Review of manuscript **se-2019-153** submitted to Solid Earth, Aubert et al. "***Diagenetic evolution of fault zones in Urgonian microporous carbonates, impact on reservoir properties (Provence - SE France)***" by Mattia Pizzati.

General remarks

Dear Authors and Editor, below you can find the review of the submitted manuscript. Revisions are made by describing the issues found line by line and also on the text file of the manuscript, in which critical points were highlighted in green. Comments on figures and figure captions are presented at the end of this file as well.

The manuscript deals with the diagenetic and petrophysical evolution of two fault zones affecting Cretaceous carbonate rocks. The adopted methodology combines field (geological survey) and laboratory analyses (petrographic observation, cathodoluminescence, stable isotopes).

Although the scientific part of the manuscript is of great interest, the quality of the written English is often limiting the full comprehension of the geological topics the authors are discussing. I fully understand how difficult can it be to translate concepts and descriptions in a fluent manner, since I'm not a native English speaker as well, still there is a lot of work to be done before this manuscript can be considered suitable for final publishing. I'm sorry to be so blunt on this, but it was also a bit disappointing noting such a huge number of errors as this version should be the fourth one and it underwent several review processes. I recommend all the authors to carefully review word by word the entire text and read it several times. As you will notice, I tried to highlight every issue found in the pages below, so you will find a lot of corrections to be made. Do not be scared though, the vast majority of them are related to typo fixing, grammar corrections and sentence reworking.

Figures are overall of good quality, and I insert a few suggestions to improve their visibility and minor corrections to be done on legends. You will find the exact position of the suggested changes also in the pdf file as sticky notes next to the figures.

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. I firmly believe that you could address this inside the discussion section, to provide much stronger constraints to the model you are presenting.

I think this paper is worth to be accepted on the Solid Earth special issue after the completion of moderate to major revisions depending on how much text has to be revised or partially rewritten. I really hope this review will be helpful to the improvement of the final version of your manuscript. Do not hesitate to contact me in case any questions or doubts arise from these comments: mattia.pizzati@studenti.unipr.it

Detailed comments line by line

Line 10: Please make plural the term "*reservoir*" changing it to "*reservoirs*"; moreover, I would erase "*high a*" before "*permeability variability*".

Lines 12-13: Please add "*diagenetic*" before "*processes*"; modify "*that modify*" with "*capable of modifying*".

Line 13: Please change "*Focussing*" with "*Focusing*".

Line 14: Please move the word "*impact*" before "*the fault zone*". Rather than using "*reservoir properties*" maybe it is better to adopt a more general term such as "*reservoir quality*".

Line 14: I would change "*It*" with "*This contribution focuses*...". Throughout all the text try to use the same writing style. If you are describing a number of analyses or samples than use the form "*69 samples*", while if you are referring to the number of fault zones, fracture sets and so on, write as "*two fracture sets*" .The number "*2*" should have been written in words "*on two fault zones*".

Line 15: Please correct "*La Fare Anticlinal*" with "*La Fare Anticline*". In the same sentence change from "*which cross-cut*" to "*cross-cutting*".

Line 16: Please correct as follows from the form "*orthogonal to the fault zones*" to "*orthogonal to fault strike*". It this way the reader is aware that you worked on exposures that cross fault zones parallel to the direction of tectonic transport.

Line 17: Please change from "*Diagenetic elements were determined on 92 thin section...*" to "*Diagenetic history was determined through the observation of 92 thin sections...*".

Line 18: Why are these words "*Polarized Light Microscopy*" in capitals? Is that necessary?

Line 18: Maybe here it is better to state more precisely "*stable isotope measurements*" rather than "*isotopic measurements*".

Line 19: Here, I would modify "*2*" with "*two*".

Line 20: Please correct "*highlight*" with the third person form "*highlights*".

Line 20: Here, I would modify "*2*" with "*two*".

Line 20: Please modify and make "*drain*" plural "*drains*".

Line 21: Please add a line separator between "*low temperature*" as follows "*low-temperature*".

Line 21: Here I would erase "*fault zone*" before "*calcite cementation*".

Line 22: Here, I would modify "*2*" with "*two*".

Line 22: You are mentioning here "*two subsequent phases*". Do you refer to tectonic activity or to diagenetic ones? Please be more specific.

Line 22: Please add "*petrophysical*" before "*properties*".

Line 25: Please change "*porosities*" with "*porosity values*".

Line 26: Please change "*heterogeneous properties*" with "*heterogeneity*".

Line 26: Please correct "*depend*" with the third person form "*depends*".

Line 27: Please erase "*they*" and add "*carbonates may*" before "*determine*".

Line 29. Please correct the beginning of the sentence as indicated "*moreover, fault zones...*".

Lines 32-33: Here, I would modify the sentence as follows: "*Fault zones in cohesive rocks are complex structures, typically composed of two separate domains, namely the fault core and the damage zone. The vast majority of deformation is usually accommodated inside the fault core, while the damage zone is subjected to delocalization and partitioning of strain and is encompassed by the undeformed host rock*". You can keep the reference list and distribute the references according to the topic they deal with (damage zone or fault core).

Line 37: Instead of "*mixed zones*", maybe is better "*structures with mixed hydraulic behaviour*".

Line 37: Please correct "*depending of*" with "*depending on*".

Line 38: Please make singular "*fluid flows*" to "*fluid flow*".

Line 39: Please correct "*Earth crust*" with "*Earth's crust*".

Line 40: Here, maybe you can change the structure of the sentence as indicated: *", and are capable of increasing the...*".

Line 40: Please correct " *fluids-rock interaction* " with "*fluid-rock interaction*".

Line 41: You can add "*diagenetic*" before "*secondary processes*".

Line 42: Please add a line separator between "*Fault related*" as follows "*Fault-related".*

Line 45: Here maybe I would change "*duplication of fluid pathways/barriers*" with "*repeating fluid pathway-barrier behaviour in time leads to...*".

Line 48: Please erase "*of the*" before "*faulting*" and restructure the sentence as indicated: "*Hence, understanding faulting and diagenetic processes is crucial...*".

Line 51: Maybe here "*formations*" should be capitalized and also please erase the space after the word "*formations*".

Line 54: To what other carbonate reservoirs are you referring here, please be more specific and if necessary list them.

Line 56: Please add a hyphen between "*poly-phasic*", as you did above.

Line 60: Here, I would modify "*2*" with "*two*".

Line 60: Please correct "*crosscutting*" with "*cross-cutting*".

Line 60: Please erase "*facies*" before "*carbonates*".

Line 61: Please capitalized "*South-East Basin*".

Line 63: With "*larger extension*" are you referring to the areal extension of the carbonate platform? If so, you should correct as follows "*The Urgonian platform carbonates reached their maximum areal extension...*".

Line 64: Is necessary the hyphen between "*Fenerci-Masse*"?

Line 65: Please correct "*bauxite deposits*" with "*bauxite deposition*".

Line 67: Please modify these words as follows: "*, and development of E-W-trending extensional faults*".

Line 67: Is necessary the hyphen between "*Guyonnet-Benaize*"?

Lines 68-69: Here I would restructure the sentence as indicated: "*During Late Cretaceous times, in a shallow-water platform environment, a transgression led to widespread deposition of rudists (Philip, 1970)*".

Line 70: Please change the structure of this part of the sentence: "...*between Iberian and Eurasian plates caused a regional...*".

Line 70: Please modify from "*cited references*" to "*references therein*".

Line 71: Please modify from "*cited references*" to "*references therein*".

Line 72: Please erase "*which*" before "*gave rise*".

Line 72: Here you should add "*E-W-trending north-verging thrust faults*" otherwise the reader may not fully understand how faults are oriented.

Line 72: Please change "*ramp folds*" with "*thrust-related folds*".

Line 73: Please modify from "*cited references*" to "*references therein*".

Line 75: Please change "*dimly*" with "*weakly*".

Line 76: To what "*structures*" are you referring? I guess they are the contractional ones.

Line 79: Here, I would modify "*2*" with "*two*".

Line 79: Maybe it is better to write "*a Km-scale*" instead of "*kilometric-scale*".

Line 79: Please change from "*...fault system on the E-W-trending...*" to "...*fault system related to the E-W-trending...*".

Line 80: Can we state that the southern limb is actually the backlimb of the La Fare Anticline?

Line 80: Please correct "*anticlinal*" with "*anticline*".

Line 82: Please add a space between "*120m-thick*" to separate the length from the measurement unit "*120 m-thick*".

Line 82: Please change "*calcarenite unit*" with "*calcarenitic unit*".

Line 83: Please add a space between "*40m-thick*" to separate the length from the measurement unit "*40 m-thick*". Try to do the same and keep this style throughout all the text.

Line 83: Please change the structure as indicated: "...*coral-rich calcarenite unit, and an upper 10 m-thick....*". Separate the length from the measurement unit.

Lines 84-85: Here, I would modify as follows: "*Santonian age coarse grained rudist limestones unconformably overlay the Barremian carbonates (Fig. 1A)*".

Line 86: Here you state that the Castellas Fault has a length of one Km, but in Fig.1A the trace of the fault is at least three Km. Please correct accordingly with the real length.

Line 86: You should also define the kinematic of the fault: I would recommend to write as follows: "*left-lateral strike-slip fault*", before the info concerning the trend and dip.

Line 87: Here change the structure of the sentence as suggested: *"(Fig. 2A, B; table 1). Its structure comprises horses, secondary faults and tectonic lenses (Fig. 2A, C; Aubert et al. (2019b))*". Check if in Solid Earth is necessary to repeat the figure number when you are citing 2 sub-images from the same figure (es. Fig. 2A, 2C or Fig. 2A, C): try to do the same in the entire manuscript. There is a parenthesis missing at the end of the sentence where you cited Aubert et al. (2019b).

Line 88: You can modify from "*The second fault zone*" to "*The second investigated fault zone*".

Line 88: Here, I would modify "5" with "*five*".

Line 89: Maybe here change "*50m-long interval*" with "*50 m-wide outcrop*". Pay attention to separate the length from the measurement unit. "*Interval*" is a too generic term, while here I guess you are describing an outcrop with 50 m of lateral extension.

Line 90: Maybe "*Sub-fault are organised in two sets*" sounds better than "*Sub-faults are made of 2 sets*".

Line 90: Instead of "*Set one*" use "*The first one*".

Line 91: Please change "*orange on Fig. 2F*" to "*orange traces in Fig. 2F*".

Line 91: Add the kinematics of the fault set "*with left-lateral strike slip...*".

Line 92: Please change "*orange on Fig. 2F*" to "*red traces in Fig. 2F*".

Line 92: Here, I would modify "5" with "*five*".

Line 93: What is this asymmetry about? Is related to a different structure or width of the hanging wall and footwall damage zones? If so it think it should be mentioned here briefly.

Line 95: Please add "*distinct*" before "*tectonic events*".

Line 96-98: I tried to modify the two sentences as indicated: "...*the Middle-Cretaceous Durancian uplift leading to extensional en echelon faults. The Castellas fault nucleated during this first extensional event and bears early dip-slip normal striations (Matonti et al., 2012).*".

Line 100: I merged the first two sentences: "...(*see references cited in Espurt et al. 2012), which reactivated the...*".

Line 101: Please change "*leads*" to "*led*".

Line 101: Please modify "*neo-formed*" with "*newly-formed*".

Line 105: Please add "*present-day*" before "*reverse throw*".

Line 108: Here, I would modify "*4*" with "*four*".

Line 108: Throughout all the text I saw that sometimes you have used numbers to identify transects (1, 2, 3, 4), but I also found abbreviations such as T1. I suggest you to use only one style and to keep it for the entire text. In the following corrections I considered the transects to be identified by their number, so maybe I would erase "*(T1 to T4)*" from this line.

Line 109: Please change "*transect T1*" with "*transect 1*".

Line 109: Instead of "*bed*", which can be misunderstood maybe here you can use "*lithostratigraphic unit*".

Line 109: Please correct "*pelloidal*" with "*peloidal*", I think it should be the correct form.

Line 110: Please erase the space in "*Fig. 2D a*" to "*Fig. 2Da*".

Lines 110-111: You can restructure the sentence as suggested: "*Transects 2 and 3 cross-cut unit 3, made of fine-grained calcarenites with peloidal grains...*". Be careful to correct "*pelloidal*" to "*peloidal*".

Line 112: Make the plural form of "*echinoderm*" to "*echinoderms*".

Line 114: Make the plural form of "*amount*" to "*amounts*".

Line 114: Make the plural form of "*bryozoan*" to "*bryozoans*".

Line 115: Eliminate the comma in the reference to the figure: "*Fig. 2G, a*" change to "*Fig. 2Ga*".

Lines 117-119: I tried to restructure the sentence as follows: "*Three different fault rock types were identified in the fault core of the two investigated fault zones (see Aubert et al. 2019b; Matonti et al. 2012)*".

Line 119: Please change "*normal*" with "*extensional*".

Line 121: Add this detail at the end of the sentence: "*...<30% of fine-grained grey matrix*".

Line 122: Add "*strike-slip*" before "*reactivation*".

Line 122: Please add "*to*" before "*the onset*".

Line 123: Please correct the third person form "*present*" with "*presents*" and also change "*2*" with "*two*".

Line 125: Here maybe modify the sentence in this way: "...*sub-rounded clasts belonging to the nearby damage zone...*".

Line 126: What is the nature of the cemented matrix? Are you able to distinguish the composition and the type of cement? If so add these details at the end of this sentence.

Line 127: Here you are mentioning the reactivation of the D19 fault zone: be more specific and define the kinematics and the age in which it occurred.

Line 128: Make the plural form of "*clast*" to "*clasts*".

Line 128: Add this word at the end of the sentence: "*from the nearby damage zone dispersed in an...*".

Line 133: Here, I would modify "*4*" with "*four*".

Line 134: Please correct the sentence as indicated: "*Microfacies were determined...*". Petrography is just too generic.

Line 136: Please, modify this detail: "*with a solution of hydrochloric acid, Alizarin Red S and potassium ferricyanide...*".

Line 137: Please erase "*The*" at the beginning of the sentence and capitalize "*Thin...*".

Line 137: Please modify "*analyzed*" with "*analysed*". Pay attention to the use of UK or USA English. Solid Earth is an European journal so it think you should always refer to the UK English.

Line 138: Please add these words: "*...the different generation of calcite cements*".

Line 140: Is this underscore necessary to identify the instrument?

Line 141: Is this underscore necessary to identify the instrument?

Line 141: Here, I would modify "*2*" with "*two*".

Line 142: Here, I would modify "*2*" with "*two*".

