REVIEWER 2 (CORRADETTI): COMMENTS AND RESPONSES

Reviewer comments in black, responses in blue. Where line numbers are specified in responses, these refer to the "track changes" version of the revised manuscript.

GENERAL COMMENTS

The manuscript by Adam Cawood and coauthors presents a remote-sensing study investigating the natural fracture patterns at Swift anticline in NW Montana. The study utilizes three datasets: satellite images, drone-derived SfM models, and field investigations with accompanying oriented photographs. According to the authors, this progression of datasets provides observations at low, medium, and high resolutions, respectively. It should be noted that one of the datasets presented has been previously published by the same authors, which is acknowledged in the manuscript.

Thank you for the detailed and thorough review. Note, the only data reproduced from Watkins et al. (2019) are the hinge trace position (e.g., Fig. 4, this manuscript) and the estimated fracture intensity, which we compare to fracture intensity derived from remote sensing data (Fig. 14, this manuscript). Fracture orientations derived from field data (e.g., Fig. 12 this manuscript) were not reported in Watkins et al. (2019) and are therefore original data for this study.

In general, the manuscript falls within the scope of the SE scientific field, and while the concepts presented are not entirely novel, they hold value for further exploration. The manuscript is well-written and exhibits clear organization. However, there are aspects of the methodology and data presentation that require additional clarification. For instance, it would be beneficial for the authors to elaborate on how the hinge trace was mapped, such as whether a 3D curvature map or bedding information was utilized.

Thank you for your comments. Your comment regarding the hinge trace is addressed in the responses to detailed comments below.

To improve clarity, I suggest including an early cautionary note in the manuscript addressing the limitations posed by vegetation cover and erosion at the study site.

Accept. We have added some text to lines 70-72 to acknowledge that vegetation cover and erosion may have impacted our results. Note that these factors are likely to influence fracture mapping at many outcrops and therefore Swift anticline is not unique in this respect.

Additionally, the explanation of fracture map analysis would benefit from further details, particularly regarding the consideration of bedding orientation.

Accept. Addressed in detailed comments below.

If available, providing a description and chronology identification of fracture types observed in the field would enhance the manuscript.

As noted in lines 102-108, the primary focus of this study is the extraction and analysis of fracture attributes from remote sensing data, with implications for extrapolating fracture properties across observation scales. As such, detailed, field-scale observations of fracture morphology (e.g., fracture cements and kinematic indicators) are beyond the scope of this work. While these types of

observations are of course important, our rationale for not including these data here are that we focus here on comparing field observations with results derived from remotely acquired data.

Below is a list of specific comments on individual lines of the manuscript, I hope the authors will find them useful and constructive.

Thank you very much. Your comments have been very insightful, constructive, and helpful. Detailed comments and questions are addressed below – we hope you find our responses satisfactory.

DETAILED COMMENTS

Line 16: Can we define a fault-related fold as a structurally complex setting, or are there additional factors to consider at the outcrop?

Accept. We have modified the text accordingly. Thank you.

Line 21: Regarding point ii, I apologize if I am misunderstanding, but it seems to suggest that any observations made approximately parallel or perpendicular to the hinge are indeed parallel or perpendicular to the hinge. Perhaps there is a clearer way to convey this, especially considering that fracture types and their intersections were not characterized in the field.

Accept. This is a good point, thank you. We have modified the text for clarity (Line 23).

Line 96: Considering the well-known relationship between fracture spacing and mechanical unit thickness, particularly in granular rocks, I wonder if any of these other parameters can be correlated without taking into account the mechanical unit thicknesses.

Our analyses did not provide any strong evidence for a relationship between bed (or mechanical layer) thickness and fracture spacing at Swift anticline (Fig. 1, this document). While we acknowledge that this relationship has been documented by numerous previous workers at other localities and that it may potentially influence fracture patterns at Swift anticline, we simply did not observe any compelling evidence for this here. As noted in the manuscript, we find that finer-grained units have higher fracture intensities. Presumably grain size relates to mechanical properties, and in this case, mechanical layer thickness does not appear to play a dominant role. As noted in the revised manuscript (512-518), it is possible that our bed thicknesses (Fig 5A in the manuscript, Fig. 1 in this document) do not accurately represent mechanical layer thicknesses. We did not assess this in detail during fieldwork and the digital outcrop resolution prohibits unequivocal determination of mechanical layer thickness in this case. It is possible that we overestimate bed thickness at the site because we do not consider internal laminations and partings within assigned units. Future studies could focus on collecting data such as Schmidt rebound measurements, fracture heights (i.e., strata-bound vs. non-strata-bound), and observations of bed boundaries. Despite these limitations, we contend that other factors can be considered without the need for explicitly accounting for bed thickness. Recent work by Bowness et al. (2022), for example, shows that mineralogy exerts a much stronger control on fracture spacing than mechanical layer thickness. We acknowledge your point about this relationship but contend that other factors may be much more important for fracture development.

