distinct domains: the future Pyrenean domain undergoing extension, the Massif Central domain uplifting, and the South-East Basin domain. At this time, the latter included the uplift of the Durancian Isthmus, the subsidence of the Vocontian Basin further north, and the Pyrenean basins in extension to the south (Tavani *et al.*,

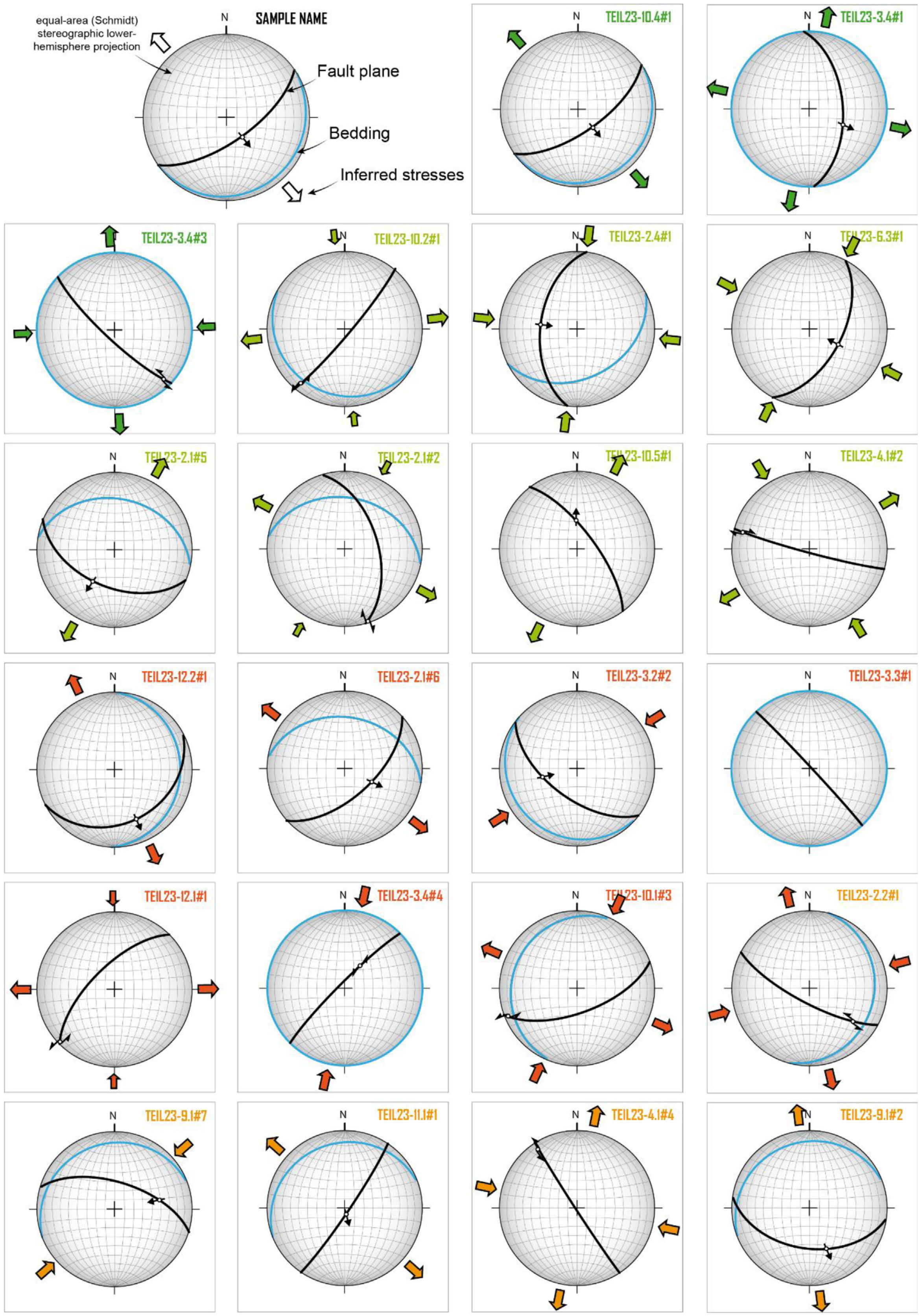

Fig. 3. Results of fault planes analysis associated with dated samples. Results are presented on the equal-area (Schmidt) stereographic lower-hemisphere projection and represent the present-day orientation of the fault plane (in black) and the bedding (in blue). State of stress is represented by orange, red, light green or dark green arrows, depending on the U-Pb age of the associated calcite sample.