Line 143: Please add "*beam*" before "*current*".

Line 143: Keep always a space between the value and the measurement unit; do this in all the text. "*20 KV*" and not "*20KV*".

Line 143: Please make the plural form of "*surface*" "*surfaces*".

Line 146: Keep always a space between the value and the measurement unit: "*80 μm*," and not "*80μm* ".

Line 147: 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.

Line 148: Please add "*isotopic*" before "*values*".

Line 149: Is correct the name of the spectrometer with the symbol "+" rather than the word "*plus*"? Please check again.

Line 151: The symbol you used for the delta is not the same adopted previously in Line 144. Choose only one and keep it in the entire text. I would keep this form "*$\delta^{13}C$, $\delta^{18}O$"*.

Lines 151-152: I modified the sentence as follows, check if suits you: "*The standard deviation (SD) of the measurements is <0.1‰ and <0.2‰ for $\delta^{13}C$ and $\delta^{18}O$, respectively*".

Lines 159-160: I tried to fix in this way: "*Porosity measured on 92 plug samples show a strong decrease towards the fault core (Fig. 3): it drops from more than 10% in the undeformed host carbonates...*".

Line 161: Please change "*in*" with "*within*".

Line 163: Please add these words at the beginning of the sentence: "*Along transects, some porosity variations...*".

Line 164: Insert a space between the value and the measurement unit: "*60 m*" and not "*60m*".

Line 164: Please change "*transect T2*" to "*transect 2*".

Line 165: Please change "*low < 7%*" to "*lower than 7%*".

Line 165: Delete the space after 1.53.

Line 165: Substitute the comma at the end with a full stop.

Line 166: Here I would write "*is wider than 40 m*" rather than "*is >40m*".

Line 166: Insert a space between the value and the measurement unit: "*30 m*" and not "*30m*".

Line 167: Here please change "*In a 10m-thick*" with "*In a 10 m-wide*".

Line 168: If you want to keep the nomenclature used above than change "*T1 and T3*" with the form "*transect 1 and 3*".

Line 169: Please add "*found*" between "*are in narrow*".

Lines 169-170: I tried to write as follows this part of the sentence: "...*in narrow zones (less than 2 m-wide) around the faults...*".

Line 170: With the term "*lens*" are you describing the rock volume comprised between F4 and F5?

Lines 172-173: Please modify the beginning of the sentence as indicated: "*Microscope observations of thin sections impregnated with blue-epoxy resin allowed to identify a porous rock-type with $\phi>10\%$, mainly composed of micritised grains...".*

Line 173: Please remove the space in "*Fig. 3C a*" to "*Fig. 3Ca*".

Line 174: Add a comma after "*$\phi<5\%$"*.

Line 174: Please remove the space in "*Fig. 3C b, c*" to "*Fig. 3Cb, c*".

Line 174: It is not clear to me what do you mean with "*barren stylolites*". Is this word related to the incipient nature of stylolites? Please correct also the spelling of the word "*styloliths*" with "*stylolites*".

Line 174: Erase "*are distinguished*" at the end of the sentence.

Line 177: Please correct "*micritized*" with "*micritised*", if you want to keep the UK version of the word.

Line 177: Here, I would modify "*2*" with "*two*".

Line 178: Here, I would modify "*2*" with "*two*".

Line 179: Why is this citation reported in italics?

Line 180: The reference to "*Fig. 4A, 4B*" should be "*Fig.4A, B*".

Line 181: Here I'm really struggling with the terminology you used "*puntic and serrate*" are terms not widely used in literature.

Line 182: Please put the porosity value between parenthesis and erase the space before the comma.

Line 183: Please insert the porosity percentage in parenthesis.

Lines 177-183: Inside this paragraph you should also give some info concerning the crystal size of the micrite.

Line 185: Please add "*different*" between "*Eight cement*".

Line 185: "*Alizarin Red S*" should be with all first letters in capitals.

Line 185: Add "*and*" after "*coloration*".

Line 186: Please correct "*made up of*" with "*made of*".

Line 186: Please correct from the third person form to plural "*exhibits*" to "*exhibit*".

Line 188: Here, I would modify "*2*" with "*two*".

Line 189: With "*thickness*" here are you describing the maximum thickness of the isopachous calcite fringe? Is that possible to assimilate this data to the crystal size?

Line 189: Here, I think it would be more correct to use this symbol "~" to indicate the word "*about*"; also insert a space between "*10*" and "*µm*".

Line 190: Here, I would modify "*2*" with "*two*".

Line 190: Add an hyphen between "*dog-tooth*".

Line 192: Again, here is that possible to describe the crystal size rather than the "*thickness*" of the cement?

Line 192: Here, I think it would be more correct to use this symbol "~" to indicate the word "*about*"; also insert a space between "*100*" and "*µm*".

Line 192: Be more specific concerning the reference to the figure: I believe here you are referring to Fig. 5A, is that right?

Line 193: Better than "*C1b values*" maybe you should use "*C1b areal occurrence*".

Line 193: Please correct the third person form "*increases*" instead of "*increase*".

Line 201: Please change the sequence of words from "*replacive phases occur largely...*" to "*replacive phases extensively occur...*".

Line 203: Use the hyphen between "*dull orange*" "*dull-orange*".

Line 203: Please change the structure as indicated from "*...only found in fault core veins*" to "*...only found in veins of the fault core*".

Line 204: Please erase "*elements*" after "*Si and Al*".

Line 205: Please erase "*an*" and add at the end of the sentence "*and have black luminescence.*"

Lines 203-205: Please add also some info relative to the size of the cement crystals you are describing in this section.

Line 206: Use the hyphen between "*red dull*" "*red-dull*".

Line 208: Add "*only*" before "*to the fault zone*".

Lines 206-208: Please add also some info relative to the size of the cement crystals you are describing in this section.

Line 211: Please insert a space between "*500*" and "*μm*".

Line 211: Please insert "*previous*" before "*dolomitization phase*".

Lines 212-213: Please change here from "*micritic inclusion in the crystal and...*" to "*micritic inclusions inside crystals and...*".

Line 215: Please insert a space between "3*00*" and "*μm*".

Line 217: Please correct the reference to "*Fig. 5G, 5H*" with "*Fig. 5G, H*".

Line 219: Here, I would modify "*2*" with "*two*".

Line 219: Please erase "*which*" after "*C4a*".

Line 220: Please correct the plural form of "*band*" with "*bands*".

Line 220: Please add "*thin*" before "*non-luminescent zones*". Change also "*bands*" with "*zones*" to avoid any repetition.

Line 221: Correct the nomenclature of transects, here maybe use "*transects 1 and 3*" as you did in the text above.

Line 223: Use the hyphen between "*red dull*" "*red-dull*".

Line 227: Please change "*formation*" with "*karst deposit*".

Lines 228-229: See if this correction suits you: "*This karst deposit present a stack of alternating micrite-rich and grain-rich layers, the latter composed of former blocky calcite cement belonging to dissolved grainstones*".

Line 230: Please correct "*clasts fall*" with "*grain fall*". Keep in mind that the term clast is used for fault rock material, while grain is more generic and does not mean that any deformation occurred. Following this, use clasts to describe a fault breccia and grains if you are dealing with undeformed sediments or rocks.

Line 230: Please correct the singular "*has*" to plural form "*have*".

Lines 230-231: I tried to improve the clarity of the sentence: "*Micritic layers have been observed under SEM, and the micrite composing them appears tight with subhedral mosaic crystals (Fig. 4F)*".

Line 233: Please change "*proportion*" with "*areal amount*" and also modify the third person form of "*increase*" to "*increases*".

Lines 236-238: I fell this is a repetition of what was previously presented inside the method section, maybe it is better to do not duplicate this inside the results.

Line 239: Again, what is the meaning of "*bulk rock*"? If you are referring to the undeformed host carbonates than you should be more precise and state clearly. Do this in all the manuscript. I highlighted this issue every time I noticed it.

Line 239: "*Intergranular volume*" is better than "*intergranular space*".

Lines 241-242: If it is more correct change the reference to the figure from "*Fig. 6A, 6B*" to "*Fig. 6A, B*".

Line 242: Again, "*bulk rock*" isn't this the "*host rock*"?

Line 243: Here, I would modify "*2*" with "*two*".

Line 243: For "*Set one*" you can use the number "*Set 1*". I believe to identify the type of fracture sets, isotopic datasets and so on you can adopt the number instead of the spelled word.

Line 244: I don't think that using the symbol "*&*" is suitable here, just write "*and*".

Line 245: As above, "*Bulk values*" is too generic. If you are describing the isotopic dataset of the undeformed carbonates adopt "*Host rock isotopic values*".

Line 247: Please erase "*the*" before "*transect 3*".

Line 247: Please erase "*along transect*" after "*slightly vary*".

Line 248: At the end of this sentence after "*$\delta^{13}C$* " add "*, respectively*".

Line 248: Change "*Contrarily*" with "*On the contrary, ...*".

Lines 248-251: I tried to fix these sentences as follows: "*On the contrary, values are more variable along the D19 transect; they range from -9.18‰ to -5.20‰ for $\delta^{18}O$ and from -4.80‰ to -0.60‰ for $\delta^{13}C$ (Fig. 6C, table 2). The $\delta^{13}C$ values decrease approaching to faults, especially south of F2.*". Please check carefully this statement, because in Fig. 6C the isotopic data for D19 do not show values of $\delta^{18}O$ lower than -8.00‰ and $\delta^{13}C$ values lower than -3.50‰. So check back the values reported in the graph and correct the text accordingly.

Line 252: Please change "*spaces*" with "*volume*".

Line 252: Maybe "*infillings*" is better than "*fills*".

Line 252: Please make the plural form "*fault rocks*".

Line 253: Here, I would modify "*5*" with "*five*".

Line 254: Personally I modified the sentence as follows and fell like it is clearer: "*isotopic values of C1 cement ...*".

Line 256: Similar to the comment above: "*isotopic values of C3 cement...*".

Line 258: Again: "*isotopic values of C4 cement...*".

Line 258: Maybe "*infillings*" is better than "*fill*".

Line 259: Please add a space between "*from-5.10‰*" to have "*from -5.10‰*".

Line 260: Please erase the space between "*FR 2*" to "*FR2*".

Line 260: Please add a space between "*from-6.55‰*" to have "*from -6.55‰*".

Line 261: Maybe "*infillings*" is better than "*fill*".

Line 262: Please restructure the last part of the sentence as follows: *"...for $\delta^{18}O$ and $\delta^{13}C$, respectively*".

Line 263: Here, I would modify "*4*" with "*four*".

Line 263: Here, I would modify "*2*" with "*two*".

Line 264: Please add a semicolon "*;*" at the end of the sentence.

Lines 265-266: Please start the sentence as follows: "*isotopic values of C5 cement, sampled in FR1 matrix display mean...*". Add also a semicolon "*;*" at the end of the sentence.

Lines 267-268: Please start the sentence as follows: "*isotopic values of FR3 matrix have a mean...*". Add also a semicolon "*;*" at the end of the sentence.

Line 275: Please change "*thanks to*" with "*via*".

Line 275: Please pluralise "*cross-cutting relation*" to "*cross-cutting relations*".

Line 276: I modified the order and position of some words here: "*Indeed, the veins filled with C2 cement cross-cut C1a and C1b cements (Fig. 5B)*".

Line 277: I would change this sentence as follows: "*Thus, C2 cementation postdated C1 cement*".

Line 277: Please erase "*The*" at the beginning of the sentence.

Line 278: Here there is a missing reference to the correct figure. I guess it should be "*Fig. 5B*".

Line 278: Please change "*is ante-FR1...*" with "*formed prior to FR1...*".

Line 279: Please change "*post-C2*" with "*after C2*".

Line 279: I would use "*extensional*" rather than "*normal*".

Line 281: Please remove the comma after "*formation and, are related...*".

Lines 281-282: Please modify the sentence as indicated: "*Replacive dolomite is found within FR1...*".

Line 282: Here I guess that this is the wrong reference to the figure. I believe it should be "*Fig. 5E*" and not "*Fig. 3E*".

Line 282: Please make the past simple version of "*develop*" "*developed*".

Line 282: Please, move "*C4*" before "*cement*".

Line 283: Please change "*postponed*" with "*postdated*".

Line 284: Please modify the order of the words: "*...developed during the strike-slip reactivation of the studied faults*".

Line 287: Please correct "*La Fare anticlinal*" with "*La Fare anticline*".

Line 287: Here, I would modify "*3*" with "*three*". Also substitute "*important*" with "*major*".

Line 291: I don't know if this is the right term, but perhaps "*micro-boring organisms*" sounds better than "*micro-bores*".

Line 294: Please add a hyphen between "*low and energy*" "*low-energy*".

Line 294: Please add "*environment*" at the end of the sentence after "*inner platform*".

Line 295: Move "*C0*" before "*cement*".

Lines 295-296: I tried to fix this sentence: "*...formed around grains giving rise to a solid envelop, inducing the preservation of the original grain shape during the late-stage burial compaction (Step 0 in Fig. 8)*".

Line 299: Here, I would modify "*2*" with "*two*".

Line 299: Please substitute "*points*" with "*pairs*", and "*sampled of*" with "*pertaining to*".

Line 300: Please add "*isotopic*" before "*depletion*".

Line 304: Please modify "*characteristic for*" with "*characteristic of*".

Line 307: Please change "*meteoric flow*" with "*meteoric fluid circulation*".

Line 308: Please add "*to the*" before "*development*".

Line 315: Please add a hyphens as indicated: "*low-to-moderate matrix....*".

Lines 316-318: I did some changes to this sentence: "*Even if Barremian limestones of La Fare anticline show porosity > 10%, it is mainly intra-granular, thus limiting flow pathways*".

Line 318: Please change "*Resulting from this event,...*" with "*Due to this characteristic,...*".

Line 320: Please add a hyphen between "*Fault and related*" "*Fault-related*".

Line 324: Better that "*impacting*" maybe you should try with "*affecting*".

Line 327: Please erase "*, and*" just after the references in parenthesis and also add a hyphen between "*low confining pressure*" "*low-confining pressure*".

Line 327: Add a space between "*<100KPa*" to have "*<100 KPa*".

Line 327: Modify the reference to "*Alikarami & Torabi 2015*" as "*Alikarami and Torabi, 2015*".

Lines 329-330: Here I fixed in this way: "*...of deformation band development (Heiland et al., 2001; Lothe et al., 2002), enhancing fluid flow.*".

Line 331: "poorly" sounds better than "*dimly*".

Lines 331-332: Add a hyphen between "*low confining pressure*" "*low-confining pressure*".

