Dear editor,

I am pleased to send you the revised version of my paper on “Diagenetic evolution of fault zones in Urgonian microporous carbonates, impact on reservoir properties (Provence – SE France).

You will see that most of the corrections have been respected as requested.

You will find below, the comments to all remarks. In addition, I made a table to survey the reviewer comments with the following colour code

- Corrections validated are in **green**
- Corrections in **red** have been considered un-useful or inappropriate
- Corrections in **blue** refer to comments at the bottom of the table

Best regards,

Irène Aubert

I. General remarks

“Relative to the scientific part of the manuscript, my main concern is related to the final model in which the permeability contribution was calculated. To me it feels like a good-faith effort, but it would need to be grounded on your field data. To be more explicit, the percentage you calculate for permeability from fault core, fracture network and matrix, should be calibrated according to the width of the fault structure, fracture connectivity and so on.”

The comment of the reviewer is interesting, but cannot be realized in this manuscript because:
- Such a quantification in our field case is too much uncertain because the fault zones are too heterogeneous to do this exercise.
- This is too apart from the subject of the paper,
- this would be much too much and could represent another paper itself.
- Therefore we mentioned this issue in the text as follows: “"The percentage assigned to the fault core or to the matrix are qualitatively estimated. Further quantification could be evaluated, for instance, with the width of the fault core and damage zone domains, or by estimating the fracture network volume. However, no recent study have provided such quantification." **(line 534 to 537)**

II. Specific Comments

N° line	validat.	not app.	com.	Reviewer’s remarks p
10	ok			Please make plural the term "reservoir" changing it to "reservoirs"; moreover
10-12	ok			Please add "diagenetic" before "processes"; modify "that modify" with
13	ok			Please change "Focussing" with "Focusing".
14	ok			Please move the word "impact" before "the fault zone". Rather than using
14	ok			I would change "It" with "This contribution focuses...". Throughout all the text try to
15	ok			Please correct "La Fare Anticlinal" with "La Fare Anticline". In the same sentence
16	ok			Please correct as follows from the form "orthogonal to the fault zones" to
17	ok			Please change from "Diagenetic elements were determined on 92 thin section..."
18	ok			Why are these words "Polarized Light Microscopy" in capitals? Is that necessary?
18	ok			Maybe here it is better to state more precisely "stable isotope measurements"
19	ok			Here, I would modify "2" with "two".
20	ok			Please correct "highlight" with the third person form "highlights".
20	ok			Here, I would modify "2" with "two".
20	ok			Please modify and make "drain" plural "drains".
21	ok			Please add a line separator between "low temperature" as follows "lowtemperature".
21	ok			Here I would erase "fault zone" before "calcite cementation".
22	ok			Here, I would modify "2" with "two".
22	ok			You are mentioning here "two subsequent phases". Do you refer to tectonic
22		x		Please add "petrophysical" before "properties".
25	ok			Please change "porosities" with "porosity values".
26		x		Please change "heterogeneous properties" with "heterogeneity".
26	ok			Please correct "depend" with the third person form "depends".
27	ok			Please erase "they" and add "carbonates may" before "determine".
29	ok			Please correct the beginning of the sentence as indicated "moreover, fault
32-33		x		Here, I would modify the sentence as follows: "Fault zones in cohesive rocks
37	ok			Instead of "mixed zones", maybe is better "structures with mixed hydraulic
37	ok			Please correct "depending of" with "depending on".
38		x		Please make singular "fluid flows" to "fluid flow"
39	ok			Please correct "Earth crust" with "Earth's crust".
40	ok			Here, maybe you can change the structure of the sentence as indicated: ", and are capable o increasing the...".
40	ok			Please correct " fluids-rock interaction " with "fluid-rock interaction"
41	ok			You can add "diagenetic" before "secondary processes".
42	ok			Please add a line separator between "Fault related" as follows "Fault-related".
45	ok			Here maybe I would change "duplication of fluid pathways/barriers" with
48	ok			Please erase "of the" before "faulting" and restructure the sentence as indicated
51	ok			Maybe here "formations" should be capitalized and also please erase the space
56		x		Please add a hyphen between "poly-phasic", as you did above
60	ok			Here, I would modify "2" with "two".
60	ok			Please correct "crosscutting" with "cross-cutting".
60	ok			Please erase "facies" before "carbonates".
61	ok			Please capitalized "South-East Basin".

63	ok			With "larger extension" are you referring to the areal extension of the carbonate
64		x		With "larger extension" are you referring to the areal extension of the carbonate
65	ok			Please correct "bauxite deposits" with "bauxite deposition".
67	ok			Please modify these words as follows: ", and development of E-W-trending
67		x		Is necessary the hyphen between "Guyonnet-Benaize"?
68-69		x		Here I would restructure the sentence as indicated: "During Late Cretaceous
70	ok			Please change the structure of this part of the sentence: "...between Iberian and
70	ok			Please modify from "cited references" to "references therein
71	ok			Please modify from "cited references" to "references therein".
72	ok			Please erase "which" before "gave rise".
72	ok			Here you should add "E-W-trending north-verging thrust faults" otherwise the
72		x		Please change "ramp folds" with "thrust-related folds".
73	ok			Please modify from "cited references" to "references therein
75		x		Please change "dimly" with "weakly"
76	ok			To what "structures" are you referring? I guess they are the contractional ones
79	ok			Here, I would modify "2" with "two".
79	ok			Maybe it is better to write "a Km-scale" instead of "kilometric-scale".
79		x		Please change from "...fault system on the E-W-trending..." to "...fault system
80	ok			Please correct "anticlinal" with "anticline".
82	ok			Please add a space between "120m-thick" to separate the length from the
82	ok			Please change "calcarenite unit" with "calcarenitic unit"
83	ok			Please add a space between "40m-thick" to separate the length from the
83	ok			Please change the structure as indicated: "...coral-rich calcarenite unit, and an
84-85	ok			Here, I would modify as follows: "Santonian age coarse grained rudist
86	ok			Here you state that the Castellas Fault has a length of one Km, but in Fig.1A the
86	ok			You should also define the kinematic of the fault: I would recommend to write as
87	ok			Here change the structure of the sentence as suggested: "(Fig. 2A, B; table 1). Its
88	ok			You can modify from "The second fault zone" to "The second investigated fault
88		x		Here, I would modify "5" with "five".
89		x		Maybe here change "50m-long interval" with "50 m-wide outcrop". Pay attention to
88	ok			Sub-fault are organised in two sets sounds better than "Sub-faults are
90	ok			Instead of "Set one" use "The first one".
91	ok			Please change "orange on Fig. 2F" to "orange traces in Fig. 2F".
91	ok			Add the kinematics of the fault set "with left-lateral strike slip...".
92	ok			Please change "orange on Fig. 2F" to "red traces in Fig. 2F".
92		x		Here, I would modify "5" with "five"
93	ok			What is this asymmetry about? Is related to a different structure or width of the
95	ok			Please add "distinct" before "tectonic events".
96-98	ok			I tried to modify the two sentences as indicated: "...the Middle-Cretaceous
100	ok			I merged the first two sentences: "...(see references cited in Espurt et al. 2012),
101	ok			Please change "leads" to "led".
101	ok			Please modify "neo-formed" with "newly-formed".
105	ok			Please add "present-day" before "reverse throw".
108		x		Here, I would modify "4" with "four".
108	ok			Throughout all the text I saw that sometimes you have used numbers to identify

109	ok			Please change "transect T1" with "transect 1".
109	ok			Instead of "bed", which can be misunderstood maybe here you can use
109	ok			Please correct "pelloidal" with "peloidal", I think it should be the correct form.
110	ok			Please erase the space in "Fig. 2D a" to "Fig. 2Da".
110-111	ok			you can restructure the sentence as suggested: "Transects 2 and 3 crosscut
112	ok			Make the plural form of "echinoderm" to "echinoderms".
114	ok			Make the plural form of "amount" to "amounts".
114	ok			Make the plural form of "bryozoan" to "bryozoans".
115	ok			Eliminate the comma in the reference to the figure: "Fig. 2G, a" change to "Fig.
117-119	ok			tried to restructure the sentence as follows: "Three different fault rock
119	ok			Please change "normal" with "extensional
121	ok			Add this detail at the end of the sentence: "...<30% of fine-grained grey matrix".
122	ok			Add "strike-slip" before "reactivation"
122	ok			Please add "to" before "the onset".
123	ok			Please correct the third person form "present" with "presents" and also change
125	ok			Here maybe modify the sentence in this way: "...sub-rounded clasts belonging to
126		x		What is the nature of the cemented matrix? Are you able to distinguish the
127	ok			Here you are mentioning the reactivation of the D19 fault zone: be more specific
128	ok			Make the plural form of "clast" to "clasts".
128	ok			Add this word at the end of the sentence: "from the nearby damage zone
133		x		Here, I would modify "4" with "four".
134	ok			Please correct the sentence as indicated: "Microfacies were determined...".
136	ok			Please, modify this detail: "with a solution of hydrochloric acid, Alizarin Red S
137	ok			Please erase "The" at the beginning of the sentence and capitalize "Thin...".
137	ok			Please modify "analyzed" with "analysed". Pay attention to the use of UK or USA
138	ok			Please add these words: "...the different generation of calcite cements".
140		x		Is this underscore necessary to identify the instrument?
141		x		Is this underscore necessary to identify the instrument?
141	ok			Here, I would modify "2" with "two".
142	ok			Here, I would modify "2" with "two".
143	ok			Please add "beam" before "current".
143	ok			Keep always a space between the value and the measurement unit; do this in all
143	ok			Please make the plural form of "surface" "surfaces
146	ok			Keep always a space between the value and the measurement unit: "80 µm,"
147			1	What do you mean with the words "bulk rock"? Are you referring to the
148	ok			Please add "isotopic" before "values".
149		x		Is correct the name of the spectrometer with the symbol "+" rather than the word
151	ok			The symbol you used for the delta is not the same adopted previously in Line
151-152	ok			I modified the sentence as follows, check if suits you: "The standard
159-160	ok			I tried to fix in this way: "Porosity measured on 92 plug samples show a
161	ok			Please change "in" with "within".
163	ok			Please add these words at the beginning of the sentence: "Along transects,
164	ok			Insert a space between the value and the measurement unit: "60 m" and not
164	ok			Please change "transect T2" to "transect 2".
165	ok			Please change "low < 7%" to "lower than 7%".

165	ok			Delete the space after 1.53.
165	ok			Substitute the comma at the end with a full stop.
166	ok			Here I would write "is wider than 40 m" rather than "is >40m".
166	ok			Insert a space between the value and the measurement unit: "30 m" and not
167	ok			Here please change "In a 10m-thick" with "In a 10 m-wide".
168	ok			If you want to keep the nomenclature used above than change "T1 and T3" with
169	ok			Please add "found" between "are in narrow".
169-170	ok			tried to write as follows this part of the sentence: "...in narrow zones (less
170	ok			With the term "lens" are you describing the rock volume comprised between F4
172-173	ok			Please modify the beginning of the sentence as indicated: "Microscope
173	ok			Please remove the space in "Fig. 3C a" to "Fig. 3Ca".
174	ok			Add a comma after "φ<5%".
174	ok			Please remove the space in "Fig. 3C b, c" to "Fig. 3Cb, c".
174	ok			It is not clear to me what do you mean with "barren stylolites". Is this word
174	ok			Erase "are distinguished" at the end of the sentence.
177	ok			Please correct "micritized" with "micritised", if you want to keep the UK version of
177	ok			Here, I would modify "2" with "two".
178	ok			Here, I would modify "2" with "two".
179	ok			Why is this citation reported in italics?
180	ok			The reference to "Fig. 4A, 4B" should be "Fig.4A, B".
181		x		Here I'm really struggling with the terminology you used "puntic and serrate" are
182	ok			Please put the porosity value between parenthesis and erase the space before
183	ok			Please insert the porosity percentage in parenthesis
177-183	ok			Inside this paragraph you should also give some info concerning the
185	ok			Please add "different" between "Eight cement".
185	ok			Alizarin Red S should be with all first letters in capitals
185	ok			Add "and" after "coloration".
186	ok			Please correct "made up of" with "made of".
186	ok			Please correct from the third person form to plural "exhibits" to "exhibit".
188	ok			Here, I would modify "2" with "two".
189		x		With "thickness" here are you describing the maximum thickness of the
189	ok			Here, I think it would be more correct to use this symbol "~" to indicate the word
190	ok			Here, I would modify "2" with "two".
190	ok			Add an hyphen between "dog-tooth".
192	ok			Again, here is that possible to describe the crystal size rather than the
192	ok			Here, I think it would be more correct to use this symbol "~" to indicate the word
192	ok			Be more specific concerning the reference to the figure: I believe here you are
193	ok			Better than "C1b values" maybe you should use "C1b areal occurrence".
193	ok			Please correct the third person form "increases" instead of "increase
201	ok			Please change the sequence of words from "replacive phases occur largely..." to
203	ok			Use the hyphen between "dull orange" "dull-orange".
203	ok			Please change the structure as indicated from "...only found in fault core veins"
204	ok			Please erase "elements" after "Si and Al".
205	ok			Please erase "an" and add at the end of the sentence "and have black
203-205	ok			Please add also some info relative to the size of the cement crystals you

206	ok			Use the hyphen between "red dull" "red-dull".
208	ok			Add "only" before "to the fault zone".
206-208		x		Please add also some info relative to the size of the cement crystals you
211	ok			Please insert a space between "500" and "µm".
211	ok			Please insert "previous" before "dolomitization phase
212-213	ok			Please change here from "micritic inclusion in the crystal and..." to "micritic
215	ok			Please insert a space between "300" and "µm".
217	ok			Please correct the reference to "Fig. 5G, 5H" with "Fig. 5G, H".
219	ok			Here, I would modify "2" with "two".
219	ok			Please erase "which" after "C4a".
220	ok			Please correct the plural form of "band" with "bands".
220	ok			Please add "thin" before "non-luminescent zones". Change also "bands" with
221	ok			Correct the nomenclature of transects, here maybe use "transects 1 and 3" as
223	ok			Use the hyphen between "red dull" "red-dull".
227	ok			Please change "formation" with "karst deposit".
228-229	ok			See if this correction suits you: "This karst deposit present a stack of
230	ok			Please correct "clasts fall" with "grain fall". Keep in mind that the term clast is
230	ok			Please correct the singular "has" to plural form "have".
230-231	ok			tried to improve the clarity of the sentence: "Micritic layers have been
233	ok			Please change "proportion" with "areal amount" and also modify the third person
236-238		x		I fell this is a repetition of what was previously presented inside the method
239	ok			Again, what is the meaning of "bulk rock"? If you are referring to the undeformed
239	ok			Intergranular volume is better than "intergranular space".
241-242	ok			If it is more correct change the reference to the figure from "Fig. 6A, 6B" to
242	ok			Again, "bulk rock" isn't this the "host rock"?
243	ok			Here, I would modify "2" with "two".
243	ok			For "Set one" you can use the number "Set 1". I believe to identify the type of
244	ok			I don't think that using the symbol "&" is suitable here, just write "and".
245	ok			As above, "Bulk values" is too generic. If you are describing the isotopic dataset
247	ok			Please erase "the" before "transect 3".
247	ok			Please erase "along transect" after "slightly vary".
248	ok			At the end of this sentence after "δ13C " add ", respectively".
248	ok			Change "Contrarily" with "On the contrary, ...".
248-251	ok			I tried to fix these sentences as follows: "On the contrary, values are more
252	ok			Please change "spaces" with "volume".
252	ok			Maybe "infillings" is better than "fills".
252	ok			Please make the plural form "fault rocks".
253		x		Here, I would modify "5" with "five".
254	ok			Personally I modified the sentence as follows and fell like it is clearer: "isotopic
256	ok			Similar to the comment above: "isotopic values of C3 cement...".
258	ok			Again: "isotopic values of C4 cement...".
258	ok			Maybe "infillings" is better than "fill".
259	ok			Please add a space between "from-5.10‰" to have "from -5.10‰".
260	ok			Please erase the space between "FR 2" to "FR2".
260	ok			Please add a space between "from-6.55‰" to have "from -6.55‰".