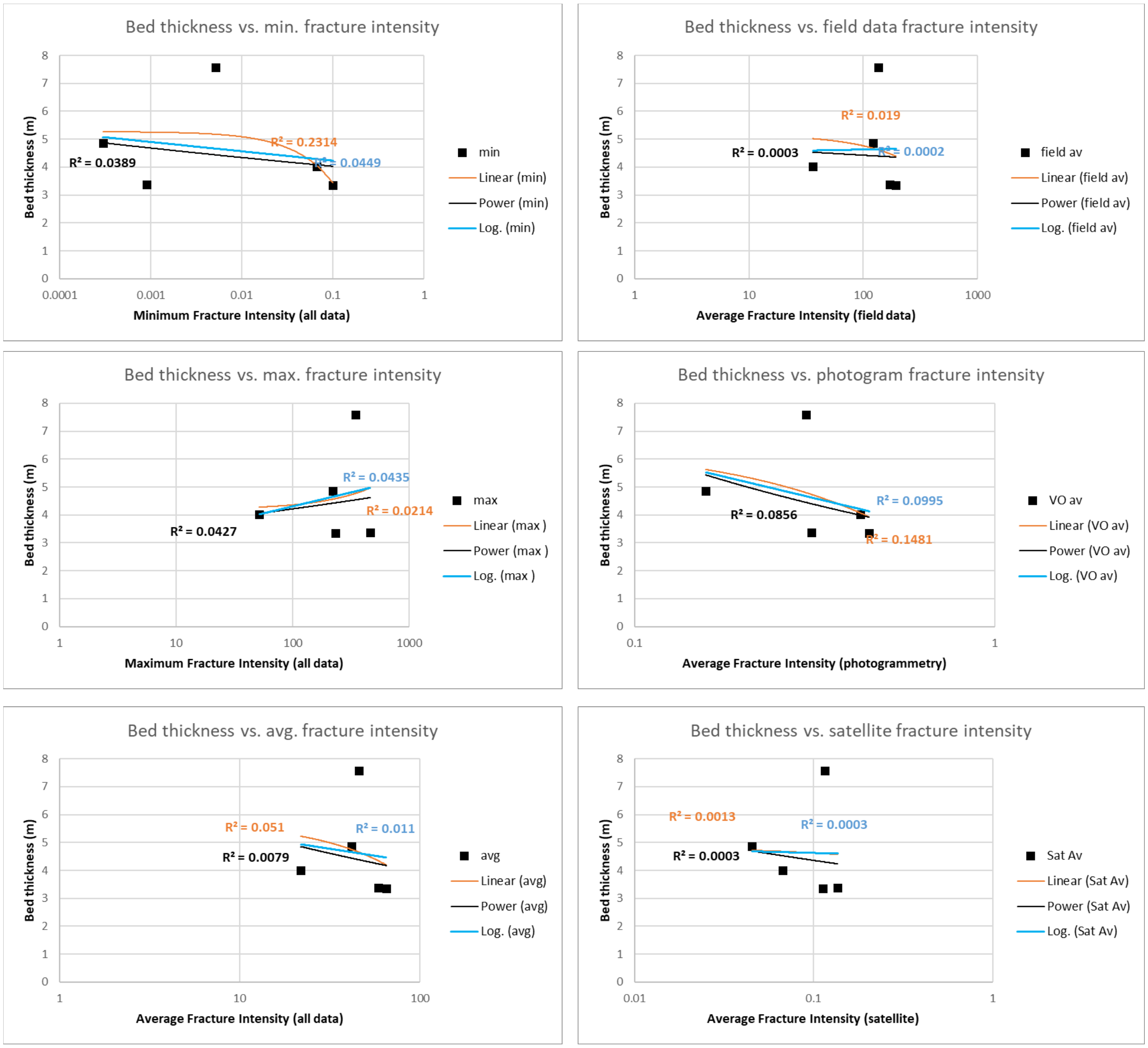

Figure 1. Fracture intensity vs. bed thickness for the five mapped units (S1-S5). Left column shows correlations between minimum, maximum, and average fracture intensity for all data. Right column shows average fracture intensity for mapped units vs. bed thickness, separated by data type (field data, digital outcrop, and satellite image). Colored lines show different fits (power, logarithmic, and linear) to data.