Line 332: Please change the term "*pattern*" with "*regime*".

Line 332: Add a space between "*<1Km*" to have "*<1 Km*".

Lines 333-334: I reworked this sentence as indicated: "*Under these conditions, Barremian host rocks were likely characterised by mechanical and petrophysical properties close to porous granular media described above.*".

Line 334: Please correct "*showned*" with "*showed*".

Line 335: Please add "*of deformation*" after "*early stages*".

Line 336: Please add "*in carbonates*" after "*deformation bands*".

Line 336: Please change "*sector*" with "*area*".

Line 337: Please correct to the singular form "*circulation*" instead of "*circulations*".

Lines 337-338: Please erase "*These*" at the beginning of the sentence and make the singular of "*fluid flows*" "*fluid flow*".

Lines 338-339: I would change the sentence as follows: "*however, dilation bands were likely unstable and grain collapse occurred...*".

Line 340: Please modify to the singular form "*loading stress*" instead of "*loading stresses*".

Line 342: Here maybe start the sentence as indicated. "*This could be the explanation...*".

Line 343: Add a space between "*<30m*" to have "*<30 m*".

Line 345: Add a space between "*<188m*" to have "*<188 m*".

Line 345: Here adjust the reference to "*Fig. III 6A*" with "*Fig. 6A*".

Line 345: Modify the beginning of the sentence as suggested: "*Dilation bands have also been...*".

Line 346: Please correct "*Sicilly*" with "*Sicily*".

Line 347: Please add "*selective*" before "*cementation*". Also pluralise "*rock*" to "*rocks*".

Lines 348-349: I tried to change the structure of this sentence: "*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)*".

Line 349: Add a hyphen between "*low porosity*" "*low-porosity*".

Line 350: Please change the last part of the sentence as suggested: "*...is known to increase fault permeability*".

Line 351: Please erase "*an*" before "*Al-rich*".

Line 352: Please pluralise "*fluid*" to "*fluids*".

Line 352: You may explain this with "*fine-grained*" instead of "*micro-metric*".

Line 352: Again the term "*barren*" is very unfamiliar to me. Are you referring to an incipient open fracture? If so you can state "*early-stage fractures*" or "*incipient open fracture*".

Line 352: If you feel this is an option try to put this last part of the sentence as indicated: "*...fractures, leading to precipitation of C2 cement*".

Line 358: Use "*may*" and not "*must*" you are not 100% sure that this happened, you are doing discussions constrained with the petrographic observations.

Line 361: A few adjustments to this sentence: "*As the fault grew, new fracture sets formed, leading to a new phase of calcite...*".

Lines 364-365: Please correct "*at high depth*" with "*in deep burial conditions*". in parenthesis correct from "*depth of maximum 500m; Fig. 9C4*" to "*maximum depth of 500 m; Fig. 9C4*". Be careful to the space between "*500 and m*".

Lines 365-366: A bit of reworking on this sentence: "*...corroborate the hypothesis of cementation acted by meteoric fluids rather than marine ones*".

Line 367: Please change the beginning of the sentence from "*Resulting from*" to "*Due to*".

Line 368: Before "*down to <5%*" insert "*with porosity*".

Line 368: Cancel the space in "*Fig. 9 B5*" to "*Fig. 9B5*". Also in Fig. 9 what is stage 5 since it not reported anywhere? Are you referring to the time interval existing between stages 4 and 6?

Line 371: Please change "*Implicitly*", with "*Following this*".

Line 371: Please add "*in this stage*" before "*was a barrier*".

Line 372: I would change the beginning of the sentence: "*Fluids responsible for precipitation of C3 cement...*".

Line 375: Please insert a space between "*100*" and "*µm*".

Line 376: I modified the sentence as indicated: *"...came from silica found inside C2 cement described above...*".

Line 377: Please modify the beginning of the sentence: "*Silica crystals in C2 veins...*".

Line 377: Please insert a space between "*100*" and "*µm*".

Line 378: Please add "*grains*" before "*quartz*".

Line 379: Please add "*also*" before "*Aptian rocks*".

Line 380: Please substitute "*Implicitly*" with "*According to this,*".

Line 381: Add a hyphen between "*Uncemented*" "*Un-cemented*".

Line 381: Please change to the pas simple form "*formed*" instead of "*form*".

Line 383: Please add "*lateral extent of the...*" before "*drainage area*".

Line 384: Add a hyphen between "*high permeable*" "*high-permeable*".

Lines 385-386: I would change as follows: "*...formations within fault core of strike-slip and extensional faults (Billi et al., 2003, 2008; Storti et al., 2003)*".

Line 390: Please make the past simple form of "*lead*" to "*led*".

Line 392: Please substitute "*can be*" with "*could have been*".

Line 395: Please add a reference at the end of this sentence, relative to the difference in grain surface area from the clasts to matrix.

Line 398: I would change a bit the end of the sentence as indicated: "*...not favourable for extensive dolomitization outside fault zones*".

Line 399: Add a hyphen between "*Low temperature*" "*Low-temperature*".

Line 400: Add a hyphen between "*high temperature*" "*high-temperature*".

Line 402: Here you can change from "*high Mg fluid circulation*" to "*Mg-rich fluid circulation*".

Line 403: Please add "*domain*" after "*fault core*" at the end of the sentence.

Line 405: Please insert a space between "*23*" and "*Km*".

Lines 405-406: Please change from "*compressive conditions*" to "*contractional stress regime*".

Line 406: At the beginning of the sentence please change from "*From these authors...*" to "*according to these authors...*".

Line 407: Add a hyphen between "*low temperature*" "*low-temperature*".

Line 407: After "*upwelling fluids*" add "*, likely Mg-enriched*".

Line 409: Add a hyphen between "*low temperature*" "*low-temperature*".

Line 410: Please correct "*were*" with "*was*".

Line 412: Please correct "*reduce*" with "*reduces*".

Line 415: Please change "*to*" with "*into*". Also check the reference to "*Fig. 9 B6 and C6*" there is a space you should erase "*Fig. 9B6 and C6*".

Line 417: Please substitute "*finally*" with "*eventually*".

Line 419: Please erase the hyphen between "*back-ground*" to "*background*".

Line 420: Please change from "*lead to FR2...*" to "*formed FR2...*".

Line 422: Please erase the hyphen between "*back-ground*" to "*background*".

Lines 423-424: I would modify the structure of the sentence as indicated: "*This fluid flow is witnessed by the cementation...*".

Line 424: Please correct "*micritized*" with "*micritised*".

Line 425: Please change "*what led*" with "*leading to*".

Line 425: Erase the comma and space in the reference to figure "*Fig. 9, B7 and C7*" to "*Fig. 9B7 and C7*".

Line 426: Please change "*the*" before "*fracture porosity*" with "*that.*"

Line 426: At the end of the sentence modify as follows: "*...permeability was still partially preserved*".

Line 427: Use italics for the term "*sensu*".

Line 428: I would modify this as indicated: "*...and high fracture-related secondary permeability*".

Line 429: Maybe here is better to use "i*nfillings*" rather than "*fill*".

Line 429: After "*dissolution/cementation*" add the term "*processes*".

Line 431: Please add "*cement*" after "*C4*".

Line 432: Maybe here is better to use "i*nfillings*" rather than "*fill*".

Line 433: I did a few changes to this part of the sentence: "*...fluid circulation in the vadose zone, with alternating*".

Line 435: Maybe the last part of this sentence would sound better as: "*... of meteoric and marine origin with different burial depth*". At the end add also a reference to Fig. 6 where you reported the isotopic data.

Lines 436-437: Please change "*these*" with "*this*" and also make the singular form of "*circulations*" to "*circulation*".

Line 437: Please add "*cement*" after "*C4*".

Line 437: Please change "*on*" with "*in*" in reference to Fig. 8.

Line 438: "*Higher*" is not the most precise term to describe isotopic data. if you are talking about values more negative you should use the term "*depleted*", while less negative or positive values are usually addressed with the word "*enriched*". Try to do the same in all the text.

Line 439: Please add "*cement*" after "*C1*".

Line 440: Please add "*cement*" after "*C4*".

Line 440: Move "*C4*" before "*cement*", and change from the plural to the singular form "*cements*" to "*cement*".

Line 441: Please change "*are*" with "*is*".

Lines 441-442: I tried to fix this sentence in this way: "*Transect 2 cross-cuts the Castellas fault along a relay zone (Fig. 2A)*".

Line 442: Here, I would modify "*2*" with "*two*".

Line 446: Please erase the term "*local*" before "*permeability*" and also change "*allowed*" to "*favoured*".

Line 447: Please make the singular of "*circulations*" to "*circulation*".

Line 448: Move "*C4*" before "*cement*.

Line 449: Please change "*Contrarily*" with "*On the contrary,*".

Line 450: Please erase the word "*a*" before "*drains*".

Line 451: Please change "*That*" with "*This*".

Line 452: Please correct "*formation*" with "*development*".

Line 453: Please change "*normal*" with "*extensional*".

Line 453: I modified the last part of the sentence as follows: "*...C4 fluids to flow through the fault zone*".

Line 455: Please change "*T2*" with "*transect 2*".

Line 455: Please insert a space between "*60*" and "*m*".

Line 456: Use "*transect 1 and transect 3*" instead of "*T1 and T3*", add a space between "*30 and 40*" and "*m*", change also the symbol for "about" using this one "~".

Line 461: 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.

Line 462: Please correct "*de-dolomitization*" with "*de-dolomitized*".

Line 466: Please correct "*recrystallized*" with "*recrystallised*".

Line 469: I would put also "*alpine*" in capitals as you did for "*Pyrenean*".

Line 471: I tried to fix this part as indicated: "*This implies fluids percolating soils, as results from...*".

Line 475: Please correct "*Finally*" with "*Eventually*".

Line 475: Please change from "*incurring*" to "*inducing*".

Line 476: Please change from "*triggered*" to "*produced*".

Line 477: Please change from "*flows*" to "*fluids*".

Lines 481-482: I tried to adjust this part as: "*...reservoir where fractures behave as pathways towards fluid flow, but the production comes mainly from the matrix...*".

Line 483: Please change "*polyphase*" with "*polyphasic*".

Lines 490-491: See if these changes suit you: "*...Castellas fault zone, permeability evolves from a stage with exclusive contribution from the host rock...*".

Line 493: Here, I would modify "*2*" with "*two*".

Line 493: Please change "*fracture*" with "*fracturing*".

Line 493: Please change "*link*" with "*linked*".

Line 494: If you feel it could be an option you can use the extended form "*fault core*" instead of "*FC*".

Lines 495-496: I adjusted the second part of the sentence: "*permeability contribution is solely provided by the fault core...*".

Line 497: Again here if you can use the extended version of the name "*fault core*".

Line 498: Please correct "*at 20%*" with "*for 20%*".

Lines 488-499: 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.

Line 501: Here, I would modify "*2*" with "*two*".

Line 501: Erase "*the*" before "*reservoir*".

Line 502: Please pluralise "*fault*" to "*faults*".

Line 503: I think you should capitalise "*SE basin"* as "*SE Basin*".

Line 508: Please correct "*their*" with "*its*".

Line 511: Please change "*thinly*" with "*slightly*".

Line 512: Please substitute "*formation*" with "*development*".

Line 514: Please change "*the flows*" with "*flowing fluids*".

Lines 516-517: Add a hyphen between "*low temperature*" "*low-temperature*".

Line 517: Please correct "*flows*" with "*fluids*".

Line 517: Please correct "*This*" with "*These*".

Line 517: Add a hyphen between "*low temperature*" "*low-temperature*".

Line 517: Please add "*fluid*" before "*flows*".

Line 519: Add a hyphen between "*high temperature*" "*high-temperature*".

Line 519: Please change "*flows*" with "*fluids*".

Line 519: Please add "*significant*" before "*hydrothermal influence*".

Line 520: I tried to improve the last part as: "*...broader rules for complex faults with polyphasic activity affecting granular carbonates at shallow burial conditions (Fig. 9)*".

Line 522: Please correct "*extensive*" with "*extensional*".

Line 522: See if this is better: "*...can lead to the development of dilation bands acting...*".

Line 523: I tried to improve the clarity: "*Carbonates are very sensitive to rock-fluid interactions*".

Lines 529-531: Again a bit of reworking: "*Late-stage fluids flowed preferentially within the permeable breccia rather than in the highly fractured damage zone*".

Line 566: Check and erase the highlighted space.

Line 568: There are too much spaces that must be corrected.

Line 569: Check and erase the highlighted space.

Line 570: Check and erase the highlighted space.

Line 571: Erase the highlighted full stops.

Line 573: Erase the highlighted full stop.

Line 580: Erase the highlighted full stop.

Line 586: Check and erase the highlighted space.

Line 590: Check and erase the highlighted space.

Line 607: Please erase the comma.

Line 610: Check and erase the highlighted space.

Line 611: The name of the institution is not complete.

Line 621: Check and erase the highlighted space.

Line 621: Please erase the comma.

Line 639: Please erase the comma.

Line 641: Erase the highlighted part since it is a repetition and should not be in front of the reference title.

Line 656: Please capitalise "*jurassic*" to "*Jurassic*".

Line 664: Erase the highlighted full stop.

Lines 669-670: Check and erase the highlighted spaces.

Line 679: Check and erase the highlighted space.

Line 705: Check and erase the highlighted spaces.

Line 714: Check and erase the highlighted spaces and comma.

Line 721: Check the spelling of the journal title.

Line 728: Check and erase the highlighted full stops.

Lines 741-742: Please eliminate the duplicated title.

Lines 754-755: Check and erase the highlighted full stops.

Lines 772-773: Check and erase the highlighted spaces.

Lines 774-775: Check and erase the highlighted space and full stop.

Line 791: Check and erase the highlighted space.

Line 803: Check and erase the highlighted space.

Line 809: Check and erase the highlighted space.

Line 814: Check and erase the highlighted space and comma.

Lines 816-817: Check and erase the highlighted space and comma.

Line 819: Check and erase the highlighted comma.

Line 821: Check and erase the highlighted space.

Comments on figures and figure captions

Comments concerning figures have been reported also in the pdf file with the exact position as sticky notes.

Fig. 1

You should insert the symbol of the La Fare anticline in Fig. 1A.

The kinematic indicators alongside faults are missing in Fig. 1B.

These names in the legend of Fig. 1A should be all in capitals "Upper Cretaceous, Lower Cretaceous."

Maybe better than "thin calcarenite" you can use "fine-grained", if you are referring to the grain size.

Fig. 1 caption

You should erase the space between "*Figure 1 :*" to "*Figure 1:*".

Please add "*trace of*" before "*stratigraphic column*".