261	ok			Maybe "infillings" is better than "fill".
262	ok			Please restructure the last part of the sentence as follows: "...for $\delta^{18}O$ and $\delta^{13}C$
263		x		Here, I would modify "4" with "four".
263	ok			Here, I would modify "2" with "two".
264	ok			Please add a semicolon ";" at the end of the sentence.
265-266	ok			Please start the sentence as follows: "isotopic values of C5 cement
267-268	ok			Please start the sentence as follows: "isotopic values of FR3 matrix have a
275	ok			Please change "thanks to" with "via".
275	ok			Please pluralise "cross-cutting relation" to "cross-cutting relations".
276	ok			modified the order and position of some words here: "Indeed, the veins filled
277	ok			I would change this sentence as follows: "Thus, C2 cementation postdated C1
277	ok			Please erase "The" at the beginning of the sentence
278	ok			Here there is a missing reference to the correct figure. I guess it should be "Fig.
278	ok			Please change "is ante-FR1..." with "formed prior to FR1...".
279	ok			Please change "post-C2" with "after C2".
279	ok			would use "extensional" rather than "normal".
281	ok			Please remove the comma after "formation and, are related...".
281-282	ok			Please modify the sentence as indicated: "Replacive dolomite is found
282	ok			Here I guess that this is the wrong reference to the figure. I believe it should be
282	ok			Please make the past simple version of "develop" "developed".
282	ok			Please, move "C4" before "cement".
283	ok			Please change "postponed" with "postdated
284	ok			Please modify the order of the words: "...developed during the strike-slip
287	ok			Please correct "La Fare anticlinal" with "La Fare anticline".
287	ok			Here, I would modify "3" with "three". Also substitute "important" with "major".
291		x		I don't know if this is the right term, but perhaps "micro-boring organisms"
294	ok			Please add a hyphen between "low and energy" "low-energy".
294	ok			Please add "environment" at the end of the sentence after "inner platform".
295	ok			Move "C0" before "cement".
295-296	ok			I tried to fix this sentence: "...formed around grains giving rise to a solid
299	ok			Here, I would modify "2" with "two".
299	ok			Please substitute "points" with "pairs", and "sampled of" with "pertaining to".
300	ok			Please add "isotopic" before "depletion".
304	ok			Please modify "characteristic for" with "characteristic of".
307	ok			Please change "meteoric flow" with "meteoric fluid circulation".
308	ok			Please add "to the" before "development".
315	ok			Please add a hyphens as indicated: "low-to-moderate matrix....".
316-318	ok			did some changes to this sentence: "Even if Barremian limestones of La
318	ok			Please change "Resulting from this event,..." with "Due to this characteristic,...".
320	ok			Please add a hyphen between "Fault and related" "Fault-related".
324	ok			324: Better that "impacting" maybe you should try with "affecting".
327	ok			Please erase ", and" just after the references in parenthesis and also add a
327	ok			Add a space between "<100KPa" to have "<100 KPa".
327	ok			Modify the reference to "Alikarami & Torabi 2015" as "Alikarami and Torabi,
329-330	ok			Here I fixed in this way: "...of deformation band development (Heiland et

331		x		poorly sounds better than "dimly".
331-332	ok			Add a hyphen between "low confining pressure" "low-confining pressure".
332	ok			Please change the term "pattern" with "regime".
332	ok			Add a space between "<1Km" to have "<1 Km".
333-334	ok			I reworked this sentence as indicated: "Under these conditions, Barremian
334	ok			Please correct "showned" with "showed".
335	ok			Please add "of deformation" after "early stages".
336	ok			Please add "in carbonates" after "deformation bands".
336	ok			Please change "sector" with "area".
337		x		Please correct to the singular form "circulation" instead of "circulations".
337-338	ok			Please erase "These" at the beginning of the sentence and make the
338-339	ok			would change the sentence as follows: "however, dilation bands were
340	ok			Please modify to the singular form "loading stress" instead of "loading stresses".
342	ok			Here maybe start the sentence as indicated. "This could be the explanation...".
343	ok			Add a space between "<30m" to have "<30 m".
345	ok			Add a space between "<188m" to have "<188 m".
345	ok			Here adjust the reference to "Fig. III 6A" with "Fig. 6A".
345	ok			Modify the beginning of the sentence as suggested: "Dilation bands have also
346	ok			Please correct "Sicilly" with "Sicily".
347	ok			Please add "selective" before "cementation". Also pluralise "rock" to "rocks".
348-349	ok			tried to change the structure of this sentence: "Cementation (C1a and
349	ok			Add a hyphen between "low porosity" "low-porosity".
350	ok			Please change the last part of the sentence as suggested: "...is known to
351	ok			Please erase "an" before "Al-rich".
352	ok			Please pluralise "fluid" to "fluids".
352	ok			You may explain this with "fine-grained" instead of "micro-metric".
352	ok			Again the term "barren" is very unfamiliar to me. Are you referring to an incipient
352	ok			If you feel this is an option try to put this last part of the sentence as indicated:
358	ok			Use "may" and not "must" you are not 100% sure that this happened, you are
361	ok			A few adjustments to this sentence: "As the fault grew, new fracture sets formed,
364-365	ok			Please correct "at high depth" with "in deep burial conditions". in
365-366	ok			A bit of reworking on this sentence: "...corroborate the hypothesis of
367	ok			Please change the beginning of the sentence from "Resulting from" to "Due to".
368	ok			Before "down to <5%" insert "with porosity".
368	ok			Cancel the space in "Fig. 9 B5" to "Fig. 9B5". Also in Fig. 9 what is stage 5 since
371	ok			Please change "Implicitly", with "Following this".
371		x		Please add "in this stage" before "was a barrier".
372	ok			I would change the beginning of the sentence: "Fluids responsible for
375	ok			Please insert a space between "100" and "µm".
376	ok			I modified the sentence as indicated: "...came from silica found inside C2 cement
377	ok			Please modify the beginning of the sentence: "Silica crystals in C2 veins...".
377	ok			Please insert a space between "100" and "µm".
378		x		Please add "grains" before "quartz".
379	ok			Please add "also" before "Aptian rocks".
380	ok			Please substitute "Implicitly" with "According to this,".

381	ok			Add a hyphen between "Uncemented" "Un-cemented"
381	ok			Please change to the pas simple form "formed" instead of "form".
383	ok			Please add "lateral extent of the..." before "drainage area".
384	ok			Add a hyphen between "high permeable" "high-permeable".
385-386	ok			I would change as follows: "...formations within fault core of strike-slip and
390	ok			Please make the past simple form of "lead" to "led".
392	ok			Please substitute "can be" with "could have been".
395	ok			Please add a reference at the end of this sentence, relative to the difference in
398	ok			I would change a bit the end of the sentence as indicated: "...not favourable for
399	ok			Add a hyphen between "Low temperature" "Low-temperature".
400	ok			Add a hyphen between "high temperature" "high-temperature".
402	ok			Here you can change from "high Mg fluid circulation" to "Mg-rich fluid
403	ok			Please add "domain" after "fault core" at the end of the sentence.
405	ok			Please insert a space between "23" and "Km".
405-406	ok			Please change from "compressive conditions" to "contractional stress
406	ok			At the beginning of the sentence please change from "From these authors..." to
407	ok			Add a hyphen between "low temperature" "low-temperature".
407	ok			After "upwelling fluids" add ", likely Mg-enriched".
409	ok			Add a hyphen between "low temperature" "low-temperature".
410	ok			Please correct "were" with "was".
412	ok			Please correct "reduce" with "reduces".
415	ok			Please change "to" with "into". Also check the reference to "Fig. 9 B6 and C6"
417	ok			Please substitute "finally" with "eventually".
419	ok			Please erase the hyphen between "back-ground" to "background".
420	ok			Please change from "lead to FR2..." to "formed FR2...".
422	ok			Please erase the hyphen between "back-ground" to "background".
423-424	ok			I would modify the structure of the sentence as indicated: "This fluid flow is
424	ok			Please correct "micritized" with "micritised".
425	ok			Please change "what led" with "leading to".
425	ok			Erase the comma and space in the reference to figure "Fig. 9, B7 and C7" to
426	ok			Please change "the" before "fracture porosity" with "that."
426	ok			At the end of the sentence modify as follows: "...permeability was still partially
427	ok			Use italics for the term "sensu".
428	ok			would modify this as indicated: "...and high fracture-related secondary
429	ok			Maybe here is better to use "infillings" rather than "fill".
429	ok			After "dissolution/cementation" add the term "processes".
431	ok			Please add "cement" after "C4".
432	ok			Maybe here is better to use "infillings" rather than "fill".
433	ok			did a few changes to this part of the sentence: "...fluid circulation in the vadose
435		x		Maybe the last part of this sentence would sound better as: "... of meteoric and
436-437		x		Please change "these" with "this" and also make the singular form of
437	ok			Please add "cement" after "C4".
437		x		Please change "on" with "in" in reference to Fig. 8.
438	ok			Higher is not the most precise term to describe isotopic data. if you are talking
439	ok			Please add "cement" after "C1".

440	ok			Please add "cement" after "C4".
440	ok			Move "C4" before "cement", and change from the plural to the singular form
441	ok			Please change "are" with "is".
441-442	ok			I tried to fix this sentence in this way: "Transect 2 cross-cuts the Castellas
442	ok			Here, I would modify "2" with "two".
446	ok			Please erase the term "local" before "permeability" and also change "allowed" to
447		x		Please make the singular of "circulations" to "circulation".
448	ok			Move "C4" before "cement.
449	ok			Please change "Contrarily" with "On the contrary,".
450	ok			Please erase the word "a" before "drains".
51	ok			Please change "That" with "This".
452	ok			Please correct "formation" with "development".
453	ok			Please change "normal" with "extensional".
453	ok			I modified the last part of the sentence as follows: "...C4 fluids to flow through the
455	ok			Please change "T2" with "transect 2".
455	ok			Please insert a space between "60" and "m".
456	ok			Use "transect 1 and transect 3" instead of "T1 and T3", add a space between "30
461			2	I don't think that the word "sieve" is appropriate to describe the evolution of th
462	ok			Please correct "de-dolomitization" with "de-dolomitized".
466	ok			Please correct "recrystallized" with "recrystallised".
469	ok			I would put also "alpine" in capitals as you did for "Pyrenean".
471	ok			tried to fix this part as indicated: "This implies fluids percolating soils, as results
475	ok			Please correct "Finally" with "Eventually".
475	ok			Please change from "incurring" to "inducing".
476	ok			Please change from "triggered" to "produced".
477	ok			Please change from "flows" to "fluids".
481-482	ok			tried to adjust this part as: "...reservoir where fractures behave as
483	ok			Please change "polyphase" with "polyphasic".
490-491	ok			See if these changes suit you: "...Castellas fault zone, permeability evolves
493	ok			Here, I would modify "2" with "two".
493	ok			Please change "fracture" with "fracturing".
493	ok			Please change "link" with "linked".
494	ok			If you feel it could be an option you can use the extended form "fault core"
495-496	ok			I adjusted the second part of the sentence: "permeability contribution is
497	ok			Again here if you can use the extended version of the name "fault core".
498	ok			Please correct "at 20%" with "for 20%".
498-499			3	The calculation of the permeability contribution is nice and to me it
501	ok			Here, I would modify "2" with "two".
501	ok			Erase "the" before "reservoir".
502	ok			Please pluralise "fault" to "faults".
503	ok			I think you should capitalise "SE basin" as "SE Basin".
508	ok			Please correct "their" with "its".
511	ok			Please change "thinly" with "slightly".
512	ok			Please substitute "formation" with "development".
514	ok			Please change "the flows" with "flowing fluids".

516-517	ok			Add a hyphen between "low temperature" "low-temperature".
517	ok			Please correct "flows" with "fluids".
517	ok			Please correct "This" with "These".
517	ok			Add a hyphen between "low temperature" "low-temperature
517	ok			Please add "fluid" before "flows".
519	ok			Add a hyphen between "high temperature" "high-temperature".
519	ok			Please change "flows" with "fluids".
519	ok			Please add "significant" before "hydrothermal influence".
520	ok			tried to improve the last part as: "...broader rules for complex faults with
522	ok			Please correct "extensive" with "extensional".
522	ok			See if this is better: "...can lead to the development of dilation bands acting...".
523	ok			tried to improve the clarity: "Carbonates are very sensitive to rock-fluid
529-531	ok			Again a bit of reworking: "Late-stage fluids flowed preferentially within the
566	ok			Check and erase the highlighted space
568	ok			There are too much spaces that must be corrected
569	ok			Check and erase the highlighted space.
570	ok			Check and erase the highlighted space.
571	ok			Erase the highlighted full stops.
573	ok			Erase the highlighted full stop.
580	ok			Erase the highlighted full stop.
586	ok			Check and erase the highlighted space.
590	ok			Check and erase the highlighted space.
607	ok			Please erase the comma
610	ok			Check and erase the highlighted space.
611	ok			The name of the institution is not complete.
621	ok			Check and erase the highlighted space.
621	ok			Please erase the comma.
639	ok			Please erase the comma.
641	ok			Erase the highlighted part since it is a repetition and should not be in front of the
656	ok			Please capitalise "jurassic" to "Jurassic".
664	ok			Erase the highlighted full stop
669-670	ok			Check and erase the highlighted spaces.
679	ok			Check and erase the highlighted space.
705	ok			Check and erase the highlighted spaces
714	ok			Check and erase the highlighted spaces and comma.
721	ok			Check the spelling of the journal title.
728	ok			Check and erase the highlighted full stops.
741-742	ok			Please eliminate the duplicated title.
754-755	ok			Check and erase the highlighted full stops.
772-773	ok			Check and erase the highlighted spaces.
774-775	ok			Check and erase the highlighted space and full stop.
791	ok			Check and erase the highlighted space.
803	ok			Check and erase the highlighted space.
809	ok			Check and erase the highlighted space.
814	ok			Check and erase the highlighted space and comma.

816-817	ok			Check and erase the highlighted space and comma.
819	ok			Check and erase the highlighted comma.
821	ok			Check and erase the highlighted space.
comment on figures and figure captions				
fig 1	ok			You should insert the symbol of the La Fare anticline in Fig. 1A.
fig 1	ok			The kinematic indicators alongside faults are missing in Fig. 1B.
fig 1	ok			These names in the legend of Fig. 1A should be all in capitals "Upper Cretaceous, Lower
fig 1	ok			Maybe better than "thin calcarenite" you can use "fine-grained", if you are referring to the
fig 1 cap	ok			You should erase the space between "Figure 1 :" to "Figure 1:".
fig 1 cap	ok			Please add "trace of" before "stratigraphic column".
fig 1 cap	ok			Please correct the reference to "C" part of the figure rather than "B".
fig 2	ok			The kinematic indicators in both stereo-nets are indistinguishable from the fault traces.
fig 2	ok			I would mirror the transect 3 to have SSE on the left and NNW on the right side, just like
fig 2	ok			What are the red stars? Are they the positions of samples? If so you should mention them
fig 2 cap	ok			You should erase the space between "Figure 2 :" to "Figure 2:".
fig 2 cap	ok			Please change the term "localization" with "position".
fig 2 cap	ok			What are the "red points" you are referring in the stereo-nets? I can't seen anything but red
fig 2 cap	ok			In the third line please add "C: Photos of transect 1 and 2."
fig 2 cap	ok			In the third line please add "D: Photomicrographs of carbonate host-rock facies...".
fig 2 cap	ok			In the fourth line add "FR1 and FR2" after "fault rock 1 and 2".
fig 2 cap	ok			In the fifth line please add "G: Photomicrographs of host-rock facies...".
fig 3	ok			Try to improve the visibility of the three petrographic images in Fig. 3C, change the
fig 3 cap	ok			In the first line correct "&" with "and".
fig 3 cap	ok			In the third line correct "b&c" with "b and c".
fig 4 cap	ok			You should erase the space between "Figure 4 :" to "Figure 4:".
fig 4 cap	ok			In the first line please pluralise "white arrow" to "white arrows".
fig 4 cap	ok			In the first line add a space between "MF1micrite" to "MF1 micrite".
fig 4 cap	ok			In the second line add a space between "2.5m" to "2.5 m".
fig 4 cap	ok			In the second line add a space between "MF1micrite" to "MF1 micrite".
fig 4 cap	ok			In the second line add a space between "2m" to "2 m".
fig 4 cap	ok			In the second line please erase the "C" which is duplicated.
fig 4 cap	ok			In the third line add a space between "188m" to "188 m".
fig 4 cap	ok			In the third line add a space between "95m" to "95 m".
fig 4 cap	ok			In the fourth line please change "F." to "F:".
fig 5 cap	ok			You should erase the space between "Figure 5 :" to "Figure 5:".
fig 5 cap	ok			In the first line please change "micritized" with "micritised".
fig 5 cap	ok			In the second line please change "space" with "volume".
fig 5 cap	ok			In the second line please substitute "a&b" with "a and b".
fig 5 cap	ok			In the second line please pluralize "clast" to "clasts".
fig 5 cap	ok			In the second line please change "micritized" with "micritised".
fig 5 cap	ok			In the third line I modified as follows: "C: C3 veins, cements and intergranular volume in...".
fig 5 cap	ok			In the third line please substitute "a&b" with "a and b".
fig 5 cap	ok			in the fourth line after "replacive dolomite" add "(RD)".
fig 5 cap	ok			In the fifth line please correct "quart" with "quartz".