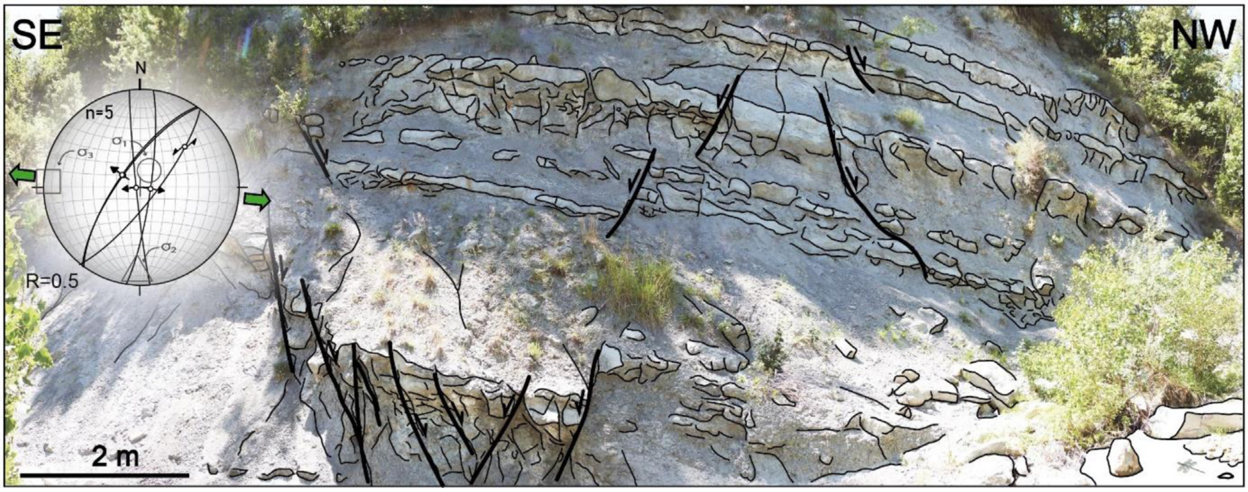

Fig. 4. Outcrop of Upper Aptian marls cut by normal fault planes showing an extensive syn-sedimentary episode to the west of Le Teil town (coordinates: 44.544526̂ N 4.662370̂ E).

2018) (Fig. 5). In this context, the Cévenol Fault System could have acted as a reactivated inherited crustal weakness zone accommodating at least a part of the differential vertical motion between the Massif Central highly exhumed, >1000 m according to Barbarand *et al.*, (2020) and the South-East Basin (less exhumed, 140 m according to Guyonnet-Benaize *et al.*, (2010) (Fig. 5).

The extensional reactivation of the Cévenol Fault System during Campanian-Paleocene times in the Montélimar region is unexpected, especially as it occurred in an overall compressional context. Indeed, at this period, southern France underwent an overall general North-South compression, associated with the convergence of the Iberian and Eurasian plates which have been initiated during the Santonian (84 Ma: Grool *et al.*, 2018). Gébelin *et al.* (2024) obtained U-Pb ages testifying to the activity of the La Rouvière fault between 90 and 75 Ma which the authors associate with thermal subsidence in the Ardeche region at this time. However, prior to this study, some authors were already discussing probable Cévenol Fault System activity at this time but without strong evidence. This is the case of Arthaud and Mattauer (1972), who suggested a strike-slip activity of the structure as early as the Upper Cretaceous and which would be at the origin of a shift between the Pyrenean and Provençal areas. In addition, Séranne *et al.* (2002) speculate on a “differential motion on either side of the Cevennes Fault during the Late Cretaceous”, linked to an uplift of the Massif Central with respect to the South-East basin. The extensional activity identified on the Cévenol Fault System seems to support this idea, and it would thus accommodate such a differential movement between both domains (Fig. 5). As suggested by Arthaud and Mattauer (1972), it cannot be excluded that the Cévenol Fault System had a strike-slip component at that time.

