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Far-field brittle deformation record in the eastern Paris Basin (France)

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► **To cite this version:**

Thomas Blaise, Sid Ahmed Ali Khoudja, Cédric Carpentier, Benjamin Brigaud, Yves Missenard, et al.. Far-field brittle deformation record in the eastern Paris Basin (France). *Geological Magazine*, 2022, Faults and fractures in rocks: mechanics occurrence, dating, stress history and fluid flow, 159 (11-12), pp.2095-2109. 10.1017/S0016756822000772 . insu-03826209

HAL Id: insu-03826209

<https://insu.hal.science/insu-03826209v1>

Submitted on 25 Oct 2022

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3 **1 Far-field brittle deformation record in the eastern Paris Basin (France)**

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6 **2 Original Article – Special issue “Faults and fractures in rocks: mechanics,**
7 **3 occurrence, dating, stress history and fluid flow”**
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35
36 14 **Keywords**

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38 15 Calcite U-Pb geochronology, Jurassic limestones, Paris Basin, tension gash, far-field
39 16 deformation
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42 17 **Abstract**

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44 18 Jurassic carbonate strata in the eastern Paris Basin exhibit several generations of
45 19 faults, tension gashes and stylolites. Although their relative chronology can sometimes
46 20 be determined according to crosscutting relationships, the duration of major deformation
47 21 phases and their influence on fluid flow and carbonate cementation are still uncertain.
48 22 This contribution aims to clarify the timing of brittle deformation and associated calcite
49 23 cementation. Tension gashes filled by calcite in Jurassic carbonates were sampled in
50 24 outcrops and boreholes and dated through U-Pb geochronology. Almost all the sampled
51 25 fractures were cemented during the Cenozoic period. Continuous deformation spreads
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3 26 from approximately 50 to 30 Ma. Tension gashes oriented N10° to N20° dated at 48 –
4 27 43 Ma show the main Pyrenean contractional stage. A second set of calcites were
5 28 dated around 35-33 Ma and document a Late Eocene - Oligocene extension. A
6 29 transition from the compressional to the extensional regime is expressed by tension
7 30 gashes dated between 43 and 35 Ma. Finally, tension gashes oriented N150° to N175°,
8 31 dated between 32 and 18 Ma, may result from the propagation of the horizontal stress
9 32 generated by the Alpine orogen or by late Pyrenean deformation. Clumped isotope
10 33 thermometry on five samples revealed both low crystallization temperatures (from 27 to
11 34 53 °C) and also the meteoric origin of calcite-precipitating fluids. Our research therefore
12 35 documents a continuous fracturing from the Ypresian to the Rupelian, and less
13 36 expressed brittle deformation during the Miocene period.

37 1. Introduction

38 Plate interiors can record far-field deformation as a consequence of tectonic events at
39 their boundaries (e.g., Lacombe et al., 1996; Lacombe & Mouthereau, 1999). The
40 propagation of stress regimes within the intraplate domain may result in long-
41 wavelength folding, reactivation of existing discontinuities, differential erosion of titled
42 blocks and the development of faults, joints, tension gashes or stylolites, especially in
43 sedimentary strata of intracratonic basins (e.g., Bergerat, 1987; Lacombe & Obert,
44 2000; Parrish et al., 2018). In carbonate rocks, these deformation patterns may
45 enhance fluid flow in permeable strata and favor calcite dissolution-recrystallization, the
46 cementation of primary intergranular porosity or the creation of a secondary pore space
47 (e.g., Bruna et al., 2013). Such far-field deformations have long been recognized in the
48 European plate and paleostress reconstructions were proposed using the inversion of
49 fault slip data or the orientation of calcite twins (e.g., Lacombe et al., 1990).

50 In the context of radioactive waste storage within sedimentary rocks, the knowledge of
51 the precise chronology of paleostress fields is essential to understand the development
52 of fracture networks and the self-sealing capacities of the sedimentary system (e.g.,
53 Sutcliffe et al., 2020). It also brings a source of valuable information regarding the
54 paleo-fluid flow in carbonates and the potential advective flows within claystones

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3 55 (Mazurek et al., 2018; Pagel et al., 2018). In the eastern Paris Basin, tectonic markers
4 56 have been investigated in detail within and around the Underground Research
5 57 Laboratory (URL) of the French National Agency for Radioactive Waste Management
6 58 (Andra) (André et al. 2010, and references therein). All studies converge in
7 59 demonstrating that most of the brittle deformations has developed during Cenozoic
8 60 times. Defining the succession of paleostress regimes from microtectonic analyses in
9 61 this area is, however, complicated due to many uncertainties. The relation between a
10 62 tectonic marker and a corresponding deformation event can indeed be ambiguous (e.g.,
11 63 in the eastern Paris Basin, bedding stylolites have developed both during sedimentary
12 64 burial and in response to extensional stresses during the Eocene – Oligocene, while this
13 65 portion of the basin was subjected to inversion (André et al., 2010). The cross-cutting
14 66 relationships and the relative chronology of tectonic features are sometimes unclear
15 67 (André et al., 2010; Vandeginste et al., 2012; Hoareau et al., 2021). If the same
16 68 paleostress regime occurred during distinct deformation events, the orientation of
17 69 tectonic markers may fail to provide genetic information. For instance, in the eastern
18 70 Paris Basin, NW-SE compression may either be attributed to Late Cimmerian
19 71 Unconformities (LCU, Guillocheau et al., 2000) during the Jurassic/Cretaceous
20 72 transition or to Alpine compression during the Miocene (André et al., 2010). Moreover,
21 73 the orientation of the main stress axes orientation rotated through time during the
22 74 propagation of contractional deformation related to the Pyrenean and Alpine orogens
23 75 (André et al., 2010).

24 76 Based on the orientation of tension gashes and the petrogeochemical characteristics of
25 77 calcite filling fractures, vugs, and intergranular pore spaces, Carpentier et al. (2014)
26 78 proposed a conceptual cementation model for the Middle and Upper Jurassic
27 79 carbonates in the eastern Paris Basin. The synthetic paragenetic sequence of
28 80 Carpentier et al. (2014) is based on relative chronologies of cements, fractures, and
29 81 stylolites, together with the correlation of several petro-geochemical characteristics of
30 82 calcite cements, including cathodoluminescence, major and trace elemental
31 83 concentrations, and on oxygen and carbon stable isotope compositions. Such
32 84 correlations should however be taken with caution, since all these properties are
33 85 controlled by the physical-chemical parameters prevailing locally during calcite

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3 86 precipitation, such as the temperature, the intensity of fluid-rock interaction and the
4 87 fluid/rock ratio, the elemental and isotopic composition of calcite-crystallizing fluids, and
5 88 finally the vertical and lateral variations in the diagenetic medium (pore sizes, presence
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7 89 of stylolites, composition of the host carbonate rocks).

10
11 90 By contrast, calcite U-Pb geochronology constitutes a far more robust tool to provide
12
13 91 absolute temporal correlation of cementation phases and their genetic relationship to
14
15 92 large scale brittle deformation events (Hansman et al., 2018; Beaudoin et al., 2018;
16
17 93 Lawson et al., 2018; Roberts et al., 2020). So far, three U-Pb ages in calcite cement
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19 94 filling either vugs or fractures were evidenced in the studied area using either isotope
20
21 95 dilution-TIMS (Pisapia et al., 2018) or LA-ICP-MS (Pagel et al., 2018; Brigaud et al.,
22
23 96 2020). The first age is around 150 Ma, found exclusively in the Middle Jurassic
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25 97 limestones. The second and third ages are around 43 Ma and 33 Ma, respectively.
26
27 98 Although these ages offer a better understanding of the cementation events within the
28
29 99 studied area, their link with geodynamical events, the duration of deformation (episodic
30
31 100 vs. continuous) and the relationship with paleostress regimes remain uncertain.
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33 101 Moreover, the absence of calcite cement younger than ca. 33 Ma puts into question the
34
35 102 role of the Alpine orogen located closer to the investigated area when compared to the
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37 103 Pyrenean front. Finally, the origin of fluids involved in calcite precipitation in fractures,
38
39 104 vugs, or in the intergranular pore space still requires further investigation. The oxygen
40
41 105 stable isotope composition of calcite in tension gashes was systematically measured by
42
43 106 André et al., 2010, but the nature of mineralizing fluid was not fully resolved because
44
45 107 crystallization temperatures were not known.

46
47 108 In this contribution, we integrated in situ U-Pb geochronology with clumped isotope
48
49 109 thermometry in calcite-filled tension gashes, hydraulic breccias and intergranular pore
50
51 110 space to constrain the origin, impact and duration of the main deformation phases that
52
53 111 affected the eastern Paris Basin. We discuss the nature and temperature of calcite
54
55 112 parent fluids and the impact of brittle structures on the cementation of the Middle and
56
57 113 Upper Jurassic limestones. We compare our ages obtained on calcite cements with
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59 114 those documented by previous authors in the Paris Basin (Mangenot et al., 2018; Pagel
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115 et al., 2018; Pisapia et al., 2018; Brigaud et al., 2020) and in the northern and southern

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3 116 Pyrenees (Parizot et al., 2021; Cruset et al., 2020, respectively). Our results contribute
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5 117 to the understanding of the relationship between intraplate deformation and the
6
7 118 cementation of carbonate rocks in intracratonic sedimentary basins.

9 119 **2. Geological setting**

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11
12 120 A detailed view of facies and diagenesis in the Jurassic strata of the eastern Paris Basin
13
14 121 is given in Brigaud et al., (2014) and Carpentier et al. (2014). A succession of blocky
15
16 122 calcite phases was evidenced, that precipitated either during burial (Vincent et al., 2006;
17
18 123 Brigaud et al., 2020), or during the inversion phase that occurred throughout the
19
20 124 Cenozoic period (Buschaert et al., 2004; Pagel et al., 2018; Brigaud et al., 2020; Blaise
21
22 125 et al., 2022). Blocky calcite of Cenozoic ages precipitated from meteoric fluids
23
24 126 (Buschaert et al., 2004) and display a typical dull brown cathodoluminescence
25
26 127 (Carpentier et al., 2014). Below, we will first focus on the sedimentary cycles and facies
27
28 128 of the Middle and Upper Jurassic limestones, and subsequently on major faults and
29
30 129 paleostress regimes.

