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Solid Earth
Discussions

Interactive comment on "Mapping the fracture network in the Lilstock pavement, Bristol Channel, UK: manual versus automatic" *by* Christopher Weismüller et al.

Christopher Weismüller et al.

c.weismueller@nug.rwth-aachen.de

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We thank Roberto Emanuele Rizzo for the detailed and helpful comments on the manuscript.

A main criticism was that the manuscript was quite hard to read, particularly in the results section where it goes back and forth discussing the data obtained from manual and automatic methods. In the new version of the manuscript we have taken special care to clarify which methods we are referring to in the narrative. We revised the results section accordingly and further divided the section into sub-sections for a clearer structuring therein. Throughout the manuscript, we further improved the narrative for

a better readability. Another major point of criticism was that some of the claims presented in the manuscript were not always well justified. We agree that some of our claims required further explanations and citations and provided those for the addressed cases whenever possible. For the cases where we were not able to provide a sufficient amount of evidence or citations, or when the latter would raise questions out of the scope of this study, we removed the claims from the manuscript accordingly. Detailed comments on the individual points raised by the reviewer are provided below.

Lines 147-148: Can you please provide an example for this, e.g. image/figure

Reply: The section was moved a few lines up according to the suggestion of the other reviewer. We added a figure showing examples of the ground truthing to the supplement (new S1).

Lines 150 – 151: I don't disagree, but I would not say that is "obvious"; for example someone else can claim that they choose to manually pick all fractures because this yields the best results, due to the topography of an outcrop or light exposure during image acquisition.

Reply: We agree that "obvious" was not the best choice of words. The "obvious" was replaced according to the suggestion of the other reviewer to clarify, that we refer to the need of a more rapid technique.

How long is a "reasonable time"? How do you account for it?

Reply: The initial choosing of words did not provide clear information, we have revised the sentence for clarity and provide quantitative estimations. More information about the time required and extrapolated to the complete outcrop was added to the section below.

In this regards, can you please give an overall estimate on the time needed by the automatic process to extract all the fractures from one of the tiles (including all the steps for preprocessing an image and the number of trials needed before finding the

right set of parameters to extract the fractures) and compare this on how long it takes manually? In my opinion this would be a very interesting information. In addition, for someone that has never done fracture tracing would learning and using the software make the job faster/easier or it would take longer than do it directly manually? Can you please comment?

Reply: We agree that these points are very interesting for the reader. This was also one of the main comments of the other reviewer, therefore, we added a narrative in the methods parts explaining the required time under different aspects for each of the two methods in detail, incorporating the tracing itself and the time required for the removal of artifacts. Further points were added in the discussion giving an estimate what time would be required to trace the whole dataset using either technique. Also, we have added a short explanation to highlight the pros and cons for someone who has never done fracture tracing for both techniques. As explained in the manuscript, the dataset requires the interpreter to make judgment calls on several occasions, thus this task might be challenging for someone who has never done fracture tracing before. With the help of the automatic trace extraction, the results would be unbiased and easier to reproduce by another interpreter. Timewise, an unexperienced interpreter must either face the learning curve of the GIS software (or any other software used to manually trace the fractures) or MATLAB for which the automatic trace extraction code is written. Depending on personal preferences, either learning curve might be steeper. For small datasets and an unexperienced interpreter, it might be faster to do everything manually, but if larger datasets are to be processed, the time invested for learning the automatic trace extraction is compensated by the time saved during the application of the method.

Line 156: Can you please report which software have you used during the manual digitalization of fractures? Was it one of the vector graphics editors (e.g., Adobe Illustrator, Corel Draw, Inkscape), or a geographic information system-based software?

Reply: This information was accidentally removed during an earlier revision of the manuscript. We now clearly mention the use of ArcGIS at this point.

Lines 170 – 173: You never mentioned before any “intensity” parameter; can you please clarify? In addition, when discussing the needs for applying an ‘intensity threshold’ do you mean that this process is needed in order to make the automatically detected maps look similar to the original photograph from which you extracted the fractures? If this is the case, this sentence needs to be clarified.