The so-called “Pyrenean” phase occurs during the Eocene and is associated with the main convergence phase (Fitzgerald *et al.*, 1999; Grool *et al.*, 2018). In particular, this period is characterized by the evolution of the landscapes of southern France, with the formation of 1. the present-day orogen, 2. large regional structures in the foreland and 3. structures resulting from lower-intensity deformation in the intraplate domain (Lacombe *et al.*, 1996; Lacombe and Mouthereau, 1999; Lacombe and Obert, 2000; Parizot, 2021). Regarding the Cévenol Fault System, this study shows a reactivation from the Eocene to the Lower Oligocene with a sinistral – transpressive motion (Fig. 5). This result is in agreement with all previous studies showing activity contemporary with the formation of the Pyrenean orogen (Séguret and Proust, 1965; Arthaud and Mattauer, 1969; Guérin, 1973; Bodeur, 1976; Bergerat, 1982; Blès *et al.*, 1989; Hemelsdaël *et al.*, 2021; Séranne *et al.*, 2021; Parizot *et al.*, 2022; Gébelin *et al.*, 2024; Lacombe and Jolivet, 2005) (Fig. 2). This activity may have accommodated the differential horizontal motion between the “Massif Central” domain on the one hand and the “South-East Basin” domain on the other (Fig. 5).

The latest Cévenol Fault System activity revealed by the geochronological study combined with the structural study indicates normal motion of the structure in the Upper Oligocene (Fig. 5). This event is contemporaneous with the rifting of the Gulf of Lion and can be linked to the extensional regional episode that occurred in the Corbières (Mauffret *et al.*, 2001; Parizot, 2021; Parizot *et al.*, 2023), Provence (Lacombe *et al.*, 1992; Hippolyte *et al.*, 1993; Mauffret and Gorini, 1996; Espurt *et al.*, 2012), Languedoc (Séranne, 1999; Hemelsdaël *et al.*, 2021; Séranne *et al.*, 2021) and Ardèche (this study). These U-Pb ages also support previous studies showing reactivation of the Cévenol Fault System in the Oligocene (Séguret and Proust, 1965; Le Pichon *et al.*, 1971; Bergerat, 1987; Blès *et al.*, 1989; Roure *et al.*, 1992; Séranne, 1999; Sanchis and Séranne, 2000; Hemelsdaël *et al.*, 2021; Gébelin *et al.*, 2024).

Although the Cévenol Fault System seems to constitute a weak domain very sensitive to plate boundary evolution and associated vertical deformations, the lack of any record of post-Oligocene deformation that may be related to the Alpine phase on the Cévenol Fault System still remains surprising. It cannot be ruled out that the lack of Miocene U-Pb ages in the region is the consequence of a fluid chemistry at the origin of the fault related calcites that is unfavorable to U-Pb dating (too much common Pb and or too low U concentration, for instance). Nevertheless, Gébelin *et al.* (2024) as well as a