Figure 4: While I have not personally visited this anticline, based on the provided figure, particularly panels A and C, it appears that the exposed forelimb is limited, potentially due to erosion or vegetation cover. This prompts questions about how the hinge zone was delineated. Since a detailed 3D model of the fold is available, obtaining the curvature of the structure should be relatively straightforward. I suggest delving into this aspect further.

Thank you for the comment. Watkins et al. (2019) constructed a 3D surface of the top Castle Reef Formation from bedding data and field observations (see Fig. 5; Watkins et al., 2019). This constructed surface was used in part by Watkins et al. (2019) to define the hinge position. As you note, much of

the forelimb is missing at Swift anticline and therefore precisely defining the hinge position is not straightforward. Further, the stepped erosional profile and vegetation at the site make construction of a "clean" 3D model challenging. For consistency, we have used the hinge line of Watkins et al. (2019). We acknowledge that the position of this hinge line could be different from what is shown here and in Watkins et al. (2019) but because of the missing forelimb exposure, any estimation of the hinge position would have to be generated through construction techniques and this would be subject to uncertainties. We have added text (Lines 189-191) to clarify that the Watkins et al. (2019) hinge position was used in this study.

Lines 166: Please clarify what is meant by "characterizing overall structural geometries." The manuscript would have benefitted from a description of fracture types and their chronological identification in the field.

Accept. We have modified the text for clarity. As noted above, the primary focus of this study is the use of remote sensing data for fracture characterization. As such, detailed field-based observations (e.g., documentation of kinematic indicators) or laboratory analyses (e.g., U-Pb dating of fracture filling calcite) were not the primary focus of this study. We take your point about fracture timing etc. but this paper is essentially focused on the use of remote sensing data for fracture analysis – as such, we limited our analyses to observations of fracture patterns at multiple scales.

Lines 173-183: As a point of discussion, it is evident that the ground pixel resolution of these two datasets is insufficient to represent a change in scale; in fact, they are at the same scale.

While these data have pixel resolutions within the same order of magnitude, they have different scales if scale is considered as a graduated range of values.

I wonder if the difference in mapped fracture orientation can be attributed to variations in vegetation cover (assuming the datasets were acquired in different years or seasons) or differences in mapping strategies. For example, it is conceivable that the satellite photoset was analyzed solely in a vertical (nadir) direction, whereas the 3D model could have incorporated bedding attitude, thus always being perpendicular to the bedding. In this context, it remains unclear whether the bedding attitude was considered as it should be. Oblique fracture traces in relation to the hinge may exhibit different orientations when observed obliquely to the bed-perpendicular direction. Please provide a clearer explanation of how the data were handled.

This is a good point. In response to your concern regarding variations in vegetation, our images were collected in June 2016 and the Google Earth imagery is dated from July 2014. Based on the similar times of year that our data and the satellite imagery were collected, it is unlikely that major seasonal variations can account for changes in vegetation between the datasets. It is possible that more vegetation may be present at the site in our imagery than in the satellite data due to vegetation growth over two years (we saw no evidence for recent wildfires at the site so the converse is unlikely). This doesn't explain the lower fracture intensities from satellite imagery, however – if anything we might expect fewer fractures to be observed after several years of vegetation growth (i.e., in the digital outcrop data). Further, based on visual comparisons between satellite imagery (Fig. 4A in the manuscript) and our data (Fig. 4B and: https://sketchfab.com/3d-models/swift-anticline-montana-4c60c376a2984166843fc3391b2a85b7) there do not appear to be significant differences in vegetation patterns between July 2014 and June 2016.

Regarding orientations (again this is a good point), we conducted fracture mapping in 2D for satellite imagery and in 3D for the digital outcrop (by 3D polyline interpretation in in MOVE). 3D polylines from digital outcrop mapping were projected onto a horizontal plane for orientation and intensity analysis. While this approach does not correct for bed dip and the effects of orientation and intensity distortion, it allows 2D satellite and 3D digital outcrop interpretations to be directly compared within equivalent reference frames. There is no straightforward way to account for geometric artefacts in satellite imagery (e.g., steeper beds may appear to have more closely-spaced fractures in the dip direction than is real) and therefore we elected to treat all fracture maps as essentially horizontal. While this may lead to overestimates of fracture intensity in fractures oriented perpendicular to the dip direction, we consider this effect to be relatively minor at the scale of the analysis area. Note that most of the pavements exposed on the crest of Swift anticline have dips around 20^{O} or less and therefore we expect the effects of intensity distortion to be relatively minor. We do not account for orientation distortions because we do not have a reliable method (using the remote sensing approach) for estimating the 3D orientation of fracture traces. We could have rotated fracture traces using bedding orientations based on the assumption that all fractures are perpendicular to bedding. This assumption is not valid at Swift anticline, however, because of the variable dips of fractures with respect to bedding (Fig. 5B in the manuscript). Field images were interpreted in 2D with images oriented according to bed dip at each field station (i.e., images were rotated and scaled so that they had the same orientation as bedding). Fracture interpretations were projected to a horizontal plane for intensity and orientation analysis. Again, while this may introduce some minor geometric artefacts, this approach was taken so that consistency between datasets could be maintained. Text added to lines 211-225.

