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Solid Earth
Discussions

Interactive comment on "Fracture attribute scaling and connectivity in the Devonian Orcadian Basin with implications for geologically equivalent sub-surface fractured reservoirs" *by* Anna M. Dichiarante et al.

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Comments on MS: "Fracture attribute scaling and connectivity in the Devonian Orcadian Basin with implications for geologically equivalent sub-surface fractured reservoirs" Dichiarante et al.

Referee: Vincent Heesakkers

The paper in question covers a topic that, as the MS mentions, significantly adds to the scientific community by covering multi-scale observations of fracture aperture and frac-

ture lengths in order to establish a scaling laws for fracture attributes over several order of magnitudes. I agree with the authors that there is a need for additional studies like this in order to assist sub-surface modeling of fracture systems, which often is confined to limited wellbore data, covering a given scale. In order to reduce the uncertainty in sub-surface fracture models, and scale wellbore observations to reservoir scale models, outcrop observations are critical. This MS covers outcrop observations of fracture attributes with regional and micro scale to establish scaling laws that can be used in a similar geological setting. Direct use of the scaling laws in this MS might be limited to reservoirs with key geological similarities, after one establishes that the observations in this MS are a reasonable analogue. However, the thorough study of fracture attributes at multiple scales, and the establishment of scaling laws over 8 orders of magnitude, is an example of techniques that hopefully will be used more often within other geological settings. The topic, workflow and findings in this MS are therefore very suitable this journal, and a significant scientific contribution.

The MS is very well written with minor grammatic errors. The technical organization of the MS is properly ordered, with clearly stated problem statements and scientific methods. The results are presented clearly and straight forward, and derived conclusions match the observations stated in the MS. I support acceptance and publication of this MS, as I deem it suitable for this journals special edition.

I have enjoyed reading the MS and do see tremendous value in its study and utilization of its observations and conclusions. Very well organized and well-written.

I do have several general comments/suggestions about the MS listed below, followed by more specific comments referenced to line items in the MS. Hopefully, my comments / suggestions will further improve the quality of the MS.

General comments:

1) There is a general lack of guidance on specific use of the observations and conclusions of the scaling laws for sub-surface reservoir models: results in fig 8 span multiple

orders of magnitude (8), but with a degree of uncertainty. Fig 13 attempts to address these points, but the text is lacking a discussion on utilization of these findings for sub-surface reservoir scale fracture modeling. The authors did state that this is one of their main drivers for this study, thus a more elaborate discussion is warranted.

2) Although specified within the MS, confusion remains on how faults and large lineaments (regional scale) can be used to infer length / aperture in subsurface or micro scale. More discussion is needed. I would have liked to see the analysis of shear fractures separate from opening mode fractures (joints). It gives the impression that, if we can map faults from seismic, we can infer the attributes of joints system. Often the two are not coupled as faults do form associated fracture systems within their damage zones, but this happens independently from pervasively distributed joint systems throughout the reservoir. More discussion needed on why the shear and opening mode fractures are treated similarly over multiple scale of observations.

3) Each fracture system is unique. Even fracture systems in similar host rocks and tectonic regime could vastly differ in their attribute distribution, based on local variations of geological factors. The fracture systems reflect details in the geological hysteresis, and are sensitive to local variations of many geological aspects: local stress field, pore pressure evolution, chemistry, strain rates, diagenesis, geochemistry, etc. The claim the Caithness outcrop is a valid analogue for sub-surface fractured reservoirs like Clair Field is a fair statement, and I don't disagree. But it needs a bit more attention to understand the differences and similarities. The MS tries to convince the reader that the analogue is appropriate, but minimal evidence is provided on why that claim has been made.

In addition, the MS would benefit from a discussion on outcrop vs sub-surface fracturing processes in general. Outcrops often are saturated with fractures, as existing fracture systems get enhanced (saturated) during exhumation processes. In this example, I expect the effect of enhancement due to exhumation to be significant at the studied coastal sections. It deserves a discussion on what assumptions have to be made to

assume the outcrop dataset and its scaling relationships over multiple scales, are valid to use in sub-surface modeling efforts. To apply this technique for a different reservoir, one would need to find compatible outcrops that allow a similar sampling of micro / meso / regional scale fractures as analogue for the reservoir. That might be a difficult task. The MS would benefit from a more elaborate discussion on the use of outcrop analogues for sub-surface fracture systems, and guidance on how the resulting scaling relationships can be used.