Reply: The “intensity” in this case refers to the chosen parameter combination during the automatic extraction. We have slightly revised the sentences to clarify and cited Prabhakaran et al. (2019) for further information on the topic for the interested reader.

Line 175: For completeness, can you please briefly explain the ‘polygon sampling’ strategy?

Reply: We added a narrative to briefly explain the polygon sampling strategy as discussed in Nyberg et al. 2018.

Lines 179 – 180: The sentence “2D fracture networks ...” needs a citation. Can you please clarify the meaning of “spatial graph”? In addition, can you please clarify the terms ‘node’ and ‘edge’? In the context of fracture networks, these can mean different things, depending on whether the fractures themselves are viewed as graph vertexes (and therefore they are the ‘nodes’), or if they are considered as links (the ‘edges’) between fracture intersections and terminations.

Reply: We added a citation as suggested (Sanderson et al. 2019) and also added some sentences to better explain the meaning of “spatial graph” and our use of the terms ‘node’ and ‘edge’ with respect to their use in literature.

Lines 187 – 188: On lines 156 – 157 you mentioned that when manually tracing the fracture these are “traced as polylines”. From the use of the prefix ‘poly-’ I have understood that one fracture trace is already made of many segments. So, can you please explain the need to further subdivide the fracture traces?

Reply: The term “polyline” is used according to its definition within the ArcGIS envi-

ronment: “A Polyline object is a shape defined by one or more paths, in which a path is a series of connected segments.“ Therefore, it is correct that one manually mapped fracture trace consists of a polyline made of many segments that share the ID of the polyline. However, NetworkGT only allows single segments (stored with an individual ID) as input, therefore we had to dissolve the polylines first. We have added a narrative to point this out for the reader along with a more detailed explanation.

Lines 191 – 192: Can you please clarify if the correction for node degree > 3 was your improvement on the software, or it is already and option within of the original NetworkGT?

Reply: In the manuscript we state that nodes with a degree > 4 (X-node) are not supported/implemented in the code of NetworkGT and, thus, returned as error. To fix these resulting errors, we developed our own method to correct these errors resulting from the application of NetworkGT. We revised the sentence to make this point clear.

Lines 192 – 194: Can you please clarify and give more details on the use of the “spatial join function”? How does it work?

Reply: The spatial join function is provided in the ArcGIS Analysis Toolbox and can be used to join features based on different parameters of their spatial location. We added a few sentences to give more details on the topic and provide a better explanation on how we applied this function to our data.

Lines 214 – 215: What is Passchier et al., interpretation? The paper is not published yet, so unless you clarify it is not possible to know how these features have been interpreted. Even if the paper was published, it would be more helpful if you could briefly explain this interpretation here, otherwise the reader would be forced to read another paper to understand what you mean.

Reply: In Passchier et al. (in prep.) we introduce the initial interpretations of the generations on a larger scale of the outcrop, which helped to identify the criteria on which we

base our interpretation of the generations in this manuscript. However, the criteria we used and present in this work are self-sustained, explained in detail in section 3.4 and do not require the citation of Passchier et al. (in prep). We now refer to this citation as a companion paper only once and earlier in the manuscript and rewrote the narrative to clarify, that the interpretation of the generations is based on the criteria explained in this manuscript.

Line 218: You can avoid the brackets here because you are directly mentioning the authors.

Reply: We revised the sentence according to the suggestions of the other reviewer. In the revised sentence, the brackets are now necessary.

Lines 223 – 224: Can you please explain why have you chosen to show exclusively fracture intensity maps? To my knowledge NetworkGT allows also for fracture density maps, why have you opted for not showing these?

