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1 **Early, far-field and diffuse tectonics records in the North Aquitaine**  
2 **Basin (France)**

3

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13 **Abstract**

14 In Western Europe, the deformations related to the opening of the Bay of Biscay and the  
15 formation of the Pyrenean belt are well described in the southern part of the Aquitaine  
16 basin, but little is known about the impact of these geodynamic events towards the  
17 Northern Aquitaine Platform. In this paper, we combine field observation with Unmanned  
18 Aerial Vehicle (UAV) imagery and calcite U-Pb geochronology to determine precisely the  
19 tectonic evolution in the Vendée Coastal domain. We evidence two main tectonic events: (1)  
20 At the transition between the Late Jurassic to Early Cretaceous, WNW-ESE striking normal  
21 faults formed horsts and grabens at the onset of the opening of the Bay of Biscay. The  
22 reactivation of Variscan faults during this tectonic event is consistent with oblique extension.  
23 This event triggered ascending fluid flows that mix with basin fluids responsible for barite-  
24 pyrite-quartz mineralizations near the unconformity. (2) During the Late Cretaceous,  
25 fractures, wide-open folds, veins, and joints are consistent with the N-S shortening direction  
26 during the earliest stages of the Pyrenean compression.

27 In both cases, the Northern Aquitaine Platform records the early stages of the main regional  
28 tectonic events in a far-field position. In the northern Aquitaine Basin, as in many other  
29 places in Europe, the tectonic study of sedimentary platforms located far from the plate  
30 boundaries provides new constraints on the early diffuse deformation process that predate  
31 the main tectonic phases.

32 Keywords: Intraplate deformation / Calcite U-Pb geochronology / Northern Aquitaine  
33 Platform / Biscay Bay / Pyrenees / U.A.V. imaging

34 **Résumé - Enregistrements tectoniques précoces, lointains et diffus dans le Nord du Bassin**  
35 **aquitain**

36 Au cours des périodes du Mésozoïque et du Cénozoïque, l'Europe a connu plusieurs  
37 évènements tectoniques interprétés comme de la tectonique lointaine. Il peut s'agir d'une  
38 tectonique diffuse qui se produit au début d'un évènement tectonique majeur ou de la  
39 propagation au loin de la déformation des fronts orogéniques. En Europe de l'Ouest, les  
40 déformations liées à l'ouverture du Golfe de Gascogne et à la formation de la chaîne des  
41 Pyrénées sont bien décrites dans le sud du Bassin aquitain, là où la plate-forme Nord

42 aquitaine reste peu étudiée. Nous avons combiné les observations de terrain, l'imagerie par  
43 drone et la datation laser U-Pb sur la calcite pour déterminer l'évolution tectonique du  
44 domaine côtier de la Vendée. Nos résultats mettent en évidence l'existence de deux  
45 évènements tectoniques majeurs depuis le début du Jurassique : (1) À la transition du  
46 Jurassique supérieur au Crétacé inférieur, des failles normales orientées ONO-ESE  
47 présentent une organisation en hosts et grabens au début de l'ouverture du Golfe de  
48 Gascogne. Leur association avec des failles décrochantes varisques réactivées est cohérente  
49 avec une organisation oblique de l'extension. Cet évènement tectonique est accompagné  
50 par la circulation d'un fluide profond. (2) Durant le Crétacé supérieur, la mise en place de  
51 fractures, de plis ouverts, de veines et de joints est cohérent avec la direction de  
52 raccourcissement N-S qui se produit au premiers stades de la compression N-S des Pyrénées.

53 Dans les deux cas, les premiers stades des principaux épisodes de déformation régionale ont  
54 été enregistrés par une tectonique lointaine sur la plateforme Nord aquitaine, avant la  
55 localisation de la déformation dans les rifts et dans les Pyrénées. Dans le Bassin aquitain,  
56 comme dans de nombreux endroits en Europe, l'étude tectonique des plates-formes  
57 sédimentaires situées loin des zones principales de déformation à l'échelle des plaques  
58 apporte de nouvelles contraintes sur les processus de déformations précoces et diffus  
59 antérieurs aux principales phases tectoniques.

60 Mots clés : Déformation intraplaque / Tectonique précoce et diffuse / Déformation lointaine  
61 / Géochronologie U-Pb sur calcite / Plateforme Nord aquitaine / Golfe de Gascogne /  
62 Pyrénées

## 63 **1 Introduction**

64           The plate tectonics theory defines lithospheric plates as rigid blocks bounded by  
65 deformable boundaries (McKenzie and Parker, 1967). However, numerous observations  
66 have evidenced intra-plate deformations, also called “far-field deformations” (e.g., Ziegler et  
67 al., 1995). Within the basin, intra-plate deformations induce burial or uplift, hydrocarbon  
68 maturation, fluid flow changes, and mineral depositions (Boiron et al., 2010; Burisch et al.,  
69 2022; Gorczyk et al., 2013; Turner and Williams, 2004).

70           Far-field deformations occurred in divergence and convergence contexts, and their  
71 timing relative to rifting or mountain building is variable. In the divergence context, diffuse  
72 extensions predating strain localization within rifts are highlighted by uplift, tectonic  
73 reactivation, and fracture networks formation (Huerta and Harry, 2007; Seymour et al.,  
74 2016; Szymanski et al., 2016). However, this strain focusing within rifts is sometimes  
75 counterbalanced by the activation of several décollement levels in the context of  
76 multilayered lithosphere leading the deformation to propagate far from the main thinning  
77 zone (Clerc et al., 2016; Lagabrielle et al., 2020; Dhifaoui et al., 2020). In a convergence  
78 context, intra-plate deformations occur during orogenic processes several hundred  
79 kilometers away from the mountain belt front (Jolivet et al., 2021; Lacombe & Mouthereau,  
80 1999). They are accompanied by uplifting following lithospheric folding (Gerbault et al.,  
81 1999; Ziegler et al., 1995), tectonic reactivation (Gorczyk et al., 2013; Navabpour et al., 2017;  
82 Parizot et al., 2022), and the formation of new fault and joint networks (Duperret et al.,  
83 2012; Missenard et al., 2017). However, far-field deformation takes place sometime at the  
84 onset of convergence resulting in the inversion of pre-existing structures such as rift (Frizon  
85 de Lamotte et al., 2000) or passive margins (Leffondré et al., 2020, Strzeczynski et al., 2021);  
86 and in the folding of the lithosphere (Cloetingh and Burov, 2011). Whatever the tectonic  
87 context, far-field deformation is always linked with vertical motion, tectonic reactivation of  
88 basement structure, and fracture network formation.

89           In Western Europe, two periods are particularly suitable for intra-plate tectonics: 1)  
90 the Late Jurassic to early Cretaceous, in a framework of extensional tectonics, which relates  
91 to the opening of the North Atlantic Ocean (Ziegler., 1990; Ziegler and Dèzès, 2005). In the  
92 Aquitaine Basin, deformation is concentrated on a limited area between the Celtaquitaine  
93 flexure in the north and the North Pyrenean Fault in the south (Figure 1; B.R.G.M., 1974;

94 Jammes et al., 2009; Issautier et al., 2022; Tugend et al., 2014) suggesting that no diffuse  
95 extension is recorded. However, it has also been proposed that the early deformations were  
96 not localized and extended north of the Celtaquitaine flexure (Asti et al., 2022). 2) The  
97 period from the Late Cretaceous to Eocene, in a setting of coeval compression, related to the  
98 Pyrenees orogeny. Late Cretaceous to Eocene intra-plate deformation is particularly well  
99 described in Iberia (De Ruig et al., 1990), in the Paris Basin (Blaise et al., 2022; Lacombe and  
100 Obert, 2000; Lacombe et al., 1990), southern England (Duperret et al., 2012; Parrish et al.,  
101 2018) and the North sea and Central Europe (Dielforder et al., 2019; Evans et al., 2003).

102         The North Aquitaine Platform is located along the western coast of France, at 100  
103 and 300km north of the Bay of Biscay and Pyrenees front, respectively (Figure 1). Here,  
104 geophysical investigations point to the absence of large-scale deformation, such as rifts or  
105 inverted structures (Bois et al., 1997; Jammes et al., 2009). However, at the outcrop scale,  
106 several deformation phases have been described, but no consensus exist: For some authors  
107 (Burbaud-Vergneaud, 1987; Bouton et al., 2007), no tectonic events occurred during the  
108 Mesozoic and at least six deformation episodes take place during the Cenozoic. Their timings  
109 are only constrained by the analogy of the stress direction with the peri-alpine domain  
110 (Bergerat, 1985). For others (Cathelineau et al., 2012, Strzeczynski et al., 2020), normal faults  
111 crossing the first Mesozoic sedimentary formation are associated with fluid circulation and  
112 mineral deposition. Here, the timing of faulting is indirectly constrained by the datation of  
113 the basement alteration and adularization, in a possible relationship with fluid circulation  
114 and mineral deposition (Cathelineau et al., 2012). No direct time constraints are available on  
115 the Mesozoic to Present tectonic event of the North Aquitaine Platform. No studies  
116 encompass the relationship between brittle deformation in the basement units and the  
117 sedimentary cover.

118         The following paper provides new structural and time constraints on North Aquitaine  
119 Platform to constrain fra-field tectonics in this area and better understand how this can  
120 modify the fluid pathways and impact mineral deposition. We especially focused on the  
121 criteria characterizing the far-field deformation without a large-scale structure, such as  
122 tectonic reactivation of basement structure and fracture network formation. We conducted  
123 a geological study across the unconformity that separates the Armorican basement and the  
124 Aquitaine Basin. The exceptional outcrop conditions of the Vendée coast allow us to perform

125 a structural survey based on detailed maps assisted by Unmanned Aerial Vehicle (UAV). In  
126 addition, we provide new time constrain on the syn-kinematic mineral by direct dating of  
127 calcite filling fractures using Laser ablation ICP-MS U-Pb geochronology. Then, we discuss the  
128 relationships between outcrop scale deformations and the main tectonic events of the  
129 Aquitaine basin, such as the Bay of Biscay opening and the Pyrennee orogeny.

130

## 131 **2 Geological setting**

132 The Mesozoic North Aquitaine Platform emplaced over the Armorican basement that  
133 well recorded the latest stage of the Variscan evolution (Ballèvre et al., 2009; Cagnard et al.,  
134 2004; Gapais et al., 2015; Goujou et al., 1994). The latter is characterized by HT-LP  
135 metamorphism in a WNW-ESE extension context (Cagnard et al., 2004; Goujou et al., 1994;  
136 Iglésias and Brun, 1976) and that has been dated further north at ca. 320 Ma (Augier et al.,  
137 2015; Turrillot et al., 2011). The Armorican basement consists of migmatitic gneiss at the  
138 Anse aux Moines, kyanite and sillimanite bearing gneiss that is intruded by aplo-pegmatitic  
139 dikes in Cayola Bay and kyanite micaschists in Mine des Sards and Anse de Saint-Nicolas  
140 (Figure 2). Such a distribution of metamorphic rocks is consistent with a decrease of  
141 Barrovian-type metamorphism from the N.W. to the S.E., as proposed by Goujou et al.  
142 (1994). Ductile structures associated with this metamorphism gradually evolve into brittle  
143 structures such as N-S normal faults and a large shear zone at ca. 300 Ma (Turrillot et al.  
144 2011).

145 Erosion and peneplanation occurring during the late Paleozoic to Triassic periods are  
146 responsible for the continued exhumation of the basement rocks. At the end of the Jurassic,  
147 the Armorican basement from Vendée was buried under a thick layer (~1 km) of platform  
148 sediments, causing a maximum temperature rise of 60°C at the bottom of the basin  
149 (François et al., 2020).

150 Fluid flows, inducing authigenic minerals precipitation near faults and along  
151 sedimentary strata, occurred during the Jurassic - Cretaceous transition as attested by  
152  $^{40}\text{Ar}/^{39}\text{Ar}$  and K-Ar dating on adularia and clays (illite, smectite, and kaolinite) of Cathelineau  
153 et al. (2012), in an N-S extensional setting (Strzeczynski et al., 2020). The numerous normal  
154 faults of the Aquitaine Mesozoic units are successively filled by barite, pyrite, quartz, or

155 calcite (Figure 2c; Strzeczynski et al., 2020). Fluids responsible for mineral deposition have  
156 variable temperatures and salinities, suggesting different fluid sources from secondary  
157 brines such as the basin and sea water mixed with rising warm water (Cathelineau et al.,  
158 2012). The latter is particularly important along the Vendée coast north of the Aquitaine  
159 basin, as evidenced by the high fluid temperatures (Cathelineau et al., 2012).