Please correct the reference to "C" part of the figure rather than "*B*".

Fig. 2

The kinematic indicators in both stereo-nets are indistinguishable from the fault traces.

I would mirror the transect 3 to have SSE on the left and NNW on the right side, just like the other images.

What are the red stars? Are they the positions of samples? If so you should mention them in the caption.

Fig. 2 caption

You should erase the space between "*Figure 2 :*" to "*Figure 2:*".

Please change the term "*localization*" with "*position*".

What are the "*red points*" you are referring in the stereo-nets? I can't seen anything but red fault traces there, where are the points you are describing?

In the third line please add "C: *Photos of transect 1 and 2.*"

In the third line please add "*D: Photomicrographs of carbonate host-rock facies...*".

In the fourth line add "*FR1 and FR2*" after "*fault rock 1 and 2*".

In the fifth line please add "G*: Photomicrographs of host-rock facies...*".

Fig. 3

Try to improve the visibility of the three petrographic images in Fig. 3C, change the brightness-contrast.

Fig. 3 caption

In the first line correct "*&*" with "*and*".

In the third line correct "*b&c*" with "*b and c*".

Fig. 4 caption

You should erase the space between "*Figure 4 :*" to "*Figure 4:*".

In the first line please pluralise "*white arrow*" to "*white arrows*".

In the first line add a space between "*MF1micrite*" to "*MF1 micrite*".

In the second line add a space between "*2.5m*" to "*2.5 m*".

In the second line add a space between "*MF1micrite*" to "*MF1 micrite*".

In the second line add a space between "*2m*" to "*2 m*".

In the second line please erase the "*C*" which is duplicated.

In the third line add a space between "188*m*" to "*188 m*".

In the third line add a space between "*95m*" to "*95 m*".

In the fourth line please change "*F.*" to "*F:*".

Fig. 5 caption

You should erase the space between "*Figure 5 :*" to "*Figure 5:*".

In the first line please change "*micritized*" with "*micritised*".

In the second line please change "*space*" with "*volume*".

In the second line please substitute "*a&b*" with "*a and b*".

In the second line please pluralize "*clast*" to "*clasts*".

In the second line please change "*micritized*" with "*micritised*".

In the third line I modified as follows: "*C: C3 veins, cements and intergranular volume in...*".

In the third line please substitute "*a&b*" with "*a and b*".

in the fourth line after "*replacive dolomite*" add "*(RD)*".

In the fifth line please correct "*quart*" with "*quartz*".

In the fifth line please substitute "*a&b*" with "*a and b*"; do it twice.

Fig. 6

To me it would be more logical to invert Fig. 6A and 6B, to show the reader first all bulk data from fault zones and then the details of each cement phase, veins...

In both graphs insert the X axis labels for every increment of 2 per mil (2, 4, 6...).

In the legend of Fig. 6A it is written "*Bulk rock*", I wonder if this is actually the undeformed host rock, if so please correct accordingly.

In Fig. 6C the title of the graph states "*Distance to Castellas Fault plane*", maybe "*Fault plane*" should be in lower case.

Fig. 6 caption

You should erase the space between "*Figure 6 :*" to "*Figure 6:*".

In the first line please correct the symbols you used for the delta notation, it should be "$\delta^{13}C$, $\delta^{18}O$".

In the first line you state again "*bulk rock*" why not "*host rock*"?

In the third line please correct the symbols you used for the delta notation, it should be "$\delta^{13}C$, $\delta^{18}O$".

Fig. 7

The three photomicrographs are too small to appreciate the details. You have plenty of space, just make them bigger.

Fig. 7 caption

In the second line I slightly modified as follows: "*... development (blue), cementation (orange) and fault zone activation events (red)*".

Fig. 8

Again, photomicrographs are quite small, but still the reader should be able to see everything. This is a very nicely done image!

In the legend please correct "*Micro-facies & cement types*" with "*Micro-facies and cement types*".

Fig. 8 caption

You should erase the space between "*Figure 8 :*" to "*Figure 8:*".

Fig. 9

It would be nice to have bigger sketches in Fig. 9A.
Also why stage 5 is not reported? In the text it is mentioned. You should consider to implement this in the figure as well.

Fig. 9 caption

You should erase the space between "*Figure 9 :*" to "*Figure 9:*".

In the second line I would modify "*2*" with "*two*".

In the second line please correct "*curved*" with "*curve*".

Fig. 10

Also here size matters! Please make these sketches bigger otherwise you will lose al lot of details.

Fig. 10 caption

You should erase the space between "*Figure 10 :*" to "*Figure 10:*".

In the third line please add spaces between "*1to 8correspond*" to "*1 to 8 correspond*".

At the end of the caption you should add also explanations of the symbols used: FZ, DZ, MF1, MF2, MF3, K...

Table 1

In the caption add a full stop at the end as highlighted.

In the table header increase the width to include entirely the words "*Fault zones*", check also the spelling because "*Fault*" is misspelled as "*Faut*".

Check also the French name "*Faille*" and correct it accordingly.

Capitalize "*pitch striation*" to "*Pitch striation*".

Add a space between the cardinal point and angular value every time has been highlighted. Do the same with length and measurement unit.

"*Non constant*" is not precise, I would use "*variable*".

Table 2

Please eliminate "*vs*" from the table header.

Check also the nomenclature of the transects to be the same to the symbols adopted in the text.

In the caption it is not clear what do you mean for "*bulk carbonates*", "*bulk measurements*".

Pay attention also to put the reference always to the singular form (es. micrite value, isotopic value and so on). I highlighted every time where changes are needed.

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]**

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Microporous carbonate rocks form important reservoir with high a permeability variability depending on sedimentary, structural and diagenetic factors. Carbonates are very sensitive to fluid-rock interactions that lead to secondary processes like cementation and dissolution that modify the reservoir properties. Focussing on fault-related diagenesis, the aim of this study is to identify the fault zone impact on reservoir properties. It focuses on 2 fault zones east to La Fare Anticlinal (SE France) which cross-cut Urgonian microporous carbonates. 122 collected samples along four transects orthogonal to the fault zones were analysed. Porosity values have been measured on 92 dry plugs. Diagenetic elements were determined on 92 thin sections using Polarized Light Microscopy, cathodoluminescence, red alizarin, SEM and isotopic measurements ($\delta^{13}C$ and $\delta^{18}O$). Eight different calcite cementation stages and 2 micrite micro-fabrics were identified. As a main result, this study highlight that the 2 fault zones acted as drain canalizing low temperature fluids at their onset, and induced fault zone calcite cementation during 2 subsequent phases 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 porosities up to 35% (Deville de Periere et al., 2011). Due to their heterogeneous properties which depend on sedimentary, structural and diagenetic factors, they 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). 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 zones (Matonti et al., 2012) depending of their architecture and diagenetic evolution. Because of their hydraulic properties, fault zones influence the fluid flows in the upper part of Earth crust (Bense et al., 2013; Evans et al., 1997; Knipe, 1993; Sibson, 1994; Zhang et al., 2008), and increase the fluids-rock interactions. Carbonates are very sensitive to these interactions, which lead to 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 poly-phasic fault zone, duplication of fluid pathways/barriers lead to very complex diagenetic modifications. The initial vertical and lateral compartmentalization of microporous limestones is, therefore, accentuated by fault-related diagenesis. Hence, understanding of the 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 2 faults crosscutting microporous Valanginian-to-Early Aptian Urgonian facies 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 larger 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 deposits (Guyonnet-Benaize et al., 2010; Lavenu et al., 2013; Léonide et al., 2014; Masse and Philip, 1976; Masse, 1976), and E-W-trending normal faults (Guyonnet-Benaize et al., 2010; Masse and Philip, 1976). During the Late-Cretaceous, 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 cited references) led to a regional N-S shortening (e.g. Molliex et al. 2011 and cited references). The so-called “Pyrénéo-Provençal” shortening, which gave rise to E-W north-verging thrust faults and ramp folds (e.g. Bestani et al. 2016, and cited references). 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 2 faults pertaining to kilometric-scale fault system on the E-W-trending La Fare anticline near Marseille (Fig. 1A). The southern limb of this anticlinal 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 120m-thick calcarenite unit with cross-beddings, a 40m-thick massive coral-rich calcarenite unit, and a 10m-thick calcarenite unit (Masse, 1976; Matonti et al., 2012; Roche, 2008). Unconformable Santonian rocks are made of coarse rudist limestones (Fig. 1A).

The Castellas fault zone is a kilometre-long 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 fault zone "D19" is composed of 5 sub-fault zones (F1 to F5) restricted in a 50m-long interval (Fig. 2E, H; Table 1; (Aubert et al., 2019a)). Sub-faults are made of 2 sets. Set one comprises F3 and F4, N040 to N055-trending, 60-80°NW-dipping (orange on Fig. 2F). Set 2 is N030-trending, dipping 80°E, with strike-slip slickensides pitch 20 to 28°SW (F1, F2, F5, red on Fig. 2F). The 5 sub-fault zones show an asymmetric architecture (Aubert et al., 2019a).

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

- the Durancian uplift dated as mid-Cretoceous leading to extension and to normal *en echelon* normal faults. The Castellas fault is one of them 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). This event reactivates the Castellas fault as sinistral (Matonti et al., 2012) and leads to the neo-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 reverse throw (Aubert et al., 2019a).

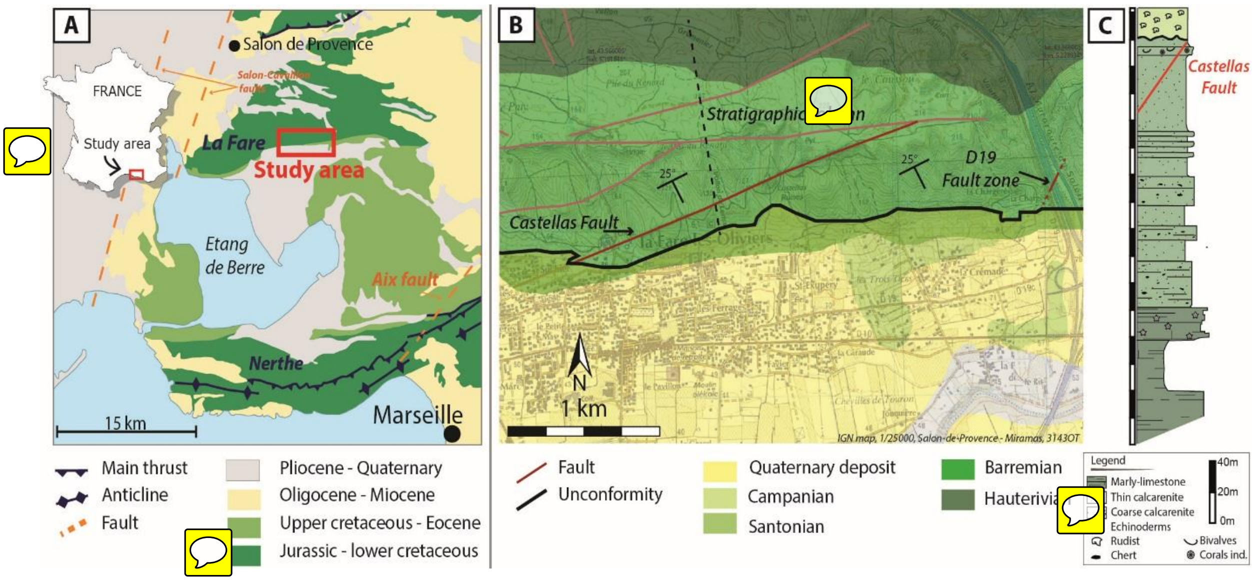

Figure 1 : Geological context of the study area. A: geological map of Provence, B: Simplified structural map with the location of the Castellas fault and the stratigraphic column (black dashed line); B: Stratigraphic column of exposed Cretaceous carbonates (modified from Roche, 2008)

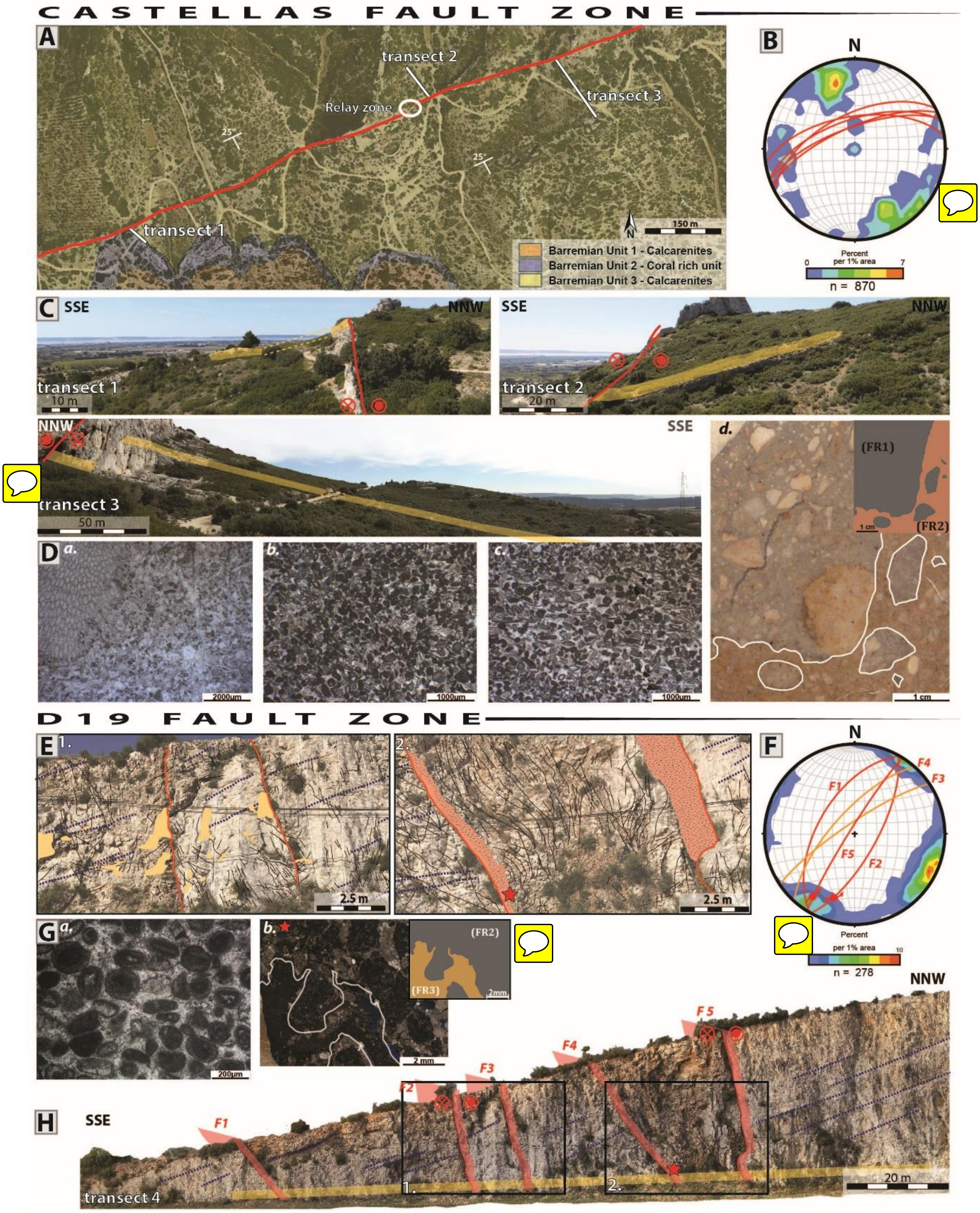

Figure 2 : A: Castellas fault map on aerial photo with localization of the studied transects and the relay zone; B: stereographic projections of poles to fractures (density contoured) and faults (red points) (Allmendinger et al., 2013; Cardozo and Allmendinger, 2013)*; C: Photos of transects; D: Carbonate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