31
32 130 The Early Bajocian consists of about 30 m-thick bioclastic limestones together with
33
34 131 bioherms, called *Calcaires à Polypiers* Formation (Durlet & Thierry, 2000, Brigaud et al.,
35
36 132 2014), changing to marly sedimentation during the Early/Late Bajocian transition
37
38 133 (*Marnes de Longwy* Formation). A new carbonate ramp then developed in the
39
40 134 northeastern Paris Basin from Late Bajocian to Early Callovian, with a typical inner ramp
41
42 135 depositional environment (oolitic shoal or lagoon: *Oolites miliaire* and *Calcaires de*
43
44 136 *Chaumont* Formations) at the origin of about 150 m-thick oolitic, bioclastic or mud-
45
46 137 dominated limestones (Brigaud et al., 2009). A general flooding of the platform resulting
47
48 138 in the deposition of locally thick (>100 m) clay-rich sediments started during the
49
50 139 Callovian and lasted until the Early Oxfordian. The carbonate sedimentation started
51
52 140 again during the Middle Oxfordian, with about 150 m-thick reefal-dominated limestones
53
54 141 (*Complexe récifal* Formation) and oolitic limestones (*Oolithe de Lamothe* and *Oolithe de*
55
56 142 *Saucourt* Formations, Brigaud et al., 2014). Flooding of the platform coeval with a
57
58 143 climate cooling (Brigaud et al., 2008; Carpentier et al., 2007; Olivier et al., 2004)
59
60 144 favoured a decrease in the carbonate production and the increase of siliciclastic inputs

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3 145 at the beginning of the Late Oxfordian with the deposition of the *Argiles à huîtres*
4 (Carpentier et al., 2010; Brigaud et al., 2014). A major carbonate production crisis
5 146 (Carpentier et al., 2010; Brigaud et al., 2014). A major carbonate production crisis
6 occurred during the Oxfordian/Kimmeridgian transition (Lefort et al., 2011), with marls-
7 147 occurred during the Oxfordian/Kimmeridgian transition (Lefort et al., 2011), with marls-
8 148 dominated sedimentation (*Marnes à Exogyres* Formation), followed by a mixed
9 149 carbonate, evaporite and siliciclastic ramp environment during the Tithonian (Brigaud et
10 149 carbonate, evaporite and siliciclastic ramp environment during the Tithonian (Brigaud et
11 al., 2018).
12 150 al., 2018).

13
14 151 The major tectonic discontinuities in the eastern Paris Basin are reported in Figure 1. A
15 152 detailed description of the main fault systems can be found in Le Roux (1980), Bergerat
16 152 detailed description of the main fault systems can be found in Le Roux (1980), Bergerat
17 et al. (2007) and André et al. (2010). Some faults correspond to Variscan sutures that
18 153 et al. (2007) and André et al. (2010). Some faults correspond to Variscan sutures that
19 later were reactivated during Meso-Cenozoic times, such as the E-W *Vittel* fault, the E-
20 154 later were reactivated during Meso-Cenozoic times, such as the E-W *Vittel* fault, the E-
21 W to NE-SW *Metz* fault and the NNW-SSE to NW-SE *Marne* fault. By contrast, the
22 155 W to NE-SW *Metz* fault and the NNW-SSE to NW-SE *Marne* fault. By contrast, the
23 156 NNE-SSW *Gondrecourt* and *Joinville* grabens are rooted within the Keuper halite
24 156 NNE-SSW *Gondrecourt* and *Joinville* grabens are rooted within the Keuper halite
25 157 Formation and did not propagate through the basement. These symmetric troughs are
26 157 Formation and did not propagate through the basement. These symmetric troughs are
27 158 related to the European Cenozoic Rift System (ECRIS, Coulon, 1992; Ziegler & Dèzes,
28 159 2007; Ring & Gerdes, 2016). Roughly perpendicular to the *Gondrecourt* graben, the
29 159 2007; Ring & Gerdes, 2016). Roughly perpendicular to the *Gondrecourt* graben, the
30 160 *Poissons* fault system constitutes the western border of the area currently investigated
31 160 *Poissons* fault system constitutes the western border of the area currently investigated
32 161 by Andra.
33
34

35 162 At the regional scale, the orientations and relative chronology of minor faults, tension
36 163 gashes and stylolites can be correlated with the major deformation events recorded in
37 164 the western European domain during the Meso-Cenozoic period (Bergerat, 1985, 1987;
38 164 the western European domain during the Meso-Cenozoic period (Bergerat, 1985, 1987;
39 165 Villemin, 1986; Letouzey, 1986; Coulon & Frizon de Lamotte, 1988; Coulon, 1992;
40 165 Villemin, 1986; Letouzey, 1986; Coulon & Frizon de Lamotte, 1988; Coulon, 1992;
41 166 Rocher et al., 2004; Bergerat et al., 2007; André, 2010).
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43

44 167 While the Triassic was a period of tectonic quiescence, a first E-W extensional regime is
45 168 recorded during the Late Triassic and lasts until the Middle Liassic (Guillocheau et al.,
46 168 recorded during the Late Triassic and lasts until the Middle Liassic (Guillocheau et al.,
47 169 2000). A second extension of similar orientation occurred during the Late Jurassic,
48 169 2000). A second extension of similar orientation occurred during the Late Jurassic,
49 170 attributed to the Central Atlantic opening. This regime evolved into an E-W to NE-SW
50 170 attributed to the Central Atlantic opening. This regime evolved into an E-W to NE-SW
51 171 compression during the Early Cretaceous, with two discrete episodes that generated
52 171 compression during the Early Cretaceous, with two discrete episodes that generated
53 172 significant uplift and erosion (Guillocheau et al., 2000, Brigaud et al., 2018): (1) The
54 172 significant uplift and erosion (Guillocheau et al., 2000, Brigaud et al., 2018): (1) The
55 173 Late Cimmerian Unconformities (LCU) corresponding to a succession of two distinct
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3 174 truncations in the Paris Basin and (2) the Late Aptian Unconformity (LAU). For some
4
5 175 authors however, these Early Cretaceous deformations more likely relate to an
6
7 176 extensional regime in the eastern Paris Basin (André et al., 2010).

8
9 177 Early Paleocene NNW–SSE to N–S shortening is reported by André et al. (2010) in the
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11 178 eastern Paris Basin. Briaies et al. (2016) show that long wavelength deformation
12
13 179 occurred in the central Paris Basin during the intra-Maastrichtian to pre-Thanetian. This
14
15 180 deformation, known as the Laramian or Laramide phase (Ziegler et al., 1990), is well
16
17 181 documented in western Europe and is coeval with the North Atlantic opening (Briaies et
18
19 182 al., 2016 and references therein). Briaies et al. (2016) document two other deformation
20
21 183 phases during the Ypresian: a minor medium-wavelength deformation during Early
22
23 184 Ypresian that could be a far-field consequence of the North Atlantic rifting, and a long
24
25 185 wavelength deformation during the uppermost Ypresian, with the emersion of the
26
27 186 central Paris Basin in response to the convergence between the Iberian and Eurasian
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29 187 plates. So far, these Ypresian phases are not documented in the eastern border of the
30
31 188 Paris Basin.

32
33 189 During Eocene times, the Pyrenean compression generated a NNE–SSW transcurrent
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35 190 regime (Pyr1, André et al., 2010) that will rotate into NE-SW (Pyr2, André et al., 2010).
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37 191 According to André et al., (2010), Pyr2 is strongly expressed in the area, but its age
38
39 192 remains uncertain. Indeed, for some authors, a NE-SW compression more likely
40
41 193 occurred after the Oligocene extension (Bergerat, 1985).

42
43 194 A NW-SE to E-W extension prevailed during the Late Eocene - Oligocene, and the
44
45 195 discontinuities generated during the Pyr1 and Pyr2 strike-slip movements were
46
47 196 reactivated as normal and oblique faults (Lacombe et al., 1990). The *Gondrecourt* and
48
49 197 *Joinville* grabens formed at that time, together with the main grabens constituting
50
51 198 ECRIS. Bedding stylolites developed in the Middle and Upper Jurassic carbonates in
52
53 199 response to this extensional deformation (Coulon, 1992). Bergerat et al. (2007)
54
55 200 considered this Oligocene event as the most strongly expressed in the area.

201 A ENE–WSW shortening, which post-dates the Oligocene extension was recognized by
202 Bergerat (1987) and André et al. (2010) and may correspond to a later expression of the
203 Pyrenean compression (Pyr3, André et al., 2010).

204 The Oligocene NW-SE extension switched into a NE-SW extensional regime during the
205 Oligocene - Miocene transition through a σ_2/σ_3 permutation. The Alpine compression
206 is then expressed during Miocene-Pliocene times by a clockwise rotation of σ_1 from
207 WNW–ESE to NNW–SSE (André et al., 2010).

208 It is worth noting that, due to the lack of syn-deformation sedimentary record, all age
209 attributions only rely on correlations with the better-constrained tectonic agenda of
210 adjacent domains such as Rhine graben, Alpine belt or Pyrenean domain.

