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Interactive comment on "A new methodology to train fracture network simulation using Multiple Point Statistic" *by* Pierre-Olivier Bruna et al.

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Overall quality: This is potentially a valuable contribution on the topic of understanding fracture networks. Outcrop fracture studies are being revolutionized by the rapid acquisition of fracture patterns from drones and photogrammetry. Developments in statistical approaches to process these observations are needed. This paper makes a credible contribution on the statistical front. And the written presentation and illustrations are fairly clear and compelling. I do think that there is room for improvement to increase the impact of the paper.

Specific comments

In the presentation encompassing figures 3 through 5, I didn't completely follow how

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you defined ‘fracture facies’ and ‘elementary zones’. Is there some sort of statistical measure of deviation from random you used (as in, for example, Marrett et al. 2018). Or are the ‘facies’ just qualitatively identified as ‘looking similar’? My apologies if I just missed the explanation.

The Abstract reads too much like an Introduction. This part of the text needs to be more information rich. Instead of saying the paper proposes a multiple point statistics method, the Abstract should try to explain the specifics in a highly succinct way. Likewise, how was the method tested; don’t just use a passive construction to tell the reader that the method ‘was tested’. Bring forward some of the specifics from the Conclusions.

The Introduction could also use improvement. For one thing, the Introduction does not make a very coherent case for why outcrop studies of fractures are so essential. The reason isn’t necessarily because fracture networks have ‘intrinsic complexity’ (line 65)âĂŤsome networks are quite simpleâĂŤbut because the elements of fracture patterns that govern fluid flow, like connectivity and height and length distribution and the apparent clustered distributions evident in figs 3-5 cannot be adequately sampled in the subsurface. Some attributes like length distribution cannot be sampled at all in the subsurface. Outcrops are where these features can be measured. The Introduction would be stronger if it spelled out this challenge in clear, simple terms.

It would also help if the cited literature included some more explicit examples of how these hard- or impossible-to-measure attributes affect fluid flow (for example, Long & Witherspoon 1985 on connectivity; Olson et al. 2009 on length distribution in unconnected networks in porous rocks). Right now the Introduction ‘lacks motivation’. Many of the parts are there but the case needs to be made stronger. See some of the specific comments below.

Ok; the following might seem like a tangential issue. But generalist readers need to have a clear explanation of what problems there might be in using outcrop fracture

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patterns as analogs for those in the subsurface. In section I.2 about surface rocks as reservoir analogs, an incautious reader would never suspect from the text here that there might be problems with using outcrops fractures for this purpose. This omission needs to be fixed. Some outcrop fractures provide close matches to those in subsurface areas of interest (e.g., Gomez-Rivas et al., 2014) but others do not (e.g., Laubach et al., 2009). In many cases, outcrop fractures provide demonstrably misleading guidance for the subsurface (Corbett et al., 1987 and subsequent work on the Austin Chalk cited in Laubach et al. 2009; Li et al., 2018).

Studies typically seek to omit fractures that result from near-surface processes unrelated to fractures at depth (Stearns & Friedman, 1972). But subsurface sampling over the past two decades shows that in the moderate- to deep subsurface (1 km+) in sedimentary basins, many fracture pattern elements differ from those found in more readily sampled outcrops even if the fractures in those outcrops formed in the subsurface, and for unsurprising reasons. Comparative studies in the same rock type and structural setting of fracture spacing observed in outcrop and sampled in long fracture-perpendicular cores shows that patterns in exposures can differ markedly from those in the nearby subsurface (Li et al., 2018, J. Struct. Geol.). The differing temperature-pressure paths of outcrops and rocks at depth and associated differences in rock properties are key reasons that the evidence outcrop patterns provide on fracture patterns in the deeper subsurface needs to be used with caution. The need for caution should be mentioned even if this particular outcrop is a good subsurface analog.

Part of the process of using outcrop fractures is figuring out to what extent the outcrops are guides, and to what circumstances, of the subsurface. This part of the Introduction should acknowledge this issue and mention that the authors addressed it (I notice that later in the MS the outcrops are said to be good analogs; can the authors mention why?).

I'm sure the authors recognize this issue and despite the length of my comments a brief but complete acknowledgment of the issue is all that is needed in my opinion.

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The statistical approach seems like a reasonable one. But I think the paper would benefit from a clearer explanation perhaps aimed at a generalist audience, as well as featuring a compare-and-contrast with other similar approaches. I noticed that the Liu et al. 2002 citation in your reference list is incomplete. [Liu, X., Srinivasan, S., & Wong, D. (2002, January). Geological characterization of naturally fractured reservoirs using multiple point geostatistics. In SPE/DOE Improved Oil Recovery Symposium. Society of Petroleum Engineers.] If you go to OnePetro you can get the doi for papers like this one.

I'd be interested in seeing a comparison with the Hanke et al 2018 directional semivariogram (J. Struct. Geol. 108 [March]).

I didn't find the analysis of aperture variation to really be much of a test and the whole exercise seems a bit extraneous to the statistical analysis of the pattern. The text needs to explain more clearly in what sense this is a test (even if that turns out to underline that it is a limited test). As noted below, it would also be appropriate to present the 'stress sensitivity' (or not) of fractures in a more nuanced way. Why no direct measurements of aperture size distributions?