fig 5 cap	ok			In the fifth line please substitute "a&b" with "a and b"; do it twice.
fig 6		x		To me it would be more logical to invert Fig. 6A and 6B, to show the reader first all bulk
fig 6	ok			In both graphs insert the X axis labels for every increment of 2 per mil (2, 4, 6...).
fig 6		x		In the legend of Fig. 6A it is written "Bulk rock", I wonder if this is actually the undeformed
fig 6	ok			In Fig. 6C the title of the graph states "Distance to Castellas Fault plane", maybe "Fault
fig 6 cap	ok			You should erase the space between "Figure 6 :" to "Figure 6:"
fig 6 cap	ok			In the first line please correct the symbols you used for the delta notation, it should be
fig 6 cap		x		In the first line you state again "bulk rock" why not "host rock"?
fig 6 cap	ok			In the third line please correct the symbols you used for the delta notation, it should be
fig 7	ok			The three photomicrographs are too small to appreciate the details. You have plenty of
fig 7 cap	ok			In the second line I slightly modified as follows: "... development (blue), cementation
fig 8		x		Again, photomicrographs are quite small, but still the reader should be able to see
fig 8	ok			In the legend please correct "Micro-facies & cement types" with "Micro-facies and cement
fig 8 cap	ok			You should erase the space between "Figure 8 :" to "Figure 8:".
fig 9	ok			It would be nice to have bigger sketches in Fig. 9A.
fig 9		x		Also why stage 5 is not reported? In the text it is mentioned. You should consider to
fig 9 cap	ok			You should erase the space between "Figure 9 :" to "Figure 9:".
fig 9 cap	ok			In the second line I would modify "2" with "two".
fig 9 cap	ok			In the second line please correct "curved" with "curve".
fig 10	ok			Also here size matters! Please make these sketches bigger otherwise you will lose al lot of
fig 10cap	ok			You should erase the space between "Figure 10 :" to "Figure 10:".
fig 10cap	ok			In the third line please add spaces between "1to 8correspond" to "1 to 8 correspond".
fig 10cap	ok			At the end of the caption you should add also explanations of the symbols used: FZ, DZ,
table 1	ok			In the caption add a full stop at the end as highlighted.
table 1	ok			In the table header increase the width to include entirely the words "Fault zones", check
table 1	ok			Check also the French name "Faille" and correct it accordingly.
table 1	ok			Capitalize "pitch striation" to "Pitch striation".
table 1	ok			Add a space between the cardinal point and angular value every time has been
table 1	ok			Non constant" is not precise, I would use "variable".
table 2	ok			Please eliminate "vs" from the table header.
table 2	ok			Check also the nomenclature of the transects to be the same to the symbols adopted in
table 2	ok			In the caption it is not clear what do you mean for "bulk carbonates", "bulk measurements".
table 2	ok			Pay attention also to put the reference always to the singular form (es. micrite value,

Comment N°1

"What do you mean with the words "bulk rock"? Are you referring to the undeformed host rock *outside the damage zone, if so I think you should correct this and be more precise."*
Done.

"Bulkk rock" is a conventional wording commonly used in papers dealing with isotopes. Anyway, to respect the reviewer's comment, we defined the word "bulk" as follows: "The Bulk rock values are related to a non-selective sampling giving information on the whole rock isotopic values. These values do not capture the signature of isolated cement (Swart, 2015)." (**lines 168-170**)

Comment N°2

"I don't think that the word "sieve" is appropriate to describe the evolution of the hydraulic properties of a fault zone. Maybe "valve" is more suitable, since you are describing media behaving as a drain and then as a barrier."

In this study we show that the **faults in carbonates are not valves**. The valve concept for fault zones is not fully appropriate for carbonates. Indeed, the valve induces that it is alternatively closed or open. Our study shows that the most appropriate concept would be a sieve, because in this analogy, it is synchronously closed in places and open in other places, what rather reflects the hydraulic behavior of the studied fault zones. We added in the text: "In this case, the most appropriate concept would be a sieve, because in this analogy, it is synchronously closed in places and open in other places." (**Lines 503-504**)

Comment N°3

"The calculation of the permeability contribution is nice and to me it provides useful info relative to the hydraulic evolution of the fault zone in time. I'm sorry for being so blunt here, but maybe you should ground you statement and discussion on the field data. What I mean is try to explain why you assigned such percentage contribution to the fault core or to the matrix and so on... Maybe you can do this by evaluating the width of the fault core and damage zone domains, or by estimating the fracture network volume."

The comment of the reviewer is interesting, but cannot be realized in this manuscript because:
- Such a quantification in our field case is too much uncertain because the fault zones are too heterogeneous to do this exercise.
- This is too much apart from the subject of the paper,
- this would be much too much for one paper and could rather represent another paper itself.
- Therefore we mentioned this issue in the text as follows: "The percentage assigned to the fault core or to the matrix are qualitatively estimated. Further quantification could be evaluated, for instance, with the width of the fault core and damage zone domains, or by estimating the fracture network volume. However, no recent study have provided such quantification." **(line 534 to 537)**

Diagenetic evolution of fault zones in Urgonian microporous carbonates, impact on reservoir properties (Provence – SE France).

Irène Aubert [a]***, Philippe Léonide*** [a]***, Juliette Lamarche*** [a]***, Roland Salardon*** [a]

[a] *Aix-Marseille Université, CNRS, IRD, Cerege, Um 34, 3 Place Victor Hugo (Case 67), 13331 Marseille Cedex 03, France*

Microporous carbonate rocks form important reservoirs with permeability variability depending on sedimentary, structural and diagenetic factors. Carbonates are very sensitive to fluid-rock interactions that lead to secondary diagenetic processes like cementation and dissolution capable of modifying the reservoir properties. Focusing on fault-related diagenesis, the aim of this study is to identify impact of the fault zone on reservoir quality. This contribution focuses on two fault zones east to La Fare Anticline (SE France) cross-cutting Urgonian microporous carbonates. 122 collected samples along four transects orthogonal to fault strike were analysed. Porosity values have been measured on 92 dry plugs. Diagenetic elements were determined through the observation of 92 thin sections using polarized light microscopy, cathodoluminescence, red alizarin, SEM and stable isotopic measurements ($\delta^{13}C$ and $\delta^{18}O$). Eight different calcite cementation stages and two micrite micro-fabrics were identified. As a main result, this study highlights that the two fault zones acted as drains canalizing low-temperature fluids at their onset, and induced calcite cementation which strongly altered and modified the local reservoir properties.

1. INTRODUCTION

Microporous carbonates form important reservoirs (Deville de Periere et al., 2017; Lambert et al., 2006; Sallier, 2005; Volery et al., 2009), with porosity values up to 35% (Deville de Periere et al., 2011). Due to their heterogeneous properties which depends on sedimentary, structural and diagenetic factors, microporous carbonates may determine a high variability of reservoir permeability (Bruna et al., 2015; Deville de Periere et al., 2011, 2017; Eltom et al., 2018; Florida et al., 2009; Hollis et al., 2010). Moreover, fault zones in carbonates play an important role on reservoir properties (Agosta et al., 2010, 2012; Caine et al., 1996; Delle Piane et al., 2016; Ferraro et al., 2019; Knipe, 1993; Laubach et al., 2010; Rossetti et al., 2011; Sinisi et al., 2016; Solum et al., 2010; Solum and Huisman, 2016; Tondi, 2007; Wu et al., 2019). Fault zones are complex structures composed of damage zones and the fault core encompassed by the host rock (Caine et al., 1996; Chester and Logan, 1986, 1987; Hammond and Evans, 2003). Faults can act as barriers (Agosta et al., 2010; Tondi, 2007), drains (Agosta et al., 2007, 2008, 2012; Delle Piane et al., 2016; Evans et al., 1997; Molli et al., 2010; Reches and Dewers, 2005; Sinisi et al., 2016; Solum and Huisman, 2016), or mixed hydraulic behaviour zones (Matonti et al., 2012) depending on their architecture and diagenetic evolution. Because of their hydraulic properties, fault zones influence the fluid flows in the upper part of Earth's crust (Bense et al., 2013; Evans et al., 1997; Knipe, 1993; Sibson, 1994; Zhang et al., 2008), and are capable of increasing the fluid-rock interactions. Carbonates are very sensitive to these interactions, which lead to diagenetic secondary processes like cementation and dissolution (Deville de Periere et al., 2017;

Fournier and Borgomano, 2009; Lambert et al., 2006). Fault-related diagenesis locally modifies the initial rock properties (mineralogy and porosity), and therefore the reservoir properties (Hodson et al., 2016; Knipe, 1993; Knipe et al., 1998; Laubach et al., 2010; Woodcock et al., 2007). In case of a polyphasic fault zone, repeating fluid pathways-barriers behaviour in times leads to very complex diagenetic modifications. The initial vertical and lateral compartmentalization of microporous limestones is, therefore, accentuated by fault-related diagenesis. Hence, understanding faulting processes and diagenesis is crucial for a better exploration and production in carbonates. Urgonian microporous carbonates of Provence, are made of facies and reservoir properties analogue to Middle East microporous carbonate reservoirs (Thamama, Kharaib and Shuaiba Formations; Borgomano et al. 2002, 2013; Sallier 2005; Fournier et al. 2011; Leonide et al. 2012; Léonide et al. 2014). Although Urgonian microporous carbonates of Provence are analogue to Middle East reservoirs, the analogy can be extended to other faulted microporous carbonate reservoirs. To have a better comprehension of diagenetic modifications linked to fault zones on these rocks, the aim of this paper is (i) to determine the diagenetic evolution of polyphasic fault zones; (ii) to identify their impact on reservoir properties and (iii) to link the fault evolution with the fluid flow and geodynamic history of the basin.

2. GEOLOGICAL CONTEXT

We studied two faults cross-cutting microporous Valanginian-to-Early Aptian Urgonian carbonates of the South-East Basin (Provence-SE France) deposited along the southern margin of the Vocontian Basin (Léonide et al., 2014; Masse and Fenerci Masse, 2011). The "Urgonian" platform carbonates (Masse, 1976) reached their maximum areal extension during the late Hauterivian–Early Aptian (Masse and Fenerci-Masse, 2006). From Albian to Cenomanian, the regional Durancian uplift triggered exhumation of Early Cretaceous carbonates, bauxitic deposition (Guyonnet-Benaize et al., 2010; Lavenu et al., 2013; Léonide et al., 2014; Masse and Philip, 1976; Masse, 1976), and development E-W-trending extensional faults (Guyonnet-Benaize et al., 2010; Masse and Philip, 1976). During the Late-Cretaceous times, platform environment led to a transgressive rudist platform deposition (Philip, 1970). From Late Cretaceous to Eocene, the convergence between Iberia plate and Eurasia plates (e.g. Bestani 2015, and references therein) caused a regional N-S shortening (e.g. Molliex et al. 2011 and references therein). The so-called "Pyrénéo-Provençal" shortening, gave rise to E-W-trending north-verging thrust faults and ramp folds (e.g. Bestani et al. 2016, and references therein). From Oligocene to Miocene, the area underwent extension associated to Liguro-Provençal Basin opening (e.g. Demory et al. 2011). During Mio-Pliocene times, the Alpine shortening dimly impacted the studied area (Besson, 2005; Bestani, 2015), and reactivated the "Pyrénéo-Provençal" structures (Champion et al., 2000; Molliex et al., 2011).

We studied two faults pertaining to a Km-scale fault system on the E-W-trending La Fare anticline near Marseille (Fig. 1A). The southern limb of this anticline dips 25° S, and is constituted by Upper Hauterivian, Lower Barremian and Santonian rocks (Fig. 1B). The Upper Barremian carbonates are composed, from bottom to top, of a 120 m-thick calcarenitic unit swith cross-beddings, a 40 m-thick massive coral-rich calcarenite unit, and an upper 10 m-thick calcarenite unit (Masse, 1976; Matonti et al., 2012; Roche, 2008). Santonian age coarse rudist limestones uncomfortably overlap the Barremian carbonates (Fig. 1A).

The Castellas fault zone is a 2.14 km-long left-lateral strike-slip fault, N060 to 070-trending and 40° to 80°N-dipping (Fig. 2A, 2B; table 1) composed horse structures, secondary faults and lenses (Fig. 2A, 2C; Aubert et al. (2019b)). The second investigated fault zone "D19" is composed of 5 sub-fault zones (F1 to F5) restricted in a 50m-long extension (Fig. 2E, 2H; Table 1; (Aubert et al., 2019a)). Sub-faults are organised into two sets. The first one comprises F3 and F4, N040 to N055-trending, 60-80°NW-dipping (orange traces on Fig. 2F). Set 2 is N030-trending, dipping 80°E, with left-lateral strike-slip slickensides pitch 20 to 28°SW (F1, F2, F5, red traces on Fig. 2F).

The internal structure of both fault zones results from three distinct tectonic events:

- the Durancian uplift dated as mid-Cretaceous leading to extension and to normal *en echelon* normal faults. The Castellas fault nucleated during this first extensional event and bear early dip-slip normal striations (Matonti et al., 2012),
- the Early Pyrenean compression with N000° to N170°-trending σ_H (see cited references in Espurt et al. 2012) whichreactivated the Castellas fault as sinistral (Matonti et al., 2012) and led to the newly-formed strike-slip faults of the D19 outcrop (Aubert et al., 2019a).
- the Pyrenean to Alpine folding, triggering the 25°S tilting of the strata and fault zones. Faults of the D19 outcrop were reactivated while the Castellas fault tilting led to an apparent present-day reverse throw (Aubert et al., 2019a).

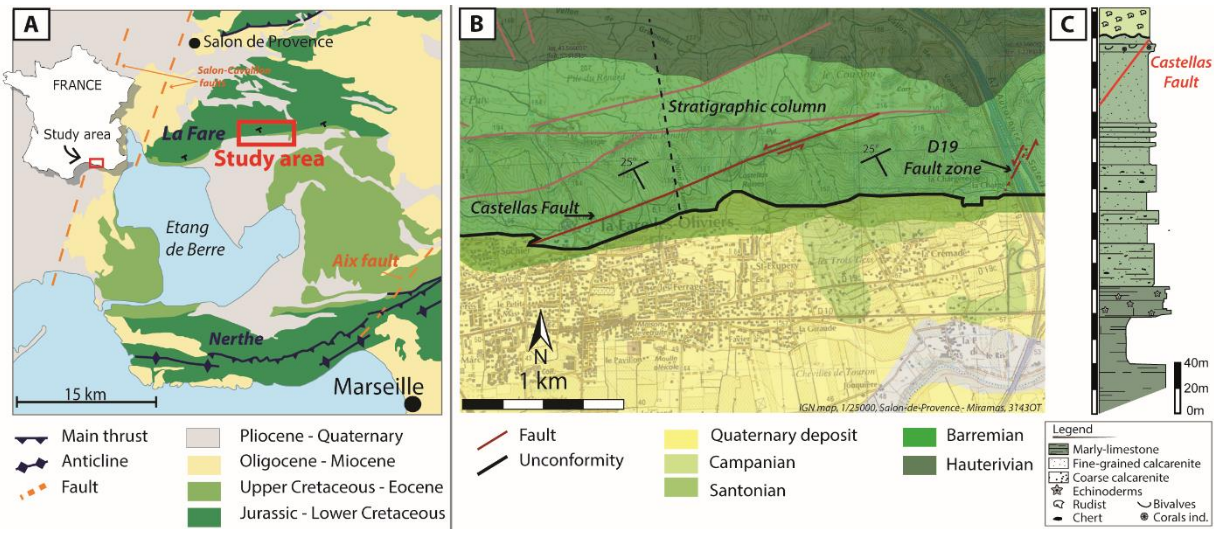

Figure 1 *: Geological context of the study area. A: geological map of Provence, B: Simplified structural map with the location of the Castellas fault and the stratigraphic column (black dashed line); C: Stratigraphic column of exposed Cretaceous carbonates (modified from Roche, 2008)*