160         These fluid circulations and the associated tectonic event coincide with a major  
161 marine regression that induces the emersion of the North Aquitaine Platform in the lower  
162 Cretaceous (Figure 1; Biteau et al., 2006; B.R.G.M., 1974; Curnelle and Dubois, 1986). At that  
163 time, the Variscan basement rocks begin to exhume due to the erosion of the Aquitaine  
164 Basin sedimentary cover (François et al., 2020). Exhumation is relatively fast as the basement  
165 rocks have been near the surface since Cretaceous times (François et al., 2020). Cenozoic  
166 structures have been dated by the relationship between continental deposits and regional  
167 tectonic (Burbaud-Vergneaud, 1987; Bouton et al., 2007). It attests to (i) N-S shortening in  
168 the Eocene, consistent with Pyrenean orogeny, (ii) an NNE-SSW extension in the Oligocene,  
169 compatible with the European Cenozoic rift system (Ziegler and Dèzes, 2005), followed by  
170 (iii) an E-W shortening in the Miocene and (iv) an NW-SE shortening from the Pliocene to the  
171 present day, which may relate to the Alpine orogeny (Bergerat, 1987).

## 172 **3 Methods**

173         Our approach is based on three main steps: 1) structural characterization. Thanks to  
174 excellent outcrop conditions on the rocky coastal plateau, we propose detailed structural  
175 maps constrained by UAV imagery coupled with orientation and length measurements of the  
176 structure. 2) relative chronology based on cross-sectional relationships of structural maps,  
177 and 3) absolute dating of authigenic minerals.

### 178 **3.1. Structure characterization**

179         The study focuses on fractures, a group of structures encompassing joints and faults  
180 (Peacock et al., 2016). Joints are characterized by opening from either side of the fracture  
181 (rupture mode I), and faults are associated with movement in the same direction as the  
182 fracture (rupture mode II) (Pollard and Aydin, 1988). Fractures can be filled by minerals that  
183 form veins and slickensides in the case of mode I openings and mode II slips, respectively  
184 (Bons et al., 2012).



185 We systematically measured the structure' strike, dip, and dip direction in the field  
186 with a compass and reported mineral fills (G.P.S. coordinates and sampling).

### 187 **3.2. UAV imagery**

188 UAV imagery was deployed in all areas on the tidal rocky shelf. The UAV is a DJI  
189 Phantom 4 equipped with a 12 Mpixels camera. Picture acquisition was made at an altitude  
190 of 70 m. Then, photographs were merged into four high-resolution orthomosaics. The spatial  
191 resolution is 30x30 mm/pixel.

192 We provide a high-resolution geological map of the tidal rocky shelf by manually  
193 digitizing fractures and remarkable levels under the G.I.S. environment (QGIS 3.16 software).  
194 We selected fractures at least 10m long for better clarity on high-resolution geological maps.  
195 Indeed, shorter fractures could be the response to rearrangement with little deviation due  
196 to a small-scale stress field. Strike and length were calculated from fractures traces in  
197 Q.G.I.S., and length-weighted rose diagrams were produced by multiplying the number of  
198 each fracture measurement by its length (for example, an N90° striking fracture of 3m long is  
199 considered as "N90; N90; N90" in the rose diagram). Length-weighted rose diagrams were  
200 displayed with GeoRose 0.5.1 software.

### 201 **3.3 Relative chronology**

202 The relative chronology between fractures is based on three topological relationships  
203 (Figure 3; Sanderson and Nixon, 2015): isolated, intersecting, and abutting fracture  
204 terminations. Isolated fracture terminations, with an "I" geometry and "X" shape  
205 intersection without mineral fillings, don't allow a precise relative chronology to be  
206 obtained. If the fractures have an "X" shape intersection that could form under the same  
207 stress field and for faults opposite shear senses, in that case, they are considered  
208 synchronous as conjugated fractures (Anderson, 1951; Daubrée, 1878; cited by Dennis,  
209 1967). Abutment geometry refers to a "T" shape geometry with one fracture stopping  
210 against another, meaning it terminates against a pre-existing fracture (Sanderson and Nixon,  
211 2015).

212 Mineral precipitation could be synchronous, anterior, or posterior to the fractures  
213 (Figure 3). Synchronous mineral fills joints, veins, and slickenfibres on fault planes (Bons et  
214 al., 2012). Except for slickenfibres, other observations, such as the mineral texture and

215 microstructure, help to decipher the synchronicity of the mineral filling. If the duration  
216 between fault activity and mineral precipitation is smaller than the dating uncertainties, they  
217 are interpreted as synchronous (Roberts and Holdsworth, 2022). Anterior mineral fillings in a  
218 new fracture are interpretable with an abutment or crosscutting geometry on the anterior  
219 mineral filling. The late mineral filling requires additional chronological evidence, such as a  
220 crosscutting relationship with other geological features, to be distinguished from  
221 synchronous mineral fillings. In all cases, inherited fractures that reopen by forming veins do  
222 not open in type I mode and have an oblique component (Figure 3). They act as a relay  
223 structure between newly formed veins (Virgo et al. 2014) unless there is a separate tectonic  
224 event with the same stress field, which is unlikely.

### 225 **3.4. Calcite U-Pb geochronology**

226 We selected calcite samples from veins with a clear orientation and chronology. The  
227 selected calcite samples comprise rhombohedral blocky crystals 0.5 to 3 cm wide.

228 Individual calcite crystals from the three samples were hand-picked and polished in  
229 an epoxy mount. They were imaged using cold cathodoluminescence, and no zoning was  
230 observed. U-Pb analyses on calcite were performed at the Plateforme GeOHeLiS,  
231 Géosciences Rennes (Université de Rennes) using an ESI NWR193UC Excimer laser coupled  
232 to an Agilent 7700x, Q-ICP-MS equipped with a dual pumping system to enhance sensitivity.  
233 Ablation spots of 100  $\mu\text{m}$  diameter with a repetition rate of 10 Hz and a fluence of 6  $\text{J}/\text{cm}^2$   
234 were used. The general protocol follows the one in Coltat et al. (2019) and is fully described  
235 in the Supplementary data with the instrumental condition table. WC1 (Roberts et al., 2017)  
236 is the primary reference material. Data reduction was performed with Lolite v4 software  
237 (Paton et al., 2011) using U-Pb VizualAge UComPbine D.R.S. (Chew et al., 2014). Sample age  
238 calculations and Tera-Wasserburg diagrams were made using IsoplotR (Vermeesch, 2018).  
239 All uncertainties are quoted at the  $2\sigma$  level. Propagation of excess scatter on primary R.M. is  
240 propagated to individual ratio measurements. Systematic uncertainty on the ratios of  
241 primary R.M. and decay constants uncertainties are propagated to the final age calculation.  
242 Propagation is made by quadratic addition following Horstwood et al. (2016).

## 243 **4. Results**

244 The field observations assisted by UAV imaging of the different lithologies and the  
245 brittle structure are obtained on six outcrops along the Vendée Coast from northwest to  
246 southeast (Figure 2) as follows: the Anse aux Moines (Figure 4), the Cayola Bay (Figure 5),  
247 the Mine des Sards (Figure 6), the Payré Estuary (Figure 7), the Anse de Saint-Nicolas (Figure  
248 8) and Four à Chaux (Figure 9).

### 249 **4.1. Lithologies**

#### 250 4.1.1 Basement unit

251 The basement unit (B.U.) has been studied in detail at four sites from west to East:  
252 Anse aux Moines, Cayola Bay, Mine des Sards, and Anse de Saint-Nicolas (Figure 2a). Each  
253 site has a similar pattern corresponding to a tidal rocky shelf of several tens of meters wide  
254 separated from a 10 to 15 meters high coastal cliff by a more or less-developed beach, such  
255 as the cliff of the Anse aux Moines (Figure 4). In each site, the basement unit occupies the  
256 tidal rocky shelf, and the unconformity separating the basement unit and the sedimentary  
257 cover can be observed along the coastal cliff in many places. Horizontal and panoramic  
258 orthoimages obtained by UAV (Figures 5a, 6c, and 8b and in Supplementary material)  
259 provide practical support for G.I.S. tectonic structure mapping and field observation  
260 localization (Figures 5, 6, 8).

261 In the B.U., the gneissic foliation is synchronous with metamorphism (Goujou et al.,  
262 1994) and magmatic intrusion (Cagnard et al., 2004). The foliation strikes between N90° and  
263 N110° and plunges to the N with an angle between 40° and 60° at the Anse aux Moines  
264 (Figures 2a and 4), Cayola Bay (Figure 5), the Mine des Sards (Figure 6) and turns to N160-  
265 50°E at the Anse de Saint-Nicolas (Figure 8). In Cayola Bay, dikes are more or less transposed  
266 into the foliation (Figure 5a-b).

#### 267 4.1.2. Sedimentary units

268 We divided the Aquitaine Basin series into five sedimentary units called SU1, SU2,  
269 SU3, SU4, and SU5 (Figure 2b) based on the sediment's age and lithologies and, thus,  
270 different mechanical behavior. The shallow dip (10°) of the bedding to the N or the S defines  
271 several large open folds offering good outcrop conditions on the plateau in each unit (Figure  
272 2a).

273 SU1 and SU2 have been dated from the Hettangian age on paleontological contents  
274 (Bouton, 2004; Goujou et al., 1994; Granier et al., 2015). They can be observed along the  
275 coastal cliffs of each site and on the part of the tidal rocky shelf in the Anse aux Moines,  
276 Cayola Bay, the Mine des Sardes, and the Anse de Saint Nicolas (Figures 4, 5, 6, and 8). SU1  
277 lies directly on the B.U. (Figure 4a, 5d-e, 6a-b, and 8a). It consists of a 1 to 4 m thick grey  
278 clay-rich unit intercalated with layers of yellow dolomitic limestones (Figure 4a, 5d-e, and  
279 6b) except at the Anse de Saint-Nicolas area where it is replaced by a 20 cm thick  
280 conglomerate bed (Figure 8a; Goujou et al., 1994).

281 The SU2 consists of a layer of dolomitic limestones 5 to 10 m thick with bed thickness  
282 ranging from 5 to 30 cm (Figure 4a, 5d-e, and 6b). In this unit, karsts are abundant in some  
283 places, especially at the Mine des Sardes and the Anse de Saint-Nicolas, filled with barite and  
284 quartz (Figure 6g-h). Karst shapes are mostly lenticular (Figure 6g), parallel to the bedding  
285 with elongated WNW-ESE-tubular shapes. Silicification of SU2 limestones is very common in  
286 the Anse aux Moines, the Mine des Sardes, and the Anse de Saint-Nicolas (Figure 4a, 5d-e, 6a,  
287 and 8a). In Cayola Bay (Figure 5d-e), silicification only develops around faults crosscutting  
288 the BU/SU1 unconformity.

289 The SU3 is dated to the Plienbachian (Fauré and Bohain, 2017). The hardground at  
290 the top of SU2, the pebbles layer at the base of SU3, and the absence of Early Sinemurian  
291 fauna have been interpreted as evidence of emersion of the area between the Late  
292 Hettangian and Early Sinemurian (Fauré and Bohain, 2017). SU3 is visible on the coastal cliffs  
293 of the Mine des Sardes and the Payré estuary (Figures 7a and 10c) and has been mapped on  
294 the tidal rocky shelf of the Anse de Saint-Nicolas (Figure 8b). It consists of limestones with  
295 abundant Pecten and Belemnite fossils alternating with a shale-rich layer. Similarly to SU2,  
296 SU3 is silicified in places such as the Mine des Sardes.

297 The SU4 has been dated from the Toarcian to the Aalenian using paleontological  
298 contents (See reference in Goujou et al., 1994). It is observed at the Anse de Saint-Nicolas  
299 coastal cliff (Figure 8b) and, depending on the amount of sand and the tide, at the foot of  
300 the beach between the Anse de Saint-Nicolas and the Four à Chaux (Figure 9a). It consists of  
301 a 20 m thick succession of blue shale and rare limestones that forms an impermeable layer  
302 on the scale of the northern Aquitaine Basin (Cathelineau et al., 2012).

303           Based on paleontological contents, the SU5 has been dated from the Bajocian to the  
304 Callovian (Goujou et al., 1994, and references therein). It outcrops at Four à Chaux and  
305 extends several kilometers to the East. It is a 100 m thick unit. It comprises white limestone  
306 beds 10 to 50 cm thick alternating with centimetric marl layers (Figure 9d).

## 307           **4.2. Brittle structure of the Vendée coastal domain**

308           In the field, we observed fractures with sometimes mineral filling (veins) and faults  
309 with offset up to 10m from the B.U. to SU5. Slickensides are preserved in SU2 and SU5,  
310 giving the offset's orientation, but alteration (argillization and silicification) has erased them  
311 in B.U., making this measurement impossible. We estimate movement mainly by considering  
312 remarkable markers offsets such as dike, unconformity, lithological contacts, quartz lenses,  
313 and sedimentary beds.