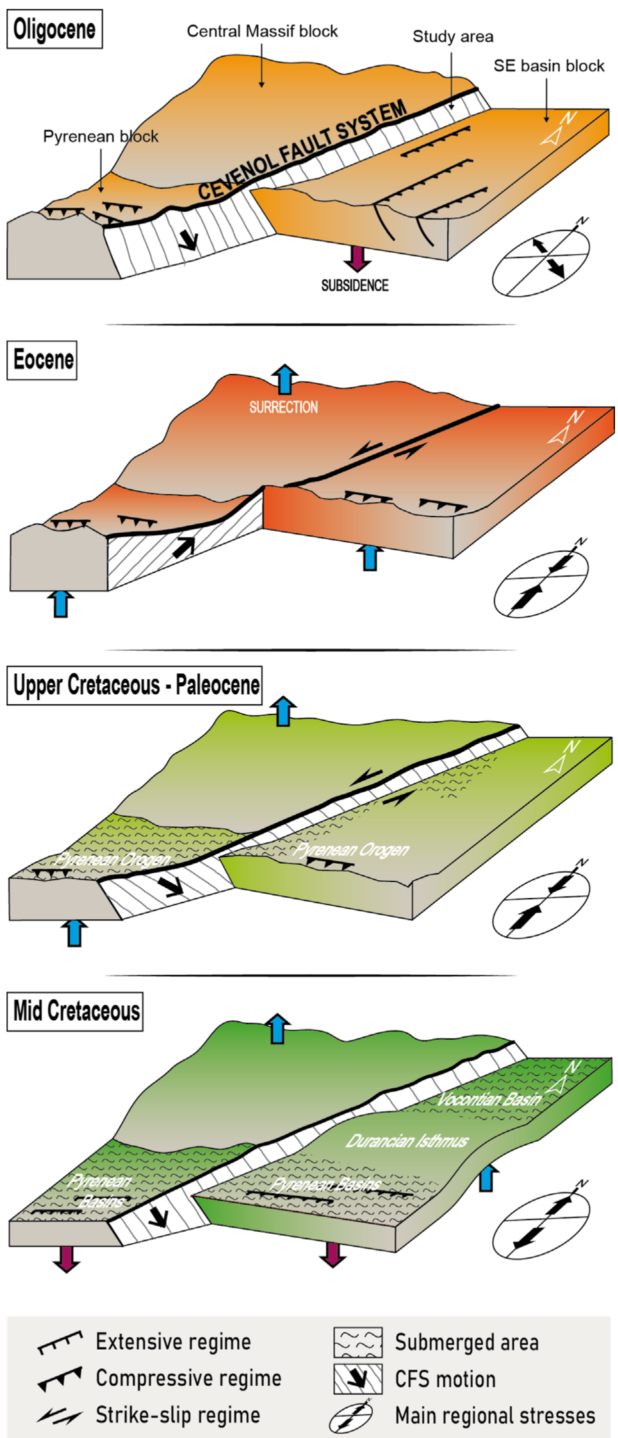

Fig. 5. Various sketches describing the Cévenol Fault System activity since the early Cretaceous and associated with the vertical and horizontal accommodation of three blocks: the Massif Central, the Pyrenean orogen and the South-East basin. See text for discussion.

recent study based on new deep seismic reflection profiles in the same area also highlight the lack of mio-pliocene deformation (related to the Alpine phase) on the Cévenol Fault System (Thomasset *et al.*, 2024). Strikingly, the mio-pliocene alpine deformation dated by the U-Pb geochronology within the orogen (Bilau *et al.*, 2023) has not been characterized by this method in the Paris Basin either (Blaise *et al.*, 2022), although it is expressed by low-intensity and small-scale deformations features such as diaclase networks (Lacombe and Obert, 2000; Rocher *et al.*, 2005; Missenard *et al.*, 2017). This raises the question of a possible limited propagation of the stresses responsible for the formation of the alpine orogen in the intraplate domain, in contrast to the Eocene pyrenean phase identifiable through folds and faults 1000 km from the orogen (Lacombe and Mouthereau, 1999; Parrish *et al.*, 2018).

6 Conclusion

Many previous studies had already shown the sensitivity of the Cévenol Fault System through its recurrent reactivation over geological time. This study, based on the dating of fault related calcites, nevertheless reveals a more complete calendar for the tectonic evolution of this structure. Although this new study could not bring a hint about the age of the tectonic change from the Cenozoic extensional regime related to the rifting of the Gulf of Lion to the Current times contraction revealed by the Le Teil earthquake, it underlines the sensitive nature of the Cévenol Fault System to regional stresses. Indeed, this Fault System records deformation from the mid-Cretaceous to the Upper Oligocene, characterized by both known events (*e.g.*, related to the formation of the Pyrenean orogen and to the rifting of the Gulf of Lion) and unexpected ones (*e.g.*, linked to its extensional reactivation in the Campanian-Paleocene or to the developing of the Pyrenean basins). In addition to being an archive for the geodynamic history of southern France, this emblematic structure appears to be key in accommodating both horizontal and vertical deformation between the Massif Central, the Pyrenean domain and the South-East basin. Overall, this study shows that an intraplate fault system is thus able to record a continuum of deformation rather than discontinuous tectonic events.

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Conflict of interests

The authors declare there is no conflict of interest.

Data availability statement

The data that supports the findings of this study are available in the supplementary information of this article.

Supplementary material

Table S1: Ablation parameters and characteristics of U-Pb dating on fault-related calcite

The Supplementary Material is available at https://www.bsgf.fr/10.1051/bsgf/2025027/olm.

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