211 3. Material and methods

212 3.a. Sampling and petrography

213 Twenty-seven samples were collected from the Middle Jurassic (Bajocian and
214 Bathonian) and Upper Jurassic (Oxfordian) limestones, from outcrops, quarries, and
215 boreholes (Fig. 1). They mostly correspond to tension gashes filled by calcite affecting
216 mudstones or grainstones from well-identified sedimentary formations (Fig. 2). The
217 orientation of nine tension gashes is reported. Five samples correspond to calcite filling
218 coral or moldic vugs, sometimes connected to fractures. Two samples, collected at
219 Leurville (Fig. 1), are hydraulic breccias found as isolated rock fragments dispersed in
220 agricultural crops. Eleven samples contain several tension gashes, either parallel or
221 crossing each other. In three samples, calcite cements filling the intergranular porosity
222 were targeted for U-Pb geochronology.

223 Samples were either mounted in epoxy or prepared as 30 μm thin sections and
224 polished. All samples were observed under the optical microscope using transmitted
225 polarized light and under cathodoluminescence (CL) microscopy at 13 keV et 130 mA.
226 For each sample, a series of photomicrographs were gathered to create a composite
227 image (supplementary materials).

228 3.b. Calcite U-Pb geochronology

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3 229 The method which has been employed is similar to that described in Brigaud et al.
4 230 (2020). Sampling and analysis were performed using a Sector Field Inductively Coupled
5 231 Plasma Mass Spectrometer (SF-ICP-MS) Element XR (Thermo ScientificTM, Waltham,
6 232 MA, USA) coupled to a 193 nm ArF Laser Ablation System (TELEDYNE, Thousand
7 233 Oaks, CA, USA) at the Geosciences Paris-Saclay (GEOPS) laboratory of the University
8 234 of Paris-Saclay.

9
10 235 Samples and calcite reference materials were ablated at a frequency of 8 Hz and a
11 236 fluence of 1 to 2 J.cm⁻² with a circular-shaped beam diameter of 150 µm. Glass
12 237 reference material NIST614 was ablated at a frequency of 10 Hz, a fluence of 6.25
13 238 J.cm⁻² and a beam size of 110 µm. Each analysis consisted of 30 s background
14 239 acquisition followed by 30 s of sample ablation and 30 s washout. Prior to analysis,
15 240 each spot was pre-ablated during 4 s at a frequency of 8 Hz and with a fluence of 2
16 241 J.cm⁻². NIST614 was used to correct for ²⁰⁷Pb/²⁰⁶Pb fractionation, while ²³⁸U/²⁰⁶Pb were
17 242 corrected using WC-1 (Woodhead et al., 2016; Roberts et al., 2017). To ensure
18 243 accuracy, two secondary calcite reference materials were included in each analytical
19 244 session: Duff Brown Tank (DBT), dated at 64.0 ± 0.7 Ma by U-Pb isotope dilution (Hill et
20 245 al., 2016), and B6, dated at 43.0 ± 1.0 Ma by LA-ICP-MS (Pagel et al., 2018). Each
21 246 analytical sequence is composed of five reference material analyses (one NIST614, one
22 247 WC-1, one DBT and two B6) inserted at between 10 and 15 spots on unknown calcites.
23 248 Data was acquired overnight in five sequences of around 400 analyses.

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26 249 Data was reduced in Iolite[®] (Paton et al., 2011) using the NIST614 glass as the primary
27 250 reference material for baseline subtraction, to correct for Pb isotope mass bias and for
28 251 the estimation of ²⁰⁶Pb/²³⁸U and ²⁰⁷Pb/²⁰⁶Pb instrumental drift over the sequencing time.
29 252 No down-hole fractionation correction is applied in Iolite[®] (Nuriel et al., 2017).

30
31
32 253 The 2 standard errors in the mean ²⁰⁷Pb/²⁰⁶Pb and ²⁰⁶Pb/²³⁸U ratios measured on
33 254 NIST614 during the analytical session were propagated to the final age uncertainty of all
34 255 calcite samples by quadratic addition. Data was plotted on Tera-Wasserburg graphs
35 256 using IsoplotR online (Vermeesch, 2018), without anchoring the initial ²⁰⁷Pb/²⁰⁶Pb value.
36 257 Error ellipses of each spot and the error in the Tera-Wasserburg intercept age are at a
37 258 level of two sigma. In each Tera-Wasserburg graph, a first age uncertainty is given that

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3 259 does not include uncertainty propagations. A second age uncertainty is given, by
4 260 propagating the systematic uncertainty of the age of primary reference material WC-1
5 261 (2.6%), and the 2 standard errors of the $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{206}\text{Pb}/^{238}\text{U}$ of the analytical
6 262 session by quadratic addition. Sample ages and uncertainties are listed in Table 1 and
7 263 detailed metadata for LA-ICP-MS calcite U-Pb geochronology is available in
8 264 supplementary materials.

14 265 3.d. Oxygen and carbon stable isotope composition and clumped isotope thermometry

16 266 For oxygen and carbon stable isotope analysis, eleven calcite crystals from fracture in-
17 267 fills were fragmented and collected with tweezers under the magnifying glass. The
18 268 crystals were subsequently grounded into a homogeneous powder in an agate mortar.
19 269 Oxygen and carbon isotopes were analysed in the Geosciences Laboratory of Rennes
20 270 University (France) following the methodology described in Malfilatre, 2012. All isotopic
21 271 values are reported to the V-PDB standard (Table 2).

22 272 Five samples consisting of large in-fillings were selected for clumped isotope analysis.
23 273 30 mg of calcite was sampled using a micro-drilling tool. Δ_{47} measurements were
24 274 performed at the California Institute of Technology (USA) in two analytical sessions
25 275 (April and May 2021) with an automated acid digestion and gas purification device
26 276 coupled to a dual inlet Thermo MAT253, as described in Passey et al., 2010. Samples
27 277 were weighed into silver capsules (~ 8 mg) and reacted in a common phosphoric acid
28 278 bath (~ 103 %) for 20 minutes at 90 °C under static vacuum. The resulting CO₂ was
29 279 passed through an ethanol/dry ice U-trap (~ -80 °C) before being collected on a liquid
30 280 nitrogen temperature (-196 °C) U-trap. Following the 20 minutes reaction period, the
31 281 collected CO₂ was thawed, entrained in helium, and carried through a Porapak Q
32 282 120/80 mesh gas column held at -20 °C using He as the carrier gas. The purified CO₂
33 283 was analyzed using a Thermo Scientific MAT 253 Mass Spectrometer set to collect
34 284 masses 44-49. Mass 48 was only monitored to detect any hydrocarbon contaminant.
35 285 $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ data was also acquired as part of each Δ_{47} analysis and calculated using
36 286 the parameters reported relative to the PDB reference frame based on the calibrated
37 287 composition of the laboratory working gas and the correction scheme and constants
38 288 from Brand et al., (2010). In order to account for the temperature dependence of oxygen

isotope fractionation between CO₂ gas and carbonate resulting from the reaction with phosphoric acid at 90 °C, a fractionation factor of 1.00811 was used for calcite (following Swart et al., 1991). The raw Δ_{47} data was corrected for instrument non-linearity and scale compression (Dennis et al., 2011) using several heated (at 1000°) and equilibrated gases (at 25°C) of various bulk isotopic compositions that were run during each session. These gases were used to convert measurements into the inter-laboratory absolute reference frame (Dennis et al., 2011). To guarantee accuracy of the Δ_{47} data, we routinely analyzed two carbonate reference materials (Carrara marble and TV04). One of these two carbonate standards was analyzed once for every five analyses of the unknown samples in order to check for procedural analytical stability and accuracy, and to determine the long-term external reproducibility of our measurements. The Δ_{47} values obtained for these carbonates over the course of this study (May to July 2019) are: $\Delta_{47\text{-CDES25}} = 0.409 \pm 0.016\text{‰}$ (1SD, n = 10) for Carrara; $\Delta_{47\text{-CDES25}} = 0.666 \pm 0.011\text{‰}$ (1SD, n = 8) for TV04, i.e., within accepted Δ_{47} values for TV04 ($\Delta_{47\text{-CDES25}} = 0.655\text{‰}$) and Carrara ($\Delta_{47\text{-CDES25}} = 0.405\text{‰}$). Finally, the corrected Δ_{47} values were converted into temperatures using the composite $\Delta_{47}\text{-T}$ calibration of Bonifacie et al. (2017), which has been shown to be appropriate for calcite and dolomite between 0 and 300 °C, and which has been shown to be consistent with measurements made at Caltech. The oxygen isotopic compositions of the water ($\delta^{18}\text{O}_{\text{water}}$) from which the carbonates precipitated were calculated for each estimated $T_{\Delta_{47}}$ using the bulk $\delta^{18}\text{O}_{\text{carb}}$ values and the calcite-water fractionation equation from O'Neil et al. (1969).

4. Results

4.a. Calcite petrography

All samples consist of blocky calcite filling tension gashes (Fig. 3) and vugs, apart from the hydraulic breccia sampled at Leurville (LEU samples, Fig. 4). Crystal sizes vary from a few hundred micrometers in small tension gashes to a few millimeters in hydraulic breccias. No syntaxial or antitaxial growth orientation are identified (*sensu* Bons et al., 2012). While most samples contain clean crystals, a few of them (e.g., SOM1-1, SOM1-2, REM1) incorporated micrite inclusions from the host rocks during crystallisation (Fig. 5). Most samples contain non-luminescent or weakly brown luminescent crystals under

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3 319 CL, without clear successive growth stages. No evidence of multi-phase fracture
4 320 opening was observed. Apart from samples SOR6-c and DGSM29-1, all fractures are
5 321 entirely cemented by blocky calcite. No dissolution features, such as corrosion gulfs,
6 322 were observed. Samples SR6 and SOR6 display ambiguous cross-cutting relationships
7 323 between at least two distinct generations of tension gashes that are filled with calcite
8 324 displaying the same cathodoluminescence (Fig. 6). Petrographic illustrations of all
9 325 samples are available in supplementary materials.