### 314           4.2.1. Anse aux Moines outcrop

315           The westernmost outcrop is located at the Anse aux Moines (Figures 2a and 4). It  
316 consists of a 150 m-long coastal cliff-oriented NNW-SSE. Here, the tidal rocky shelf is rarely  
317 visible at low tide, and a thick pebble beach limits observation of the cliff (Figure 4). The  
318 outcrop consists of SU1 and SU2 rocks bounded north and south by the migmatitic gneisses  
319 forming the B.U. To the north, the B.U. is covered by SU1 and SU2 (Figure 4a). The contact  
320 between the B.U. and the SU1 and SU2 bedding are parallel and inclined together to the  
321 south, suggesting that the unconformity outcrops here (Figure 4a-d). The contact between  
322 B.U. and SU1 is steeper to the south and underlined by an N116-69°NNE normal fault plane  
323 (Figure 4a). The fault zone is underlined by a 4 m thick fault gouge zone and strongly  
324 deformed SU1 beds (Figure 4a-c). Silicification is well-developed, especially within the SU2  
325 and the fault gouge breccias. Quartz also fills a 50 cm thick vein striking parallel to the fault  
326 (Figure 4b). The structural pattern is consistent with a half-graben structure bounded by a  
327 north-dipping fault and tilted toward the south.

### 328           4.2.2. Cayola Bay outcrop

329           Cayola Bay is located at the estuary of the Combe River (Figure 2a). It is a triangular-  
330 shaped bay bounded by two 500-m-long coastal cliffs. The one situated west is striking NNE-  
331 SSW, and the other, NW-SE. B.U.'s tidal rocky shelf is present primarily on either side of the

332 bay, and rocks from the SU1 and SU2 are visible on the coastal cliff. We focused here on the  
333 eastern part of the bay, where the unconformity is more visible.

334 On Cayola Bay (Figure 5), we measured three populations of oriented brittle  
335 structure: N160° to N-S, N30° to N50° and N110° to N130° respectively. The N110-130° fault  
336 population is the only one to displace the unconformity suggesting an activity post-dating  
337 the Hettangian (Figure 5d-e). In contrast, faults oriented N160° to N-S and N30° to N50° are  
338 sealed by the unconformity, suggesting a pre-Hettangian activity (Figure 5d-e).

339 Aplo-pegmatitic dikes injected into the B.U. allow us to estimate the apparent offset  
340 of the faults. N160° to N-S striking faults cut aplo-pegmatitic dikes with an apparent dextral  
341 offset (Figure 5a-b). At several locations, their orientation continuously evolves from an NW-  
342 SE to an N-S strike with the same sense of shearing (Figure 5a-b). This suggests that N160° to  
343 N-S oriented faults may have been active during the dike emplacement. N30° to N50°  
344 striking faults cut aplo-pegmatitic dikes with apparent sinistral offsets (Figure 5c). Together,  
345 the N160° to N-S striking faults and the N30° to N50° striking faults may have been active  
346 simultaneously as conjugated faults.

347 Three major N110° to N130° striking faults were mapped on the tidal flat and the  
348 coastal cliff (Figure 5a-d-e). No dike offsets were observed because these faults strike in the  
349 same direction as metamorphic foliation and aplo-pegmatitic dikes (Figure 5a-e). However,  
350 in the coastal cliff, the unconformity is crosscut by these three faults with normal motion  
351 (Figure 5d-e). Around N110° to N130° striking normal faults, SU2 limestones are locally  
352 silicified over a width of 1 to 3 m (Figure 5d-e). In the B.U., the northernmost fault is filled  
353 with pyrite mixed with host rocks (Figure 5a). The opposite dipping of N110° to N130°  
354 striking normal faults toward Cayola Bay delineates a graben where the unconformity is  
355 lowered by 5 to 10 m (Figure 5a).

#### 356 4.2.3. Mine des Sardis outcrop

357 The Mine des Sardis is located between Cayola Bay and Bourgenay (Figure 2a). It is a  
358 large area where B.U. is observed on the tidal rocky shelf, and SU1 and SU2 are primarily  
359 visible on the coastal cliff (Figure 2a). Unfortunately, the unconformity is rarely visible as it is  
360 covered by beach pebble deposits.

361 The area's western boundary consists of an N160° and vertical fault that cuts SU1 to  
362 SU3 and uplifts B.U. (Figure 2a). Here, we estimate a vertical offset of 5 to 10 m high because  
363 the uppermost SU3 is in direct contact with B.U. The latter changes from kyanite micaschists  
364 to the East of the fault to kyanite-sillimanite gneisses to the west. Such a change suggests  
365 that either the vertical offset was underestimated or the fault developed on a pre-existing  
366 contact (Figure 2a). To the East, the B.U. is progressively covered by sedimentary units and  
367 disappears on the east side of Bourgenay (Figure 2a).

368 The orthoimage in Figure 6 is located around 500 m east of the Mine des Sardes  
369 (Figure 2a) in an area where the unconformity is well exposed. Here on the tidal rock  
370 platform, we measured four populations of brittle structure according to their orientations:  
371 N-S, N40° to N60°, N110° to N130°, and N140° to N160°. On the coastal cliff, the main N110°  
372 to N130° striking fault (oriented N118°-73°ENE) cuts the unconformity, SU1 and SU2 (Figure  
373 6a-c) and therefore is active after the Hettangian. The activity of the N-S, N40 to N60 striking  
374 fault population predates the Hettangian as they are always sealed by the unconformity  
375 (Figure 6b). The relationship between the N140° to N160° striking fault population and the  
376 sedimentary units (SU1 and SU2) is more controversial as most of the structures are sealed  
377 by the unconformity (Figure 6b) except one fault (oriented N151°-57°ENE) that produces a 1  
378 m offset (Figure 6a-c).

379 The N-S faults are vertical or dip mainly to the East, and their movement is not  
380 constrained because of bad outcropping conditions (Figure 6b-c). The N40° to N60° and  
381 N140° to N160° striking faults are left and right lateral strike-slip faults, as evidenced by the  
382 offset of the foliation and the quartz lenses (Figure 6d-e). They form an "X" shaped  
383 intersection compatible with conjugated fault abutting on N-S faults (Figure 6f). All these  
384 faults are sealed by the unconformity (Figure 6b) except one fault oriented N140° to N160°  
385 that cuts the unconformity (Figure 6a-c).

386 A main N110° to N130° striking fault can be followed at the foot of the pebble beach  
387 and on both sides of a little cape (Figure 6a-c). Here, the 3-4 m high unconformity offset is  
388 consistent with a normal motion. In SU2, pervasive silicification follows the normal fault  
389 planes and, in some places, propagates horizontally into the inter-stratum spaces. To the  
390 East, this normal fault abuts the N140° to N160° normal fault that cuts the unconformity  
391 (Figure 6a-c). Despite their different orientations, both of these normal faults are filled by

392 pyrite (Figure 6c). This N140° to N160° normal fault could have been reactivated at the same  
393 time as the N110° to N130° faults.

#### 394 4.2.4. Payré Estuary outcrop

395 The Payré Estuary is a 250 m-long cliff area where SU2 and SU3 outcrop (Figures 2a  
396 and 7a).

397 SU2 and SU3 are cut by a network of minor normal faults showing an offset of up to  
398 10 cm (Figure 7a). Besides, vertical E-W fractures (Figure 7c) are filled with barite and calcite  
399 abutting on the previous normal fault network (Figure 7a). At the fracture scale, the calcite  
400 veins crosscut the barite vein (Figure 7b). A Last calcite mineralization stage is locally  
401 observed in the coating (concretionary habit) both in the fractures and the interbeds.

#### 402 4.2.5. Anse de Saint-Nicolas outcrop

403 The Anse de Saint-Nicolas is a large area where unconformity can be followed in the  
404 middle of the coastal cliff over a distance of 1.5 km (Figure 2a). The mapped zone is located  
405 at the eastern boundary of the cliff where B.U. and SU2 to SU3 are observed on the tidal  
406 rocky shelf (Figure 8b). In the following section, we described the structure within the B.U.  
407 and those in SU2 to SU3.

408 The B.U. outcrops on the western half of the map (Figure 8a-b). The foliation of the  
409 B.U. is striking N135° to N0° and dips to the East. In the field, we measured two populations  
410 of faults: 1) a west-dipping, N160°-trending normal faults spaced 20 to 50 cm apart (Figure  
411 8a) and 2) N40° to N60°-trending vertical left-lateral strike-slip faults (Figure 8h). Both  
412 populations are sealed by the unconformity (Figure 8a) and predate the Hettangian. The  
413 N40° to N60° striking faults are less numerous and locally form deformation corridors where  
414 pyrite is abundant (Figure 8b). The orthoimage reveals N90° to N110° striking faults parallel  
415 to the coastal cliff (Figure 8a-b). They abut on N40° to N60° striking faults (Figure 8c) and are  
416 locally filled with barite, pyrite, and quartz (Figure 8f).

417 SU2 and SU3 outcrop on the eastern half of the map (Figure 8a-b) in this area, the  
418 structural pattern is dominated mainly by N90° to N110° striking fractures consisting of  
419 faults, veins, and joints (Figure 8b). The fault offsets are consistent with a normal motion and  
420 coherent with a vertical slickenside on a fault plane (Figure 8e). The N90° to N110° striking  
421 veins are filled mainly with barite, pyrite (Figure 8g), and occasionally with quartz (Figure 2a).



422 Geodic barites are abundant in the E-W corridors (Figure 8b-d-g). The unconformity is visible  
423 on the coastal cliff and in most distal parts of the rocky tidal shelf, where a 500 m-long  
424 outcrop of silicified SU2 is preserved (Figure 8b). As at the Anse aux Moines, Cayola Bay, and  
425 the Mine des Sardes (Figures 4, 5, and 6), silicification of SU2 develops over a few meters  
426 around N90° to N110° striking normal faults, potentially increasing SU2's resistance to  
427 erosion.

428 In SU2 and SU3, two further populations of smaller fractures striking from N30° to  
429 N50° and N150° to N170° (Figure 8b-d-g-h). As no offsets of the sedimentary beddings are  
430 observed here, this suggests a type I rupture mode (i.e., joints). These smaller fractures are  
431 locally filled with pyrite, while barite is always absent (Figure 8g). No structure striking  
432 between N150° and N170° are visible at the map scale, but they do appear at high resolution  
433 (Figure 8d-g). In many locations, abutment relationships indicate that N150° and N170°  
434 striking joints post-dates N90° to N110° striking fractures (Figure 8d-g). The N30° to N50°  
435 striking fracture population is well expressed at the map scale, where it forms a linear  
436 corridor with abundant pyrite embedding angular clasts but with no visible motion (Figure  
437 8b). However, the geometric relationship between this corridor and the N90° to N110°  
438 striking faults remains unclear. At high resolution, the "X" shape geometry of the N150° to  
439 N170° striking joints and the N30° to N50° striking joints (Figure 8d-g) suggests that they act  
440 as conjugated joints.

#### 441 4.2.6. Four à Chaux outcrop

442 Four à Chaux is located east of Anse de Saint-Nicolas (Figure 2a), where SU4 and  
443 especially SU5 are observed on the tidal rocky shelf and the coastal cliff (Figure 9a-d). A  
444 major fault described by Ters and Gabilly (1986) draws SU5 down to the level of SU4 in the  
445 north-western part of the mapped area.

446 Field measurements (Figure 9c) and the ortho-image in Figure 9a-b highlight three  
447 fracture populations oriented respectively: N100° to N120°, N40° to N60° and N160° to N-S°.  
448 Fractures oriented N100° to N120° are the longest structure with local barite and calcite  
449 fillings (Figure 9a-e). On the coastal cliff, the slickensides on a fault plane oriented N104°-  
450 75°SW are compatible with a normal motion (Figure 9e).

451 The N40° to N60° and N160° to N-S° fractures are the shortest; they are visible only  
452 at a high resolution between the beach and the coastal cliff (Figure 9b). These two fracture  
453 populations are abutting and thus post-dated on the N100° to N120° striking fractures  
454 (Figure 9b). The geometrical relationship between the N40° to N60° and the N160° to N-S°  
455 striking fractures are an “X” shape intersection suggesting that these two populations are  
456 coeval (Figure 9b). No offsets of the sedimentary bedding are observed here, suggesting a  
457 type I opening mode (i.e., joints). No mineralization fills these joints (Figure 9d).

#### 458 **4.3 Calcite U-Pb geochronology**

459 The three samples for U-Pb dating are from calcite veins sampled at Four à Chaux  
460 (ASN201 sample; Figure 9a) and at the Payré Estuary (PN201 and PP5 samples; Figure 7a).