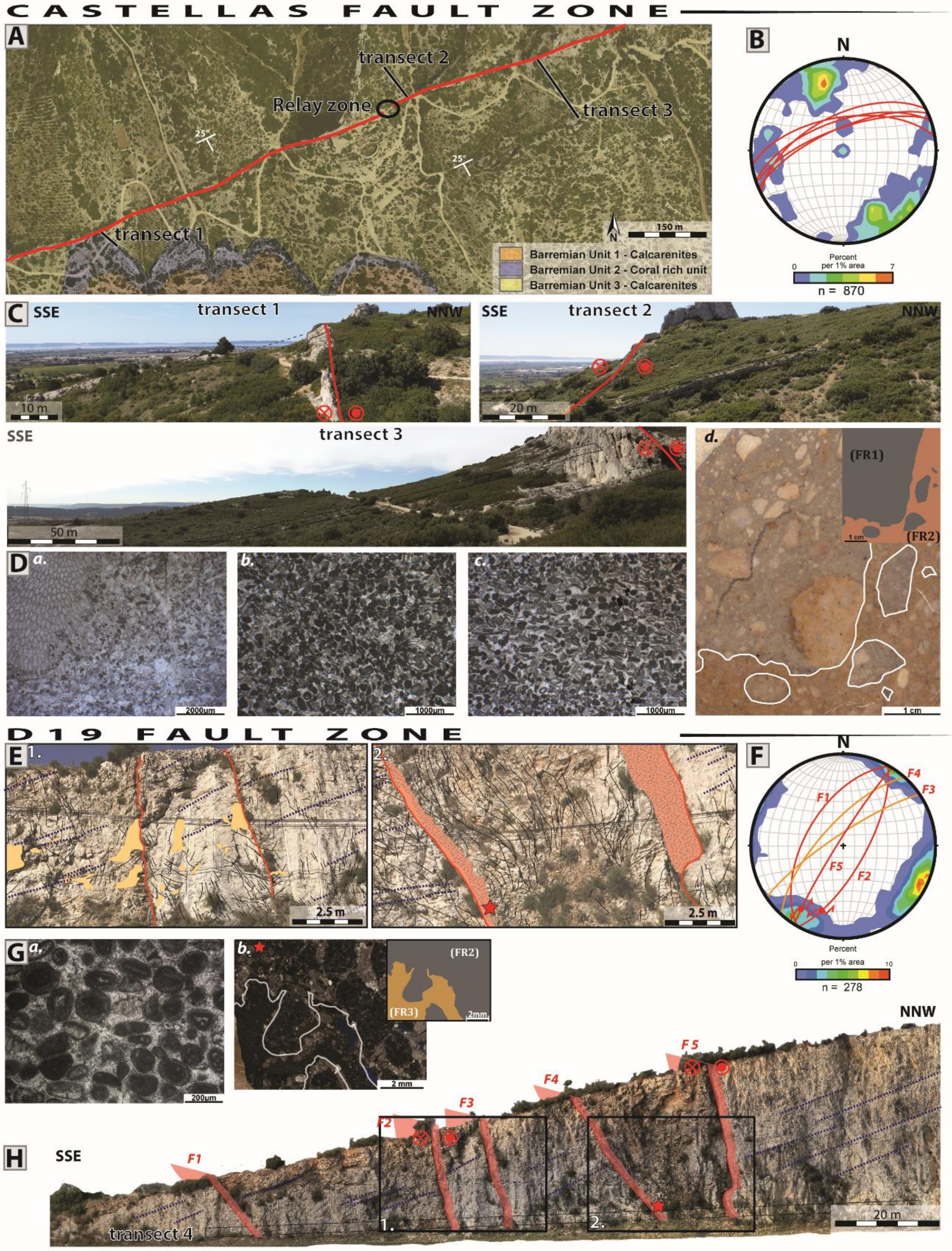

Figure 2 : A: Castellas fault map on aerial photo with position of the studied transects and the relay zone; B: stereographic projections of poles to fractures (density contoured) and faults (red lines) (Allmendinger et al., 2013; Cardozo and Allmendinger, 2013); C: Photos of transects 1 to 3; D: Photomicrographs of carbonate host-rock facies (a) transect 1 coral rich unit, (b) transect 2 calcarenites, (c) transect 3 calcarenites and (d) fault rocks 1 and 2 (FR1 and FR2); E: Pictures of D19 outcrop F: Stereographic projections of poles to fractures (density contoured), set one faults (orange line) and set 2 faults (red line) G: Photomicrograph of host rock facies (a) and of fault rocks (b; red stars on the pictures)); H: D19 outcrop including the five faults F1 to F5.

***Table 1**: structural properties of the fault zones.*

Fault zones	Fault	Direction	Dip	Dip direction	Pitch striation	Fault core thickness	Fault Rocks		
							FR1	FR2	FR3
Castellas	Castellas	060 - 070	40 to 80	N	14 W -	0 to 4 m	sparsely present	majoritarely present	/
D19	F1	030	56	W		20	/	<10 cm	/
	F2	029	70	E	28 S	10 to 15	/	?	variable thickness
	F3	056	80	N		0 to 15	/	?	?
	F4	042	70	W		20	/	in the clasts of FR3	variable thickness
	F5	032	85	N	20 SW	50 to100	/	/	variable thickness

3. DATA BASE

We performed 4 transects across the Castellas Fault and the D19 Fault (Fig. 2). Transect 1 is located along the coral rich unit 2. This lithostratigraphic unit is essentially composed of peloidal grains and bioclasts (corals, bivalves and stromatoporidae; Fig. 2Da). Transects 2 and 3 cross-cut in unit 3, made of fine calcarenites with peloidal grains and a rich fauna (foraminifera, bivalves, ostracods and echinoderms; Fig. 2Db, c). Transect 4 was conducted along the D19 outcrop (Fig. 3), which exposes Barremian outer platform bioclastic calcarenite with current ripples. The grains are mainly peloids with minor amounts of bioclasts (solidary corals, bryozoans, bivalves and some rare miliolids; Fig. 2Ga).

The different tectonic events impacted the fault zone and fault core structure. Three different fault rock types were identified in the fault core of the two investigated fault zones (see Aubert et al. 2019a; Matonti et al., 2012). Fault rock 1 (FR1) results from the extensional activation of the Castellas fault during Durancian uplift. It is a cohesive breccia composed of sub-rounded to rounded clasts from the nearby damage zone and <30% of fine-grey matrix (Fig. 2Dd). Fault rock 2 (FR2), is linked to the strike reactivation of the Castellas fault and to the onset of D19 fault zone during the Pyrenean shortening. FR2 presents two morphologies depending on the fault zones. Within Castellas fault, FR2 is an un-cohesive breccia with an orange/oxidized matrix with angular to sub-rounded clasts belonging to the nearby damage zone and from FR1 (Fig. 2Dd). In the D19 fault zone, FR2 is a cohesive breccia with rounded clasts of the damage zone and a white cemented matrix (Fig. 2Gb). Fault rock 3 (FR3) is formed by the reactivation of D19 fault zone. The timing of D19 fault reactivation is tricky to determine as it can be related both to Pyrenean or alpine shortening. FR3 is composed of angular to sub-angular clasts from FR2 and from the nearby damage zone dispersed in an orange/oxidized matrix (<20%) (Fig. 2Gb).

4. METHODS

The data set comprises 122 samples, 62 from Castellas and 60 from D19 outcrops, collected along the 4 transects. Porosity values were measured on 92 dry plugs with a Micromeritics AccuPyc 1330 helium pycnometer. Microfacies were determined on 92 thin sections. Impregnation with a blue-epoxy resin allowed us to decipher the different pore types. Thin sections were coloured with a solution of hydrochloric acid, Alizarin red S and potassium ferricyanide to distinguish carbonate minerals (calcite and dolomite). Thin sections were analysed using cathodoluminescence to discriminate the different generation of calcite cements.

The paragenetic sequence was defined based on superposition and overlap principles observed on thin sections using a Technosyn Cold Cathode Luminescence Model 8200 Mk II coupled to an Olympus_BH2 microscope and to a Zeiss_MR C5. Micrite micro-fabric and major element composition of two samples from the fault zone, two from the host rock and 1 from the D19 karst infilling were measured using PHILIPS XL30 ESEM with a beam current set at 20 kV on fresh sample surfaces and on thin sections. To determine stable carbon and oxygen isotopes ($\delta^{13}C$ and $\delta^{18}O$), 204 microsamples (<5 mg) were drilled, 194 of them were micro-drilled from polished thin sections with an 80 µm diameter micro-sampler (Merkantec Micromill) at the VU University (Amsterdam, The Netherlands). We micro-sampled bulk rocks (57), sparitic cements (101), fault rocks (9) and micrite (27). The Bulk rock values are related to a non-selective sampling giving information on the whole rock isotopic values. These values do not capture the signature of isolated cement (Swart, 2015). Carbon and oxygen isotopic values were acquired with Thermo Finnigan Delta + mass spectrometer equipped with a GASBENCH preparation device at VU University Amsterdam. The internationally used standard IAEA-603, with official values of +2.46‰ for $\delta^{13}C$ and -2.37‰ for $\delta^{18}O$, is measured as a control standard. The standard deviation (SD) of the measurements is respectively < 0.1‰ and < 0.2 ‰ for $\delta^{13}C$ and $\delta^{18}O$, respectively. Ten whole rock samples were analysed using a Gasbench II connected to a Thermo Fisher Delta V Plus mass spectrometer at the FAU University (Erlangen, Germany). Measurements were calibrated by assigning $\delta^{13}C$ values of +1.95‰ to NBS19 and -47.3‰ to IAEA-CO9 and $\delta^{18}O$ values of -2.20‰ to NBS19. All values are reported in per mil relative to V-PDB.

5. RESULTS

1. MICROPOROSITY AND POROSITY

Porosities measured on the 92 samples show a strong decrease towards the fault core (Fig. 3): dropping from more than 10% in the host carbonates (mean: 15%, SD: 2.68 for Castellas and mean 12.3%, SD: 2.52 for D19) to less than 5% within fault zones (mean: 4.8%, SD: 2.07 for Castellas and mean: 3.16%, SD: 2.35 for D19).

Along transects, some porosity variations occur as follows:

- North of the Castellas fault, along the 60 m-long transect 2 the porosity is constantly lower than7% (mean of 4.4%, SD: 1.53; Fig. 3A).
- South of the Castellas fault, the reduced porosity zone is wider than 40 m in transect 3 and 30 m in transect 1 (Fig. 3A). In a 10 m-thick zone from the fault plane, porosity reduction occurs with lower values in transect 1 (average 4.9%) than in transect 3 (average 5.6%).
- In the D19 fault zone, the lowest porosity values are found in narrow zones around the faults (less than 2 m-wide) and in the lens between F4 and F5. Though, this porosity decrease is not homogeneous in fault zone and high values are found north of F1 and F3 (Fig. 3B).

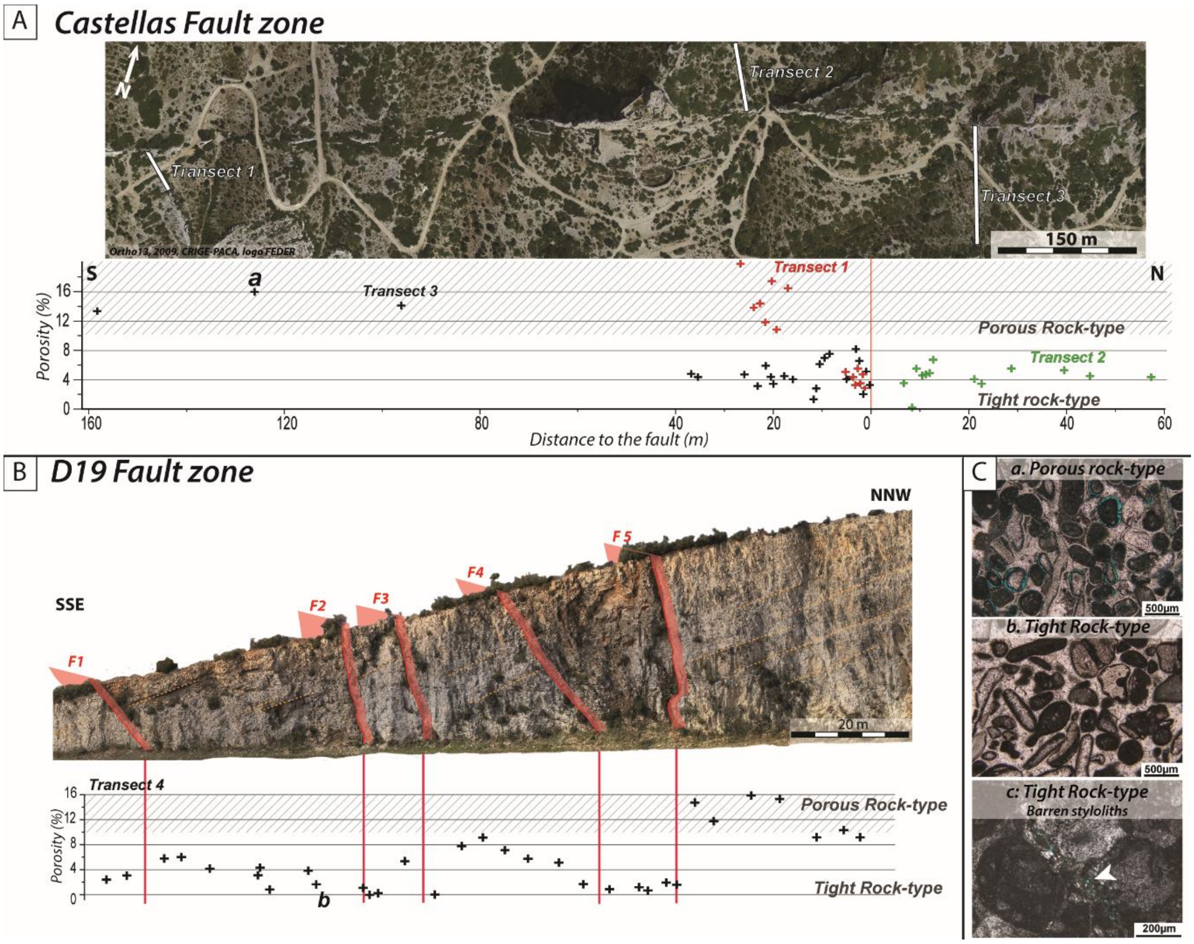

***Figure 3**: A: Castellas fault zone aerial view (Ortho13, 2009, CRIGE-PACA, logo FEDER) and porosity values measured along transect 1 (Red Cross), transect 2 (green cross) and transect 3 (black cross); B: porosity values measured along D19 fault zone; C: Pore types in the host rock (a) and in the fault zones (b and c).*

Microscope observation of thin sections impregnated with blue-epoxy resin allowed to identified a porous rock-type with ϕ>10% mainly in micritized grains as microporosity and moldic porosity (Fig. 3Ca), and a tight rock-type with ϕ< 5%, where the porosity is mostly linked to barren stylolites (Fig. 3Cb, c).

2. DIAGENETIC PHASES

a. Micrite micro-fabric

Micritised bioclasts, ooids and peloids were observed after SEM analysed of two fault zones samples and two host rock samples. Two micro-fabrics of micrite occur with specific crystal shape, sorting and contacts according to Fournier et al. (2011). Within both fault zones, the micrite is tight, with compact subhedral mosaic crystals of less than 10 µm-wide (MF1; Fig. 4A, B). In the host rock, the micrite is loosely packed, and partially coalescent with puntic rarely serrate, subhedral to euhedral crystals of less than 5 µm-wide (MF3; Fig. 4C, D, E). MF1 correlates with low porosity values (< 5%), while MF3 with higher porosity (> 10%).

b. Diagenetic cements

Eight different cement stages were identified (Fig. 5). The red stain links to Alizarin Red S coloration and shows that all visible cements made of calcite, which exhibit variable characteristics (morphology, luminescence, size and location).

The first two cement phases occur in both fault zones. The first cement (C0) is non-luminescent isopachous calcite of constant thickness (~10 µm) around grains (Fig. 5A). The second cement (C1) is divided in two sub-phases: a non-luminescent calcite, C1a, with a crystal size ranging from 50 µm to more than 200 µm, a dog-tooth morphology in intergranular spaces, and a bright luminescence calcite, C1b, covering C1a with a maximum thickness of 100 µm (Fig. 5A, B, D, G). C1b also fills micro-porosity in micritised grains (Fig. 5B). C1b areal occurrence strongly increases in Castellas fault zone.