16 326 4.b. U-Pb ages

18 327 Among the 27 samples collected for the purpose of this study, 4 were not amenable to
19 328 U-Pb geochronology and were thus excluded. A total of 32 U-Pb ages are reported
20 329 (Table 1). The oldest age measured in tension gashes is found in the Upper Bathonian
21 330 sampled in the Montcornet borehole (sample A901-22), dated at 92.9 ± 10.3 Ma. In the
22 331 same sample, another population of tension gashes is dated at 68.4 ± 4.0 Ma. In the
23 332 Sarazinère quarry, a tension gash oriented N50 (sample SR6a) gives an age of $58.9 \pm$
24 333 1.8 Ma. Most of the ages obtained are between 50.4 ± 2.4 Ma (sample PPA1073) and
25 334 27.4 ± 2.8 Ma (sample MXV9a). A hydraulic breccia sampled at Leurville (sample LEU-
26 335 2) gives an age of 22.2 ± 1.2 Ma. Finally, a tension gash oriented N150 gives a younger
27 336 age of 18.7 ± 1.0 Ma (sample SR6b).

28 337 In addition, three ages were measured in the intergranular calcite cements, yielding
29 338 ages of 100.9 ± 22.7 Ma (sample A901-22e), 57.7 ± 2.6 Ma (sample SR6c), and $30.6 \pm$
30 339 7.0 Ma (sample DGSM29-2b).

43 340 4.c. Oxygen and carbon stable isotope composition and clumped isotopes

45 341 $\delta^{18}\text{O}$ values range between -7.0 ‰_{V-PDB} (sample SOR6ab) and -10.5 ‰_{V-PDB} (samples
46 342 BAZX90a and LEU1-1), while $\delta^{13}\text{C}$ are between 1.1 ‰_{V-PDB} (sample A901-22a) and 3.4
47 343 ‰_{V-PDB} (sample VCLD). $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values measured by clumped isotopy are
48 344 identical within the limits of analytical uncertainty to the ones obtained from the
49 345 traditional method where C and O stable isotope compositions are measured
50 346 separately. The highest Δ_{47} temperature is obtained for sample BAZX90a (53 ± 5 °C),
51 347 and the lowest for sample SR6b (27 ± 3 °C). Three other samples give temperatures of

348 37 ± 2 °C (VCLD), 41 ± 1 °C (25209) and 42 ± 2 °C (25229). Sample types and
349 associated isotopic values are summarized in Table 2.

350 **5. Discussion**

351 5.a Ages, impact and duration of brittle deformation

352 Since no syntaxial or antitaxial growth orientation were identified (sensu Bons et al.,
353 2012), the syn-kinematic precipitation of calcite crystals within tension gashes is unclear
354 (Roberts and Holdsworth (2022)). Field observations have revealed that tension gashes
355 are generally associated with tectonic stylolites, suggesting syn-kinematic calcite
356 dissolution and recrystallization (André et al., 2010). Furthermore, although CL sectorial
357 zoning is observed in some samples, no successive calcite growth stages can be
358 clearly determined, suggesting that all crystals filling a given tension gash or vug are
359 monogenic. An isochron obtained from the sampling of several crystals filling a given
360 tension gash proves that calcite formed during a single precipitation event. Yet, calcite
361 cements can post-date fracture opening. Such uncertainty is somehow minimized by the
362 large number of samples considered for this research, and by the good agreement
363 between the orientation of fractures and their U-Pb ages, which will be discussed below.

364 Calcite mechanical twinning is observed in some samples (LEU1-1, VCLD, BAZX90a,
365 REM-3-2, REM1, OT-1-2, SOM1-1, SOM1-2). The development of such twinning cannot
366 be correlated with the age or location of the samples. The absence of calcite twinning in
367 most samples may be due to the small size of blocky calcite crystals filling tension
368 gashes (Lacombe et al., 1990).

369 The tension gash showing the oldest age was sampled in the Montcornet borehole,
370 located around 200 km north-west of the Andra URL, in the vicinity of the Ardennes
371 massif (Fig. 1). The U-Pb age of 92.9 ± 10.3 Ma suggests the Albian to Santonian
372 period that may be related to a major inversion phase documented in northern France
373 (Bergerat & Vandycke, 1994). Interestingly, this calcite U-Pb age matches with the age
374 obtained on the first dolomite cement identified in the Middle Jurassic at depth in the
375 central Paris Basin (Mangenot et al., 2018). Our data agrees with André et al. (2010)
376 and tends to indicate the absence of this tectonic phase around the Andra URL. Another

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3 377 sample in the same borehole was dated at 68.4 ± 4.0 Ma, i.e., the Cretaceous-
4 378 Paleocene transition (Fig. 7). This age cannot be confidently interpreted and attributed
5 379 to a known deformation phase. It may either be linked to the so-called “sub-hercynian”
6 380 inversion phase defined by Ziegler (1987) or to an early stage of the Pyrenean
7 381 compression, as evidenced in the south-eastern Pyrenees (Cruset et al., 2020). In the
8 382 central Paris Basin, a second blocky calcite generation was also dated at 68.5 ± 7.7 Ma
9 383 in the deep Middle Jurassic (Mangenot et al., 2018). Whatsoever, these early phases
10 384 recorded here more than 150 km north or west of the URL are not described in the
11 385 eastern Paris Basin, where brittle structures are mostly thought to be Cenozoic in age
12 386 (André et al., 2010; Bergerat et al., 2007, this study). Indeed, the ages of tension
13 387 gashes and hydraulic breccias documented here span from 58.9 ± 1.8 Ma to 18.7 ± 1.0
14 388 Ma, i.e., from the Thanetian to the Burdigalian periods (Fig. 7).

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17 389 Our data show that tectonic quiescence then prevailed during the Paleocene and Early
18 390 Ypresian, a result in agreement with the slow rate of N-S convergence between the
19 391 Iberian and Eurasian plates during this period (Mouthereau et al., 2021; Grool et al.,
20 392 2018; Macchiavelli et al., 2017). A single tension gash oriented $N50^\circ$ is dated at $58.9 \pm$
21 393 1.8 Ma (Paleocene) in the Sarazinière quarry. This fracture may be related to an early
22 394 stage of the Pyrenean compression. Alternatively, this event may be linked to the so-
23 395 called “Laramide” phase (Ziegler, 1987), which corresponds to a major inversion period
24 396 with an uplift and erosion quantified to about 600 m in the Morvan Massif, south of the
25 397 Paris Basin, and to 300 m in the study area (Barbarand et al., 2013, Blaise et al., 2014).
26 398 This event does not seem to be restricted to the eastern border of the Paris Basin, since
27 399 a U-Pb age of 61.1 ± 2.5 was documented for calcite cements in the Middle Jurassic at
28 400 depth in the central Paris Basin (Mangenot et al., 2018).

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31 401 A continuous deformation is then recorded in the age distribution of tension gashes from
32 402 the Late Ypresian to the Rupelian, although two age clusters can be evidenced between
33 403 40-50 Ma (9 samples) and 30-35 Ma (7 samples) (Fig. 7). The first age cluster (40-50
34 404 Ma) is associated to $N10^\circ$ to $N20^\circ$ tension gashes (BAZX90a, MXV7, VCLD). The Late
35 405 Ypresian to Bartonian opening and filling of these gashes probably record the far-field
36 406 onset of the main Pyrenean compressional event at that time (Macchiavelli et al., 2017).

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3 407 Within this deformation phase, discrete tectonic pulses may have generated higher
4 408 rates of fracturing. A cluster of ages is recorded at ca. 48 Ma (samples A00607c,
5 409 SOR6ab, SOR6c, BAZX90a), synchronous to the emersion of the central Paris Basin
6 410 (Briais et al., 2016) in response to the main Pyrenean compression period (e.g., Cruset
7 411 et al., 2020). Several tension gashes are then dated at ca. 43 Ma (Fig. 7), matching the
8 412 U-Pb ages reported by Pagel et al. (2018) along the Gondrecourt graben and the age of
9 413 a vertical tension gash in HTM102 borehole close to the Andra URL (Brigaud et al.,
10 414 2020).

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12 415 A reactivation of the variscan Vittel fault south of the studied area is evidenced by two
13 416 fractures sampled in the Sommerécourt quarry and dated at 42.5 ± 3.9 Ma and $40.9 \pm$
14 417 1.7 Ma (Fig. 7). At Removille, sample REM1 was collected along a fault delimiting a
15 418 small graben of similar orientation to the Gondrecourt and Joinville grabens. The age of
16 419 this sample, 42.1 ± 2.7 Ma confirms the synchronous formation of these structures.
17 420 Finally, sample OT1-2 from the Ottange quarry dated at 40.8 ± 2.2 Ma demonstrates
18 421 that this intraplate deformation extended far north of the study area (Fig. 1). They are
19 422 also recorded in the central Paris Basin, as documented by Mangenot et al. (2018).
20 423 These deformations and cementations are all interpreted as a far-field consequence
21 424 of Pyrenean shortening.

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23 425 A few fractures are dated between 40 and 35 Ma, while another main fracturing event is
24 426 identified at around 33 Ma (Fig. 7, Table 1). Ten of the 32 measured U-Pb ages
25 427 obtained are in the 35-30 Ma range, matching previous U-Pb ages around 33 Ma
26 428 reported for fractures along the Gondrecourt faults (Pagel et al., 2018) and vug-filling
27 429 calcites in Oxfordian limestones from the Andra URL borehole cores (Pisapia et al.,
28 430 2018). Following Pagel et al. (2018) by analogy with the known tectonic agenda of the
29 431 Rhine Graben, we suggest that these dated structures are related to extensional
30 432 deformation and the opening of the ECRIS (Dezès et al., 2004; Bergerat et al., 2007;
31 433 Ring & Gerdes, 2016), an event that is strongly expressed in the eastern Paris Basin
32 434 (Bergerat et al., 2007) as attested by the formation of the small Gondrecourt and
33 435 Joinville grabens. A second generation of tension gashes collected along the Removille
34 436 graben (REM3-2) yield an age of 31.7 ± 3.8 Ma, showing that this graben was formed

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3 437 through a two-step evolution identical to the Gondrecourt graben, i.e., a strike-slip or
4 438 oblique displacement during the Lutetian, followed by extension during the Rupelian.