Reply: In the initial version of the manuscript we only presented fracture intensity because fracture intensity shows the total persistence of fracture segments within the domains, while fracture density only gives the amount of fractures segments per unit area. Fracture segment density was assumed to be of lesser interest because we already stated that automatic trace extraction produces more trace segments than manual tracing (of whole fractures and splitting them at the nodes), therefore, higher densities for the automatic extraction are just the logical consequence. To provide a better comparison of the methods presented in this manuscript we revised the section following the suggestion of the other reviewer and now also incorporate fracture segment densities throughout the domains. We have added two figures comparing the results for both methods, further material to the supplement, a new subsection introducing the results of P20 for both methods and a narrative to explain why we now investigate fracture segment density and intensity with implications for the two methods.

Lines 228 – 229: This sentence is not clear. Do you mean that number of trace seg-

ments is higher than the actual count of fractures? Or do you mean that the automatic extraction of fractures overcount the total number of fractures compared to the manual interpretation?

Reply: The automatic code generates segments, while a manual interpreter maps the complete fracture from tip to tip which represents the path along several connected segments. We revised the sentence for clarity and now better explain the difference of the results and how to process the data to make a comparison possible by splitting the manually traced fracture traces into segments analogue to the ones generated automatically.

Line 239: If not resolvable from the drone images, was the 'minimum length' measured directly on outcrop?

Reply: The section was rewritten according to the suggestion of the other reviewer. Now it is clarified that we are referring to a cutoff length within the sampling windows. These short segments are the result of the tracing and cannot be verified because they are below the resolution of the ortho-mosaics.

Lines 239 – 247: Are all these results relative to the manually traces fractures, the automatic, or both. Not clear. Moreover, can you please add few lines to describe more in details how all the statistical parameter that you show are useful to describe the fracture network? What having a positive kurtosis means? Similarly, can you please better explain what do you mean by symmetric and asymmetric branch distribution?

Reply: We revised the whole section and divided it into sub-sections to make it more clear to which results (manual or automatic) we are referring to. The section describing the statistical parameters has been extended to provide more detailed explanations of the parameters and their meaning or implication for the network.

Line 246: Data of fracture trace length distribution are only shown for the automatic trace detection method, but not for the manually derived network. Is there a reason

for this choice? Since you are discussing both methods, and relative results, I would advise to add a similar figure to Fig.7 where showing data from the manually traced network.

Reply: To follow the initial narrative of the manuscript, we stated that the results of both methods are comparable anyway and, thus, we only used the results of one method to describe the network. Now, that we have revised the narrative to an even larger focus on the comparison of both methods, we have added a similar figure presenting the manually traced segments as advised and also added a section that compares both methods using the results presented in the figures.

Lines 248 – 250: This sentence is not clear. Can you please review it? Are you referring to a limitation of the automatic extraction method?

Reply: Yes, this is what we are referring to. The sentence was revised according to the suggestion of the other reviewer for clarification.

Lines 250 – 253: For helping the reader to compare/contrast the results of automatic vs. manual method, I would suggest adding to Fig.5 and Fig.6 (which currently only show results for the automatic extraction) the fracture maps obtained by manually picking fractures. I acknowledge that these figures are shown later in the manuscript (figures13, 14 and 15), but having the fracture maps produced with the two methods one next to each other would be ideal.

Reply: We agree that a direct comparison of the networks resulting from the techniques is interesting for the reader. However, this would require another very large figure for the networks and the branches and nodes to be visible, and break the narrative at this point of the manuscript. We present a figure that directly compares all networks using P21 in which the networks are shown in the background of the plots and can be compared there with the advantage of different P21 values pointing the reader directly to locations where the methods have different results. Furthermore, we have added examples of two areas which are compared in detail using P20 along with supplementary

material that shows P20 with the networks plotted in the background in the supplement. For the interested reader, the shapefiles are also provided as supplementary material and can compared using a GIS.

Lines 223 – 261 (all section 4.1): The whole section is a bit confusing and needs to be reviewed. It is never clear if you are referring to the results obtained by the manual of the automatic method. For clearness, I would suggest to first describe the results obtained by one method, followed by those obtained by the other, but I do not want to impose any style to your paper. As long as you make it clear which method you are referring to, find a way that you like better.