4) Paper is missing a discussion on what is assessed as the "length" of the fractures measured at different scales. The length of a fracture as it grows, is different then the lengths that defines fluid flow pathways through connectivity. There is a scale dependency of observation here, that drives the measured length. For example, a single trace on the bathymetric data (Meso scale) might be mapped as several segments on the Macro scale. For example, quality control of fault maps often utilizes fault length vs displacement profiles to identify faults that are mapped with lengths too long compared to their offset, suggesting the fault likely consists of multiple shorter interconnected segments. A discussion on this during multi-scale analysis of datasets is warranted and currently missing. This could be addressed in the discussion near line 123-128. Suggestion: if available, please show the regional scale fault lengths vs displacement to ensure consistent relationships exist, and thus the proper/meaningful fault lengths are recorded.

5) I am skeptical of the micro scale dataset. It seems like the data was collected from a single sample located within or very close to a major fault (Group 3). This very specific location is likely not representative for the background micro scale fracture set as it was specifically chosen based on its micro-fractured appearance. However, this sample ties the scaling relations in Fig 8 to 8 orders of magnitude. I would have liked to see several samples and thin sections at random locations. The micro-scale data is questionable in terms of expansion of the scaling relations. A discussion around this uncertainty needs to be included.

6) The MS would benefit from an expansion through additional plots / discussions to compare observations to other multiscale studies. (for example, Hooker et al, 2014, and additional references listed in line 62)

Specific comments, referenced to line item:

19) clear separation between FAULT width and FRACTURE aperture. However, in most part of the MS faults and fractures are grouped together in the collected and analyzed dataset. Why discuss them so separately in this abstract?

24) both "fracture and fault" length. . ..be more specific consistently when faults and fractures (opening mode?) are addressed as a group and when not. (at this point the reader has not yet seen the discussion on faults / fractures being addressed as a grouping. Although the MS specifies what is meant with faults and fractures in terms of terminology, there is an inconsistent use of these terms throughout the MS.

37) Please be more elaborate on the "heterogeneous distribution of natural fracture systems". It will be good to inform the reader (through proper references; e.g. Narr et al., 2006) what the cause/implication is of this heterogeneity. Unless familiar with natural fracture systems, the reader might not find it straightforward that fracture systems have an inherent degree of heterogeneity.

62) . . .results from multi-scale sampling. . . I do like the statements made her in the MS to highlight the importance of multi-scale sampling and the fact that most outcrop studies focus on given scales. However, a discussion might be warranted here on what previous multi-scale studies have found and how this is different from this MS attempts.

78) . . ., 2019), we do (add comma)

80) fracture attribute (remove "s")

82) In most reservoir models, only a portion of the fracture system in modeled that is responsible for fluid flow to address the primary production of the reservoir. I would add the importance of this study to "secondary recovery mechanisms" and studies

associated to that, as the entire fracture system is of importance when injecting to improve sweep efficiency.

101) correct sentence but the 5 commas on one sentence is confusing. Please restructure the sentence.

105) Reference the Terzaghi method for completeness.

131) Did you mean "Ideally, the best-fit in a power-law distribution at given scale, should be consistent over several orders of magnitude."

177) Suggestion: move geological setting to Ch 2, so that the outcrops are described before the method of data collection. During the review I have gone back and forth on this, as there are pros and cons to moving it to Ch 3 as currently in the MS.

189) More discussion needed on similarity and difference of outcrop as analogue. The different tectonic setting can have a major impact. Again, I don't doubt the statement that this is a good analogue. But more detail here on details why it is a good analogue or why it might not, is necessary.

258) did the field verification add any information on the actual lengths measured on images vs lengths measured in field? This comment goes back to the influence of the scale of observation to fault/fracture length.

279) What is the evidence/observations for the statement that the sets were both active at the same geological event?

290) Single sample, chosen based on its micro-fractured appearance, within (or near) one of the major faults. I am skeptical if this Sample is a good representation of the micro-scale to extend the scaling relations, or if this sample is only representative for sections within or near faults. More samples, chosen at random locations would have strengthened the MS.

389) is this an effect of exhumation processes that have enhanced fracture apertures

of open fractures?

467) How does the exponent compare to other datasets that underwent box counting? What is the meaning of a similar exponent? Is there a physical process behind this or is this a specific character for a fracture system, confirming we are examining fractures of the same population?

568) 14cm aperture, and likely larger exist but difficult to sample with core as the change to intersect is very very slim.

602-612) Confusing terminology: refer either to fracture or fault, but be consistent

634) replace “faults” with fracture

664-665) Figure references: 11a and 11b

672) remove this section from the conclusion. Its location suggests this is a major part of the MS, but its discussion in the text does not warrant that.

Figure 3: Missing labels c and f

Figure 8: To me this is the main figure of the paper. I suggest enlarging figures a) and b) to a larger size as its challenging to read all the “extra” info in the plot. They deserve to be bigger.

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