461 ASN201 has been sampled on the tidal rocky shelf of Four à Chaux composed of SU5  
462 strata (Figure 10a), where calcite forms 10 cm thick veins with dilational vein textures (Figure  
463 10b; Roberts and Holsworth, 2022). Its orientation is N100°-52°S (Figure 10b), and at the  
464 map scale, it is the continuation of the major normal fault N104°-75°SW (Figure 9a and  
465 Figure 10a). On the cliffs, slickensides from the fault plane indicate a normal sense of  
466 shearing and the occurrence of rosette-shaped barite with calcite on the fault plane surface  
467 (Figure 9d-e). The mineral deposition is synchronous with the fault activity (Roberts and  
468 Holsworth, 2022). ASN201 sample consists of yellowish subtransparent rhombohedral calcite  
469 crystals 0.5 to 1 cm wide. At a small scale, the calcite vein hosts crackle-breccia of SU5  
470 embedded by the same blocky calcite crystals (Figure 10c). This observation demonstrates  
471 the synchronous precipitation of calcite with the faulting that affects SU5. The lower  
472 intercept on the Tera-Wasserburg Concordia diagram yields a date of  $144.1 \pm 26.2 / 26.4$  Ma  
473 ( $n=20$ , MSWD=0.68; Figure 10g).

474 Samples PN201 and PP5 come from the Payré Estuary coastal cliff (Figures 2a and 7).  
475 PN201 and PP5 are oriented N86°-84°S and N95°-88°S respectively (Figure 5d). These veins  
476 are hosted in SU2, and by place, the veins crosscut barite veins, like the sample PN201  
477 (Figure 7b and 10d). This shows that two fracturing with N-S opening occurred at the Payré  
478 Estuary, the first with fractures filled by barite and the second with calcite. In detail, the  
479 calcite consists of cloudy yellowish-white rhombohedral crystals 1 to 3 cm wide. At a small  
480 scale, in a smaller sample than PN201 from the Payré Estuary cliff, a barite vein is crosscut by

481 a calcite vein constituted of blocky crystals (Figure 10f). Another calcite veinlet filled a  
482 fracture crosscutting the same barite vein (Figure 10f). The morphology of the calcite veins  
483 could suggest a single phase opening during crack-seal, and so, possible synchronicity of  
484 calcite filling with fracturing (Roberts and Holdsworth, 2022). The lower intercept on the  
485 Tera-Wasserburg Concordia diagram yield dates of  $72.5 \pm 11.5 / 11.6$  Ma ( $n=20$ ,  
486  $MSWD=0.45$ ) and  $79.7 \pm 22.3 / 22.4$  Ma ( $n=20$ ,  $MSWD=0.85$ ), for PP5 and PN201 calcites  
487 respectively (Figure 10h-i).

## 488 **5 Discussion**

### 489 **5.1. Chronology of brittle structure**

490 From site to site, we sorted the joints and faults in the Vendée coastal domain  
491 according to their 1) orientations, 2) relationships to the Aquitaine Basin unconformity, and  
492 3) mineral fill (Table 1). We obtained five populations of faults and two populations of joints  
493 (referred to after that as FP-1 to FP-5 and JP-1 and JP-2).

494 The FP-1 fracture family consists of N-S striking normal faults crossing only B.U.  
495 (Figures 5, 6, 8). They are locally associated with the emplacement of aplo-pegmatitic dikes  
496 (Figure 5), suggesting that they were active at the end of the Variscan ductile deformation  
497 dated from Late Carboniferous by Turrillot et al. (2011) and Augier et al. (2015).

498 The FP-2 fracture family consists of NE-SW striking sinistral faults that displace  
499 beddings relics in B.U. micaschists and magmatic dikes with an apparent horizontal offset of  
500 up to 5 m (Figure 6, 8). The FP-2 is sealed by the Aquitaine Basin unconformity everywhere in  
501 the B.U., indicating that they formed before the Hettangian. Because no magmatic dike  
502 follows the fault plane of FP-2, we propose that FP-2 post-dates FP-1. In the Anse de Saint-  
503 Nicolas area, NE-SW joints of the same orientation crosscut SU2 and SU3. No strike-slip  
504 motions were observed there. As these joints are not observed in SU4 and SU5, FP-2 is  
505 potentially reactivated between Pliensbachian and Toarcian times. However, as FP-2 from  
506 B.U., SU2, and SU3 are filled with pyrite, the reactivation can also occur during the mineral  
507 deposition (referred to as FP-2 reactivated in table 1). In this case, the absence of the NE-SW  
508 joint in SU4 and SU5 may be explained by the rheologic barrier of the SU4 marls, as in the  
509 case of mineral deposits.

510           The FP-3 fracture family consists of NW-SE striking dextral faults that cut and shift  
511 bedding relics in B.U. micaschists and aplo-pegmatitic dikes (Figure 6). The relationship  
512 between FP-3 and the Aquitaine Basin unconformity is ambiguous: on the one hand, FP-3 is  
513 sealed by the unconformity in most cases, indicating that it formed before the Hettangian.  
514 At B.U., it abuts FP-1 and thus is posterior to FP-1 (Figure 6), and the intersecting  
515 relationship between FP-3 and FP-2 suggests that they formed simultaneously. On the other  
516 hand, two major faults from FP-3 crosscut the unconformity with a normal motion, and SU2  
517 and SU3 at the contact of these two faults are silicified (Figures 2 and 6). These mean the  
518 reactivation of FP-3 per place (referred to as FP-3 reactivated in Table 1).

519           The FP-4 fracture family consists of WNW-ESE striking normal faults that affect both  
520 B.U. and SU1 to SU5 (Figures 4, 5, 6, 7, 8, 9) and with the Aquitaine Basin unconformity  
521 (Figures 4, 5, 6). The FP-4 structure family forms horsts and grabens visible at map scale  
522 (Figure 2, 4, 5). FP-4 abuts FP-2 and FP-3, suggesting that these latter predate FP-4 although  
523 they crosscut the unconformity (Figure 2, 6). We observed barite, pyrite, quartz, and calcite-  
524 filled veins and fault planes in the SU1 to SU5 as previously described by Cathelineau et al.  
525 (2012) and Strzeczynski et al. (2020) but also in the B.U. (Figure 8). We also provide field  
526 evidence of focused silicification of SU2 and SU3 immediately around FP-4 faults that  
527 crosscut the unconformity (Figure 4). Given this evidence, we propose that the fluid flow  
528 related to mineral deposition and silicification is contemporaneous with normal faulting.  
529 Calcite from sample ASN201 which fills an FP-4 affecting SU5 yields a U-Pb date of  $144.1 \pm$   
530  $26.2$  Ma (Figure 10). In the same fault plane, calcite is associated with barite (Figure 9a-e).  
531 This date overlaps the 155 to 145 Ma interval proposed in the northern Aquitaine Basin  
532 ( $^{40}\text{Ar}/^{39}\text{Ar}$  and K-Ar dating on adularia and clays by Cathelineau et al., 2012). It reflects the  
533 timing of mineral deposition and WNW-ESE striking normal faulting (Figure 9).

534           The FP-4 fracture family consists of WNW-ESE striking calcite veins that affect SU2 in  
535 the Payré Estuary (Figure 7). The FP-5 veins crosscut the FP-4 barite veins (Figure 7) and abut  
536 on FP-4 normal fault. Calcite from samples PP5 and PN201 that fills FP-5 veins yield a U-Pb  
537 date of  $72.5 \pm 11.5$  Ma and  $79.7 \pm 22.3$  Ma, respectively (Figure 10). These ages are  
538 significantly younger than the 170 to 118 Ma range proposed for FP-4 and agree with the  
539 relative chronology (Figure 7).

540 The JP-1 and JP-2 joint families, oriented NE-SW and NNW-SSE, respectively (Figure  
541 9), only develop in SU5 (Figure 9). Both are abutting on, and thus they post-date FP4. The  
542 absence of barite, pyrite, quartz, and calcite filling the joints confirms that JP-1 and JP-2  
543 post-date mineral deposition (Figure 9). In the absence of observed relationships with FP-5,  
544 the relative timing remains unconstrained.

## 545 **5.2. Late-Variscan tectonic evolution**

546 Three populations of faults (FP-1, FP-2, and FP-3) sealed by unconformity take place  
547 before the Hettangian (Figure 11). The orientation and movements of FP-1 are consistent  
548 with E-W extension post-dating HT-LP Variscan metamorphism (Cagnard et al., 2004; Goujou  
549 et al., 1994; Iglésias and Brun, 1976). A population of similar faults observed in the west  
550 Armorican Massif has been dated between 302 and 298 Ma (Turrillot et al., 2011). The  
551 geometric relationship between FP-3 and FP-2 suggests synchronous and conjugate slip  
552 faults compatible with  $\sigma_1$  and  $\sigma_3$ , oriented N-S and E-W, respectively (Figure 6) and  
553 consistent with the dextral movement of the South Armorican shear zone (Figure 2) that  
554 ended circa 300 Ma (Augier et al., 2015). Considering this, we propose that brittle faults of  
555 the Vendée coastal domain sealed by the Aquitaine Basin unconformity occur during the  
556 Late Carboniferous (Figure 11). No further deformation is recognized until the deposition of  
557 SU1.

## 558 **5.3. Late-Jurassic Early Cretaceous extension and fluid event**

559 The FP-4 structure are compatible with a subhorizontal  $\sigma_3$  oriented N-S, as  
560 Strzeczynski et al. proposed (2020). Throughout the study area, tectonic activity is  
561 synchronous with fluid transfer and mineral deposition (Cathelineau et al., 2012; Strzeczynski  
562 et al., 2020) (Figure 2; Figure 11). The close relationship between high-temperature mineral  
563 deposition ( $> 250^\circ\text{C}$ ), silicification, and the rooting of FP-4 normal faults in the U.B. suggests  
564 that some of the fluids involved are crustal in origin and ascend from several kilometers  
565 depth (Cathelineau et al., 2012). Our new age on FP-4 calcite constrains the chronology of N-  
566 S extension in the Vendée coastal domain at the Jurassic-Cretaceous transition (Figures 10  
567 and 11). This age is consistent with previous dating of adularia and clay minerals  
568 (Cathelineau et al., 2012), meaning the dated minerals precipitated simultaneously. This  
569 event predates the main extensional phase of Aquitaine Basin rifting and oceanic spreading

570 in the Bay of Biscay (Figure 1; Tugend et al., 2014, 2015) and is related to the earliest  
571 extensive deformation (Asti et al., 2022).

572 The barite, pyrite, and quartz deposits that fill several faults FP-2 and FP-3 (Figure 8)  
573 show that during the Jurassic-Cretaceous transition, at the Jurassic-Cretaceous transition,  
574 fluids flow along both newly formed (FP-4) and reactivated (FP-2 and FP-3) structure. In  
575 addition, we document the tectonic reactivation of the inherited strike-slip fault FP-3 during  
576 the Jurassic-Cretaceous transition fluid event (Figure 6). The involvement of the Late  
577 Variscan inherited structure during the rifting phase of the Aquitaine Basin has been  
578 proposed before based on seismic profiles (Ducoux et al., 2021; Issautier et al., 2020;  
579 Manatschal et al., 2015) but never observed in the field. The Vendée coastal domain  
580 provides a unique opportunity to observe the association of newly formed and inherited  
581 faults during this rifting phase. This fault association agrees with the oblique rifting model  
582 for the Bay of Biscay proposed by Asti et al. (2022).

#### 583 **5.4. Pyrenean compression**

584 A calcite-filled FP-5 fracture dated between 84 and 61Ma (Figure 10) and joints JP-1  
585 and JP-2 post-date the mineralization and extension of the Jurassic-Cretaceous transition. If  
586 calcite infilling is synchronous with FP-5, the latter forms with the onset of shortening along  
587 the Eurasian-Iberian plate boundary (Figure 1). At this time, shortening is assumed to follow  
588 an NNE-SSW direction (Rocher et al., 2000) parallel to the  $\sigma_3$  opening direction of the FP-5  
589 stage veins (Figure 7; Figure 11). In convergent domains, subhorizontal  $\sigma_3$  strike in the same  
590 direction as large-scale convergence has already been described before and during thrusting  
591 (Lacombe, 2010, 2012). When it precedes horizontal shortening, subhorizontal  $\sigma_3$  stress is  
592 related to extension into the peripheral foredeep bulge (Bradley and Kidd, 1991; Doglioni,  
593 1995; Langhi et al., 2011; Tavani et al., 2015; Turcotte and Schubert, 2002). When  
594 subhorizontal  $\sigma_3$  stress coincides with shortening, it corresponds to limited extension at fold  
595 hinges (Cooper, 1992; Hancock, 1985).

596 During the Late Cretaceous (pre-Santonian), the extension observed in the Aquitaine  
597 Basin foreland is associated with mantle exhumation leading to high geothermal gradients  
598 (e.g., Angrand et al., 2018; Clerc et al., 2012; Issautier et al., 2022; Lagabrielle and Bodinier,  
599 2008; Lagabrielle et al., 2010). This thermal influence does not affect the northern Aquitaine

600 Basin. In the Vendée coastal domain, two joints (JP-1 and 2) and folds (Figure 2) could be due  
601 to NNE-SSW compressive deformations (Figure 11) after the extension of the Upper Jurassic  
602 and Lower Cretaceous. Thus, compressive tectonics related to the Campanian Iberia-Eurasia  
603 convergence (Issautier et al., 2022; Mouthereau et al., 2014; Roure et al., 1989; Vergès et al.,  
604 1995, 2002) is observed during the Late Cretaceous up to 400 km north of the Pyrenean belt.