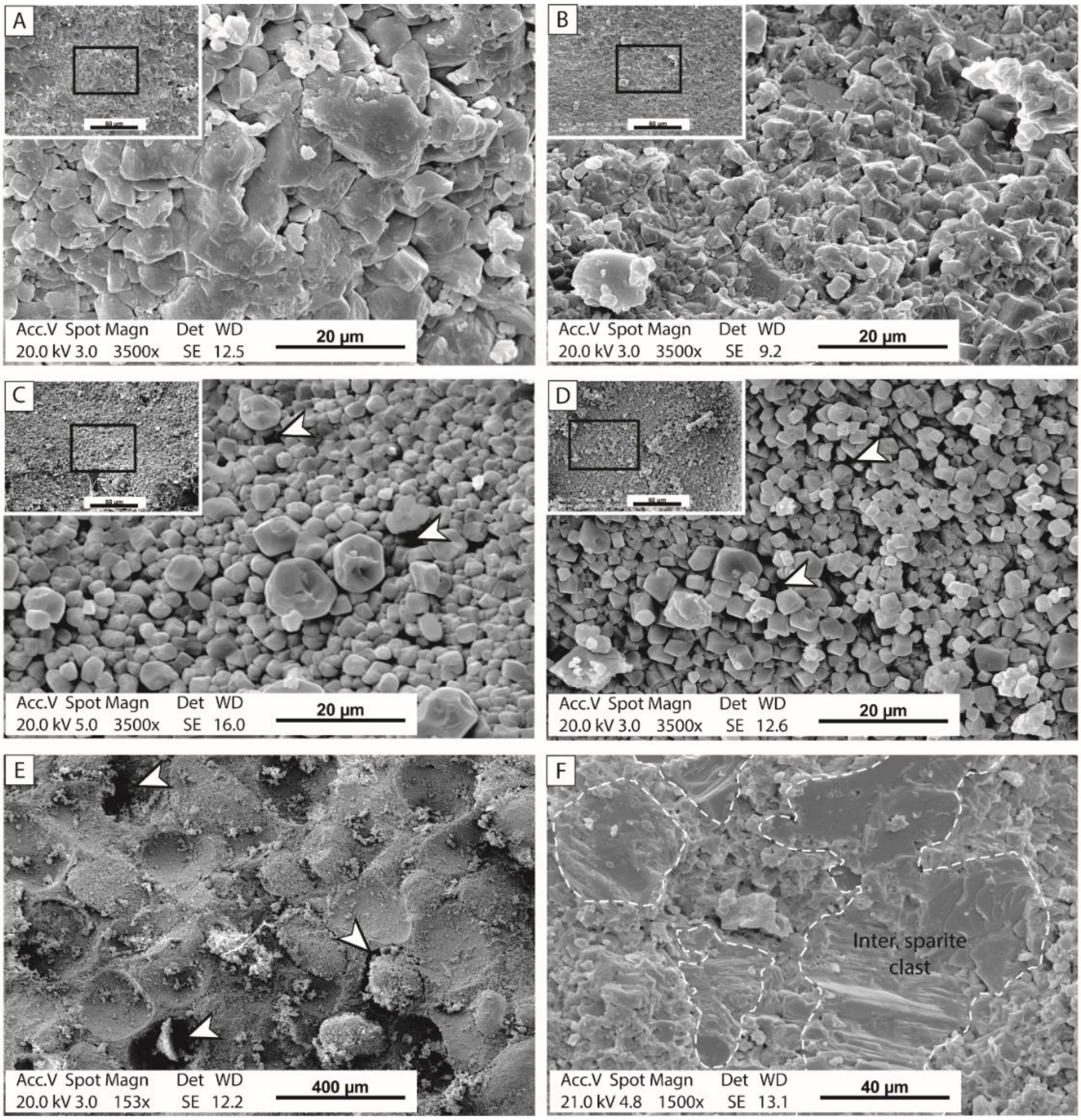

***Figure 4** : MEB pictures of micrite micro-fabric and microporosity (white arrows); A. MF1 micrite micro-fabric in Castellas fault zone (2.5 m to fault plane); B: MF1 micrite micro-fabric within D19 fault zones (2 m away from F5 fault plane); C: MF3 micrite micro-fabric within Castellas host rock (188 m away from the fault plane); D: MF3 micrite micro-fabric within D19 host rock (95 m away from F5 fault plane); E: D19 host rock moldic porosity; F: Karst infilling.*

Five cements or replacive phases extensively occur in the Castellas sector and rarely in the D19 outcrop:

- C2 is a sparitic cement, with dull-orange luminescent crystals sized of maximum 100 µm only found in veins of the fault core (Fig. 5B). SEM measurements show the Si and Al in the C2 veins. Most of Si crystals are automorphic and have black luminescence.

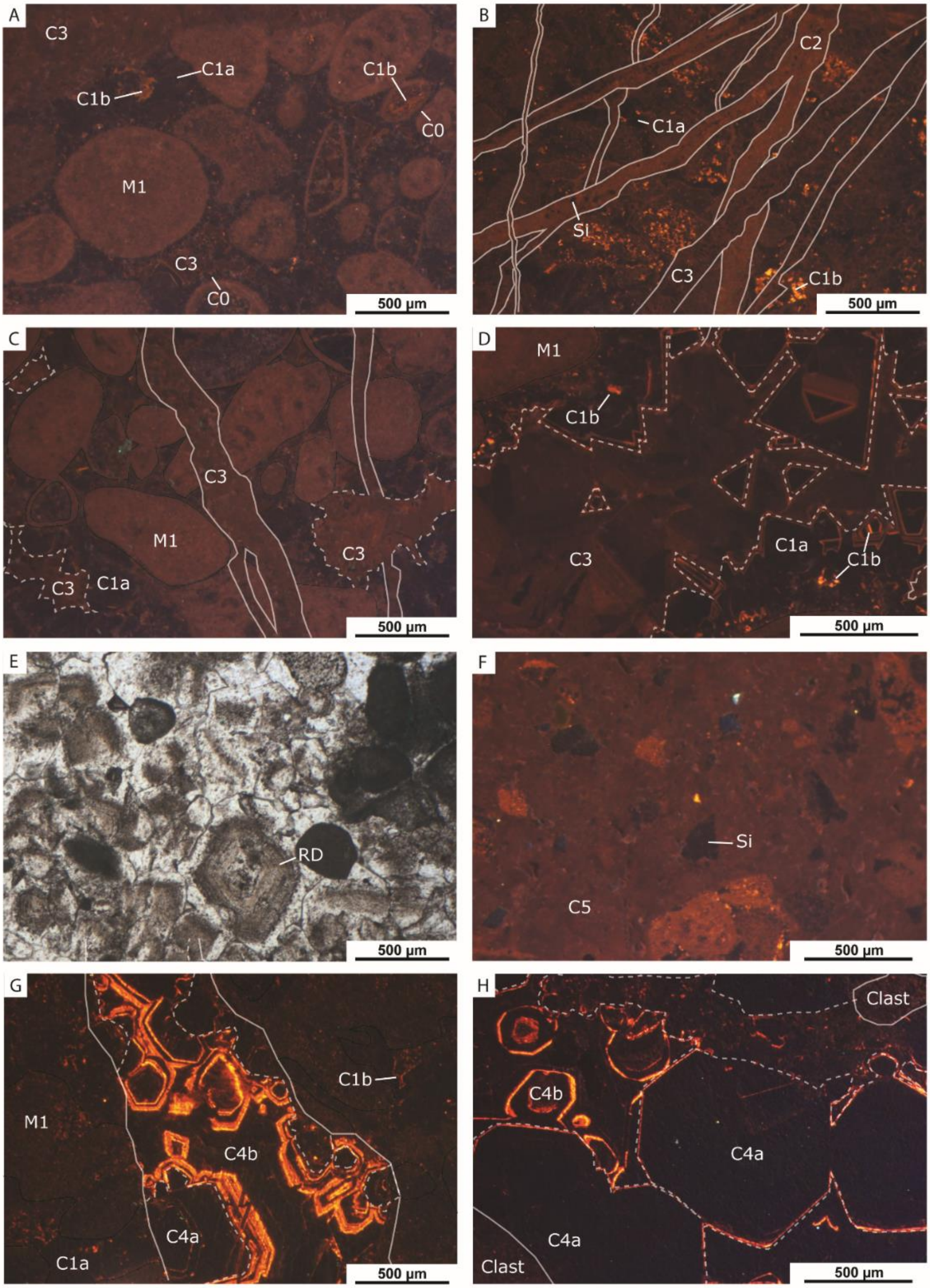

***Figure 5** : Thin-sections under cathodoluminescence; A: Calcarenite in transect 3 with micritised grain (M1), and intergranular volume cemented with C1 a and b and C3; B: C2 (with Si) and C3 veins affecting Castellas FR1 clasts with micritszed grains cemented by C1b; C: C3 veins, cements and intergranular volumes in Castellas fault zone; D: C1 (a and b) and C3 cementing moldic porosity of transect 3 calcarenite; E: FR1 matrix with phantom of cloudy appearance replacive dolomite (RD); F: FR1 matrix de-dolomitized by C5 containing quartz grains; G: C4 (a and b) cementing vein of D19 fault zone; H: matrix of D19 FR2 cemented by C4 (a and b).*

- C3 is a blocky calcite with non to red-dull luminescence in veins, moldic and intergranular pores (Fig. 5B, C, D). This cement also occurs in few veins of D19 sectors but is not restricted only to the fault zone.
- Phantoms of planar-e (euhedral) dolomite crystals (Sibley and Gregg, 1987) with a maximum size of 500 µm affect the matrix of FR1 (Fig. 5E). They are vestiges of a previous dolomitization phase. They have a cloudy appearance caused by solid micritic inclusion inside crystals and can be considered as replacive dolomite (RD; Machel, 2004). Within the FR1 matrix, an important concentration of angular grains of quartz with a maximum size of 300 µm is noticed (Fig. 5F).
- A blocky calcite C4 (referred to as S2 in Aubert et al. (2019a)) is mainly present in veins of the D19 outcrop, in matrix of FRA, and intergranular and moldic pores (Fig. 5G, H). This cement shows zonation of non-luminescent and bright luminescent bands and can be divided in two sparitic sub-phases: C4a which is non-luminescent with some highly luminescent bands and C4b is bright luminescent with some thin non-luminescent zones. C4a occurs in lesser proportion in some veins along transect 2 and 3 of the Castellas fault.
- A sparitic cement C5, with a red-dull luminescence replaces the RD phase (Fig. 5F).

c. Additional diagenetic features

In addition to cementation phases, other diagenetic elements affected both fault zones. Karst infilling occurs in the F2 fault zone of the D19 outcrop. It is composed of well-sorted grains deposited in laminated layers. This karst deposit presents a stack of alternating micrite-rich and grain-rich layersfrom the latter composed of former blocky calcite belonging to dissolved grainstones. The laminated layers are affected by veins and stylolites; some of these are deformed due to the grain fall on sediments. Micritic layers have been observed under SEM, and the micrite appeared tight with compact subhedral mosaic crystals (Fig. 4F). We observed oxide filling mainly in the Castellas area in dissolution voids affecting C1a, C1b and C3 cementation phases and in D19 in karstic fill. The areal amount of oxides increase close to stylolites.

3. CARBON AND OXYGEN ISOTOPES

Isotope measurements were realized on samples collected along transects of the fault zones. A hundred and eighty-nine measurements of C and O isotopes were performed on 16 samples and 32 thin sections (Fig. 6A, table 2).

Sampling was done in bulk rock (66), sparitic cement (101; veins, intergranular volume and fault rock cements) and in fault rocks (10) in order to determine their isotopic signature. Isotopic values range from -10.40‰ to -3.65‰ for $\delta^{18}O$ and from -7.20‰ to +1.42‰ for $\delta^{13}C$ (Fig. 6A, B, table 2). The bulk rock values range from -9.18‰ to -4.34‰ for $\delta^{18}O$ and from -4.80‰ to +1.19‰ for $\delta^{13}C$ (Fig. 6A, table 2). These values are split in two sets. Set 1 includes transect 1 and 3 of the Castellas Fault. Bulk values range from -6.07‰ to -4.34‰ for $\delta^{18}O$ and from -1.41‰ to +1.19‰ for $\delta^{13}C$. Set 2 includes transect 2 (Castellas) and transect 4 (D19). Bulk values range from -9.18‰ to -5.20‰ for $\delta^{18}O$ and from -4.80‰ to -0.60‰ for $\delta^{13}C$ (Fig. 6B, table 2). In transect 3, the isotopic values only slightly vary, ranging from -6.13‰ to -4.50‰ for $\delta^{18}O$ and from -1.41‰ to +0.47‰ for $\delta^{13}C$ respectively (Fig. 6C, table 2). On the contrary, values are more variable along the D19 transect; they range from -9.18‰ to -5.20‰

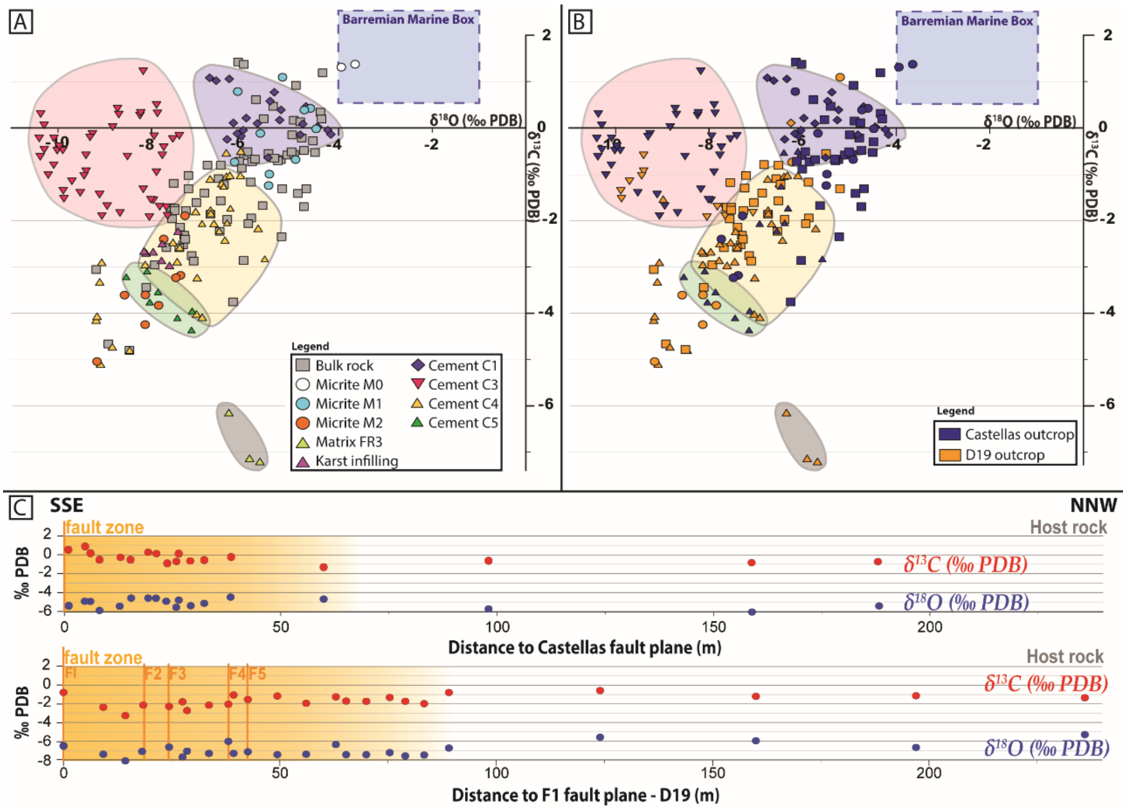

***Figure 6** : Isotopic values of δ13C and δ18O measured on bulk rock, cement phases, and micrite. Range values of "Urgonian marine box" from Moss & Tucker (1995) and Godet et al. (2006); A: set of values sorted by the nature of diagenetic phases and B: values sorted by the fault zone; C: lateral evolution of $\delta^{13}C$ and $\delta^{18}O$ bulk isotopic values in Castellas (top) and in D19 (bottom) fault zones.*

for $\delta^{18}O$ and from -4.80‰ to -0.60‰ for $\delta^{13}C$ (Fig. 6C, table 2). The $\delta^{13}C$ values depletes approaching to faults, especially south of F2.