Table 1*: structural properties of the fault zones*

aut zones	Faille	Direction	Dip	Dip direction	pitch striation	Fault core thickness	Fault Rocks FR1	FR2	FR3
Castellas	Castellas	060 - 070	40 to 80	N	14W -	0 to 4m	sparsely present	majoritarely present	/
D19	F1	030	56	W		20	/	<10 cm	/
	F2	029	70	E	28 S	10 to 15	/	?	non constant thickness
	F3	056	80	N		0 to 15	/	?	?
	F4	042	70	W		20	/	in the clasts of FR3	non constant thickness
	F5	032	85	N	20 SW	50 to 100	/	/	non constant thickness

3. DATA BASE

We performed 4 transects (T1 to T4) across the Castellas Fault and the D19 Fault (Fig. 2). Transect T1 is located along the coral rich unit 2. This bed is essentially composed of pelloidal grains and bioclasts (corals, bivalves and stromatoporidae; Fig. 2D a). Transects T2 and T3 are in unit 3, made of fine calcarenites with pelloidal grains and a rich fauna (foraminifera, bivalves, ostracods and echinoderm; 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 amount of bioclasts (solidary corals, bryozoan, bivalves and some rare miliolids; Fig. 2G, a).

The different tectonic events impacted the fault zone and fault core structure. Both faults have different fault cores (Table 1) made of 3 fault rock types in Castellas (Matonti et al., 2012) and D19 fault zones (see Aubert et al. 2019a). Fault rock 1 (FR1) results from the normal 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 grey matrix (Fig. 2Dd). Fault rock 2 (FR2), is linked to the sinistral reactivation of the Castellas fault and the onset of D19 fault zone during the Pyrenean shortening. FR2 present 2 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 from the 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. It is composed of angular to sub-angular clast from FR2 and from the nearby damage zone 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 and petrography 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 Alizarin red S and potassium ferricyanide to distinguish carbonate minerals (calcite and dolomite). The thin sections were analyzed using cathodoluminescence to discriminate the different 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 2 samples from the fault zone, 2 from the host rock and 1 from the D19 karst infilling were measured using PHILIPS XL30 ESEM with a current set at 20kV on fresh sample surface 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 80µm 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). Carbon and oxygen 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 $\partial^{13}C$ and -2.37‰ for $\partial^{18}O$, is measured as a control standard. The SD of the measurements is respectively < 0.1‰ and < 0.2 ‰ for $\delta^{13}C$ and $\delta^{18}O$. 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

Porosity measurements performed on the 92 samples show that in average, porosity strongly decreases towards the fault core (Fig. 3): from more than 10% (mean: 15%, SD: 2.68 for

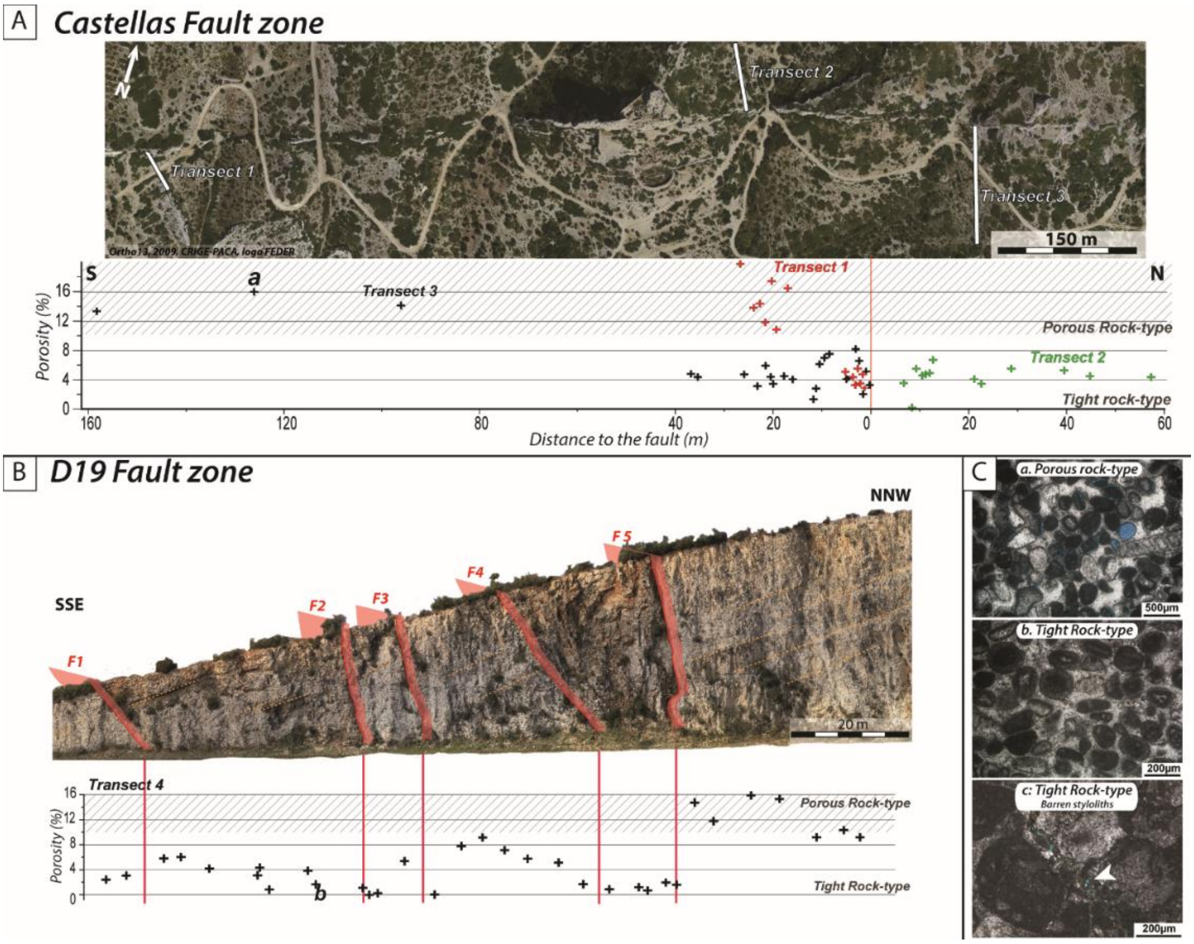

Figure 3: A: Castellas fault zone aerial view (Ortho13, 2009, CRIGE-PACA, logo FEDER) & porosity values measured along transect 1 (Red Cross), transect 2 (green cross) and transect 3 (black cross); B: porosity values measured along D19 fault zone; C: Pore types in the host rock (a) and in the fault zones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

Castellas and mean 12.3%, SD: 2.52 for D19) to less than 5% in fault zones (mean: 4.8%, SD: 2.07 for Castellas and mean: 3.16%, SD: 2.35 for D19).

Some variations occur as follows:

- North of the Castellas fault, along the 60m-long transect T2 the porosity is constantly low < 7% (mean of 4.4%, SD:1.53 ; Fig. 3A),
- South of the Castellas fault, the reduced porosity zone is >40m in transect 3 and 30m in transect 1 (Fig. 3A). In a 10m-thick zone from the fault plane, porosity reduction occurs with lower values in T1 (average 4.9%) than in T3 (average 5.6%).
- In the D19 fault zone, the lowest porosity values are in narrow zones around the faults (less than 2m) 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).

From thin sections impregnated with blue-epoxy resin, a porous rock-type with ϕ>10% mainly in micritized grains as microporosity and moldic porosity (Fig. 3C a), and a tight rock-type with ϕ< 5% where the porosity is mostly linked to barren styloliths (Fig. 3C b, c) are distinguished.

2. DIAGENETIC PHASES

a. Micrite micro-fabric

Micritized bioclasts, ooids and peloids were observed after SEM analysed of 2 fault zones samples and 2 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 (MF1; Fig. 4A, 4B). In the host rock, the micrite is loosely packed, and partially coalescent with puntic rarely serrate, subhedral to euhedral crystals (MF3; Fig. 4C, D, E). MF1 correlates with low porosity values < 5% , while MF3 with higher porosity > 10%.

b. Diagenetic cements

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

The first 2 cement phases occur in both fault zones. The first cement (C0) is non-luminescent isopachous calcite of constant thickness (≈10µm) around grains (Fig. 5A). The second cement (C1) is divided in 2 sub-phases: a non-luminescent calcite, C1a, with a dog tooth morphology in intergranular spaces, and a bright luminescence calcite, C1b, covering C1a with a maximum thickness of ≈100µm (Fig. 5). C1b also fills micro-porosity in micritised grains (Fig. 5B). C1b values strongly increase in Castellas fault zone.

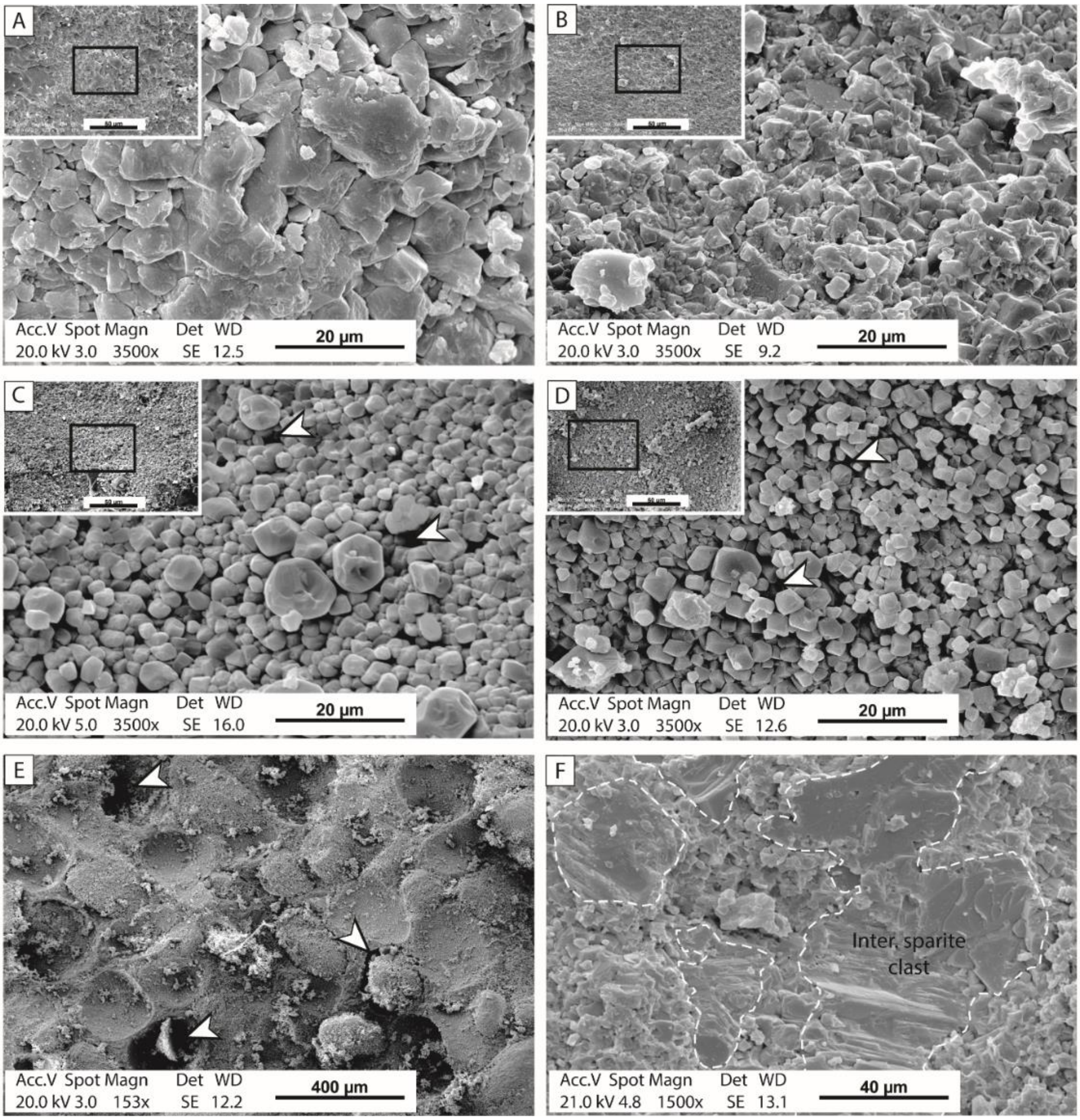

***Figure** 4 : MEB pictures of micrite micro-fabric and microporosity (white arrow); A. MF1micrite micro-fabric in Castellas fault zone (2.5m to fault plane); B: MF1micrite micro-fabric within D19 fault zones (2m away from F5 fault plane); C C: MF3 micrite micro-fabric within Castellas host rock (188m away from the fault plane); D: MF3 micrite micro-fabric within D19 host rock (95m away from F5 fault plane); E: D19 host rock moldic porosity; F. Karst infilling.*

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

- C2 is a sparitic cement with dull orange luminescence only found in fault core veins (Fig. 5B). SEM measurements show the Si and Al elements in the C2 veins. Most of Si crystals are an automorphic.
- 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 to the fault zone.