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7 439 On the other hand, we cannot fully exclude a compressional origin for all of these ca. 33
8 440 Ma tension gashes as a consequence of further Pyrenean or Alpine far-field
9 441 deformations (Cruset et al., 2020; Parizot et al., 2021). Whatsoever, we show here that
10 442 deformation in the eastern Paris Basin occurred continuously from the Late Ypresian to
11 443 the Rupelian (Fig. 7) and that the transition from a contractional regime prevailing during
12 444 the Eocene period to an extensional deformation during the Oligocene may have been
13 445 progressive.

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16 446 After this 33 Ma ECRIS-related event, few younger gashes are dated around 30 Ma.
17 447 Tension gashes developed in the quarries of Dugny-sur-Meuse and Maxey-sur-Vaise
18 448 dated around 32-27 Ma are oriented N170° and N175° and may have opened during a
19 449 compressional phase documented by Bergerat (1987) and André et al. (2010) and
20 450 interpreted as a late Pyrenean horizontal stress. This age also replicates the ones
21 451 obtained by Parizot et al. (2021) in the north Pyrenean foreland basin, and those of
22 452 Cruset et al. (2020) in the southern Pyrenees, interpreted as a short-living reactivation
23 453 of the compression at that time and whose expression is recorded up to the southern
24 454 coast of England (Parrish et al., 2018). Alternatively, such tension gashes could have
25 455 formed in response to a NE-SW extension generated from an interchange between σ_2
26 456 and σ_3 (André et al., 2010).

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29 457 Post-Rupelian brittle structures are scarce (Fig. 7). The absence of tension gashes
30 458 dated between around 27 Ma and 22 Ma suggests a period of quiescence during
31 459 Chattian before the renewal of compressive deformation. Calcite-cemented hydraulic
32 460 breccias affecting the Oolithe de Saucourt Formation precipitated during the Chattian –
33 461 Aquitanian period. In the Sarazinière quarry, a tension gash oriented N150° gave a
34 462 younger age of 18.7 ± 1.0 Ma. Thus, this renewal of deformation had a limited impact on
35 463 the opening of fractures in the eastern Paris Basin. This is in agreement with field
36 464 observations that documented poorly-developed tectonic microstructures related to
37 465 Miocene times (André et al., 2010), and the absence of reactivation of the main
38 466 discontinuities (Bergerat et al., 2007).

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3 467 Both Miocene calcites were sampled in the vicinity of the NW-SE Poissons fault system
4 468 (Fig. 1) that reactivated in response to the compression during either the earliest stages
5 469 of the Alpine contractional stress or a Late Pyrenean event during
6 470 Aquitanian/Burdigalian (Parizot et al., 2021 ; Hoareau et al., 2021).
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11 471 Finally, the absence of younger ages indicates that the growth of the nearby Jura fold-
12 472 and-thrust belt formed roughly between 11 and 3 Ma (Homberg et al., 2002; Smeraglia
13 473 et al., 2021) had no or very limited impact on the deformation of the eastern Paris Basin.
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17 474 To sum up, the deformation of the eastern Paris Basin is essentially related to far-field
18 475 propagation of compressional stress during the Pyrenean orogen growth. It has been
19 476 accommodated continuously by the opening of tension gashes and the development or
20 477 reactivation of strike-slip faults and stylolites between around 50 Ma (sample PPA1073)
21 478 and 27 Ma (sample MXV9a), with deformation pulses at ca. 48 Ma and 43 Ma, and only
22 479 interrupted shortly by the ECRIS-related extensional event at around 33 Ma.
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28 480 On a larger scale, this tectonic agenda of the eastern Paris Basin is consistent with the
29 481 U-Pb ages of slickenfibres and fracture filling calcites in the north foreland basin of the
30 482 Pyrenees (Parizot et al., 2021), in the southeastern Pyrenean fold and thrust belt and
31 483 the south foreland Ebro basin (Cruset et al., 2020) and along the Cevennes fault system
32 484 (Parizot et al., 2022). South of the Paris Basin, fluorite mineralization occurred likely in
33 485 response of this contractional event (Lenoir et al., 2021). This event is also recorded in
34 486 the Jura fold-and-thrust belt, where a pre-orogenic NE-SW strike-slip fault was recently
35 487 evidenced through U-Pb geochronology of slickenfibre calcite yielding two ages similar
36 488 to ours at 48.4 ± 1.5 and 44.7 ± 2.6 Ma (Smeraglia et al., 2021).
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44 489 5.b. Origin and Temperature of calcite-mineralizing fluids 45 46

47 490 The meteoric origin of waters from which calcite precipitated in tension gashes was
48 491 suggested by André et al. (2010) on the basis of the $\delta^{18}\text{O}$ values measured in calcite.
49 492 Yet, the oxygen stable isotope composition of parent-waters was uncertain, since the
50 493 fractionation factor between H_2O and calcite was estimated from only six two-phased
51 494 aqueous fluid inclusions that homogenized at temperatures ranging from 31 to 38 °C
52 495 (Buschaert et al., 2004). Thanks to the Δ_{47} clumped isotope composition of calcite, the
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3 496 origin of parent-waters can be determined with a higher level of confidence, especially
4 497 in low-temperature environments in which aqueous inclusions remain in a single-phase
5 498 metastable state (Goldstein & Reynolds, 1994). The $\delta^{18}\text{O}$ values of calcite-mineralizing
6 499 waters determined on five samples from their clumped isotope composition, range from
7 500 -4.6 to -2.6 ‰_{V-SMOW}, supporting the views of André et al. (2010) and Pagel et al.
8 501 (2018) regarding its meteoric origin.

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14 502 The temperature at which calcite cements precipitated in veins and hydraulic breccias
15 503 along the Gondrecourt graben was lower than 50 °C (Pagel et al., 2018), slightly higher
16 504 than the expected temperature of the host rock. Yet, Brigaud et al. (2020) reported
17 505 higher temperatures, up to 90 °C, in a calcite-filled tension gash dated at 41.5 ± 4.8 Ma
18 506 at the vicinity of the Gondrecourt graben (well HTM102 located 2 km from the graben,
19 507 Fig. 7). These temperatures suggest that hot fluid flow migrated along deeply rooted
20 508 faults during the Ypresian/Bartonian compressional regime (Brigaud et al., 2020). Here,
21 509 the highest Δ_{47} temperature is around 53 °C in the *Calcaires de Chaumont* Formation
22 510 (Bathonian), showing that meteoric waters were slightly in thermal disequilibrium with
23 511 their host rocks. In such case, meteoric waters from deeper strata may have risen
24 512 upward through the fracture network (Ge & Garven, 1992; Sibson, 1994). In addition,
25 513 the Δ_{47} temperatures may also reflect the burial depth at which calcite precipitation
26 514 occurred: the oldest fractures may have developed at a depth of 700 to 1000 m. Since
27 515 the eastern Paris Basin experienced inversion and associated erosion during Cenozoic
28 516 times, the youngest fractures (Miocene) were generated closer to the present-day
29 517 surface (Fig. 8).

30 518 5.c. Origin of intergranular calcite cements

31 519 The impact of Cenozoic intraplate deformation in the interparticle cementation of the
32 520 Jurassic limestones in the eastern Paris Basin is still unclear. André et al. (2010) and
33 521 Carpentier et al. (2014) stressed that contractional deformation generated vertical
34 522 stylolites with horizontal peaks and that a high density of bed-parallel stylolites could be
35 523 attributed to the Late Eocene – Oligocene extensional period. These tectonic stylolites
36 524 developed during the inversion of the eastern Paris Basin and may have contributed to
37 525 calcite dissolution-recrystallization and eventually to the cementation of intergranular

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3 526 pores (Buschaert et al., 2003; André et al., 2010). This scenario is supported by recent
4 527 U-Pb ages of vug-filling calcite in the Oxfordian limestones at ca. 33 Ma (Pisapia et al.,
5 528 2018), showing that the Late Eocene – Oligocene extension effectively contributed to
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7 529 occlude the pore space.
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11 530 Among the samples considered for this research, three display blocky calcite cementing
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13 531 the intergranular porosity large enough to be targeted for U-Pb dating. In sample
14 532 DGSM29-2, these blocky calcites yielded an age of 30.6 ± 7.0 Ma (DGSM29-2b, table
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16 533 1), identical, within the limits of analytical uncertainties, to the age of the nearby N170
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18 534 tension gashes (DGSM29-2a and DGSM29-1) at 32.0 ± 1.5 Ma and 31.6 ± 2.9 Ma. In
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20 535 sample A901-22, blocky calcite cements filling intergranular pores are dated at $100.9 \pm$
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22 536 22.7 Ma (A901-22e), matching the age of the nearby fracture dated at 92.9 ± 10.3 Ma
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24 537 (A901-22a). However, age uncertainties are large for this sample, which may be
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26 538 explained by low U/Pb ratios together with the presence of a younger calcite infilling
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28 539 fractures (A901-22c, dated at 68.4 ± 4 Ma), which may have induced the dissolution-
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30 540 recrystallization of the older calcite cement. A third example is illustrated in figure 9 with
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32 541 a grainstone sampled at the Sarazinière quarry (*oolithe de Lamothe* Formation, Upper
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34 542 Oxfordian), affected by two generations of tension gashes. The first generation is
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36 543 oriented N50° and yields an age of 58.9 ± 1.8 Ma (SR6a), while the second is oriented
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38 544 N150° and is dated at 18.7 ± 1.1 Ma (SR6b). Both tension gashes are filled by calcite
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40 545 crystals displaying the same cathodoluminescence (Fig. 9), hence the difficulty to
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42 546 establish a relative chronology from their cross-cutting relationship. Calcite U-Pb
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44 547 geochronology resolves this issue. Moreover, the intergranular pore space is entirely
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46 548 plugged by a blocky calcite showing a comparable dull brown cathodoluminescence.
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48 549 The U-Pb age of this blocky calcite, 57.7 ± 2.6 Ma (SR6c) is identical to the older
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50 550 tension gash (SR6a, 58.9 ± 1.8 Ma). It is worth noting that these ages match the one
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52 551 obtained on the second blocky calcite generation in the deep Middle Jurassic carbonate
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54 552 strata from the Paris Basin depocenter (Mangenot et al. 2018).
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58 553 Therefore, although tension gashes could have acted as preferential conduits for
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60 554 meteoric waters, fluid flow and associated calcite crystallization were not only restricted
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556 to the fracture network. Paleo-water flows through the intergranular porosity and

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3 556 subsequent cementation was enhanced by the development of brittle microstructures
4 557 (Hansman et al., 2018; Sun et al., 2022). This is shown by the synchronous precipitation
5 558 of calcite in tension gashes and in the adjacent intergranular pore space. However, the
6 559 spatial extension of such “tectonic-induced cementation” is unknown and needs further
7 560 research and complementary geochronological data on calcite cements occluding the
8 561 intergranular pore space.