### 605 **5.5. Diffuse versus focused strains in the Aquitaine-Pyrenean domain**

606 Our new constraints on the timing of the deformations affecting the North Aquitaine  
607 Platform provide insight into how diffused tectonics focused on limited areas during  
608 kinematic changes at plate boundaries.

609 The exhumation of the Armorican Massif and the French Massif Central began in the  
610 Upper Jurassic and/or Lower Cretaceous from the initiation of the opening of the Bay of  
611 Biscay (Figure 1 and 12; Barbarand et al., 2020; François et al., 2020). Such uplift coincides  
612 with forming of new fault networks (FP-4) on the North Aquitaine Platform, compatible with  
613 subhorizontal  $\sigma_3$  oriented N-S and the tectonic reactivation of inherited faults (FP-3). In the  
614 Paris Basin, this episode results in large-scale folding, forced regression, and unconformity  
615 deposition of Purbeck facies (Brigaud et al., 2018). These observations provide good  
616 arguments for intra-plate deformation (e.g., Parizot et al., 2022; Ziegler et al., 1995).

617 Because it occurred 30 Ma before the main Aquitaine rifting event and is located 350  
618 km north of the main rifts in the Parentis and the Arzac-Mauléon Basins, we proposed that  
619 extension in the Vendée coastal domain at the Jurassic to Cretaceous transition is an  
620 example of diffuse extension terrain preceding the focus of strain during rifting (Figure 12;  
621 Asti et al., 2022; Huerta and Harry, 2007; Seymour et al., 2016; Szymanski et al., 2016).

622 A network of calcite-filled conjugate joints and faults (FP-5) (Figure 7), crosscutting  
623 the previous fractures (FP-4), are Late Cretaceous, i.e., from the early stages of the Iberian-  
624 Eurasian convergence. At this time, no temperature drop occurred in the Armorican Massif  
625 and the French Massif Central (Barbarand et al., 2020; François et al., 2020), suggesting that  
626 shortening is not associated with significant uplift of the North Aquitaine Platform. As no  
627 relief is documented (Huygue et al., 2012), such compressive deformation cannot be related  
628 to wedge propagation. It is more likely related to far-field intra-plate tectonics (Figure 12;  
629 Gorczyk et al., 2013) predating the formation of the Pyrenean relief and the Eocene

630 propagation of the deformation in the North Aquitain Platform (Brown et al., 2021), the Paris  
631 basin (Blaise et al., 2022) and the English Channel (Parrish et al., 2018).

## 632 **6. Conclusion**

633 In this study, we applied field and UAV imagery methods in the Vendée remarkable  
634 outcrops to decipher the evolution of brittle tectonics of the north of the Aquitaine Basin  
635 during the opening of the Bay of Biscay and the Iberia-Eurasia convergence.

636 We showed that: (1) During the opening of the Bay of Biscay, newly formed normal  
637 faults associated with reactivated Late Variscan faults provide evidence of oblique rifting. (2)  
638 Compressive tectonics related to the Iberia-Eurasia convergence occurred during the Late  
639 Cretaceous 400 km north of the Pyrenean belt. (3) Both the extensional and compressive  
640 tectonics are related to diffuse intra-plate tectonics before the focus of deformation on  
641 continental rifts and the Bay of Biscay during the Early Cretaceous and on the Pyrenean-  
642 Cantabrian margin during the Cenozoic.

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932

933 **Figure captions**

934 Figure 1: Iberian-European plate boundary reconstitution from Jurassic-Cretaceous transition  
935 through present-day (spatial and temporal restoration map modified from Tugend et al. (2015) with  
936 data from Asti et al. (2022), Biteau et al. (2006) and Thomas et al. (1996); fluid circulation reports  
937 from (1) Cathelineau et al. (2012); (2) Munoz et al. (2016); (3) DeFelipe et al. (2017); (4) Corre et al.  
938 (2018), Incerpi et al. (2020), Salardon et al. (2017); (5) Boutin et al. (2016), Quesnel et al. (2019); (6)  
939 Salardon et al. (2017); (7) Barré et al. (2021); uplift movement from thermochronology studies of  
940 Barbarand et al. (2020) and François et al., (2020); maximum fore bulge extension from Angrand et  
941 al. (2018)). S.A.S.Z.: South Armorican Shear Zone.

942 Figure 2: (a) Geological map of the Vendée coastal domain modified after Ters and Gabilly (1986)  
943 based on field observations with close attention on faults shifting the unconformity and  
944 unconformity depth (B.S.L.: Below Sea Level) compiled after B.R.G.M. database (B.S.S., n.d.). (b)  
945 Simplified geological log from Strzeczynski et al. (2020). Dolo. Lim.: Dolomitic limestones (c) Pattern  
946 of vein paragenesis after Strzeczynski et al. (2020).

947 Figure 3: Relative chronology of structure and mineral fills (after Bons et al. (2012), Sanderson and  
948 Nixon (2015), and Peacock et al. (2016)). (a) The geometry of fractures and their chronology with  
949 their rupture mode. (b) Mineral fills timing concerning fractures depending on their rupture mode.

950 Figure 4: Anse aux Moines coastal cliff. (a) Composite picture and structural interpretation of the  
951 coastal cliff limited to the south by a normal fault that shifts the unconformity and tilts SU1 and SU2  
952 beddings to the south. (b) Picture of brecciated quartz veins containing silicified clasts. (c) Picture of  
953 the fault gouges with heterogeneous silicified clasts in the siliceous matrix. (d) Stereographic  
954 projection of bedding and faults orientation. See Table 1 for brittle structure' nomenclature.

955 Figure 5: Cayola Bay outcrop. (a) Interpreted UAV orthoimage of the S.E. side of the NW-SE oriented  
956 Cayola bay graben with fault motions reported and weighted rose diagram. (b) Orthoimage extract  
957 showing dextral ductile-brittle deformation of the aplo-pegmatitic dike (underlined in red) by NNW-  
958 SSE to N-S faults on the rocky shelf. (c) UAV Orthoimage extracts showing a sinistral deformation of  
959 the dike by NNE-SSW faults. (d) and (e) coastal cliff picture and interpretation of the normal faults  
960 shifting the unconformity and associated silicification of the cover. See Table 1 for brittle structure  
961 nomenclature.

962 Figure 6: Mine des Sardes outcrops. (a) Picture of two normal faults spreading in the cliff, shifting the  
963 unconformity. (b) Picture of the cliff showing B.U. to SU2 and the non-spreading of NE-SW and NNW-  
964 SSE faults from B.U. above the unconformity. (c) Interpreted orthoimage of the rocky shelf with

965 weighted rose diagram. (d) Orthoimage extract showing a dextral brittle deformation of the foliation  
966 (underlined in red) by WNW-ESE faults in B.U. (e) Orthoimage extract showing conjugate faults  
967 shifting a syn-foliation quartz dike (underlined in red). (f) Orthoimage extract showing a NE-SW  
968 fracture abutting on NNE-SSW faults. (g) and (h) pictures of stratiform karsts from the Mine des Sardes  
969 in the silicified SU2 with barite and quartz mineralization on the karst walls. See Table 1 for brittle  
970 structure nomenclature.

971 Figure 7: Payré Estuary outcrop. (a) Picture of the cliff showing the erosive surface between SU2 and  
972 SU3, and barite-calcite-filled fractures that abut on normal faults. (b) Close up in SU2 of “teeth”  
973 shape calcite in vein crosscutting a barite-vein (underlined in red). (c) Stereographic projection of  
974 structure measured (bold black lines correspond to E-W “teeth” shape calcite-veins). See Table 1 for  
975 brittle structure nomenclature.

976 Figure 8: Anse de Saint-Nicolas outcrop. (a) Picture of the cliff on the west side of the Anse de Saint-  
977 Nicolas showing B.U. covered by SU2 and NW-SE sinistral faults and N-S normal fault hosted in the  
978 B.U. crosscut by the unconformity. (b) Interpreted orthoimage of the rocky shelf made of B.U. to SU4  
979 with weighted rose diagrams. SU2 hosts WNW-ESE normal faults and NE-SW brecciated structure  
980 with pyrite. (c) Orthoimage extract showing WNW-ESE fractures abutting on NE-SW faults in B.U.  
981 with weighted rose diagrams. (d) Orthoimage extract showing N-S fractures abutting on and  
982 crosscutting WNW-ESE fractures locally filled by barite with weighted rose diagrams. (e) Picture of a  
983 fault mirror of a WNW-ESE normal fault with a pyrite patch and a zoom with vertical slickenside. (f)  
984 View of a barite vein in B.U. (g) Picture of barite filling E-W fractures in veins and geodes crosscut by  
985 E-W and NNW-SSE pyrite vein. (h) Stereographic projection of structure measured in B.U. (red lines)  
986 and SU2 (green lines). See Table 1 for brittle structure nomenclature.

987 Figure 9: Four à Chaux outcrop. (a) Interpreted UAV orthoimage of the rocky shelf and weighted rose  
988 diagrams of the digitized faults and fractures. (b) Orthoimage extract showing NNW-SSE and NW-SE  
989 fractures both abutting on and crosscutting WNW-ESE fractures with weighted rose diagrams of the  
990 digitized fractures. (c) Stereographic projection of structure measured in SU5. (d) and (e) Pictures of  
991 the fault mirror of the normal fault hosting ASN201 sample showing barite (underlined in red) and  
992 calcite (underlined in green) associated with vertical slickenside. See Table 1 for brittle structure  
993 nomenclature.

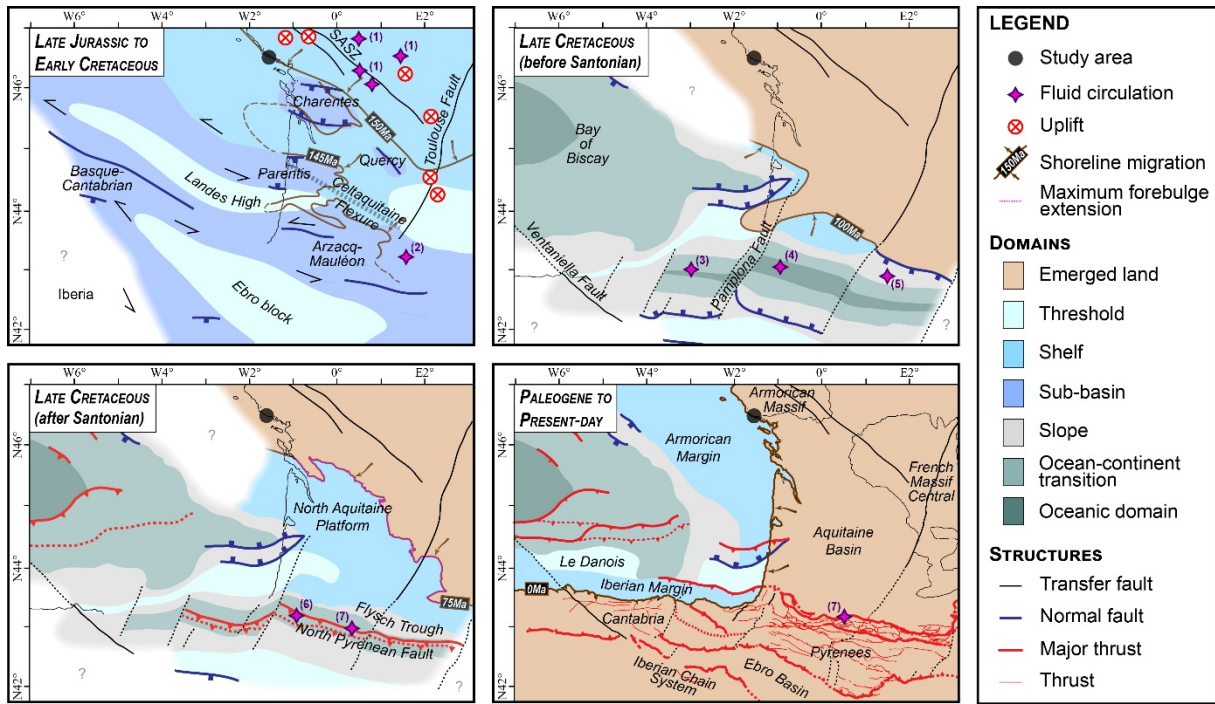
994 Figure 10: Calcite samples dating. (a) Field picture of the sampling area of ASN201 showing the  
995 disposition with the fault plane in Figure 9d. (b) Field picture of ASN201 sample with a texture similar  
996 to dilational veins (Roberts and Holdsworth, 2022). (c) A small-scale petrographic picture under  
997 polarized light of ASN201 sample. SU5-breccias along the wall of the calcite vein are embedded by

998 the same calcite crystals (same extinction orientations), attesting that calcite precipitated during  
999 fracturing. (d) and (e) field pictures of PN201 and PP5, respectively. PN201 calcite vein reopened  
1000 barite vein. (f) A small-scale petrographic picture under polarized light of a sample from the Payré  
1001 Estuary outcrop, similar to PN201. The calcite vein is crosscutting barite vein along the interface with  
1002 an SU2 clasts. Another sub-parallel calcite veinlet crosscuts the barite vein in the upper left corner.  
1003 (g), (h) and (i) Tera-Wasserburg Concordia diagrams of dated calcite samples, uncertainties are given  
1004 without and with systematic uncertainties. See Table 1 for brittle structure nomenclature.