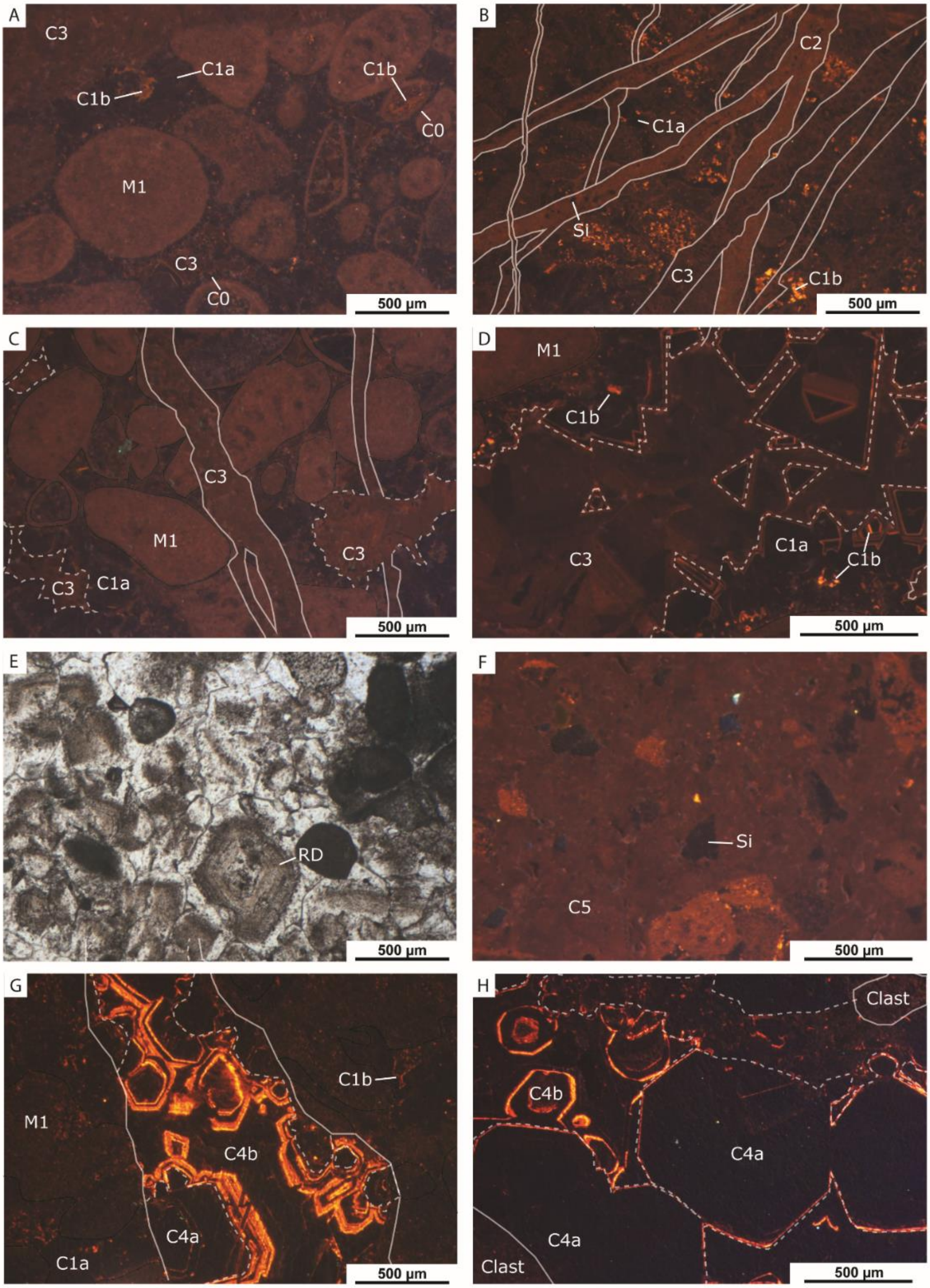

***Figure 5**: Thin-sections under cathodoluminescence; A: Calcarenite in transect 3 with micritized grain (M1), and intergranular space cemented with C1 a&b and C3; B: C2 (with Si) and C3 veins affecting Castellas FR1 clast with micritized grains cemented by C1b; C: C3 vein cement and intergranular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

- Phantoms of planar-e (euhedral) dolomite crystals (Sibley and Gregg, 1987) with a maximum size of 500µm affect the matrix of FR1 (Fig. 5E). They are vestiges of a dolomitization phase. They have a cloudy appearance caused by solid micritic inclusion in the crystal 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 300µm 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, 5H). This cement shows zonation of non-luminescent and bright luminescent bands and can be divided in 2 sparitic sub-phases: C4a which is non-luminescent with some highly luminescent band and C4b which is bright luminescent with some non-luminescent bands. C4a occurs in lesser proportion in some veins along transect T2 and T3 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 formation presents a stack of micrite-rich layers and grain-rich layers. In which grains are intergranular sparitic clasts, remaining from blocky calcite of dissolved grainstones and oxydes. The laminated layers are affected by veins and stylolites; some of these are deformed due to the clasts fall on sediments. Micritic layers has been observed under SEM, 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 proportion 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 spaces 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, 6B, 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 2 sets. Set one includes transect 1 & 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 the transect 3, the isotopic values only slightly vary along transect, ranging from -6.13‰ to -4.50‰ for $\delta^{18}O$ and from -1.41‰ to +0.47‰ for $\delta^{13}C$ (Fig. 6C, table 2). Contrarily, values vary more along the D19 transect. They range from -9.18‰ to -5.20‰ for $\delta^{18}O$ and from -4.80‰ to -0.60‰ for $\delta^{13}C$ (Fig. 6C, table 2). Indeed, the $\delta^{13}C$ values obviously decrease in the fault vicinity, especially south of F2.

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

- the group of values from C1 fluctuates from -6.76‰ to -4.45‰ for $\delta^{18}O$ and from -1.28 to +1.08‰ for $\delta^{13}C$;
- the group of values from C3 ranges from -10.40‰ to -6.73‰ for $\delta^{18}O$ and from -2.09 to +1.22‰ for $\delta^{13}C$;
- the group of values of C4 in FR1 and FR2 matrix and in karst fill 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 $\delta^{13}C$. FR 2 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 negative values than karst fill with mean values of -7.83‰ and -2.53‰ respectively for $\delta^{18}O$ and $\delta^{13}C$. (Fig. 6A). In the Castellas fault, 4 isotopic values from 2 veins are high 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.
- the group of values from C5, sampled in FR1 matrix with a mean of -7.49‰ for $\delta^{18}O$ and -4.01‰ for $\delta^{13}C$ (Fig. 6A).
- the group of values from FR3 matrix with a mean of -5.98‰ for $\delta^{18}O$ and -6.83‰ for $\delta^{13}C$ (Fig. 6A)

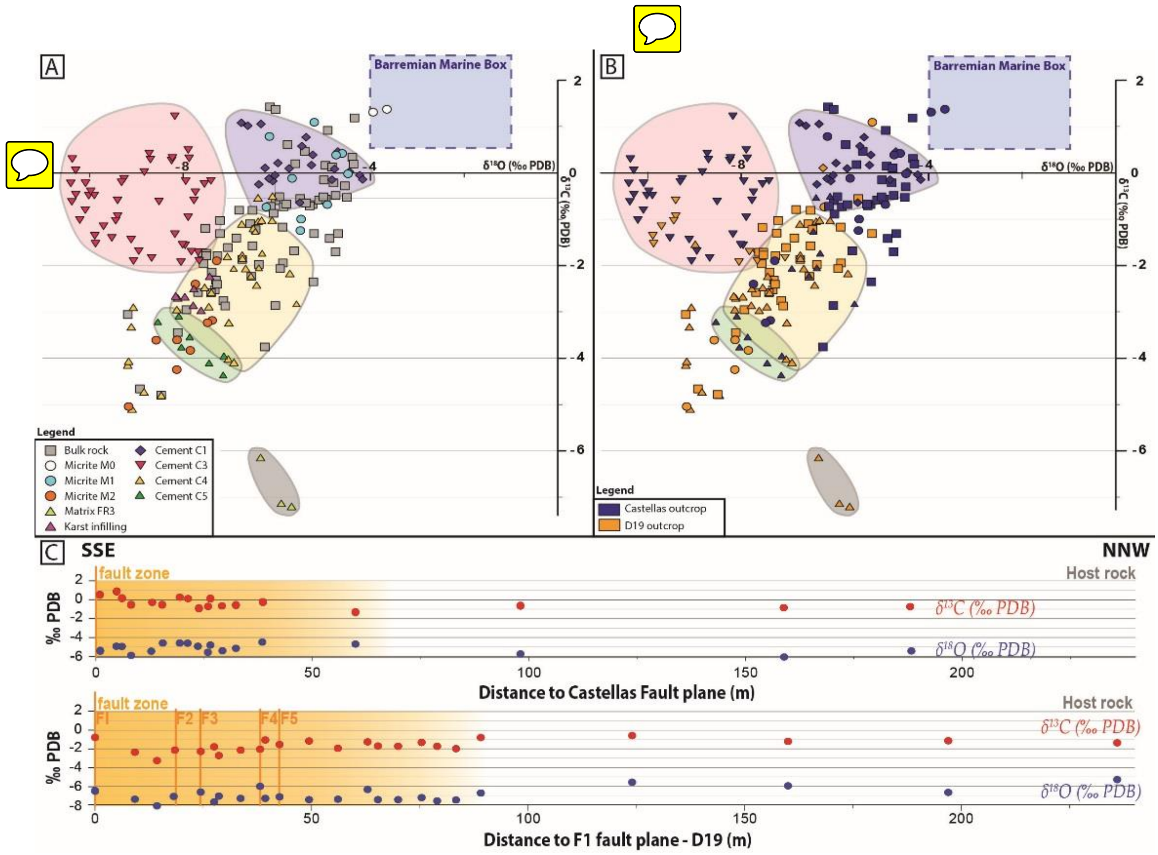

Figure 6 : Isotopic values of δ13C and δ18O measured on bulk rock, cement phases, and micrite. Range values of "Urgonian marine box" from Moss & Tucker (1995) and Godet et al. (2006); A: set of values sorted by the nature of diagenetic phases and B: values sorted by the fault zone; C: lateral evolution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

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

Transect	Sample	$\delta^{13}C$ (‰ vs VPDB)	$\delta^{18}O$ (‰ vs VPDB)	Class	Distance to F. (m)
Castellas (T 1)	201	1,19	-4,34	B	1,3
Castellas (T 1)	201	1,02	-6,62	C1	1,3
Castellas (T 1)	201	1,31	-3,94	M	1,3
Castellas (T 1)	201	1,37	-3,65	M	1,3
Castellas (T 1)	213	-0,68	-5,24	B	22,7
Castellas (T 1)	213	-0,58	-5,10	B	22,7
Castellas (T 1)	213	-0,18	-6,09	C1	22,7
Castellas (T 1)	213	0,03	-4,45	C1	22,7
Castellas (T 1)	213	0,09	-4,77	C1	22,7
Castellas (T 1)	213	-2,09	-6,92	C4	22,7
Castellas (T 1)	213	-0,68	-4,92	M	22,7
Castellas (T 2)	c3b17	-0,52	-5,95	B	4,6
Castellas (T 2)	c3b17	-2,07	-6,38	C4	4,6
Castellas (T 2)	c3b7	-0,64	-5,51	B	9,3
Castellas (T 2)	c3b26	-3,76	-6,26	B	22,6
Castellas (T 2)	c3b26	-2,85	-5,58	C4	22,6
Castellas (T 2)	c3b26	-1,31	-4,69	B	57,3
Castellas (T 2)	c3b7	-1,76	-6,31	C1	57,3
Castellas (T 2)	c3b7	-1,28	-6,46	C1	57,3
Castellas (T 2)	c3b26	-2,35	-5,22	M	57,3
Castellas (T 2)	c3b26	-1,70	-4,75	M	57,3
Castellas (T 3)	327	-0,24	-7,55	C3	0,3
Castellas (T 3)	325	-1,90	-9,06	C3	0,3
Castellas (T 3)	325	-1,69	-8,95	C3	0,3
Castellas (T 3)	327	-3,11	-8,09	C4	0,3
Castellas (T 3)	327	0,47	-5,40	B	1,0
Castellas (T 3)	327	-0,18	-7,95	C3	1,0
Castellas (T 3)	327	-0,17	-7,41	C3	1,0
Castellas (T 3)	328	0,10	-5,74	C1	1,6
Castellas (T 3)	328	-1,32	-8,18	C3	1,6
Castellas (T 3)	328	-0,59	-7,77	C3	1,6
Castellas (T 3)	328	-0,42	-7,74	C3	1,6
Castellas (T 3)	328	-0,13	-9,26	C3	1,6
Castellas (T 3)	328	0,02	-8,83	C3	1,6
Castellas (T 3)	328	0,29	-8,70	C3	1,6
Castellas (T 3)	328	0,42	-8,73	C3	1,6
Castellas (T 3)	328	0,50	-7,89	C3	1,6
Castellas (T 3)	328	1,22	-8,18	C3	1,6
Castellas (T 3)	333	-1,84	-8,67	C3	1,6