Technical questions & comments

30 Abstracts do not normally contain citations.

53 'Ubiquitous' means that fractures are everywhere but excavations and horizontal core studies show that some rocks in the subsurface lack fractures, or if fractures are present they are so widely spaced (hundreds of meters or more) that 'everywhere' is not an apt description. An outcrop example showing how resistant to fracture some rocks are is Ellis et al. 2012, J. Geol. Soc. London. A better word might be 'widespread'. Moreover, areas of completely sealed fractures are also common in the subsurface, and such fractures are rarely fluid conduits. Although I don't agree with people who don't count such rocks as fractured, it's certainly the case that some rocks lack fracture flow conduits.

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55 I think more caution is called for in citing for this point (effects of fractures on fluid flow). There are relatively few papers that document the effects of fractures on fluid flow in hydrocarbon reservoirs but many papers that repeat the contention that fractures are important for fluid flow. One of the papers that does quantify production data with respect to natural fractures is Solano et al, 2011 SPE Reservoir Evaluation & Engineering. However, although both of the papers cited here in the MS are interesting contributions, I don't think they are the right papers to cite in support of the point the authors make. All of the references mentioned in his section of the text should be reviewed with this point in mind.

58-ca. 62 Ok, so maybe a quibble, but 'well known'? really? Maybe I'm not following what the authors are trying to say here, but connecting the specific strain and stress conditions to the formation of a given fracture or fracture pattern is full of uncertainty: the timing of fracture formation is commonly very challenging to estimate unambiguously and because fracture arrays are generally low strain phenomena and through geologic time a wide range of loading paths might lead to fracture (e.g., Engelder 1985, J. Struct. Geol.) the connection between pattern and cause is frequently ambiguous. A good example relevant to this paper is fractures in outcrop. Did they form due to some process at depth (for example, elevated pore fluid pressure) or during uplift or exposure? This issue gets to the reliability of outcrop-derived fracture pattern information (which I'm all in favor of obtaining) but the challenge of determining the causes of fractures I think needs a bit more thoughtful or nuanced treatment.

67 Do you mean stresses in the past when fracture patterns formed (paleo stresses)? You seem to be claiming that fractures are highly sensitive to current stress state. I know this is a widely accepted premise, but you should at least note that many reservoirs are known to have fractures that are stiff and insensitive to current stress state (e.g., Laubach et al., 2004, Earth & Planetary Science letters).

71-86 This section needs to contain some caveats about the limitations of outcrop fracture research.

73 The use of outcrop fracture patterns to constrain the subsurface goes much deeper into the past than the recent references cited here: National Research Council 1996. Rock fractures and fluid flow: Contemporary understanding and applications. National Academy Press, Washington D.C., 551 p.

81-82 The 'how, when, and where' is rarely obvious from the pattern alone. Flagging this comment is not off topic since it relates to how outcrop data can or should be used.

89 'provide'

93-94 This sounds like jargon; provide a clearer explanation of what you mean for a general audience.

113-119 This is too late in the MS to introduce this material. Some of this could be in the Abstract.

125 What do you mean by 'full outcrops'. This seems vague. If you have a size range in mind, why not state it?

135 I'm not sure I follow you here. You didn't measure any apertures in outcrop, did you? So is this just a process of a computation applied to both the outcrop imaged fractures and the statistical realizations? Why no measured outcrop apertures?

205-206 Some of the text here sounds like it is carry over from a proposal, since you've done the work.

271 Does the karst figure into your aperture calculations?

322 This seems late in the text to have this kind of preview of goals?

365 Interesting. Are some of the >40-m-long fractures still censored by outcrop size?

572-575 There are some jumps in logic here. Yes, flow depends on open fractures. But whether or not fractures are open or not does not simply depend on in situ stress conditions. Some (many) fractures are insensitive to stress state (they are very stiff) and

some are closed because they are mineral filled. It therefore does not necessarily follow that 'contribution of fractures to fluid flow. . .can be defined by the Mohr-Coulomb. . .' etc. The development here needs to be more nuanced and include a few caveats.

It is also worth noting I think that the predominant role of aperture in fluid flow presumes a completely impermeable host rock, which is generally not a good assumption even for low porosity unconventional reservoirs (TGS; shale). If there is flow in the host rock and the fractures are not interconnected, open length distribution is what matters (Philip et al. 2005). Philip et al. varied the apertures in their simulations by a lot and got no significant difference in flow. Philip, Z. G., et al., 2005, Modeling coupled fracture-matrix fluid flow in geomechanically simulated fracture networks: SPE Reservoir Evaluation & Engineering, 8/4, 300-309.

576 'a key parameter'; if it's a key parameter, why were apertures not measured in the field?

622 'statistic'; is this the word you mean? Obscure usage.

625 What do you mean by 'aborted' fractures? Non-standard usage; suggest you pick another word.

632 Mechanical stratigraphy is readily measured in the subsurface; 'fracture stratigraphy' is more challenging.

Did you rigorously describe your fracture height patterns for the outcrops (maybe it is in one of the cited references). Height patterns and fracture stratigraphies have different patterns. There is a useful classification in Hooker et al. 2013, J. Struct. Geol.

637 'fracture family' is non-standard usage. Is there a reason not to call these groupings 'fracture sets' (Hancock, 1985)?

641 'provides'; ('The method provides a realistic. . .')

Fig. 8, caption 'Fracture. . .'

Fig. 10. Some of the colors on this figure make it hard to read.

Fig. 12 would be more informative with more labeling and explanation on the face of the figure. Add a graphic explanation/key.

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