14 562 **6. Conclusions**

17 563 We have provided evidence for a continuous fracturing of the Jurassic carbonates from
18 564 the Ypresian to the Rupelian in the eastern Paris Basin. This period coincides with the
19 565 main shortening related to the Pyrenean orogen growth, interrupted by extensional
20 566 deformation during Late Eocene – Early Oligocene. Three U-Pb age clusters are
21 567 identified, the two firsts at around 48 Ma and 43 Ma, related to the far-field propagation
22 568 of Pyrenean horizontal stress, and a third at 33 Ma corresponding to the ECRIS-related
23 569 extensional regime. Fluids of meteoric origin percolated through the fracture networks at
24 570 rather low temperatures (from 27 to 53 °C), with a progressive decrease of temperature
25 571 though time. Fluid flow and associated calcite precipitation was not restricted within the
26 572 fractures, but also occurred in the intergranular pore space.

35 573 **Acknowledgements**

37 574 This manuscript benefited from fruitful discussion with Christian Hibsich. We also thank
38 575 Frédéric Haurine for his assistance during the LA-ICP-MS U-Pb analysis. This work is
39 576 the outcome of collaborative project between the University Paris-Saclay and Andra, the
40 577 French agency for radioactive waste management, funded in part by Andra. We thank
41 578 the two anonymous reviewers for their constructive comments that helped to improve
42 579 the manuscript.

49 580 **Declaration of interest**

51 581 The authors declare none

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Samp les	Outcrop locality or well	Stratigraphic age	Sedimentary formation or member	Nature	U- Pb age	2 S.E. abs.	2 S.E. %
PPA1 073	Andra URL well	Upper Oxfordian	<i>Calcaires crayeux de Gudmont</i>	tension gash	50.4	2.4	4.7
SR6a	Sarazinière	Upper Oxfordian	<i>Oolithe de Lamothe</i>	tension gash N50°	58.9	1.8	3.0
SR6b				tension gash N150°	18.7	1.0	5.6
SR6c				Intergranu lar cement	57.7	2.6	4.5
LEU1- 1	Leurville	Upper Oxfordian	<i>Oolithe de Saucourt</i>	Hydraulic breccia	27.0	1.1	4.2
LEU-2				Hydraulic breccia	22.2	1.2	5.5
A0060 7c	A901 - Montcornet	Upper Oxfordian	unknown	tension gash	47.3	6.4	13.4

	well						
SOR6 ab	Sorcy-Saint- Martin	Middle Oxfordian	<i>Craie de Sorcy</i>	tension gash	47.7	1.7	3.6
SOR6 c				tension gash	44.7	1.6	3.5
MXV7	Maxey-sur- Vaise	Middle Oxfordian	<i>Calcaires crayeux de Maxey</i>	tension gash N20°	48.0	3.5	7.3
MXV9 a				tension gash N175°	27.4	2.8	10.3
VCLD	Vaucouleurs	Middle Oxfordian	<i>Calcaires crayeux de Maxey</i>	tension gash N10°	43.2	1.4	3.3
DGS M29-1	Dugny-sur- Meuse	Middle Oxfordian	<i>Calcaires crayeux de Maxey</i>	tension gash N170°	31.6	2.9	9.2
DGS M29- 2a		Middle Oxfordian	<i>Calcaires crayeux de Maxey</i>	tension gash N170°	32.0	1.5	4.5
DGS M29- 2b				Intergranu lar cement	30.6	7.0	22.8
DGS M7a		Middle Oxfordian	<i>Calcaires crayeux de Maxey</i>	Vug	33.8	2.5	7.4
DGS M7b				Vug	39.0	1.7	4.4
DGS M7c				tension gash N40°	32.4	7.6	23.5
VOI3b	Void-Vacon	Middle Oxfordian	<i>Calcaires coralliens d'Euville</i>	tension gash	37.0	1.7	4.7
25209	Andra URL well	Middle Oxfordian	<i>Calcaires crayeux de Maxey</i>	tension gash	34.9	1.3	3.8
25229	Andra URL well	Middle Oxfordian	<i>Calcaires coralliens d'Euville</i>	Vug	33.2	2.2	6.7

25232 B a	Andra URL well	Middle Oxfordian	<i>Calcaires coralliens d'Euville</i>	tension gash	34.5	2.0	5.9
A901- 22a	A901 - Montcornet well	Upper Bathonian	unknown	tension gash	92.9	10.3	11.1
A901- 22c				tension gash	68.4	4.0	5.9
A901- 22e				Intergranu lar cement	100. 9	22.7	22.5
433- 43240	EST433 well	Middle to Upper Bathonian	<i>Calcaires de Chaumont</i>	tension gash	33.0	5.5	16.6
BAZX 90 a	Bazoilles- sur-Meuse	Lower Bathonian	<i>Calcaires compacts de Neuchateau</i>	tension gash N10°	48.5	3.0	6.1
REM3 -2	Removille	Upper Bajocian	<i>Calcaire du Bâlin/Oolithe miliaire inf</i>	tension gash	31.7	3.8	11.9
REM1				tension gash	42.1	2.7	6.3
OT-1- 2	Ottange	Lower Bajocian	<i>Calcaire à polypiers inf</i>	Vug	40.8	2.2	5.4
SOM1 -1	Sommeréco urt	Lower Bajocian	<i>Calcaire à polypiers inf</i>	tension gash + Vug	42.5	3.9	9.1
SOM1 -2				tension gash + Vug	40.9	1.7	4.2

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867 Table 1. Samples description and associated calcite U-Pb geochronology data.

Sam ples	Stratigr aphic	Nature	δ^{18} O _{‰V}	δ^{13} C _{‰V}	δ^{18} O _{‰V} - PDB	δ^{13} C _{‰V} - PDB	T(Δ_{47}) mean	T(Δ_{47}) error	δ^{18} O _{‰V} - SMOW
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	age		-PDB	-PDB	(clumped)	(clumped)	(°C)	(°C)	water
SR6b	Upper Oxfordian	tension gash			-7.5	2.7	27	3	-4.6
LEU1-1	Upper Oxfordian	Hydraulic breccia	-10.5	2.8					
LEU-2	Upper Oxfordian	Hydraulic breccia	-8.8	1.7					
SOR6ab	Middle Oxfordian	tension gash	-7.0	3.2					
VCLD	Middle Oxfordian	tension gash	-7.7	3.4	-7.8	3.3	37	2	-2.9
VOI3b	Middle Oxfordian	tension gash	-7.1	3.1					
25209	Middle Oxfordian	tension gash	-8.4	2.9	-8.6	2.9	41	1	-2.9
25229	Middle Oxfordian	Vug	-9.0	2.9	-8.9	2.7	42	2	-3.1
A901-22a	Upper Bathonian	tension gash	-7.9	1.1					
BAZX90 a	Lower Bathonian	tension gash	-10.5	1.4	-10.3	1.4	53	5	-2.6
REM1	Upper Bajocian	tension gash	-10.3	1.5					

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	n								
SOM	Lower	tension	-9.1	2.0					
1-1	Bajocian	gash +							
	n	Vug							

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869 Table 2. Oxygen and carbon stable isotope composition and clumped isotope
870 thermometry.