Reply: We agree that the initial version of the section was a bit confusing. We revised the whole section for clarity in our narrative and divided it into several subsections to better compare both methods, following the suggestion of the other reviewer. Within the subsections we also revised the narrative to avoid confusion between the two methods and now state clearly which method we are referring to.

Lines 275 – 277: I understand that you are referring to the plot of fracture length vs. strike, however as written here it is not very clear. Please review.

Reply: We revised the sentence to clarify that we refer to the relationship of strike and length of single fractures. Also, according to the comment of reviewer 2, we rewrote the sentence to avoid confusion with statistically defined clusters in the plots.

Line 287: Is the fault to the Southeast corner of the tile NE2, or to the southeast to the whole outcrop? Please clarify.

Reply: The sentence was revised to clarify that we are referring to the relative position of the fault to the sample window.

Lines 288 – 289: This sentence is rather confusing. Can you please review it? Particularly, can you please clarify the meaning of 'perceived appearance'?

Reply: We revised the sentence and deleted the term "perceived appearance" to avoid

confusion. Now we state clearly that we refer to the generation 3 which is present in the network of the domains in the SW but not in the NE.

Lines 290 – 291: There is a 'IN' missing between 'domains' and 'the SW'.

Reply: We added the 'in'.

Line 314: Should be 'strike at angle'.

Reply: We replaced "in" with "at".

Line 390: I understand that you might don't want to engulf the paper with too many figures, however, because you discuss largely around Figure S1, in my opinion this should be incorporated in the main paper, rather than be relegated to supplementary.

Reply: We agree with this point and added the supplement S1 as figure to the manuscript within the revised section 4.1.

Line 396: Would it be more appropriate saying 'automatically extracted fracture network' rather than 'generated'? Usually the term generated is associated to Discrete Fracture Network (DFN) models.

Reply: We agree and changed the wording accordingly to avoid confusion

Lines 401 – 402: Point (i), as written, it can be interpreted that the fractures are in the 'code', while the algorithm extracts these features from an image. Please amend. Point (ii), can you please expand on this point?

Reply: We revised (i) to avoid confusion. Now it is clear that the code extracts the fractures we refer to. Furthermore, we expanded (ii) by providing more explanations and details in the following sentences

Lines 402 – 404: As written these sentences are very difficult to understand. Please review them.

Reply: We revised the sentences for clarity. As suggested by the other reviewer, we

also added a new figure with more detailed explanations to the manuscript to provide examples of the cases discussed in these sentences.

Line 404 – 405: Can you please give more details about this procedure? It is not clear to me if you have completely discarded erosional features from the network created when manually tracing the fractures. In addition, the sentence needs to be reviewed: missing 'AS' between 'not' and 'fractures'.

Reply: In this sentence we refer to wrong positives in the automatic extraction caused by a rough surface and a too high sensitivity (in terms of the chosen parameter combination) of the code. We added a more detailed explanation of the issue and rewrote the sentence to clarify.

Line 405 – 407: Can you please provide a full description of what do you mean by 'sensitivity'? This term has not been used before in the manuscript, therefore needs to be fully explained. In addition, I would avoid the use of vague adjectives like 'too high' or 'too low'. How much? Can you please quantify?

Reply: We revised the sentence and replaced "sensitivity" to clarify that we refer to the parameter combination chosen during the automatic tracing, what is explained with more details earlier in the manuscript. The sentence and complete manuscript were revised to avoid vague adjectives as suggested, using qualifications instead.

Line 409: As per my last comment before, can you please quantify 'Slightly smaller'.

Reply: We replaced "slightly smaller" by stating a quantity.

Lines 411 – 413: Rather confusing sentence. Do you mean that the dissimilarities between automatic and manual extraction of fractures are comparable to differences between two manual interpretations? Can you provide any evidence for this? Otherwise can you cite appropriate works?