Castellas (T 3)	333	-0,96	-7,89	C3	1,6
Castellas (T 3)	328	-0,14	-4,17	C4	1,6
Castellas (T 3)	328	-0,05	-4,23	C4	1,6
Castellas (T 3)	329	0,16	-4,95	B	2,4
Castellas (T 3)	333	-0,25	-6,38	C1	4,6
Castellas (T 3)	333	-0,12	-6,17	C1	4,6
Castellas (T 3)	333	-0,62	-8,52	C3	4,6
Castellas (T 3)	333	-0,12	-5,67	M	4,6
Castellas (T 3)	333	-0,02	-4,48	M	4,6
Castellas (T 3)	333	0,42	-4,60	M	4,6
Castellas (T 3)	337	0,19	-5,59	B	9,5
Castellas (T 3)	302	-0,53	-4,50	B	11,8
Castellas (T 3)	302	-0,49	-4,74	B	11,8
Castellas (T 3)	302	-0,62	-10,38	C3	11,8
Castellas (T 3)	302	-0,49	-10,02	C3	11,8
Castellas (T 3)	305	0,33	-4,38	B	16,0
Castellas (T 3)	306	0,21	-4,35	B	17,8
Castellas (T 3)	307	-0,01	-4,46	B	18,2
Castellas (T 3)	308	-0,57	-4,95	B	20,0
Castellas (T 3)	308	-1,44	-9,11	C3	20,0
Castellas (T 3)	308	-0,23	-10,40	C3	20,0
Castellas (T 3)	308	-0,22	-10,08	C3	20,0
Castellas (T 3)	309	-1,41	-4,87	B	20,5
Castellas (T 3)	309	-0,52	-5,01	B	20,5
Castellas (T 3)	309	-0,15	-4,82	C1	20,5
Castellas (T 3)	309	-1,56	-7,96	C3	20,5
Castellas (T 3)	309	-1,55	-8,01	C3	20,5
Castellas (T 3)	312	0,12	-4,81	B	23,2
Castellas (T 3)	314	-0,71	-5,30	B	25,9
Castellas (T 3)	314	-0,80	-10,09	C3	25,9
Castellas (T 3)	314	-0,49	-9,90	C3	25,9
Castellas (T 3)	314	-0,47	-10,29	C3	25,9
Castellas (T 3)	314	-0,40	-9,97	C3	25,9
Castellas (T 3)	314	0,06	-10,30	C3	25,9
Castellas (T 3)	316	-1,24	-5,50	B	29,2
Castellas (T 3)	316	-1,00	-5,48	B	29,2
Castellas (T 3)	316	-0,22	-4,79	B	29,2
Castellas (T 3)	316	-1,02	-10,21	C3	29,2
Castellas (T 3)	316	-0,18	-9,31	C3	29,2
Castellas (T 3)	316	0,30	-10,37	C3	29,2
Castellas (T 3)	318	-0,28	-4,53	B	35,4
Castellas (T 3)	320	-0,68	-5,79	B	96,1
Castellas (T 3)	322	-0,88	-6,07	B	158,0
Castellas (T 3)	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**	**δ^{13}C (‰ vs VPDB)**	**δ^{18}O (‰ vs VPDB)**	**Class**	**Distance to F1 (m)**
D19	3B	-0,81	-6,52	B	0,0
D19	3B	-1,20	-6,50	C1	0,0
D19	3B	-1,02	-6,33	C1	0,0
D19	3B	0,11	-6,25	C1	0,0
D19	3B	-0,74	-6,23	M	0,0
D19	9	-2,32	-7,30	B	9,2
D19	13a	-3,44	-8,11	B	14,3
D19	13a	-2,96	-7,93	B	14,3
D19	13C	-2,97	-7,62	M	14,3
D19	13C	-2,86	-7,79	M	14,3
D19	13C	-2,70	-8,12	M	14,3
D19	13C	-2,67	-7,96	M	14,3

D19	13C	-2,66	-8,16	M	14,3
D19	13C	-2,50	-7,77	M	14,3
D19	13C	-1,54	-8,98	M	14,3
D19	17	-2,58	-7,68	B	18,7
D19	14A	-1,97	-6,38	B	18,7
D19	14A	-1,87	-6,74	B	18,7
D19	15B	-2,23	-7,43	B	18,7
D19	17	-1,05	-6,40	C1	18,7
D19	14A	-1,77	-6,74	C1	18,7
D19	14A	-2,42	-6,43	C4	18,7
D19	14A	-2,06	-6,67	C4	18,7
D19	21	-2,23	-6,54	B	24,4
D19	RSG	-1,90	-7,66	B	28,4
D19	RSG	-1,70	-7,83	B	28,4
D19	RSD	-2,87	-7,10	B	29,5
D19	RSD	-2,76	-7,14	B	29,5
D19	RSD	-0,93	-9,40	C3	29,5
D19	RSF1	-2,40	-7,28	B	34,7
D19	RSF2	-2,14	-7,39	B	34,7
D19	RSF2	-1,78	-7,27	B	34,7
D19	RSF1	-1,03	-9,44	C3	34,7
D19	RSF2	-1,93	-8,05	C3	34,7
D19	RSF2	-0,59	-9,40	C3	34,7
D19	RSF2	-2,95	-8,14	C4	34,7
D19	RSE 1	-2,53	-7,33	B	35,0
D19	RSE 2	-2,59	-7,41	B	35,0
D19	RSE 1	-1,71	-7,68	C3	35,0
D19	RSE 2	-1,84	-6,73	C3	35,0
D19	57	-2,07	-5,93	B	38,1
D19	57	-1,94	-5,87	B	38,1
D19	57	-1,83	-7,06	C3	38,1
D19	57	-1,10	-6,75	C3	38,1
D19	57	-4,02	-7,04	C4	38,1
D19	57	-2,17	-5,72	C4	38,1
D19	57	-1,58	-6,52	FR	38,1
D19	57	-7,20	-5,68	M	38,1
D19	57	-7,13	-5,90	M	38,1
D19	28b	-1,03	-7,21	B	39,3
D19	28b	-1,03	-6,10	C3	39,3
D19	28b	-4,09	-6,92	C4	39,3
D19	28b	-2,58	-7,40	C4	39,3
D19	28b	-2,47	-7,54	C4	39,3
D19	30a	-1,61	-7,04	B	42,6
D19	30a	-1,41	-6,87	B	42,6
D19	30a	-3,23	-7,03	C4	42,6
D19	30a	-2,89	-7,45	C4	42,6

D19	24a	-1,21	-7,52	B	51,1
D19	27b	-1,92	-7,48	B	57,9
D19	31	-1,24	-6,44	B	65,0
D19	32	-1,75	-7,50	B	67,4
D19	34	-1,79	-7,49	B	72,2
D19	36	-1,32	-7,21	B	77,8
D19	38	-1,73	-7,59	B	81,5
D19	62	-1,96	-7,56	B	86,0
D19	42	-0,81	-6,80	B	91,9
D19	63	-0,55	-5,50	B	124,0
D19	64	-1,17	-5,88	B	160,0
D19	65	-1,10	-6,57	B	197,0
D19	66	-1,31	-5,21	B	236,0
D19	60a	-3,06	-9,18	B	255,2
D19	60B	-4,80	-8,47	B	255,2
D19	60B	-4,66	-8,92	B	255,2
D19	61	-1,53	-9,87	C3	255,2
D19	61	-1,36	-9,89	C3	255,2
D19	60a	-1,15	-9,70	C3	255,2
D19	60a	-3,32	-9,11	C4	255,2
D19	60B	-5,10	-9,09	C4	255,2
D19	60B	-4,73	-8,84	C4	255,2
D19	60B	-4,15	-9,18	C4	255,2
D19	60B	-4,07	-9,16	C4	255,2
D19	60B	-2,90	-9,06	C4	255,2
D19	60a	-3,83	-7,85	M	255,2
D19	60B	-5,04	-9,17	M	255,2
D19	60B	-4,25	-8,14	M	255,2
D19	60B	-3,61	-8,58	M	255,2
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 thanks to cross-cutting relation and inclusion principles. Indeed, the veins filled with cement C2 cross-cut cements C1a and C1b (Fig. 5B). Thus, C2 cementation postponed C1 cementation. The C3 veins cross-cut the C2 veins, but are included within FR1 clasts (Fig. B). Hence, C3 cement is ante-FR1 development but post-C2 cementation. The fault rock 1 (FR1) is related to the first normal fault activity, consequently, C1, C2 and C3 cementation phases occurred prior to the proper fault plane and fault core formation and, are related to the fault nucleation. Replacive dolomite is within FR1 matrix (Fig. 3E), therefore, it develop after FR1 formation. Finally, the cement C4 can be noticed within FR2 matrix indicating that C4 cementation event postponed FR2 formation. The fault rock 2 (FR2) developed during the faults strike-slip reactivation. 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).

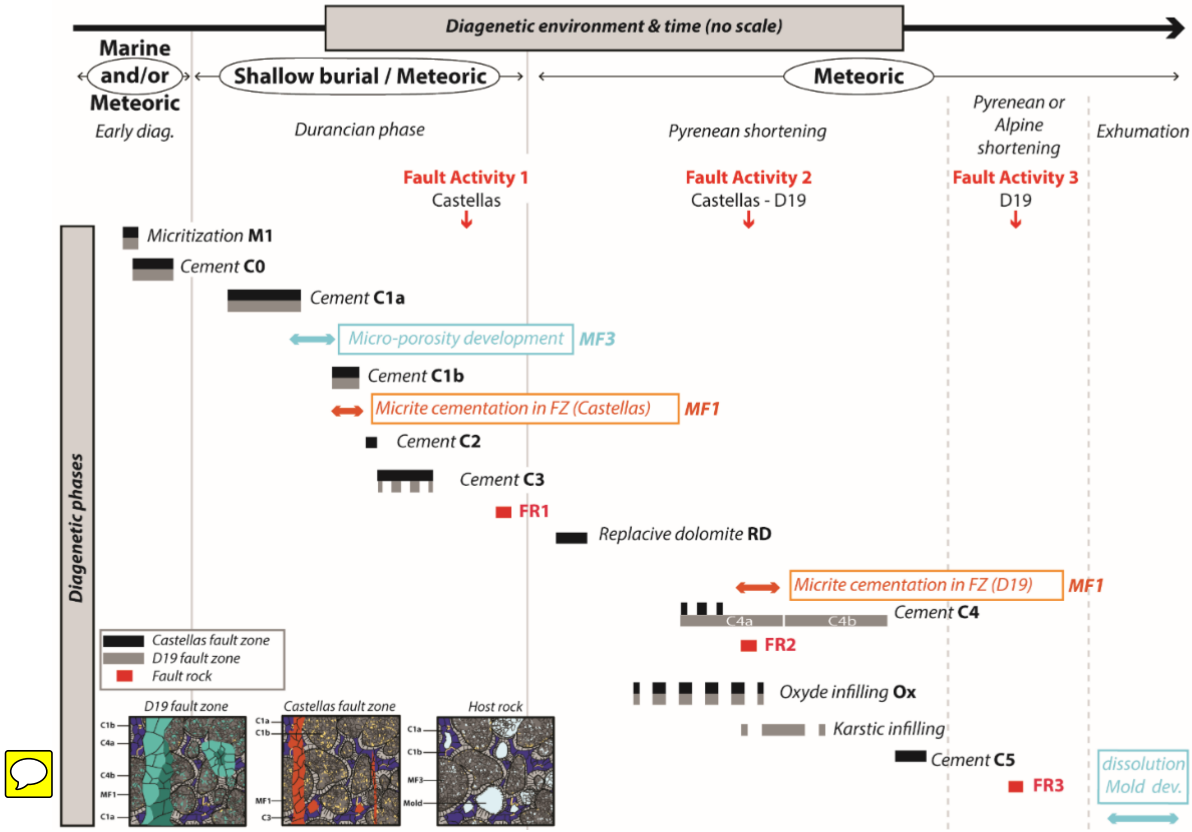

Figure 7: *Paragenetic sequence of the both fault zones (black: Castellas, grey: D19) with micro-porosity development (blue) and cementation (orange) and fault zone activation (red).*

The Urgonian carbonates in La Fare anticlinal underwent 3 important 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 (Fournier et al., 2011; Masse, 1976). Subsequently, cement C0 formed around grains and formed a solid shelve inducing the conservation of the clast 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 2 data points sampled of micritised grains show isotopic values close the Barremian sea water calcite. The 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 for 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 flow under equatorial climate during Durancian uplift. This diagenetic event led to micrite re-crystallization, and 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) Cementation of C1a, partly filling intergranular porosity (Fig. 9B1a)
(ii) Micrite re-crystallization and microporosity MF3 setup by Ostwald ripening processes (Ostwald, 1886; Volery et al., 2010).

The micrite re-crystallization strongly increased rock porosity due to enhanced microporosity (Fig. 9B1b). Microporous limestones have a high matrix porosity but low to moderate matrix permeability (Deville de Periere et al., 2011; Jack and Sun, 2003). Indeed, in the case of Barremian limestones of La Fare anticline, porosity is >10% but located in the grains, what restricts possible flow pathways. 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) impacting 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), and under low confining pressure (<100KPa; Alikarami & 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) what allows fluids to flow.
Castellas fault zone nucleated within a partially and dimly cemented host rock under low confining pressure, in an extensional stress pattern, at a depth <1km (Lamarche et al. 2012). Barremian host rock presented properties (porosity/stress pattern/confining pressure) close to the porous granular described above. Moreover, Micarelli et al. (2006) showned that, during early stages, fault zones in carbonates have a hydraulic behaviour comparable to deformation bands. Hence, in the Urgonian carbonates of La Fare sector, dilatant processes occurred as an incipient fault mechanism and enhanced fluid circulations along the deformation bands. These fluid flows led to the cementation of C1b (Step 2 on Fig. 8). However, dilation bands are unstable and grain collapse occurs swiftly after the beginning of the deformation due to an increase in the loading stresses (Lothe et al., 2002). This explains 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 30m 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 (188m; -5.37‰ for $\delta^{18}O$ and -0.65‰ for $\delta^{13}C$, Fig. III 6A). Others dilation bands has also been described by *Kaminskaite et al.* (2019) in the San Vito Lo Capo carbonates grainstones (Sicilly, Italy). These dilation bands also led to cementation of the carbonate rock.

The C1a and C1b led to a local rock embrittlement and to a porosity decrease by cementation of the microporosity. 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 the permeability (Micarelli et al., 2006). In the studied faults, the first brittle event allowed an Al-rich fluid to flow with micro-metric quartz grains in the barren fractures, and C2 to 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 must 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, a new fracture set 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 at high depth (depth of maximum 500m; Fig. 9C4).The negative $\delta^{13}C$ values tend corroborate that it would rather be a meteoric fluid than a marine fluid. Hence, C3 would correspond to a shallow burial/meteoric cementation phase. Resulting from this cementation, rocks in this zone tightened down to <5%. The porosity did not change since this event (Fig. 9 B5). 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). Implicitly, the fault zone was a barrier to fluid flow, leading to a reservoir compartmentalization. The C3 fluid flow 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 >100µm in size (Step 5 on Fig. 8). These grains either came from silica from C2 in veins describe above or from Aptian overlying rocks. C2 silica crystals in veins are scarce and smaller than 10µm. Thus, quartz grains may rather come from Aptian rocks like the quartz found in C2 veins. The presence of Aptian quartz in the fault core proves that the Castellas fault affected Aptian rocks, which were later eroded during the Durancian uplift. Implicitly, the fault activity occurred before total erosion of Aptian rocks. Uncemented breccias within the fault core form 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 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 strike and normal faults fault core (Billi et al., 2003, 2008; Storti et al., 2003).