Isotopic values of cements filling veins, intergranular volumes, karst infillings, and fault rocks are divided into 5 groups (Fig. 6A, table 2):

- Isotopic values of C1 cement fluctuates from -6.76‰ to -4.45‰ for $\delta^{18}O$ and from -1.28 to +1.08‰ for $\delta^{13}C$;
- Isotopic values of C3 cement ranges from -10.40‰ to -6.73‰ for $\delta^{18}O$ and from -2.09 to +1.22‰ for $\delta^{13}C$;
- Isotopic values of C4 cement in FR1 and FR2 matrix and in karst infillings ranges from -9.18‰ to -4.60‰ for $\delta^{18}O$ and from -5.10‰ to -0.74‰ for $\delta^{13}C$ with a positive covariance between $\delta^{18}O$ and $\delta^{13}C$. FR2 matrix values (from -6.55 to -7.06‰ for $\delta^{18}O$ and from -1.10 to -2.24‰ for $\delta^{13}C$) present slightly less depleted values than karst infillings with mean values of -7.83‰ and -2.53‰ respectively for $\delta^{18}O$ and $\delta^{13}C$ respectively. (Fig. 6A). In the Castellas fault, 4 isotopic values from two veins are enriched with means of -6.25 and -4.2‰ for $\delta^{18}O$ -0.64 and -0.09‰ for $\delta^{13}C$ having similar positive covariance than the other C4 values;
- Isotopic values of C5 cement, sampled in FR1 matrix display mean of -7.49‰ for $\delta^{18}O$ and -4.01‰ for $\delta^{13}C$ (Fig. 6A);

- Isotopic values of FR3 matrix with a mean of -5.98‰ for $\delta^{18}O$ and -6.83‰ for $\delta^{13}C$ (Fig. 6A)

***Table 2**: Carbon and oxygen isotope values of bulk carbonates for Castellas fault zone and D19 fault zones. B: bulk measurement; M: micrite value; C1, C3, C4, C5: cement isotopic value; FR: fault rock isotopic value.*

Transect	Sample	$\delta^{13}C$ (‰VPDB)	$\delta^{18}O$ (‰VPDB)	Class	Distance to F. (m)
Transect 1 (Cast.)	201	1,19	-4,34	B	1,3
Transect 1 (Cast.)	201	1,02	-6,62	C1	1,3
Transect 1 (Cast.)	201	1,31	-3,94	M	1,3
Transect 1 (Cast.)	201	1,37	-3,65	M	1,3
Transect 1 (Cast.)	213	-0,68	-5,24	B	22,7
Transect 1 (Cast.)	213	-0,58	-5,10	B	22,7
Transect 1 (Cast.)	213	-0,18	-6,09	C1	22,7
Transect 1 (Cast.)	213	0,03	-4,45	C1	22,7
Transect 1 (Cast.)	213	0,09	-4,77	C1	22,7
Transect 1 (Cast.)	213	-2,09	-6,92	C4	22,7
Transect 1 (Cast.)	213	-0,68	-4,92	M	22,7
Transect 2 (Cast.)	c3b17	-0,52	-5,95	B	4,6
Transect 2 (Cast.)	c3b17	-2,07	-6,38	C4	4,6
Transect 2 (Cast.)	c3b7	-0,64	-5,51	B	9,3
Transect 2 (Cast.)	c3b26	-3,76	-6,26	B	22,6
Transect 2 (Cast.)	c3b26	-2,85	-5,58	C4	22,6
Transect 2 (Cast.)	c3b26	-1,31	-4,69	B	57,3
Transect 2 (Cast.)	c3b7	-1,76	-6,31	C1	57,3
Transect 2 (Cast.)	c3b7	-1,28	-6,46	C1	57,3
Transect 2 (Cast.)	c3b26	-2,35	-5,22	M	57,3
Transect 2 (Cast.)	c3b26	-1,70	-4,75	M	57,3
Transect 3 (Cast.)	327	-0,24	-7,55	C3	0,3
Transect 3 (Cast.)	325	-1,90	-9,06	C3	0,3
Transect 3 (Cast.)	325	-1,69	-8,95	C3	0,3
Transect 3 (Cast.)	327	-3,11	-8,09	C4	0,3
Transect 3 (Cast.)	327	0,47	-5,40	B	1,0
Transect 3 (Cast.)	327	-0,18	-7,95	C3	1,0
Transect 3 (Cast.)	327	-0,17	-7,41	C3	1,0
Transect 3 (Cast.)	328	0,10	-5,74	C1	1,6
Transect 3 (Cast.)	328	-1,32	-8,18	C3	1,6
Transect 3 (Cast.)	328	-0,59	-7,77	C3	1,6
Transect 3 (Cast.)	328	-0,42	-7,74	C3	1,6
Transect 3 (Cast.)	328	-0,13	-9,26	C3	1,6
Transect 3 (Cast.)	328	0,02	-8,83	C3	1,6

Transect 3 (Cast.)	328	0,29	-8,70	C3	1,6
Transect 3 (Cast.)	328	0,42	-8,73	C3	1,6
Transect 3 (Cast.)	328	0,50	-7,89	C3	1,6
Transect 3 (Cast.)	328	1,22	-8,18	C3	1,6
Transect 3 (Cast.)	333	-1,84	-8,67	C3	1,6
Transect 3 (Cast.)	333	-0,96	-7,89	C3	1,6
Transect 3 (Cast.)	328	-0,14	-4,17	C4	1,6
Transect 3 (Cast.)	328	-0,05	-4,23	C4	1,6
Transect 3 (Cast.)	329	0,16	-4,95	B	2,4
Transect 3 (Cast.)	333	-0,25	-6,38	C1	4,6
Transect 3 (Cast.)	333	-0,12	-6,17	C1	4,6
Transect 3 (Cast.)	333	-0,62	-8,52	C3	4,6
Transect 3 (Cast.)	333	-0,12	-5,67	M	4,6
Transect 3 (Cast.)	333	-0,02	-4,48	M	4,6
Transect 3 (Cast.)	333	0,42	-4,60	M	4,6
Transect 3 (Cast.)	337	0,19	-5,59	B	9,5
Transect 3 (Cast.)	302	-0,53	-4,50	B	11,8
Transect 3 (Cast.)	302	-0,49	-4,74	B	11,8
Transect 3 (Cast.)	302	-0,62	-10,38	C3	11,8
Transect 3 (Cast.)	302	-0,49	-10,02	C3	11,8
Transect 3 (Cast.)	305	0,33	-4,38	B	16,0
Transect 3 (Cast.)	306	0,21	-4,35	B	17,8
Transect 3 (Cast.)	307	-0,01	-4,46	B	18,2
Transect 3 (Cast.)	308	-0,57	-4,95	B	20,0
Transect 3 (Cast.)	308	-1,44	-9,11	C3	20,0
Transect 3 (Cast.)	308	-0,23	-10,40	C3	20,0
Transect 3 (Cast.)	308	-0,22	-10,08	C3	20,0
Transect 3 (Cast.)	309	-1,41	-4,87	B	20,5
Transect 3 (Cast.)	309	-0,52	-5,01	B	20,5
Transect 3 (Cast.)	309	-0,15	-4,82	C1	20,5
Transect 3 (Cast.)	309	-1,56	-7,96	C3	20,5
Transect 3 (Cast.)	309	-1,55	-8,01	C3	20,5
Transect 3 (Cast.)	312	0,12	-4,81	B	23,2
Transect 3 (Cast.)	314	-0,71	-5,30	B	25,9
Transect 3 (Cast.)	314	-0,80	-10,09	C3	25,9
Transect 3 (Cast.)	314	-0,49	-9,90	C3	25,9
Transect 3 (Cast.)	314	-0,47	-10,29	C3	25,9
Transect 3 (Cast.)	314	-0,40	-9,97	C3	25,9
Transect 3 (Cast.)	314	0,06	-10,30	C3	25,9
Transect 3 (Cast.)	316	-1,24	-5,50	B	29,2
Transect 3 (Cast.)	316	-1,00	-5,48	B	29,2
Transect 3 (Cast.)	316	-0,22	-4,79	B	29,2
Transect 3 (Cast.)	316	-1,02	-10,21	C3	29,2
Transect 3 (Cast.)	316	-0,18	-9,31	C3	29,2
Transect 3 (Cast.)	316	0,30	-10,37	C3	29,2
Transect 3 (Cast.)	318	-0,28	-4,53	B	35,4

Transect 3 (Cast.)	320	-0,68	-5,79	B	96,1
Transect 3 (Cast.)	322	-0,88	-6,07	B	158,0
Transect 3 (Cast.)	323	-0,65	-5,37	B	188,0
Castellas (ZF1)	Z1,1	0,17	-5,26	C1	0,0
Castellas (ZF1)	Z1,1	0,39	-5,23	C1	0,0
Castellas (ZF1)	Z1,1	0,46	-4,70	C1	0,0
Castellas (ZF1)	Z1,2	0,21	-5,98	C1	0,0
Castellas (ZF1)	Z1,1	-0,55	-6,40	C4	0,0
Castellas (ZF1)	Z1,1	-0,52	-6,10	C4	0,0
Castellas (ZF1)	Z1,2	-4,12	-7,45	C5	0,0
Castellas (ZF1)	Z1,2	-0,15	-4,99	FR	0,0
Castellas (ZF1)	Z1,2	0,39	-4,73	M	0,0
Castellas (ZF1)	Z1,2	0,61	-5,77	M	0,0
Castellas (ZF1)	Z1,1	0,78	-6,16	M	0,0
Castellas (ZF2)	Z2,2	0,77	-5,38	C1	0,0
Castellas (ZF2)	Z2,7	-1,40	-9,52	C3	0,0
Castellas (ZF2)	Z2,7	-4,38	-7,15	C5	0,0
Castellas (ZF2)	Z2,7	-3,97	-7,13	C5	0,0
Castellas (ZF2)	Z2,7	-3,78	-8,04	C5	0,0
Castellas (ZF2)	Z2,7	-3,56	-7,86	C5	0,0
Castellas (ZF2)	Z2,7	-3,24	-7,48	C5	0,0
Castellas (ZF2)	Z2,7	-3,23	-8,54	C5	0,0
Castellas (ZF2)	Z2,2	0,58	-5,47	FR	0,0
Castellas (ZF2)	Z2,2	0,92	-4,91	FR	0,0
Castellas (ZF2)	Z2,7	-1,68	-5,63	FR	0,0
Castellas (ZF2)	Z2,7	-2,24	-6,55	FR	0,0
Castellas (ZF2)	Z2,7	-3,18	-7,38	M	0,0
Castellas (ZF2)	Z2,7	-2,86	-6,03	FR	1,0
Castellas (ZF5)	Z5,4	0,27	-8,25	C3	0,0
Castellas (ZF5)	Z5,4	0,31	-7,87	C3	0,0
Castellas (ZF5)	Z5,4	0,32	-8,23	C3	0,0
Castellas (ZF5)	Z5,4	1,06	-6,34	C1	0,4
Castellas (ZF5)	Z5,4	1,08	-6,76	C1	0,4
Castellas (ZF5)	Z5,4	1,05	-7,13	FR	0,4
Castellas (ZF5)	Z5,4	1,37	-6,03	FR	0,4
Castellas (ZF5)	Z5,4	1,42	-6,15	FR	0,4

Transect	**Sample**	**$\delta^{13}C$ (‰VPDB)**	**$\delta^{18}O$ (‰VPDB)**	**Class**	**Distance to F1 (m)**
Transect 4 (D19)	3B	-0,81	-6,52	B	0,0
Transect 4 (D19)	3B	-1,20	-6,50	C1	0,0
Transect 4 (D19)	3B	-1,02	-6,33	C1	0,0
Transect 4 (D19)	3B	0,11	-6,25	C1	0,0
Transect 4 (D19)	3B	-0,74	-6,23	M	0,0
Transect 4 (D19)	9	-2,32	-7,30	B	9,2

Transect 4 (D19)	13a	-3,44	-8,11	B	14,3
Transect 4 (D19)	13a	-2,96	-7,93	B	14,3
Transect 4 (D19)	13C	-2,97	-7,62	M	14,3
Transect 4 (D19)	13C	-2,86	-7,79	M	14,3
Transect 4 (D19)	13C	-2,70	-8,12	M	14,3
Transect 4 (D19)	13C	-2,67	-7,96	M	14,3
Transect 4 (D19)	13C	-2,66	-8,16	M	14,3
Transect 4 (D19)	13C	-2,50	-7,77	M	14,3
Transect 4 (D19)	13C	-1,54	-8,98	M	14,3
Transect 4 (D19)	17	-2,58	-7,68	B	18,7
Transect 4 (D19)	14A	-1,97	-6,38	B	18,7
Transect 4 (D19)	14A	-1,87	-6,74	B	18,7
Transect 4 (D19)	15B	-2,23	-7,43	B	18,7
Transect 4 (D19)	17	-1,05	-6,40	C1	18,7
Transect 4 (D19)	14A	-1,77	-6,74	C1	18,7
Transect 4 (D19)	14A	-2,42	-6,43	C4	18,7
Transect 4 (D19)	14A	-2,06	-6,67	C4	18,7
Transect 4 (D19)	21	-2,23	-6,54	B	24,4
Transect 4 (D19)	RSG	-1,90	-7,66	B	28,4
Transect 4 (D19)	RSG	-1,70	-7,83	B	28,4
Transect 4 (D19)	RSD	-2,87	-7,10	B	29,5
Transect 4 (D19)	RSD	-2,76	-7,14	B	29,5
Transect 4 (D19)	RSD	-0,93	-9,40	C3	29,5
Transect 4 (D19)	RSF1	-2,40	-7,28	B	34,7
Transect 4 (D19)	RSF2	-2,14	-7,39	B	34,7
Transect 4 (D19)	RSF2	-1,78	-7,27	B	34,7
Transect 4 (D19)	RSF1	-1,03	-9,44	C3	34,7
Transect 4 (D19)	RSF2	-1,93	-8,05	C3	34,7
Transect 4 (D19)	RSF2	-0,59	-9,40	C3	34,7
Transect 4 (D19)	RSF2	-2,95	-8,14	C4	34,7
Transect 4 (D19)	RSE 1	-2,53	-7,33	B	35,0
Transect 4 (D19)	RSE 2	-2,59	-7,41	B	35,0
Transect 4 (D19)	RSE 1	-1,71	-7,68	C3	35,0
Transect 4 (D19)	RSE 2	-1,84	-6,73	C3	35,0
Transect 4 (D19)	57	-2,07	-5,93	B	38,1
Transect 4 (D19)	57	-1,94	-5,87	B	38,1
Transect 4 (D19)	57	-1,83	-7,06	C3	38,1
Transect 4 (D19)	57	-1,10	-6,75	C3	38,1
Transect 4 (D19)	57	-4,02	-7,04	C4	38,1
Transect 4 (D19)	57	-2,17	-5,72	C4	38,1
Transect 4 (D19)	57	-1,58	-6,52	FR	38,1
Transect 4 (D19)	57	-7,20	-5,68	M	38,1
Transect 4 (D19)	57	-7,13	-5,90	M	38,1
Transect 4 (D19)	28b	-1,03	-7,21	B	39,3
Transect 4 (D19)	28b	-1,03	-6,10	C3	39,3
Transect 4 (D19)	28b	-4,09	-6,92	C4	39,3

Transect 4 (D19)	28b	-2,58	-7,40	C4	39,3
Transect 4 (D19)	28b	-2,47	-7,54	C4	39,3
Transect 4 (D19)	30a	-1,61	-7,04	B	42,6
Transect 4 (D19)	30a	-1,41	-6,87	B	42,6
Transect 4 (D19)	30a	-3,23	-7,03	C4	42,6
Transect 4 (D19)	30a	-2,89	-7,45	C4	42,6
Transect 4 (D19)	24a	-1,21	-7,52	B	51,1
Transect 4 (D19)	27b	-1,92	-7,48	B	57,9
Transect 4 (D19)	31	-1,24	-6,44	B	65,0
Transect 4 (D19)	32	-1,75	-7,50	B	67,4
Transect 4 (D19)	34	-1,79	-7,49	B	72,2
Transect 4 (D19)	36	-1,32	-7,21	B	77,8
Transect 4 (D19)	38	-1,73	-7,59	B	81,5
Transect 4 (D19)	62	-1,96	-7,56	B	86,0
Transect 4 (D19)	42	-0,81	-6,80	B	91,9
Transect 4 (D19)	63	-0,55	-5,50	B	124,0
Transect 4 (D19)	64	-1,17	-5,88	B	160,0
Transect 4 (D19)	65	-1,10	-6,57	B	197,0
Transect 4 (D19)	66	-1,31	-5,21	B	236,0
Transect 4 (D19)	60a	-3,06	-9,18	B	255,2
Transect 4 (D19)	60B	-4,80	-8,47	B	255,2
Transect 4 (D19)	60B	-4,66	-8,92	B	255,2
Transect 4 (D19)	61	-1,53	-9,87	C3	255,2
Transect 4 (D19)	61	-1,36	-9,89	C3	255,2
Transect 4 (D19)	60a	-1,15	-9,70	C3	255,2
Transect 4 (D19)	60a	-3,32	-9,11	C4	255,2
Transect 4 (D19)	60B	-5,10	-9,09	C4	255,2
Transect 4 (D19)	60B	-4,73	-8,84	C4	255,2
Transect 4 (D19)	60B	-4,15	-9,18	C4	255,2
Transect 4 (D19)	60B	-4,07	-9,16	C4	255,2
Transect 4 (D19)	60B	-2,90	-9,06	C4	255,2
Transect 4 (D19)	60a	-3,83	-7,85	M	255,2
Transect 4 (D19)	60B	-5,04	-9,17	M	255,2
Transect 4 (D19)	60B	-4,25	-8,14	M	255,2
Transect 4 (D19)	60B	-3,61	-8,58	M	255,2
Transect 4 (D19)	60B	-3,61	-8,13	M	255,2