Reply: Yes, this is what we wanted to express. We revised the sentence for clarity and added a citation of a work that compared manual interpretations of fracture networks

to back our statement.

Lines 418 – 421: Please review these three sentences as they are rather unclear. It might be necessary to add a 'the' between 'requires' and 'expertise'. What do you mean by 'several generations are possible for a single fracture'? That a single fracture can be overprinted by a series of tectonic events?

Reply: The sentences were revised according to the suggestions of the other reviewer for clarity. Now it is clear that we wanted to say that several generations can be assigned to a single fracture trace during the interpretation of the generations. Furthermore, we added a more detailed section below that includes a new figure to better explain the narrative besides providing more detailed explanations of the points discussed in the section.

Lines 422 – 423: Can you please clarify? Do you mean that pre-existing fractures can cause distortions in the orientation of later-formed fractures? How widespread such distortions need to be for not be considered just noise in the data (particularly if you have hundreds or thousands of fracture data)?

Reply: Yes, this is what we wanted to express. We rephrased the sentence to make this clear for the reader. In our cases, we have mainly observed this occurrence for old fractures that terminated at their tips within the sampling window. While this might be of minor relevance for the interpretation of generations, it is necessary to be mentioned for the analysis of the fracture network evolution with respect to its connectivity. There, we see that the tips of the old fractures (I nodes) are successively connected to other fractures until barely any isolated tips remain in the network. Therefore, we interpret this connecting of the tips as a common occurrence in this fracture network.

Line 426: Do you mean that fracture length is not a useful parameter to assign one fracture to a specific set?

Reply: Yes, this circumstance is caused by the censoring of the long fractures by our

map domains. We revised the sentence for clarity and added further explanations to point out that length as a parameter is biased in the presented case.

Lines 428 – 430: Are you still referring to the fracture set denominated Gen. 1? Not clear.

Reply: Yes, we are. We revised the sentence for clarity.

Lines 430 – 431: This sentence is not very clear and needs to be reviewed. What do mean by 'fractures as different appearances'?

Reply: We revised the sentence according to the suggestion of the other reviewer. Now we clearly state that we refer to the trend of the fractures in this case.

Lines 432 – 433: Can you please explain which one is this 'larger structure' that you are referring to? Not clear to me.

Reply: We refer to the fault as shown in fig, 1b. We have added the reference to the figure and "fault" for clarification. With the revised figure caption of figure 1, this is now clearer.

Lines 436 – 438: In the sentence before this you have argued that gen.1 and gen. 2 can be seen as belonging to one fracture set, however here you assume, without proving it, that these are instead two different fracture sets? Please either refer to a work that shows that gen1 and gen2 were indeed formed at different times, or please provide a full explanation for your assumption.

Reply: We revised the previous sentence according to the other reviewer. The explanation was expanded to further clarify, that we stuck to our initial interpretation because we cannot make a reliable decision in this case simply based on the abutting criteria, which allow several interpretations: either an interpretation as two consecutive generations, or as one generation in which the geometry of the abutting fractures simply represents the order of which fractures belonging to one generation developed. However, either interpretation leads the same result in the following analysis of the network

development because the relative order in which the fractures developed remains the same.

Lines 442 – 444: A citation is needed when you mention a mechanical cause for the lack of gen3 fracturing in the NE area.

Reply: The sentence was revised according to the suggestion of the other reviewer. The mentioning of a "mechanical cause" was been removed and we simply refer to the possibility of other reasons that are not within the scope of this study.

Line 449: what do you mean by 'complete distance'? Whole area?

Reply: Yes, we revised the sentence for clarity.

Lines 462 – 466: All these claims are not supplemented by sufficient evidences or by citating relevant works. How was the paleo-stress oriented at time when gen.4 was formed? Are there veins filling gen1 and gen2 fractures that provide cementation for the fractures? If this is the case, why are you mentioning it just now? Otherwise, do you mean that fluids circulating through gen1 and gen2 fractures caused further cementation in the host rocks near the fractures? If this is the case, you should provide evidences or cite relevant works.