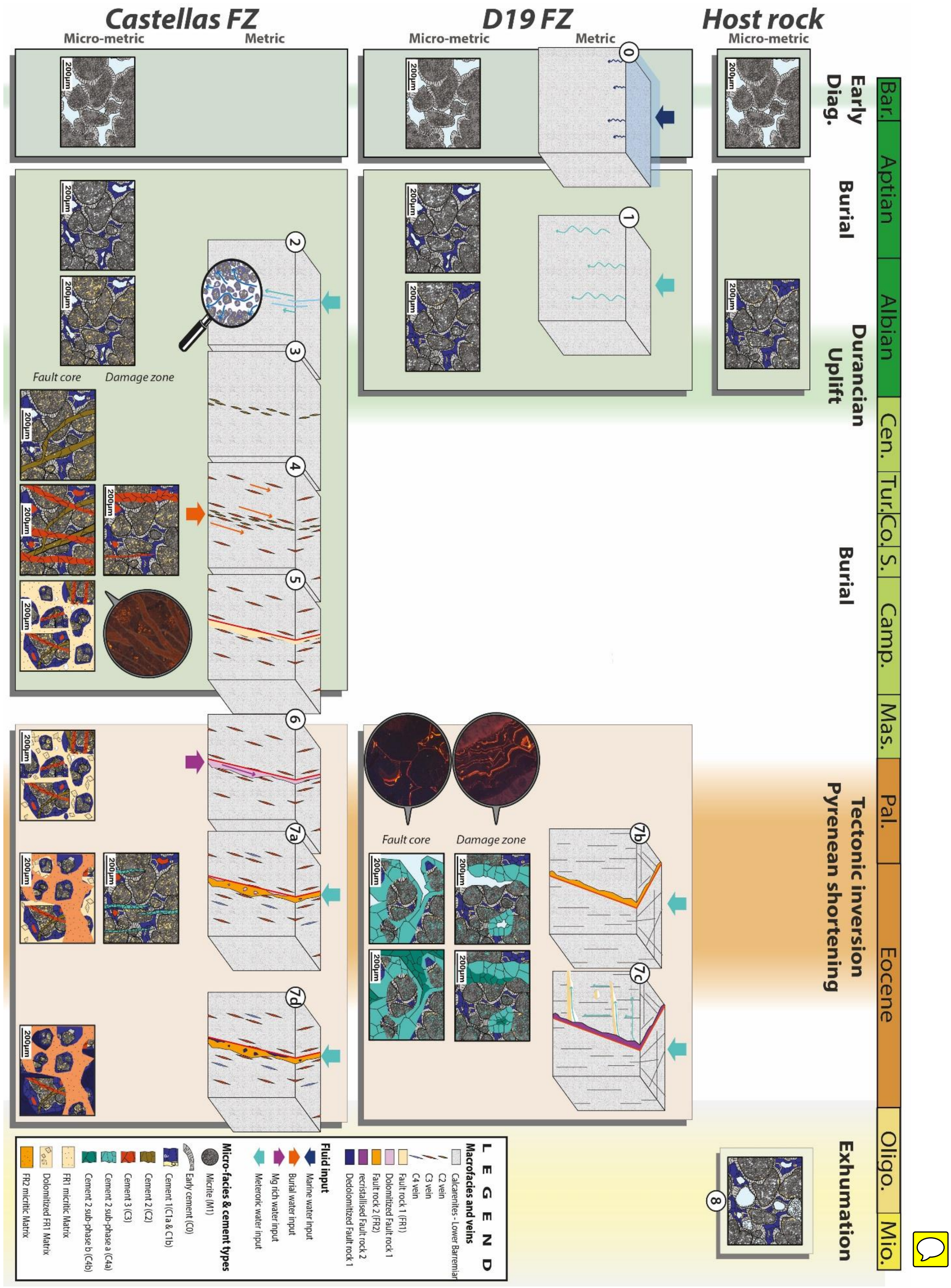

Figure 8 : *Diagenetic and geodynamic evolution since the Barremian of both fault zones and host rock at the metric and micro-metric scale. Numbers 0 to 8 correspond to the steps 0 to 8 (see text for description).*

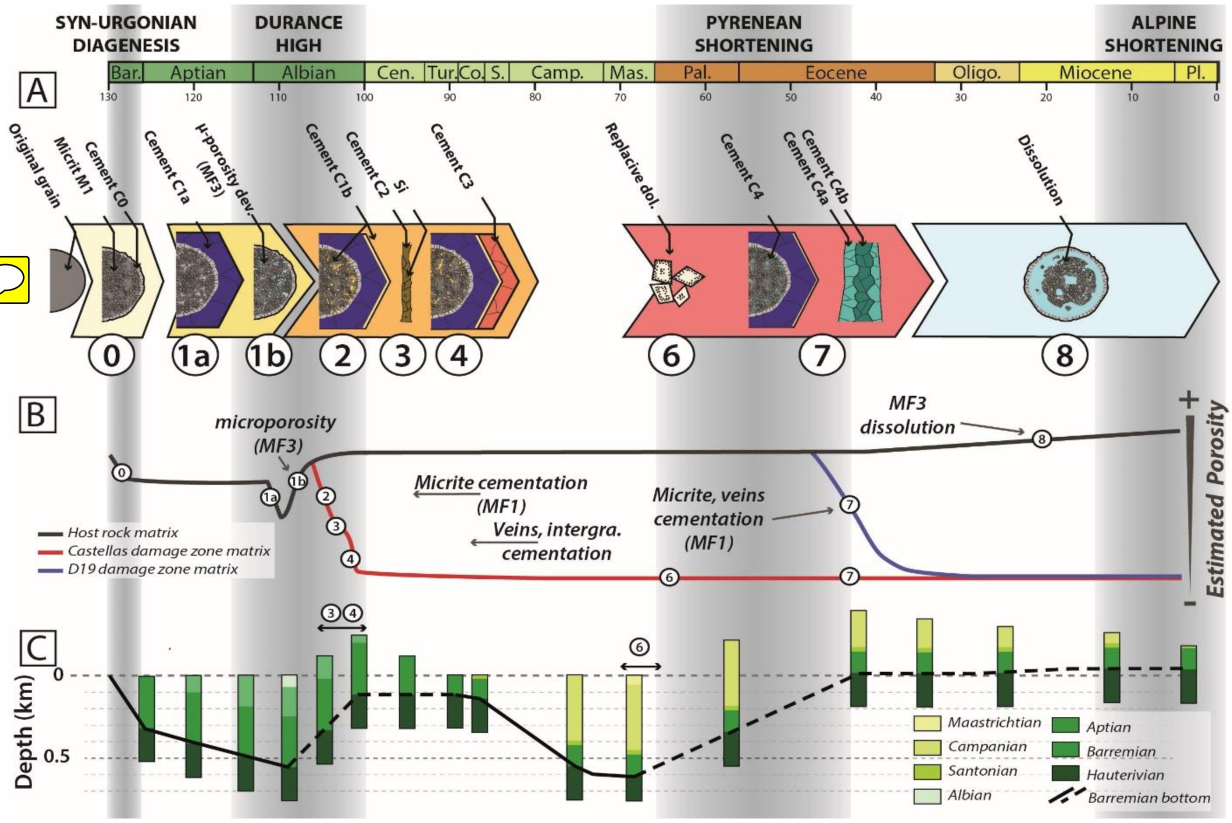

Figure 9 : Evolution of reservoir properties. A: different cementation phases; numbers 0 to 8 correspond to the steps 0 to 8 (see text for description), B: relative porosity evolution of the host rock and the 2 fault zones; C: Burial/Uplift curved of Barremian basement (modified from Matonti et al. (2012)).

Tectonic Inversion – Castellas fault-related dolomitization

At the onset of the Pyrenean shortening, compressive stresses lead 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 can be favoured by several factors:

(i) The matrix has higher permeability than cemented clasts with a smaller grain size, hence a higher grain surface area;

(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 high Mg fluid circulation to the fault core.

Gisquet et al. (2013) noticed similar fault related replacive dolomitization phase in the Etoile massif, 23km South-Est of the studied zones. They linked the dolomitization to compressive conditions during the early (Late Cretaceous) Pyrenean shortening. From these authors, the tectonic stress led to low temperature upwelling fluids 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 inter-crystalline and/or inter-particle porosity up to 13% but the later dolomite overgrowth reduce 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 to barrier (Fig. 9 B6 and C6)

Sinistral tectonic inversion – meteoric alteration of reservoir properties

The ongoing tectonic inversion with increasing compressive stresses finally 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° back-ground fractures (Step 7 on Fig. 8). This tectonic event lead to FR2 in fault cores but with specific diagenetic consequences. In the D19 fault zone, the fault nucleation and reactivation of back-ground 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 resulted in the cementation of C4a and C4b in veins and micritized grains (MF1, Step 7c on Fig. 8), what led to a strong porosity decrease in the fault zone (Fig. 9, B7 and C7). However, not all fractures were cemented by C4, so the fracture porosity/permeability was preserved. Therefore, the D19 fault zone became a type I reservoir sensu Nelson (2001) with a very low matrix porosity/permeability and high fracture permeability (Aubert et al., 2019a).

Along F2, successive fluids gave rise to karsts, karstic filling and dissolution/cementation of FR2 matrix (Step 7c on Fig. 8). Then, FR2 was sealed by C4 cementation. Isotopic values of C4 (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 fill due to fluid circulations in vadose zone, 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 occur along transect 2 and transect 3 (Step 7a on Fig. 8). Two samples have higher $\delta^{18}O$ 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 (Fig. 6A). This indicates that C4 in the Castellas fault zone was precocious in comparison to the D19. Cements C4 in Castellas area are restricted to transect 2. Transect 2 crosscut through the Castellas fault at the location of a relay zone (Fig. 2A). Relay or linkage zones occur where 2 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 local permeability and allowed local fluid circulations. In transect 2, the increase of the local permeability in the relay zone enhanced fluid flow related to cement C4. The relay zones along the Castellas fault and their consequences on the fracture permeability are, therefore, responsible for this local cementation event. Contrarily, cementation in D19 fault zone is linked to the highly permeable fault surfaces which acted as a drains (Aubert et al., 2019a). That implies that the cementation occurred only after the formation of the fault surface. In the case of Castellas, the relay zone was already present, inherited from the former normal activity, allowing early C4 fluid to flow in fault zone. This, in addition, explains why the early C4 cementation has not been recorded in D19 fault zone. The C4 cementation in T2 reduced the porosity to less than 8% on a larger zone (>60m) than in both others transects (T1 ≈30m, T3>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), such as a sieve.

After these events, the matrix of the Castellas fault core was de-dolomitization (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 recrystallized 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 soils, and thus 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.

Finally, the late exhumation of the Urgonian carbonate host rocks led to flows incurring dissolution of MF3 grains in the host rock. This phase triggered the moldic porosity and increased the porosity/permeability (Step 8 on Fig. 9B and C). These flows, 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 the fractures are pathways for flow but the production comes from the matrix (*Nelson* 2001, Fig. 10A). The fault zones present a more complex polyphase 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). Thus, for Castellas fault zone, the permeability evolves from the host rock permeability (100% matrix; step 0 on Fig. 10B) to a permeability due to 50% to the matrix and 50% to the fault core during dilation band development (step 2 on Fig. 10B). Thereafter, during the 2 fracture events permeability is mainly link to fractures (C2: 30% FC, 70% fractures; C3: 15% FC, 15% matrix, 70% fractures; step 3, 4 on Fig. 10B). Then, after fault core formation and during dolomitization event, permeability is solely located in the

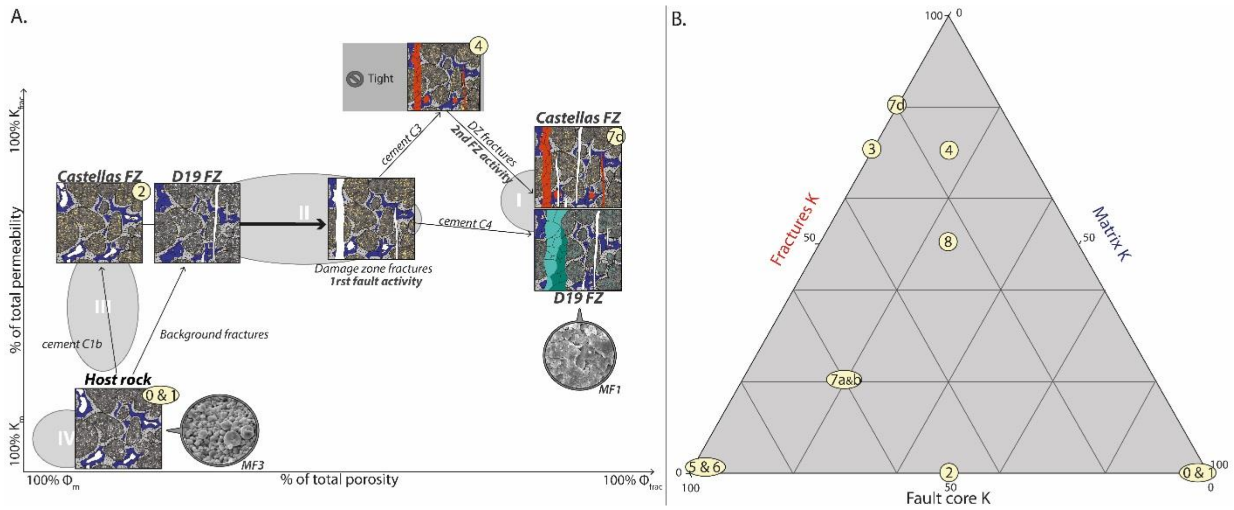

Figure 10 : *Castellas and D19 fault zone reservoir properties evolution. A: evolution of permeability and porosity taking into account fault zone fractures and matrix after Nelson (2001) and B: Triangle diagram of permeability evolution with 3 components: matrix, fractures and fault core. Numbers 1 to 8correspond to the steps 1 to 8 (see text for description).*

fault core (step 6, 7 on Fig. 10B). Lastly, after fault zone reactivation, the permeability is due to 20% to the FC and 80% to fractures (step 7c on Fig. 10B). The D19 fault zone permeability during its development was related at 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 2 fault zones and the impact on the reservoir properties of both fault 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 their 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 thinly impacts matrix porosity/permeability.
- Fault zones act as drains canalizing fluid flows in the beginning of their formation. This induces fault zone cementation but preservation of host rock microporosity. This important fluid drainage is visible on D19 outcrop where the flows led to dissolution/cementation of fault rock matrix and formed karsts.
- All diagenetic stages, including cementation and dolomitization, result from low temperature flows with important meteoric water input. This low temperature flows associated with the deformation and cementation types and, the lack of mineralisation specific to high temperature flows disprove any hydrothermal influence.

This regional study allows to draw broader rules for polyphase faults in granular carbonates at low depth (Fig. 9).

- Under extensive context, fault nucleation can lead to dilation band acting as conduits for fluid flow. Carbonates are very sensitive to fluid and 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 the later cases, fluids flowed preferentially within the permeable breccia rather than the damage zone fracture network.

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