6. DISCUSSION

1. DIAGENETIC EVOLUTION OF THE FAULT ZONES

The chronological relations between cements can be established via to cross-cutting relations and inclusion principles. Indeed, the veins filled with cement C2 cross-cut C1a and C1b cements (Fig. 5B). Thus, C2 cementation post-dated C1 cement. C3 veins cross-cut the C2 veins, but are included within FR1 clasts (Fig. 5B). Hence, C3 cement is prior to FR1 development but after C2 cementation. The fault rock 1 (FR1) is related to the first extensional fault activity, consequently, C1, C2 and C3 cementation phases occurred prior to the proper fault plane and

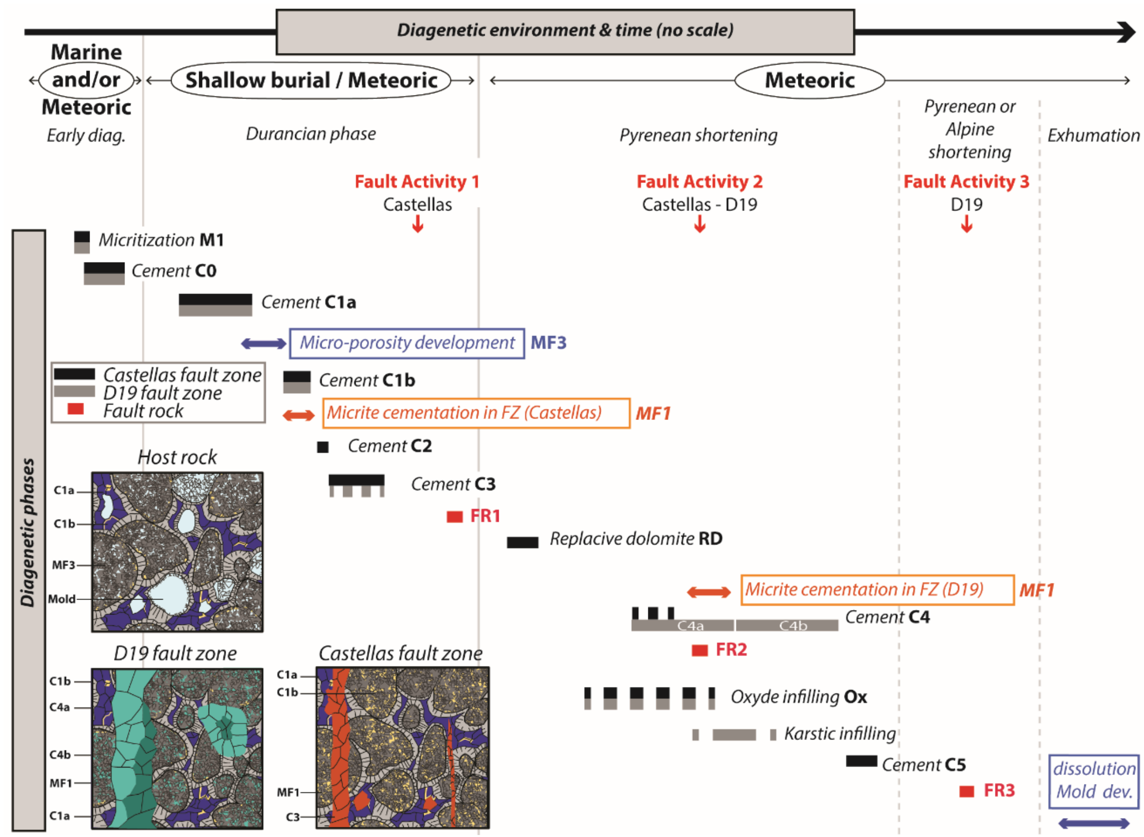

Figure 7: Paragenetic sequence of the both fault zones (black: Castellas, grey: D19) with micro-porosity development (blue),cementation (orange) and fault zone activation events (red).

fault core formation and are related to the fault nucleation. Replacive dolomite is found within FR1 matrix (Fig. 5E), therefore, it developed after FR1 formation. Finally, the C4 cement can be noticed within FR2 matrix indicating that C4 cementation event post-dated FR2 formation. The fault rock 2 (FR2) developed during strike-slip reactivation of the studied faults. The combined superposition, overlap, cross-cutting principles and isotopic signature of cements brought out the chronology between phases, and revealed the paragenetic sequence (Fig. 7).

The Urgonian carbonates in La Fare anticline underwent 3 major diagenetic events, which impacted the host rock and/or the fault zones. We discriminate among diagenetic events that occurred before and during faulting.

a. Pre fault diagenesis – microporosity development

During Upper Barremian, just after deposition, micro-bores organisms at the sediment-water interface enhanced the formation of micritic calcitic envelopes on bioclasts, ooids and peloids (Purser, 1980; Reid and Macintyre, 2000; Samankassou et al., 2005; Vincent et al., 2007). This micritisation in marine conditions is typical for Urgonian low-energy inner platform environment (Fournier et al., 2011; Masse, 1976). Subsequently, C0 cement formed around grains giving rise to a solid envelop inducing the preservation of the original grain shape during the later burial compaction (Step 0 on Fig. 8). However, the majority of isotopic values do not fit in the Barremian sea water calcite box which ranges from -1.00‰ to -4.00‰ for $\delta^{18}O$ and from +1.00‰ to +3.00‰ for $\delta^{13}C$ (Fouke et al., 1996; Godet et al., 2006). Only two data points pertaining to micritised grains show isotopic values close the Barremian sea water calcite. The isotopic depletion of other data indicates the slight impact of C0 cementation on isotopic values.

The next sub-phase of cementation C1a partly fills intergranular porosity. This non luminescent cement with isotopic values ranging from -6.8‰ to -3.9‰ for $\delta^{18}O$ and from -1.0‰ to +1.3‰ for $\delta^{13}C$ is characteristic of mixed fluids. Léonide et al. (2014) measured a calcite cement S1, near La Fare anticline with similar luminescence and isotopic range values (mean: $\delta^{18}O$= −5.49‰; $\delta^{13}C$=+2.34‰). These authors linked this cementation phase to a shallow burial meteoric fluid circulation under equatorial climate during Durancian uplift. This diagenetic event led to micrite re-crystallization, and to the development of microporosity (MF3). Since La Fare carbonates were exhumed at that time (Léonide et al., 2014) the meteoric fluids led to similar diagenetic modifications (Step 1 on Fig. 8):

(i) Micrite re-crystallization and microporosity MF3 setup by Ostwald ripening processes (Fig. 9B1a; Ostwald, 1886; Volery et al., 2010).
(ii) Cementation of C1a, partly filling intergranular porosity (Fig. 9B1b)

The micrite re-crystallization strongly increased rock porosity due to enhanced microporosity (Fig. 9B1a). Resulting from this event, Urgonian carbonates formed a type III reservoir *sensu* Nelson (2001).

b. Fault-related diagenesis – alteration of reservoir properties

Normal faulting-related diagenesis

The Castellas fault first nucleated during Durancian uplift (Aubert et al., 2019b; Matonti et al., 2012) affecting the host Urgonian carbonates.
In porous granular media, fault nucleation mechanisms can lead to dilation processes (Fossen and Bale, 2007; Fossen and Rotevatn, 2016; Main et al., 2000; Wilkins et al., 2007; Zhu and Wong, 1997) under low-confining pressure (<100 KPa; Alikarami and Torabi 2015). Because this process leads to dilatancy, it increases the rock permeability (Alikarami and Torabi, 2015; Bernard et al., 2002) in the first stage of deformation bands (Heiland et al., 2001; Lothe et al., 2002) enhancing fluid flows.
Castellas fault zone nucleated within a partially and dimly cemented host rock under low-confining pressure, in an extensional stress regime, at a depth <1 km (Lamarche et al. 2012). Under these conditions, Barremian host rock were likely characterised by mechanical and petrographical properties close to porous granular media described above. Moreover, Micarelli et al. (2006) showed that, during early stages of deformation, fault zones in carbonates have a hydraulic behaviour comparable to deformation bands in carbonates. Hence, in the Urgonian carbonates of La Fare area, dilatant processes occurred as an incipient fault mechanism and enhanced fluid circulations along the deformation bands. Fluid flows led to the cementation of C1b (Step 2 on Fig. 8). However, dilation bands were likely unstable and grain collapse occured swiftly after the beginning of the deformation due to an increase in the loading stress (Lothe et al., 2002). This could be the explanation why C1b does not fill all intergranular porosity. Consequently, as all micritic grains in fault zone are cemented by C1b, the bulk isotopic measurements are strongly influenced by C1 cement isotopic values. This is the explanation why in transect 3 the bulk isotopic values 30 m apart from the fault (means of -5.26‰ for $\delta^{18}O$ and -0.82‰ for $\delta^{13}C$) are close to bulk isotopic values far from the fault plane (188 m; -5.37‰ for $\delta^{18}O$ and -0.65‰ for $\delta^{13}C$, Fig. 6A). Dilation bands have also been described by *Kaminskaite et al.* (2019) in the San Vito Lo Capo carbonates grainstones (Sicily, Italy). These dilation bands also led to selective cementation of the carbonate rocks and to a microporosity decrease.

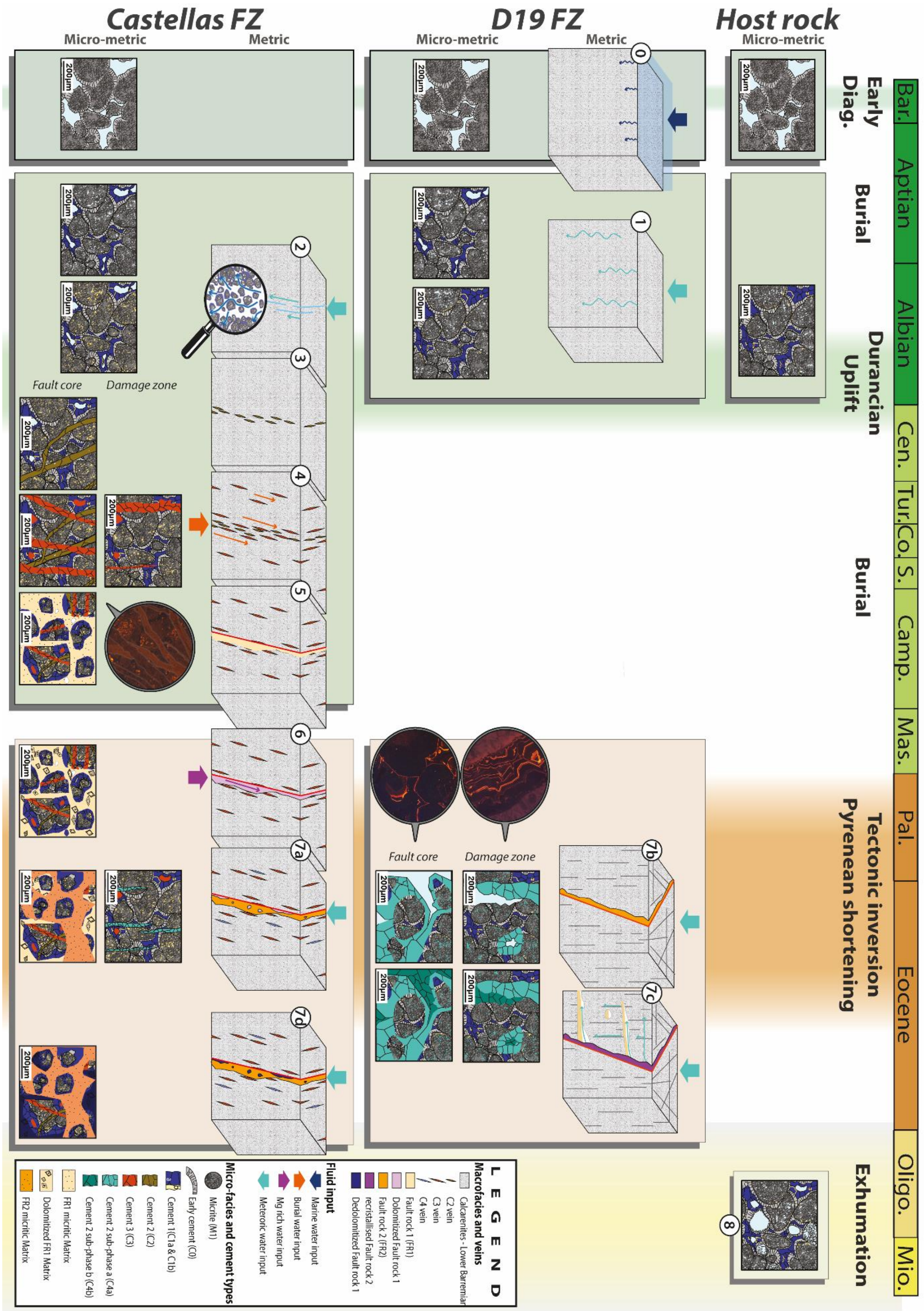

Figure 8 *: Diagenetic and geodynamic evolution since the Barremian of both fault zones and host rock at the metric and micro-metric scale. Numbers 0 to 8 correspond to the steps 0 to 8 (see text for description).*

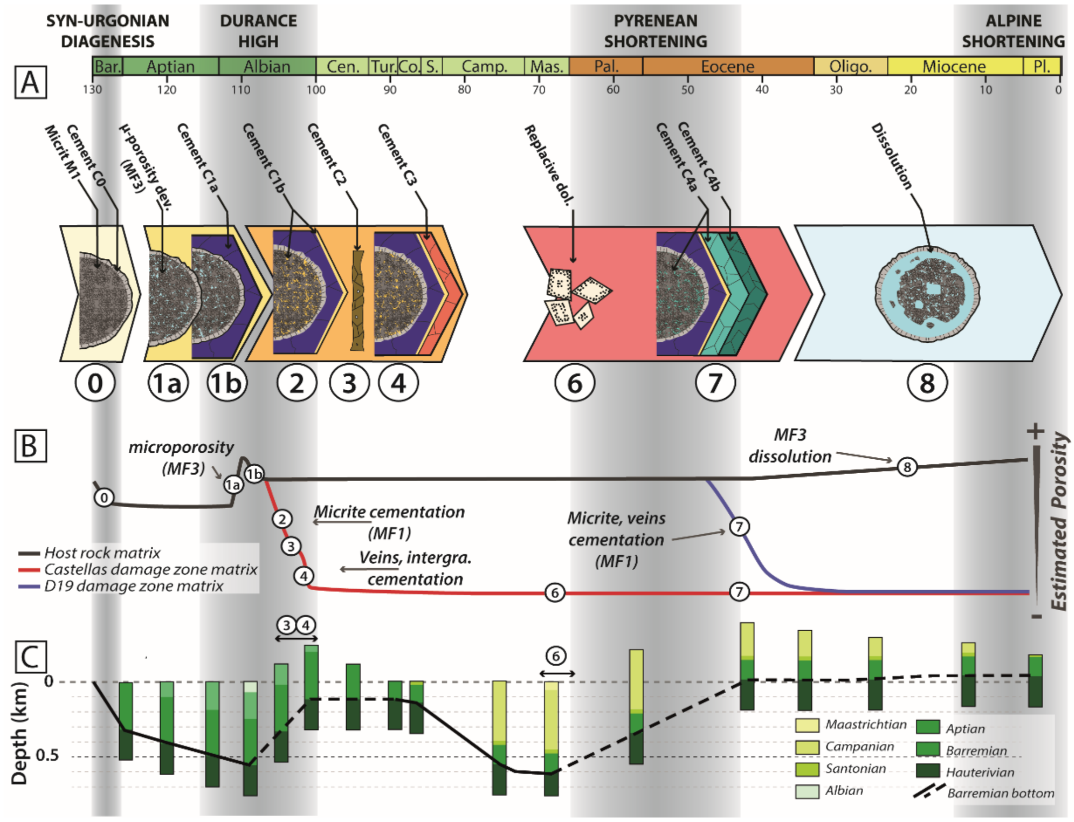

Figure 9 : *Evolution of reservoir properties. A: different cementation phases; numbers 0 to 8 correspond to the steps 0 to 8 (see text for description), B: relative porosity evolution of the host rock and the two fault zones; C: Burial/Uplift curve of Barremian basement (modified from Matonti et al. (2012)).*

Cementation (C1a and C1b) conferred a stiffer response of limestone to deformation, making it prone to deform through brittle structures (joints and veins), rather than via granular particulate flow (deformation bands). During the first stages of fault evolution in low-porosity limestones, intense fracturing of the fault zone predating fault core formation is known to increase fault permeability (Micarelli et al., 2006). In the studied faults, the first brittle event allowed Al-rich fluids to flow with fine-grained quartz grains in the incipient open fractures leading to precipitation of C2 cement (Step 3 on Fig. 8). The Urgonian facies of the studied area are composed of pure carbonates without siliciclastic input. Quartz grains and Aluminium could have been reworked from surrounding formations. The rocks underlying the studied exposed Urgonian carbonates are limestones and dolostones. Albian and Aptian rocks are marly and sandy limestones, respectively (Anglada et al., 1977). Hence, Aptian layers are very likely to be the source of quartz. The fluids may have carried small grains of quartz from the Aptian sandy limestones via the fracture network. The Al enrichment of C2 could result from the erosion of Albian and Aptian deposits during the Durancian uplift (Guendon and Parron, 1985; Triat, 1982).