1005 Table 1: Fracture populations with their properties.

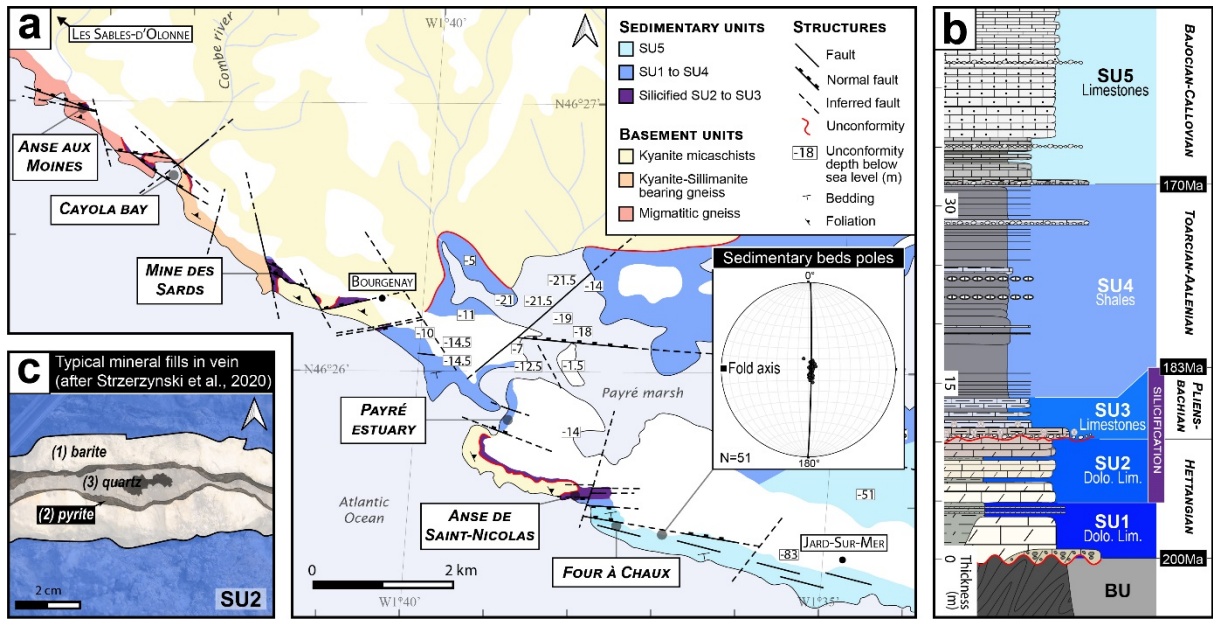
1006 Figure 11: Schematic diagrams of Vendée Coast brittle structure from the tectonics of the Late  
1007 Variscan Orogeny (FP-1, FP-2, and FP-3), the Early Jurassic transgression covering the Variscan  
1008 basement, the Atlantic Opening (FP-4 and partial reactivation of FP-2 and FP-3) and the Pyrenean  
1009 Orogeny (FP-5, JP-1, JP-2, and fold). See Table 1 for brittle structure nomenclature.

1010 Figure 12: Evolution of an N-S cross-section through the Aquitaine Basin showing the tectonic activity  
1011 and where it distributes from (a) Late Jurassic – Early Cretaceous, (b) Early Cretaceous, (c) Late  
1012 Cretaceous to (d) Paleogene.



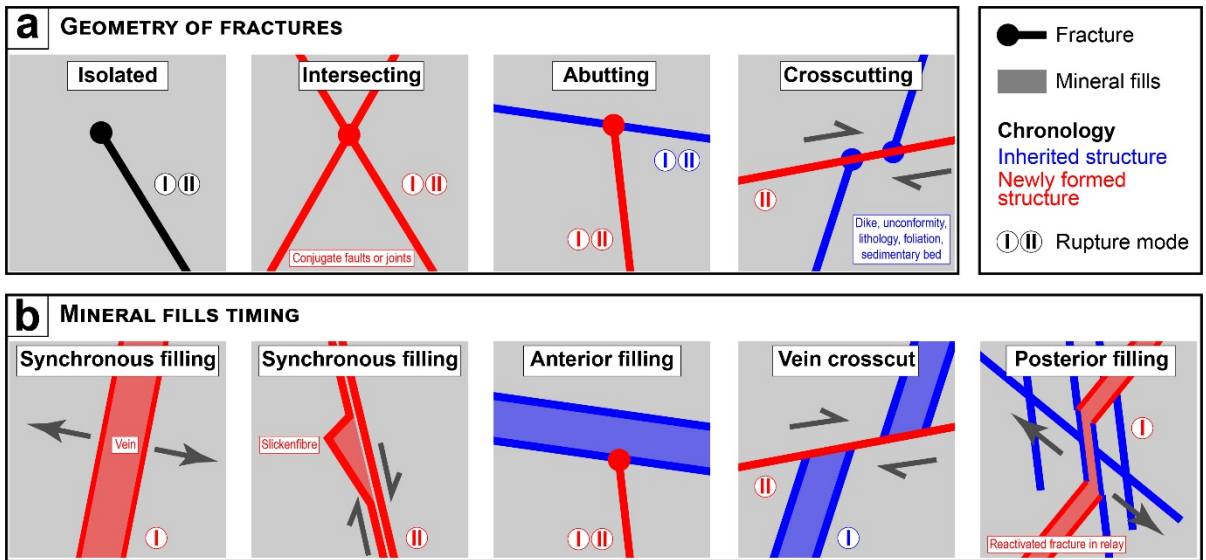
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1014 Figure 1



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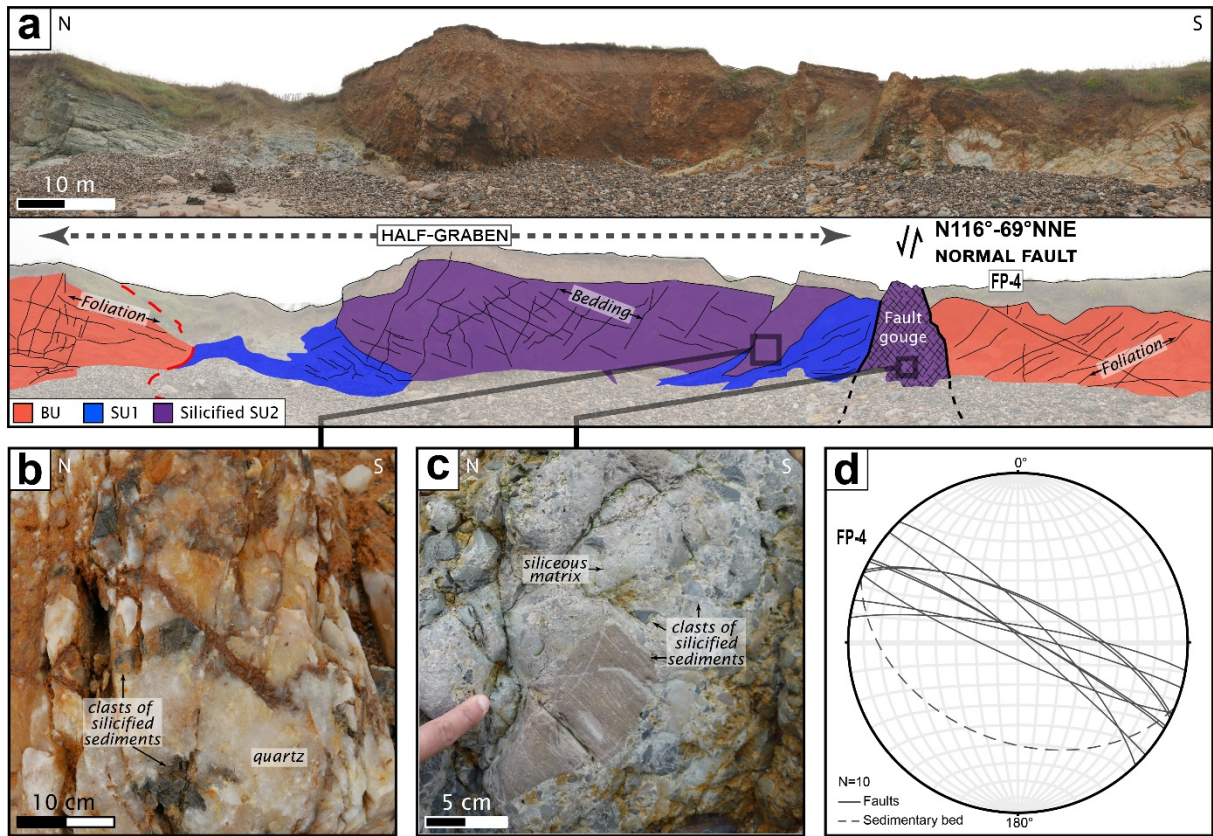
1016 Figure 2



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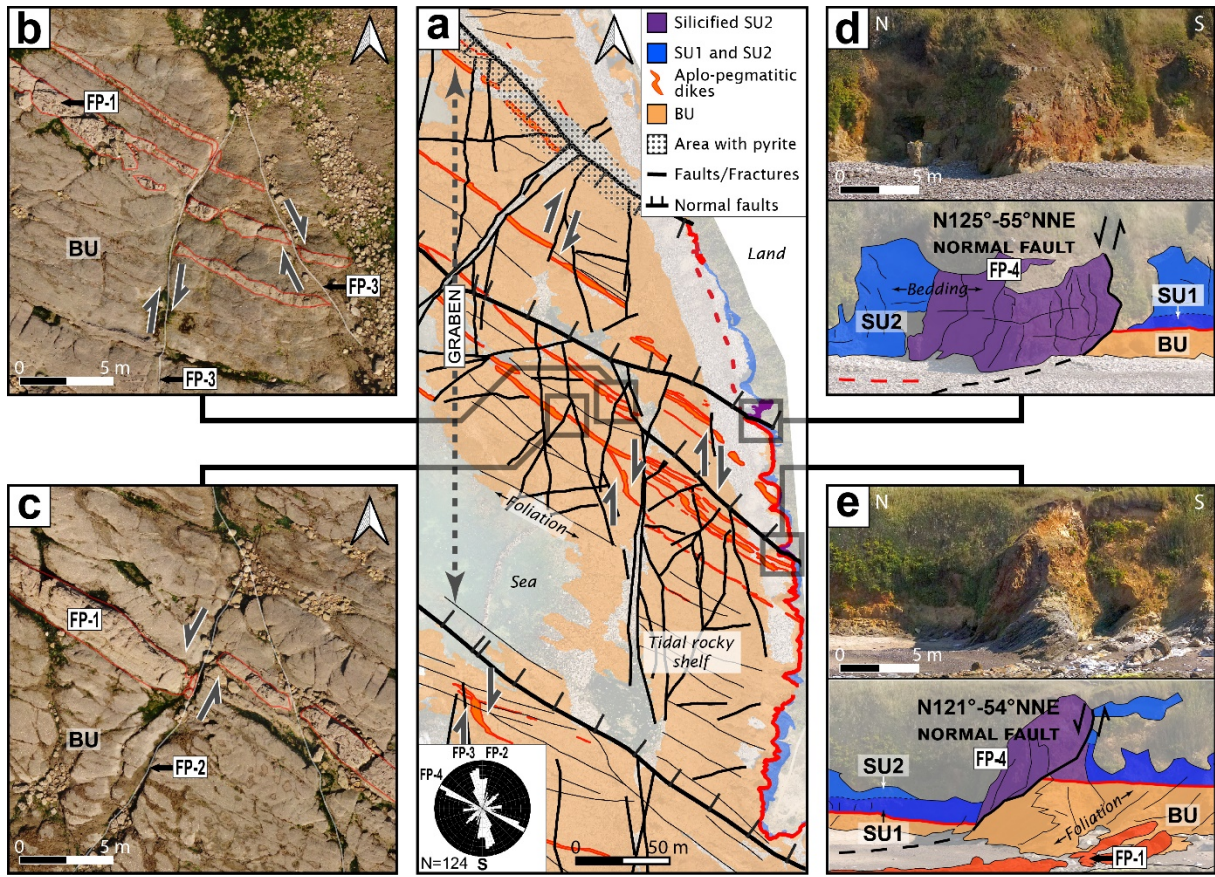
1018 Figure 3