Lines 189-190: Once again, it would be beneficial to provide more information regarding the orientation of digitization in relation to the bedding attitude and the analysis of fracture traces (which may vary accordingly).

Accept. See details above and Lines 213-227 in the revised manuscript.

Figure 6B: It appears that vegetation significantly covers large portions of the fold. Therefore, using an overall map that compares vegetated areas with bare areas might not be the most suitable approach for assessing variations in fracture intensity. I suggest adding a cautionary note to acknowledge this limitation in the dataset if the authors, who are familiar with the exposure, believe that vegetation could be a factor affecting the data.

Accept. We have added text to Lines 70-74 to acknowledge this. As noted above, these factors are likely to influence fracture mapping at many outcrops and therefore Swift anticline is not unique in this respect.

Lines 301-302: I followed the link to the low-resolution model and found that its availability does not contribute significantly to the understanding of the area. Although I understand the size restrictions on Sketchfab, it may be worthwhile to improve the texture map, which is crucial in this context, to allow readers to visualize some of the mapped fractures. Additionally, why was a link provider used instead of providing a direct link to Sketchfab?

Unfortunately, despite multiple attempts, we have not been able to upload a clearer image of the study site via Sketchfab. As you note, size restrictions on Sketchfab are often prohibitively small,

particularly for outcrops of this size. The primary justification for providing this link is so that readers can get a feeling for the 3D nature of the site, rather than being able to observe all fractures in detail. As suggested, we have replaced the shortened URL with the native link.

Lines 333-334: Please specify if these discontinuous patches are clearly separated by covered portions of the anticline.

This "patchiness" is not because of vegetated areas on the anticline crest but rather because of change in fracture intensity on exposed bedding surfaces. (see Figs. 4 and 6 in the manuscript).

Line 336: How was the hinge position identified? Was the curvature of the 3D model used?

Accept. As noted above we use the hinge line of Watkins et al. (2019). See Lines 189-191 in the revised manuscript.

Lines 395-397: It may be repetitive, as I previously mentioned in the Methods section, but I am curious about how the fracture maps were analyzed. I presume field photographs were always acquired perpendicular to the bedding; was this consideration taken into account when comparing orientation data from satellite images? If not, please clarify for better understanding.

Accept. See detailed response above and Lines 213-228 in the revised manuscript.

Line 525: It would be helpful to present these observations within the data presentation section.

Accept. We have added this information to the results section on Lines 294.

Line 529: This is the first instance where difficulties in accurately estimating the fold curvature and, consequently, the fold hinge are mentioned. It would be more appropriate to introduce some of these aspects earlier in the manuscript. Based on my understanding, although I am not familiar with the site, it seems that the maximum curvature of the fold may be located further east than its interpreted position.

Accept. As noted above, we use the hinge line of Watkins et al. (2019) for consistency. We have added to text to Lines 189-191 to make this point.

Lines 531-543: Consistent with the initial stages of layer-parallel shortening, conjugate sets of strike-slip faults may have formed, aligning with the observed orientations at Swift Anticline. For example, refer to this review paper (10.1016/j.earscirev.2014.11.013) and the references therein. Since the position of the maximum curvature is speculative and may exhibit local variations, as demonstrated in this study, some of these earlier structures should be compared with the regional shortening direction rather than solely with the hinge trace.

Accept. Text added to include this point. Lines 593-605. Again, this study is focused on mapping fractures using remote sensing data. We absolutely acknowledge that conjugate strike slip faults may have formed at this site during the early phases of contraction, but given that we do not have unequivocal data regarding this, we have decided not to include this interpretation in the study. As we note above and in the manuscript, we do not have sufficient data to determine the timing of fractures at the site. Future studies could focus on this aspect.

Line 568: Should it be "during folding" instead of "after"?

Accept. Text modified accordingly. Thanks.

References

Bowness, N.P., Cawood, A.J., Ferrill, D.A., Smart, K.J. and Bellow, H.B., 2022. Mineralogy controls fracture containment in mechanically layered carbonates. Geological Magazine, 159(11-12), pp.1855-1873.