Reply: We revised the section accordingly to the suggestions of the other reviewer. Now, we explain the situation more clearly and more simply state examples of possible causes without the need of additional citations that lead to details which are out of the scope of this study.

Lines 467 – 468: This sentence needs to be reviewed as it is not clear.

Reply: The sentence was removed due to the elimination of sinuosity in this manuscript as suggested by the other reviewer.

Lines 476 – 477: Can you please further explain the meaning of 'decreasing skewness'? How does this statistical parameter relate to the geometry of the fracture net-

work?

Reply: We added a sentence to briefly explain the reference, now also provide a clear link to the figures and tables showing the data. More details are now presented earlier in the revised section 4.1.

Lines 4879 – 481: I feel that it needs to be made clearer how the variations in the count of Y nodes and I nodes are related.

Reply: This part of section is supposed to discuss trends in the data visible throughout our domains and not intended to focus on the relationships of nodes. The appearance and relationships of different node types is discussed in detail a few lines below, still within the same section.

Line 483 – 484: How can you establish that a representative domain has been sampled? Can you show examples using your study case? It can be easy to argue that on outcrop the possibility of sampling a 'complete fracture network' are relatively scarce and relegated to few ideal outcrops.

Reply: This is the point we wanted to make at this position to highlight the necessity of a complete interpretation of the network. We present the criteria based on which we have selected our domains in section 2.2 and added further text at this part of the discussion to debate what aspects need to be considered when the domains are supposed to be representative for the complete network at this point.

Line 502: What do you mean by 'undirected fractures'? Can you please clarify?

Reply: We referred to generation 5 fractures which do not follow a clear orientation mode in all areas. We removed "undirected" to avoid confusion and revised the statement to one of a more general nature.

Lines 504 –505: Can you please provide examples that can prove this claim? And, can you please produce a conceptual model that exemplifies the described process?

Reply: This claim was non-unique and unsupported and not necessary to aid the narrative of the manuscript. Therefore, we have removed it from the manuscript according to the suggestion of the other reviewer.

Line 511: Do you mean that all subareas show comparable branch lengths? As now written is a bit unclear.

Reply: Yes, we revised the sentence for clarity.

Conclusions: While I like bullet points in the conclusion to show the main findings, I also feel that you should have few sentences that wrap up and recap your work. In addition, some of the points listed are a bit vague, specifically point 3 and point 5, as written, do not add any value to the work. So please either reformulate or delete them.

Reply: We added a introduction to the conclusion to recap our work presented in the manuscript. To account for the comment of the other reviewer on this chapter, we have also revised the bullet points. Former point 3 was reformulated and point 5 deleted.

Figure 1. Last sentence is not clear. Do you mean areas the labels show the areas where you have acquired the data?

Reply: The figure was revised earlier, and the changes of the captions were lost. We updated the caption, it now states that the map domains in which we traced the fractures are marked as the yellow (not red) squares in the figure.

Figure 4. Please add that P21 indicates 'Fracture Intensity'.

Reply: This clarification was added to the caption.

Figures 5 and 6: This is just a personal taste, so you can ignore it, but I would find useful if you can show in these figures the location of the analysed tiles.

Reply: The location of the analyzed tiles is shown in figure 1. This is now clarified by the revision of the caption of figure 1. Therefore, we do not include their locations additionally in the figures as suggested, because this would a repetition and further-

more reduce the size of the figures with the important content at this place, leading to a worse readability.

Figure 7. Since this plot refers to the automatic extraction method, can you please include in the caption that these are branch lengths and not trace (whole) fracture lengths? AS mentioned in the comments, I would suggest integrating this figure with the length distributions in the manually extrapolated network.

Reply: The caption was revised accordingly, and an additional figure showing the length distributions of the manually traced segments was added to the manuscript as suggested.

Figure 8. Similar to previous comment. Please indicate that these orientations refer to branches.

Reply: We now state explicitly that we are referring to branches in the caption.

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