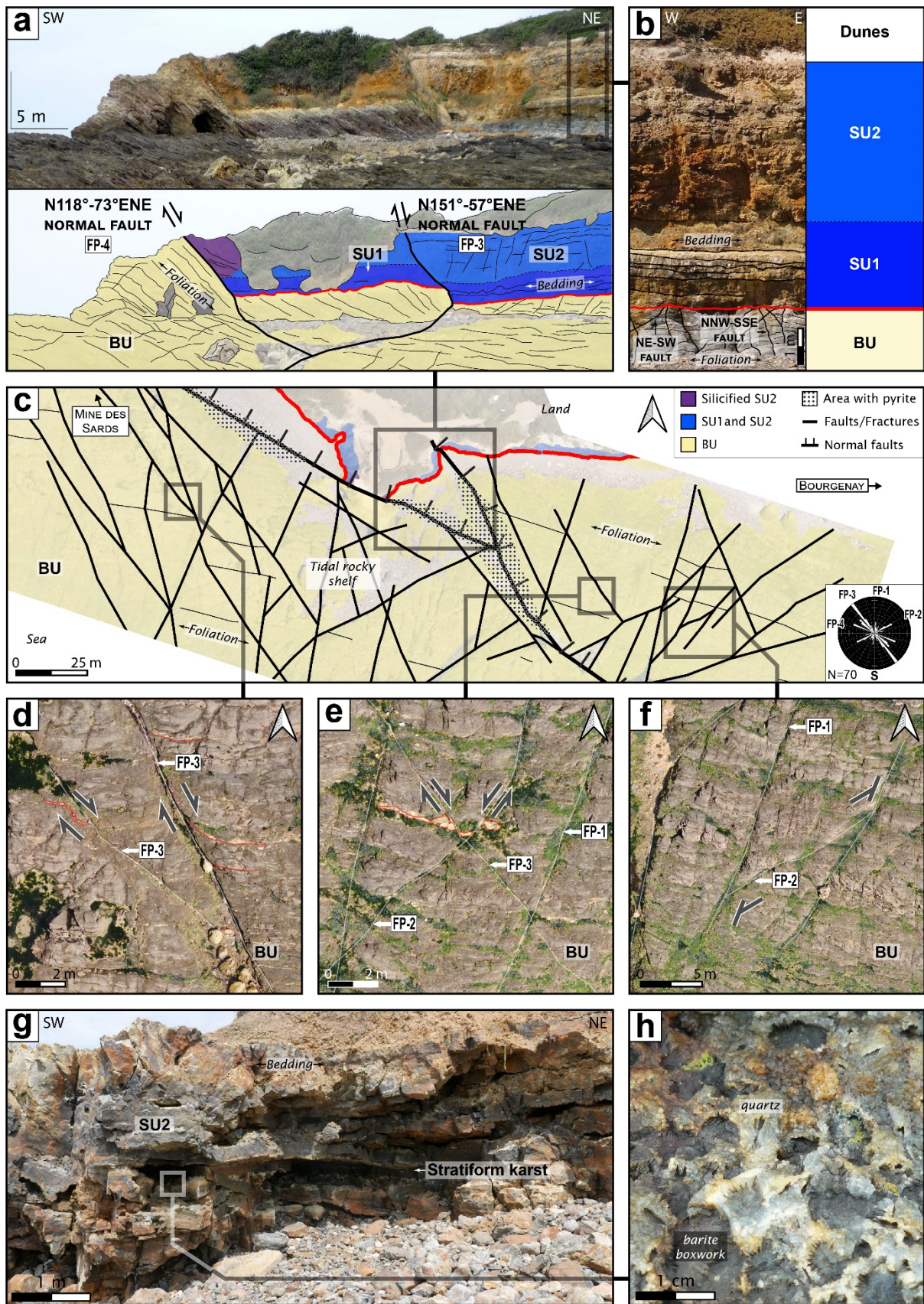
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1020 Figure 4



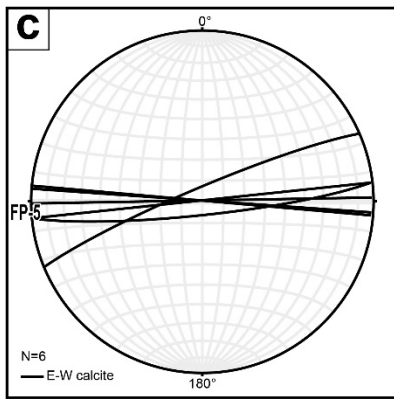
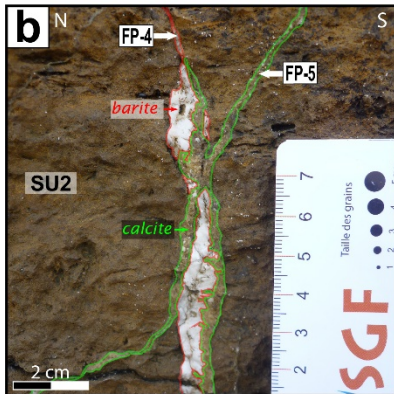
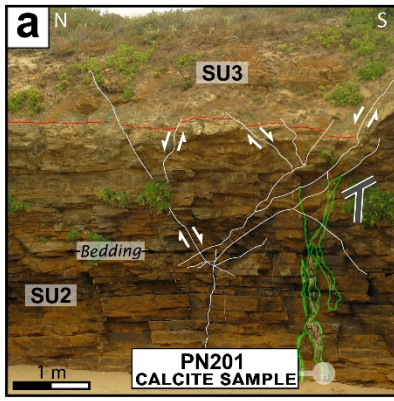
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1022 Figure 5



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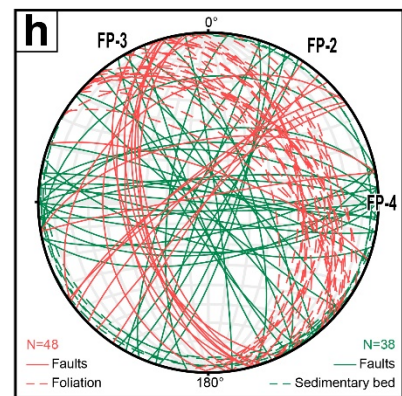
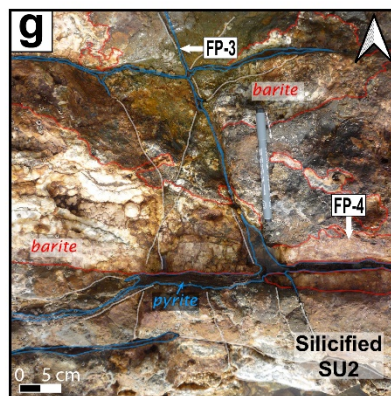
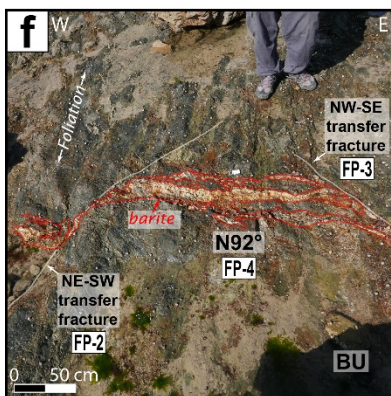
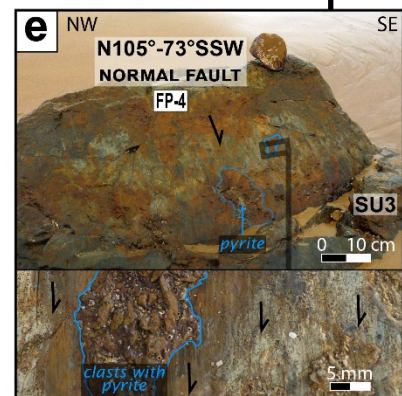
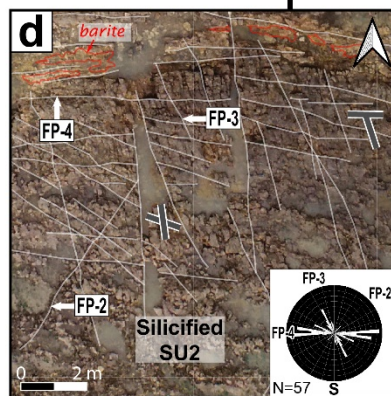
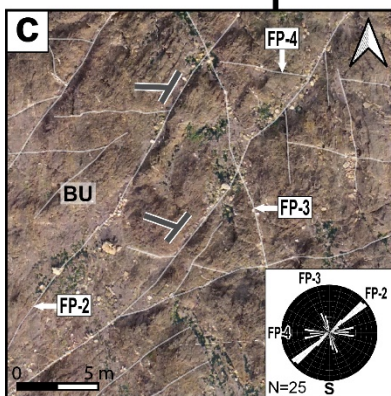
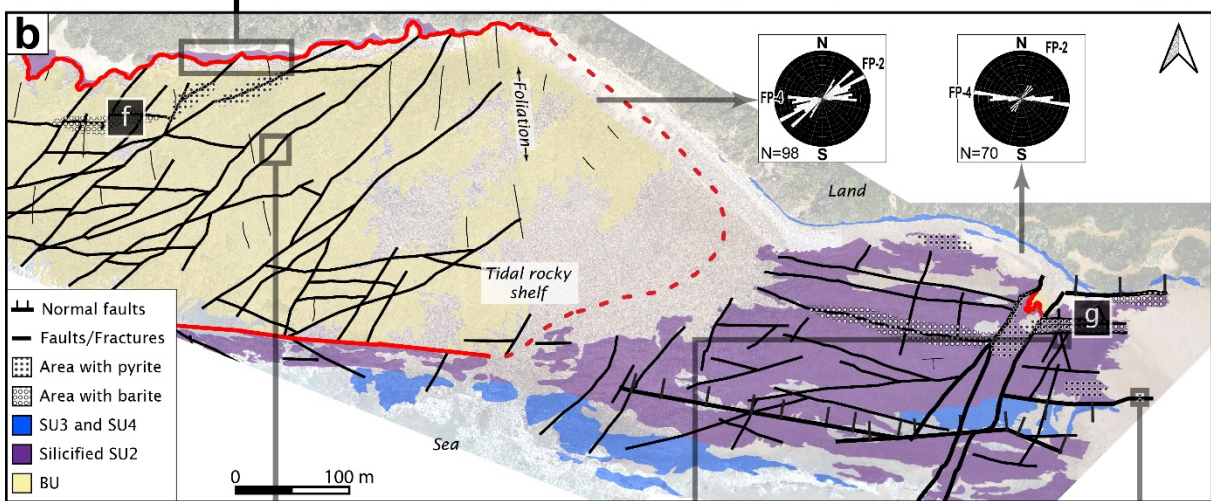
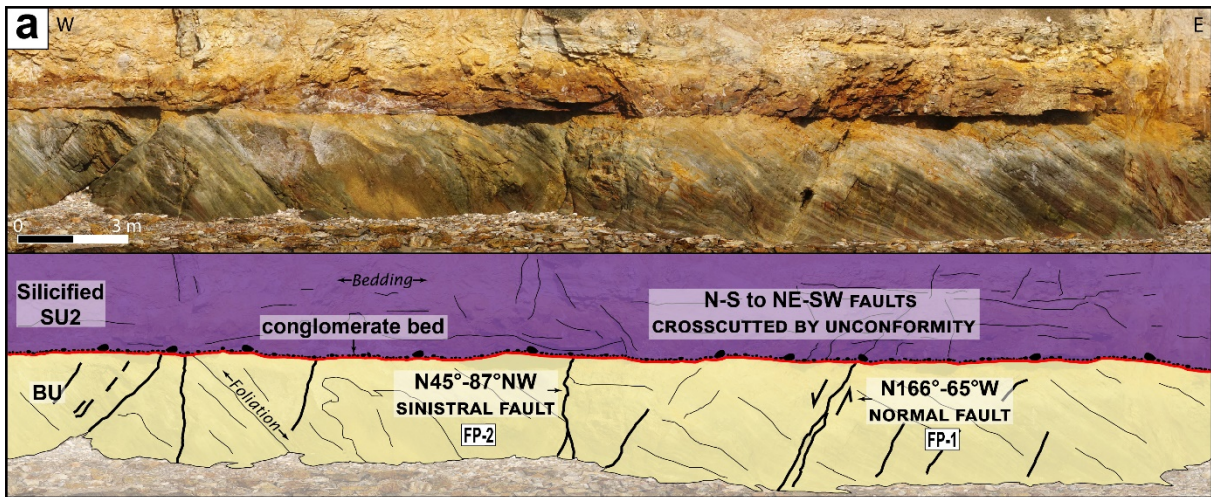
1024 Figure 6