For Peer Review

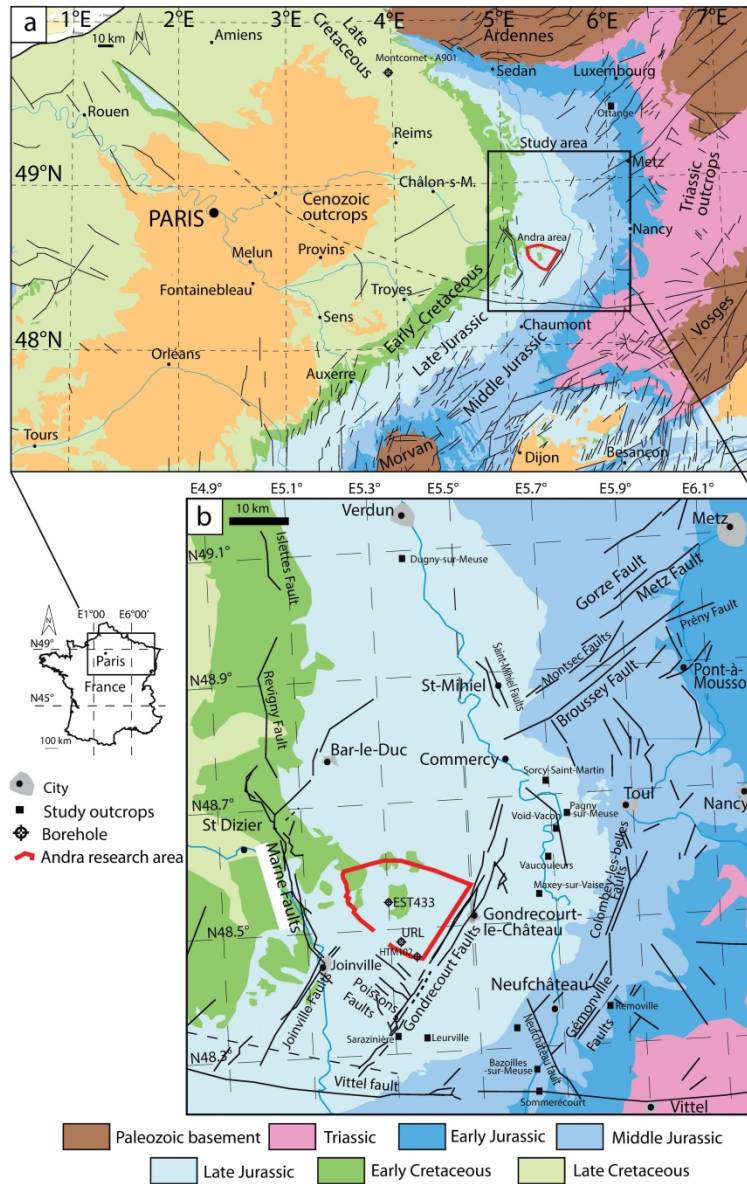


Figure 1. Geological map of the eastern Paris Basin (a), with a detailed view of the major structures in the studied area (b). Outcrop and quarries sample locations are indicated by black squares.

209x323mm (300 x 300 DPI)

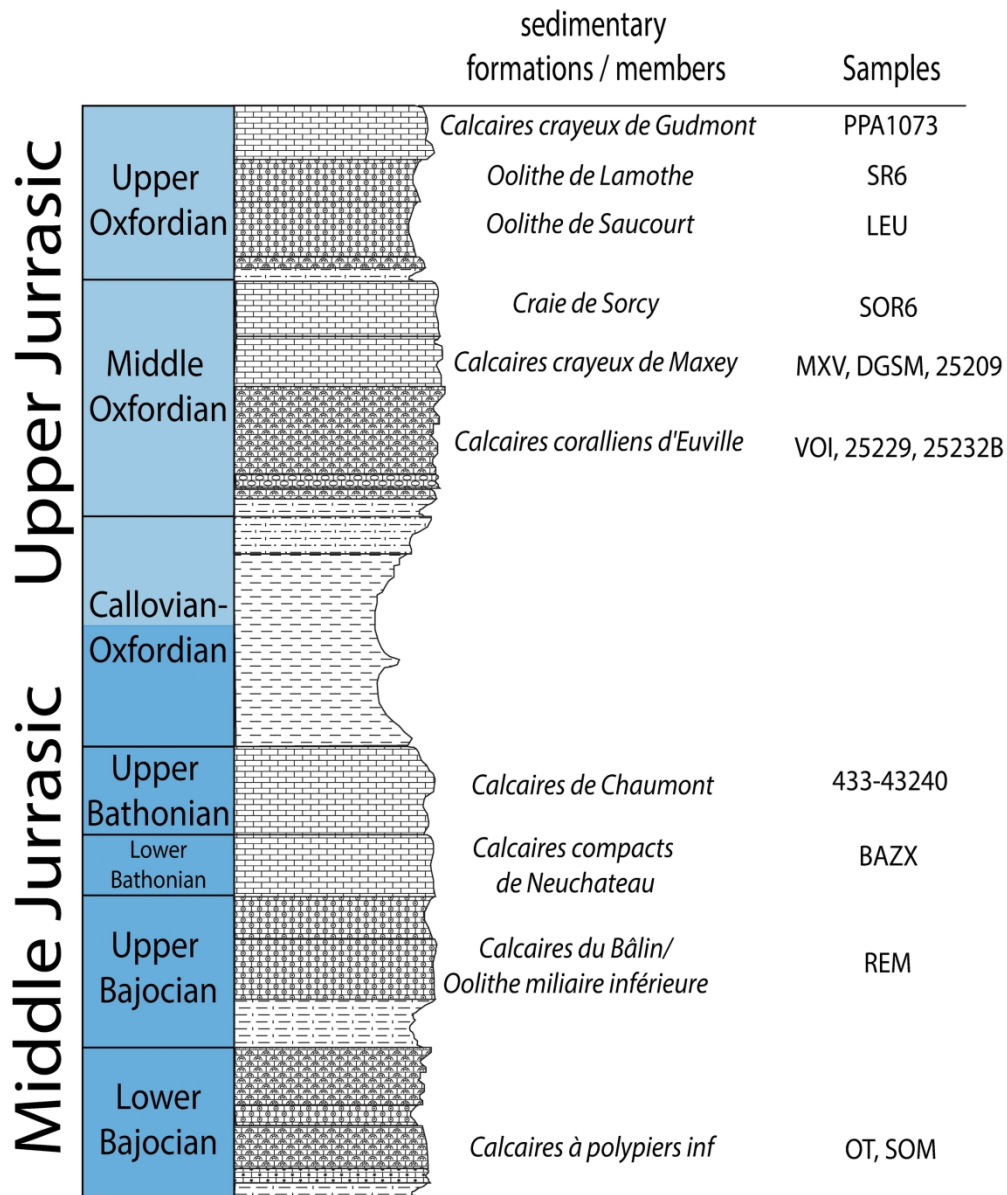


Figure 2. Simplified lithostratigraphic section in the eastern Paris Basin, showing the position of samples within the stratigraphic formations or members.

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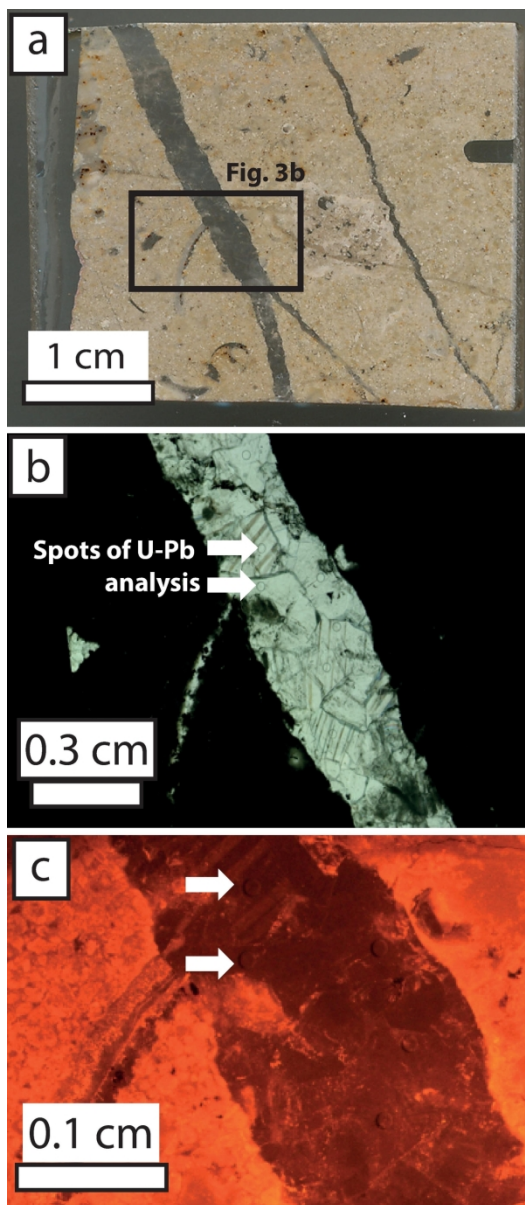


Figure 3. Example of sub-parallel tension gashes affecting a wackestone (a) sampled at Bazoilles-sur-Meuse (sample BAZX90a) in transmitted light (b) and cathodoluminescence microscopy (c). Ablation craters (150 μm in diameter) are visible in (b) and (c) (white arrows).

96x219mm (300 x 300 DPI)

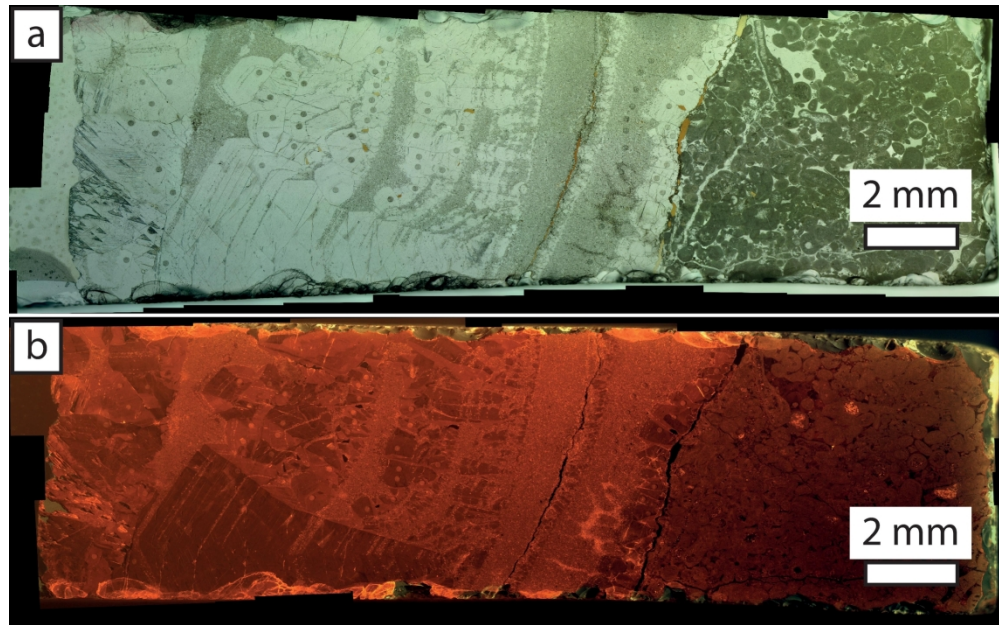


Figure 4. Hydraulic breccia developed in the oolithe de Saucourt Formation (sample LEU-2) in transmitted light (a) and cathodoluminescence microscopy (b). Ablation craters (150 μm in diameter) are visible.