As the fault zone grew, new fracture sets formed, leading to new phase of calcite cementation (C3) in veins and intergranular porosity (Step 4 on Fig. 8). The $\delta^{18}O$ isotopic values of C3 range from -10.40‰ to -6.73‰ with $\delta^{13}C$ values between -2.09‰ and +1.22‰. As C3 cementation occurred during the Durancian uplift and denudation, C3 most probably did not cement in deep burial conditions (maximum depth of 500 m; Fig. 9C4).The negative $\delta^{13}C$ values tend corroborate the hypothesis of cementation induced by meteoric fluid rather than marine ones. Hence, C3 would correspond to a shallow burial/meteoric cementation phase. Due to this cementation, rocks in this zone tightened with porosity down to <5%. The porosity did not change since this event (Fig. 9B5). This porosity reduction due to cementation has also been observed in other cases of brittle-dilatant faults (Agosta et al., 2007; Celico et al., 2006; Gaviglio et al., 2009; Mozley and Goodwin, 1995). Following this, the fault zone was a barrier to fluid flow, leading to a reservoir compartmentalization. Fluids responsible for precipitation of C3 cement also occurred along fracture clusters of the D19 sector and led to vein formation.

In a later stage, the fault core formed and the fault plane *sensu-stricto* developed, leading to FR1 breccia with a permeable matrix with quartz grains >100 µm in size (Step 5 on Fig. 8). These grains either came from silica found inside C2 cement described above or from Aptian overlying rocks. Silica crystals in C2 veins are scarce and smaller than 10 µm. Thus, quartz grains may rather come from Aptian rocks like the ones found in C2 veins. The presence of Aptian quartz in the fault core proves that the Castellas fault affected also Aptian rocks, which were later eroded during the Durancian uplift. According to this, the fault activity occurred before total erosion of Aptian rocks. Un-cemented breccias within the fault core formed good fluid pathways (Billi et al., 2008; Delle Piane et al., 2016). In the studied fault, formation of FR1 breccia allowed the fault core to act as a drain. However, the cemented surrounding host rocks constrained the lateral extent of the drainage area of this high-permeable conduit. Un-cemented breccias acting as good across- and along- fluid pathways were also described on Apennines carbonate formations within fault cores of strike and extensional faults (Billi et al., 2003, 2008; Storti et al., 2003).

Tectonic Inversion – Castellas fault-related dolomitization

At the onset of the Pyrenean shortening, compressive stresses led to underground water upwelling through the permeable fault core. This fluid flow triggered the dolomitization of FR1 matrix (Step 6 on Fig. 8). This matrix-selective dolomitization could have been favoured by several factors:

(i) The matrix has higher permeability than cemented clasts with a smaller grain size, hence a higher grain surface area (Machel, 2004);
(ii) This type of upwelling fluids, so-called “squeegee-type”, are short lived processes (Buschkuehle and Machel, 2002; Deming et al., 1990; Dorobek, 1989; Machel et al., 2000) not favourable for massive dolomitization;
(iii) Low-temperature fluids, under 50°-80°C, enabled the preservation of FR1 clast initial structure. Contrarily, high-temperature dolomitization tends to be destructive (Machel, 2004);
(iv) The tight surrounding host rock constrained Mg-rich fluid circulation to the fault core domain.

Gisquet et al. (2013) noticed similar fault related replacive dolomitization phase in the Etoile massif, 23 km South-Est of the studied zones. They linked the dolomitization to contractional stress regime during the early (Late Cretaceous) Pyrenean shortening. According to these authors, the tectonic stress led to low-temperature upwelling fluids likely Mg-enriched by the dissolution of underlying Jurassic dolomites. The Jurassic dolomites also occur in La Fare anticline. Since the fluids leading to dolomitization of fault core were low-temperature and since dolomites occur underground, it is possible that the dolomitization in La Fare and in the Etoile massif were similar and synchronous. Matrix dolomitization can increase intercrystalline and/or inter-particle porosity up to 13% but the later dolomite overgrowth reduces the porosity and permeability (Lucia, 2004; Machel, 2004; Saller and Henderson, 2001). Hence, in the first stages of dolomitization, the fault core was an important drain. After the growth of dolomite crystals, the fault core turned into barrier (Fig. 9 B6 and C6)

Sinistral tectonic inversion – meteoric alteration of reservoir properties

The ongoing tectonic inversion with increasing compressive stresses eventually led to the Castellas fault sinistral reactivation and to the onset of D19 fault zone (Aubert et al., 2019b). Aubert et al. (2019a) has shown that this compression reactivated the pre-existing early N030° background fractures (Step 7 on Fig. 8). This tectonic event formed FR2 in fault cores but with specific diagenetic consequences. In the D19 fault zone, the fault nucleation and reactivation of background fractures led to pluri-metric to kilometric fault surfaces with a permeable fault rock acting as drains and localizing the fluid flow (Aubert et al., 2019a). This fluid flow witnessed by the cementation of C4a and C4b in veins and micritised grains (MF1, Step 7c on Fig. 8), leading to a strong porosity decrease in the fault zone (Fig. 9,B7 and C7). However, not all fractures were cemented by C4, so that fracture porosity/permeability was still partially preserved. Therefore, the D19 fault zone became a type I reservoir *sensu* Nelson (2001) with a very low matrix porosity/permeability and high fracture-related secondary permeability (Aubert et al., 2019a).

Along F2, successive fluids gave rise to karsts, karstic infilling and dissolution/cementation processes of FR2 matrix (Step 7c on Fig. 8). Then, FR2 was sealed by C4 cementation. Isotopic values of C4 cement (from -9.2 to -6.1‰ for $\delta^{18}O$ and from -5.01‰ to -1.0‰ for $\delta^{13}C$) highlight the strong influence of meteoric fluids. This is coherent with the occurrence of karstic infilling due to fluid circulations in vadose zone, with alternating dissolution and cementation (Swart, 2015). However, the positive covariance between $\delta^{18}O$ and $\delta^{13}C$ of C4 suggests mixed fluids (Allan and Matthews, 1982) of meteoric water and burial or marine water.

In the Castellas fault zone, the host rocks are slightly impacted by these meteoric fluid circulations. Yet, some veins filled with C4a cement occur along transect 2 and transect 3 (Step 7a on Fig. 8). Two samples have enriched $\delta^{18}O$ and $\delta^{13}C$ isotopic values (respective means of -6.25‰ and -4.20‰ for $\delta^{18}O$; -0.64 and -0.09‰ for $\delta^{13}C$) similar to C1 cement (Fig. 6A). This indicates that C4 cement in the Castellas fault zone was precocious in comparison to the D19. C4 cement in Castellas area is restricted to transect 2. Transect 2 cross-cuts the Castellas fault along a relay zone (Fig. 2A). Relay or linkage zones occur where two fault segments overlap each other during fault grow (Kim et al., 2004; Long and Imber, 2011; Walsh et al., 1999, 2003). Consequently, the fault complexity, the fracture intensity and the fracture-strike range are increased (Kim et al., 2004; Sibson, 1996). This process in the studied area resulted in a well-connected fracture network that increased the permeability and favoured local fluid circulations. In transect 2, the increase of the local permeability in the relay zone enhanced fluid flow related to C4 cement. The relay zones along the Castellas fault and their consequences on the fracture permeability are, therefore, responsible for this local cementation event. On the contrary, cementation in D19 fault zone is linked to the highly permeable fault surfaces which acted as drains (Aubert et al., 2019a). This implies that the cementation occurred only after the development of the fault surface. In the case of Castellas, the relay zone was already present, inherited from the former extensional activity, allowing early C4 fluid to flow through the fault zone. This, in addition, explains why the early C4 cementation has not been recorded in D19 fault zone. The C4 cementation in transect 2 reduced the porosity to less than 8% on a larger zone (>60 m) than in both others transects (transect 1 ≈30m, transect 3>40m).

The reactivation of the Castellas fault formed a new fracture network that locally triggerred the fracture connectivity and permeability. The Castellas fault zone formed a type I reservoir (Nelson, 2001), but lateral variation of the fracture network implies lateral variations of the hydraulic properties. Thus, the fault zone was both a drain and a barrier (Matonti et al., 2012). In this case, the most appropriate concept would be a sieve, because in this analogy, it is synchronously closed in places and open in other places.

After these events, the matrix of the Castellas fault core was de-dolomitized (FR1) in relation to cementation C5 (Step 7d on Fig. 8). The C5 cement isotope values (mean of -7.49‰ for $\delta^{18}O$ and -4.01‰ for $\delta^{13}C$) are comprised within C4 positive covariance between $\delta^{18}O$ and $\delta^{13}C$. This indicates a continuity between C4 and C5 fluid flows. The measurements with the SEM revealed a lack of Mg in the matrix indicating that C5 totally recrystallised the replacive dolomite. Following this de-dolomitization phase, no additional diagenetic event is recorded in Castellas fault zone.

A late Pyrenean to Alpine compression reactivated the D19 fault zone what formed the new fault rock FR3. The matrix of this fault rock has very low $\delta^{13}C$ isotopic values (mean of -6.83‰) indicating an organic matter input (Swart, 2015). This implies fluids percolating soils, as results from a near surface fluid circulation. We deduce that the D19 faults was lately reactivated after the folding of the La Fare anticline. There is no such cementation with similar isotope values in the fault zone, meaning that fluids and cements did not alter the fault zone diagenetic properties.

Eventually, the late exhumation of the Urgonian carbonate host rocks led to flows inducing dissolution of MF3 grains in the host rock. This phase produced the moldic porosity and increased the porosity/permeability (Step 8 on Fig. 9B and C). These fluids, however, did not affect fault zones.

2. EVOLUTION OF FAULT ZONES RESERVOIR PROPERTIES

The host rock presents a monophasic evolution and switch from a type IV reservoir where matrix provided storage and flow, to a type III reservoir where fractures behave as pathways towards fluid flow but the production comes mainly from the matrix (*Nelson* 2001, Fig. 10A). The fault zones present a more complex polyphasic evolution than the host rock. Indeed, their reservoir properties evolved from a type IV reservoir corresponding to the host rock to a type I reservoir where fractures provide both storage and flow pathways (*Nelson* 2001, Fig. 10A). Both fault zones present slight differences. The Castellas fault zone was completely tight soon after C3 cementation. Consequently, it did not fit to the Nelson reservoir type classification. However, after fault core formation, the fault zone presents a high fault core permeability. In this study we propose a new approach with a triangle diagram taking into account fault core permeability to remove the flaws of this method (Fig. 10B). The percentage assigned to the fault core or to the matrix are qualitatively estimated. Further quantification could be evaluated, for instance, with the width of the fault core and damage zone domains, or by estimating the fracture network volume. However, no recent study have provided such quantification. Thus, for Castellas fault zone, permeability evolves from a stage with exclusive contribution from the host rock permeability (100% matrix; step 0 on Fig. 10B) to a permeability due to 50% to the

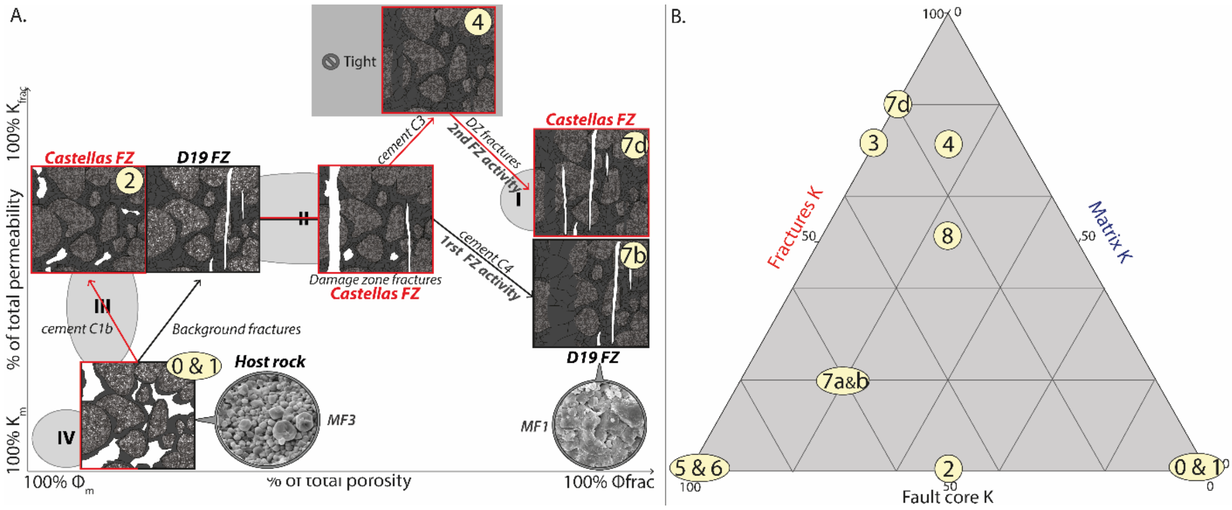

Figure 10 : *Castellas and D19 fault zone reservoir properties evolution. A: evolution of permeability and porosity taking into account fault zone fractures and matrix after Nelson (2001) and B: Triangle diagram of permeability evolution with 3 components: matrix, fractures and fault core. Numbers 1 to 8 correspond to the steps 1 to 8(see text for description). K: Permeability, Φ: porosity, FZ: Fault Zone, DZ: Damage zone, MF1 and MF3: Micrite micro-fabric.*

matrix and 50% to the fault core during dilation band development (step 2 on Fig. 10B). Thereafter, during the two fracture events permeability is mainly linked to fracturing (C2: 30% fault core, 70% fractures; C3: 15% fault core, 15% matrix, 70% fractures; step 3, 4 on Fig. 10B). Then, after fault core formation and during dolomitization event, permeability is solely provided by the fault core (step 6, 7 on Fig. 10B). Lastly, after fault zone reactivation, the permeability is due to 20% to the fault core and 80% to fractures (step 7c on Fig. 10B). The D19 fault zone permeability during its development was related for 20% to the matrix, 20% to the fractures and 60% to the fault core (step 7a and 7b on Fig. 10B).

8. CONCLUSION

This study deciphered the diagenetic evolution of two fault zones and the impact on reservoir properties of both faults and host rock in the frame of the overall geodynamic context of the SE Basin. The main outcomes are:

- Fault zones may have a complex diagenetic history, but most diagenetic phases occur during the nucleation of the fault. In the case of Castellas fault zone, the diagenetic imprint is mainly influenced by early diagenesis occurring along fractures and diffuse dilation zones prior to the proper fault plane nucleation. Regarding D19 fault zone, most of diagenetic alterations occurred just after fault onset in the first stage of its activity. In both cases, the cementation altered initial reservoir properties in the fault zone vicinity, switching from type III to type I during the first stages of fault development. Later fault reactivation slightly impacts matrix porosity/permeability.
- Fault zones act as drains canalizing fluid flows in the beginning of their development. This induces fault zone cementation but preservation of host rock microporosity. This important fluid drainage is visible on D19 outcrop where the flowing fluids led to dissolution/cementation of fault rock matrix and formed karsts.
- All diagenetic stages, including cementation and dolomitization, result from low-temperature fluids with important meteoric water input. These low-temperature fluid

flows associated with the deformation and cementation types and, the lack of mineralisation specific to high-temperature fluids disprove any significant hydrothermal influence.

This regional study allows to draw broader rules for complex faults with polyphasic activity affecting granular carbonates at shallow burial conditions (Fig. 9).

- Under extensional context, fault nucleation can lead to the development of dilation bands acting as conduits for fluid flow. Carbonates are very sensitive to rock-fluids interactions. Thus, the onset of dilation bands triggers important diagenetic reactions that strongly alter local reservoir properties. During later fault zone development, the diagenesis depends on faults zones internal architecture.
- Fracture networks related to fault nucleation in granular carbonates form good fluid pathways before proper fault plane formation. However, in the case of pre-fractured carbonates, like D19 fault zone, fault rocks early appear in fault cores. In these cases, fluids flowed preferentially within the permeable breccia rather than the damage zone.

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