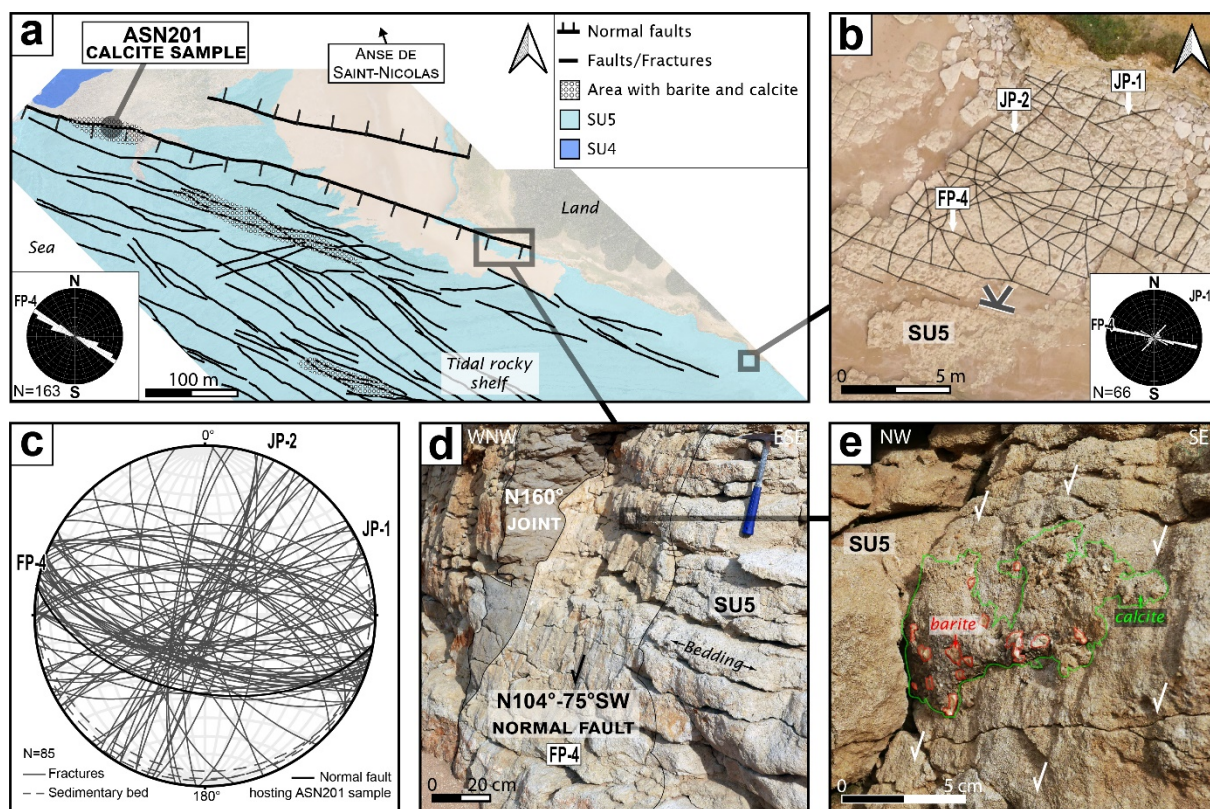
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1026 Figure 7

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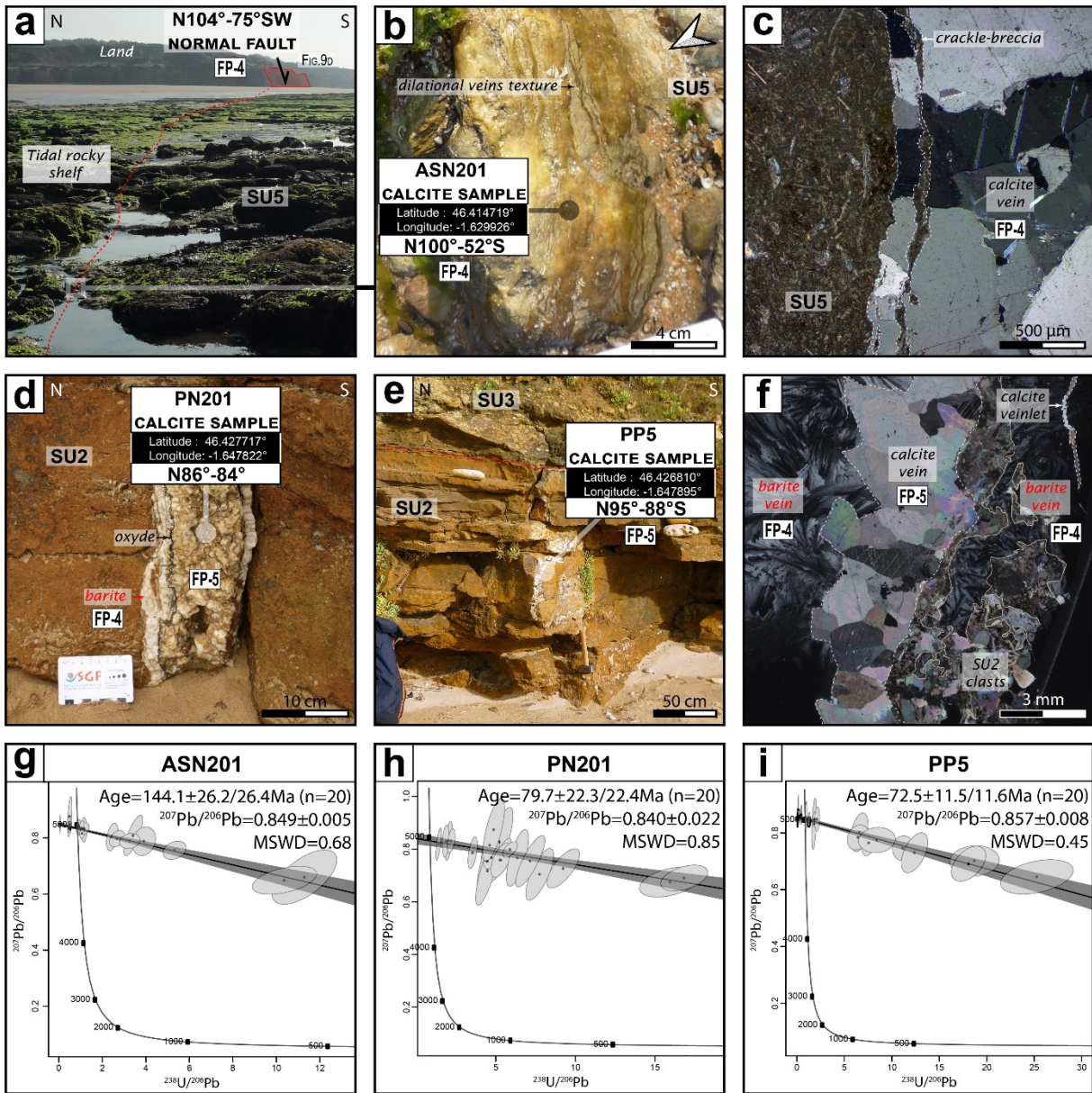


1029 Figure 8



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1031 Figure 9



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1033 Figure 10

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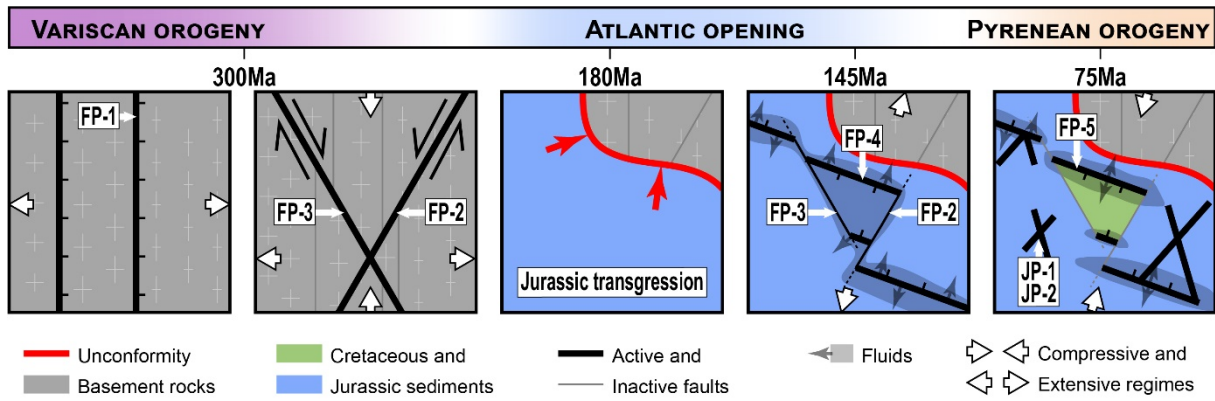
Population	Strike - Structure type	Unit affected	Figures	Unconformity	Mineral deposit (baryte, pyrite, quartz, calcite)	Relative chronology
FP-1	N-S - normal fault - dike	BU	5, 6, 8	sealed by	∅	associated with dike
FP-2	NE-SW - sinistral fault	BU	5, 6	sealed by	∅	syn FP-3
FP-2 (reactivated)	NE-SW - joint	BU to SU3	8	sealed by	Pyrite (±oxidized)	syn FP-4
FP-3	NNW-SSE dextral faults	BU	6	sealed by	∅	syn FP-2
FP-3 (reactivated)	NNW-SSE normal faults	BU to SU3	6, 8	cutting	Silification	syn FP-4
FP-4	WNW-ESE normal fault and veins	BU to SU5	4, 5, 6, 7, 8, 9	cutting	Filled + silicification	abutting on FP-2 and FP-3
FP-5	WNW-ESE calcite vein	SU2	7	unknown	Calcite only	cutting FP-4 veins
JP-1	NE-SW joints	SU5	9	unknown	cutting	syn JP-2, abutting on FP-4
JP-2	NNE-SSW joints	SU5	9	unknown	cutting	syn JP-1, abutting on FP-4

1035

Population	Strike - Structure type	Unit affected	Figures	Unconformity	Mineral deposit (baryte, pyrite, quartz, calcite)	Relative chronology
FP-1	N-S - normal fault - dike	BU	5, 6, 8	sealed by	∅	associated with dike
FP-2	NE-SW - sinistral fault	BU	5, 6	sealed by	∅	syn FP-3
FP-2 (reactivated)	NE-SW - joint	BU to SU3	8	sealed by	Pyrite (±oxidized)	syn FP-4
FP-3	NNW-SSE dextral faults	BU	6	sealed by	∅	syn FP-2
FP-3 (reactivated)	NNW-SSE normal faults	BU to SU3	6, 8	cutting	Silification	syn FP-4
FP-4	WNW-ESE normal fault and veins	BU to SU5	4, 5, 6, 7, 8, 9	cutting	Filled + silicification	abutting on FP-2 and FP-3
FP-5	WNW-ESE calcite vein	SU2	7	unknown	Calcite only	cutting FP-4 veins
JP-1	NE-SW joints	SU5	9	unknown	∅	syn JP-2, abutting on FP-4
JP-2	NNE-SSW joints	SU5	9	unknown	∅	syn JP-1, abutting on FP-4

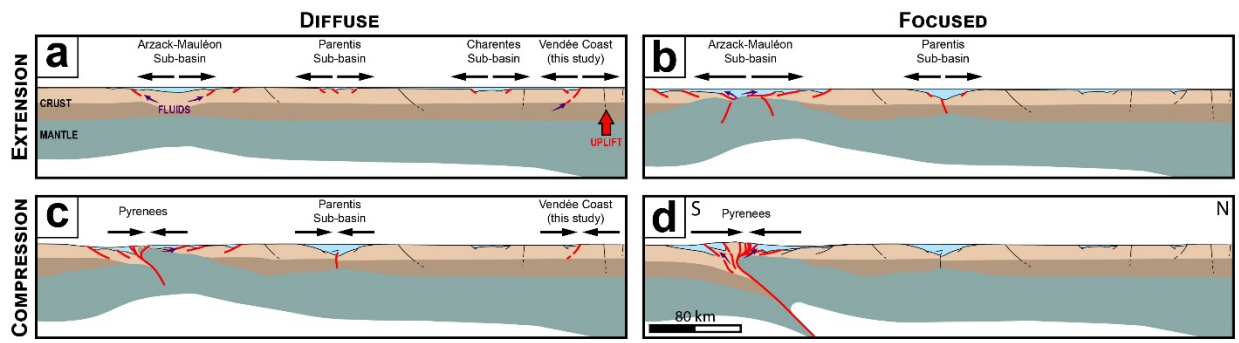
1036 Table 1





1037

1038 Figure 11



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1040 Figure 12