205x127mm (300 x 300 DPI)

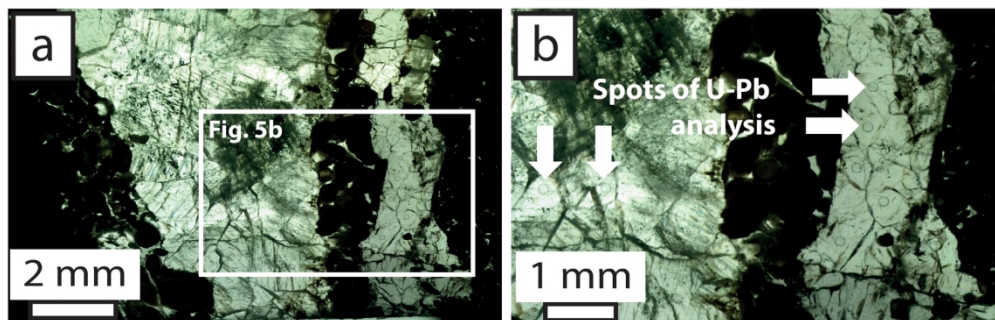


Figure 5. Tension gash in the oolithe miliaire Formation sampled at Removille (sample REM1) observed in transmitted light. The white square in photomicrograph (a) corresponds to the magnification in (b). This sample illustrates the impurities contained in some calcite cements. Ablation craters (150 μm in diameter) are visible (white arrows) and located, when possible, in the most limpid parts of the crystals.

167x61mm (300 x 300 DPI)

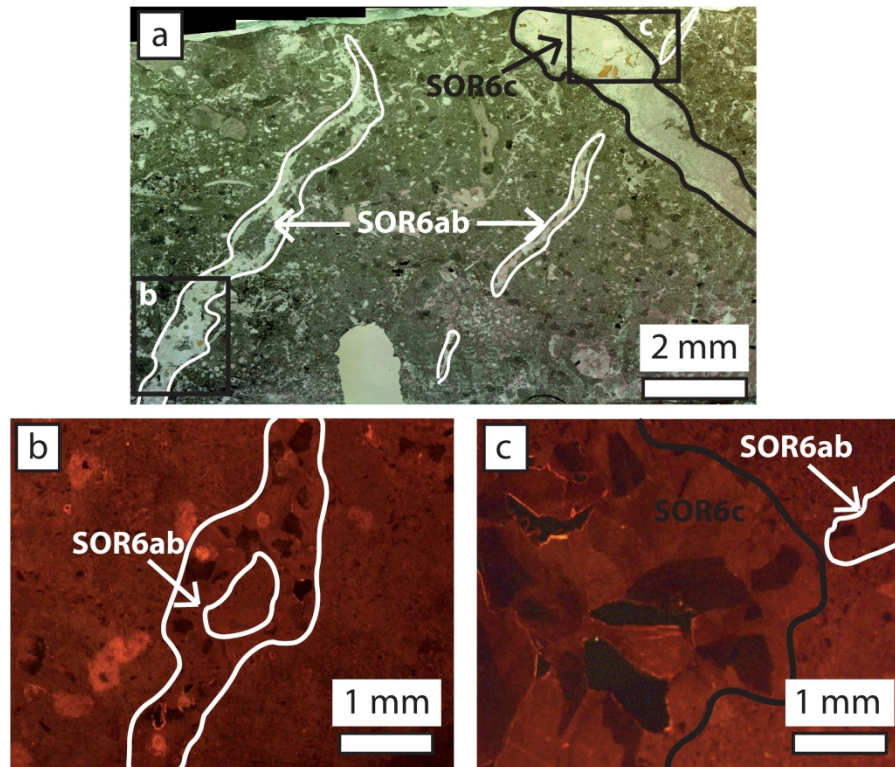


Figure 6. Tension gashes developed in sample SOR6 (Sorcy-Saint-Martin locality). The relative chronology between the fractures encircled in white (SOR6ab) and in black (SOR6c) is unclear, because no clear cross-cutting relationship is visible. Moreover, both tension gashes population is filled by blocky calcite displaying comparable cathodoluminescence.

230x213mm (300 x 300 DPI)

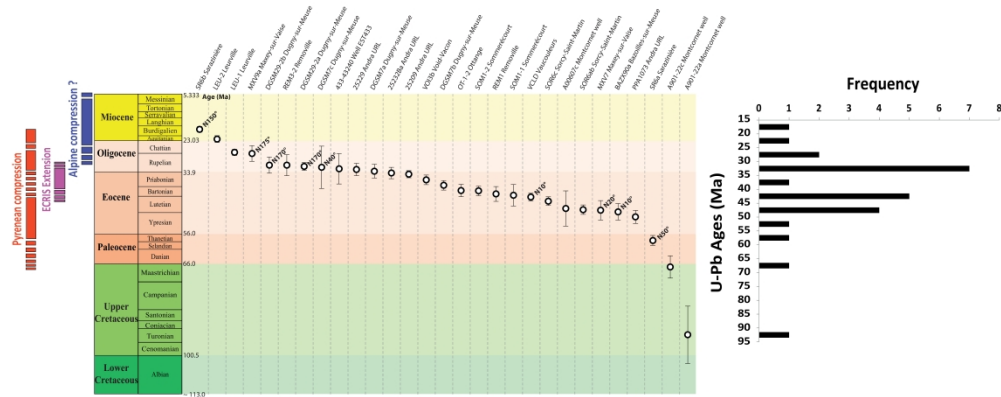


Figure 7. Compilation of calcite U-Pb ages in tension gashes and hydraulic breccias. In the histogram, data are plotted without considering the corresponding age uncertainties.

748x438mm (600 x 600 DPI)

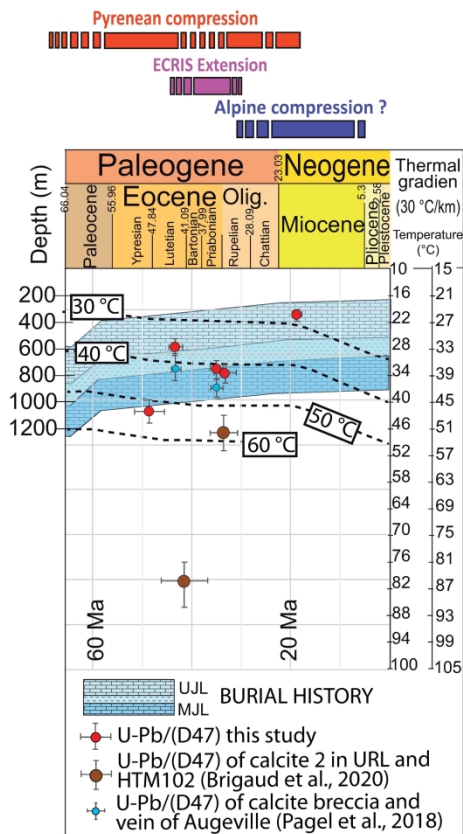


Figure 8. Calcite U-Pb age as a function of crystallization temperature determined from $\Delta 47$ thermometry.

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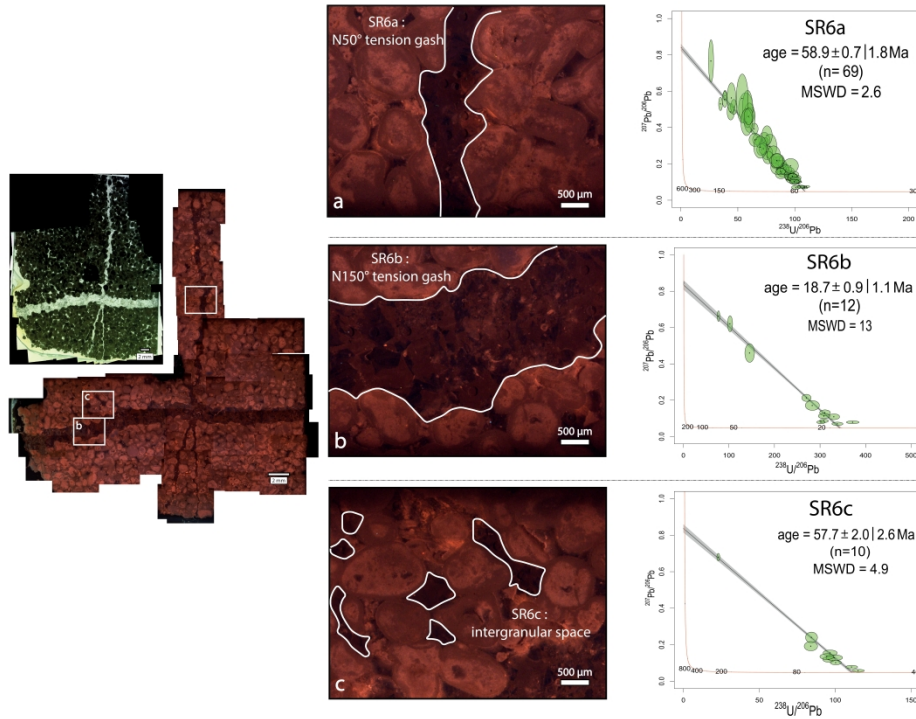


Figure 9. Calcite U-Pb ages determined in the SR6 sample (Sarazinière quarry, oolithe de Lamothe Formation, Upper Oxfordian).

1137x1119mm (600 x 600 DPI)