Solid Earth Discuss.,
https://doi.org/10.5194/se-2020-12-RC2, 2020

Interactive comment on "Stress field orientation controls fault leakage at a natural CO_2 reservoir" *by* Johannes M. Miocic et al.

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Received and published: 3 April 2020

My review comments for manuscript se-2020-12 written by Miocic and others are described herein. The authors present a body of work set on addressing how stress field orientation influences natural leakage along faults by combining geomechanical modelling of a particular fault bounding a natural subsurface CO2 accumulation with outcrop information. Although the methods and framework are not novel, the main idea communicated by the authors is that CO2 leakage occurred mainly along the northern tip of the analyzed fault, which coincides with the location of travertine deposits as well as areas of high fault slip tendency and fracture stability modeled along the fault zone using three potential stress fields derived from regional measurements. The authors go on to discuss the importance of valid stress orientation parameters in relation to CO2 stor-

age site modeling and evaluation. The key contribution that this manuscript provides is a strong correlation between unfavorable stress orientation and field evidence of CO2 leakage, where areas of leakage occur where the modeled fault approaches geomechanical failure under a plausible stress state. In general, the quality of the manuscript is high, often demonstrating appropriate levels of scientific thought, valid conclusions, adequate visual aids, and clear language. Section lengths are of appropriate length and the number of figures is satisfactory. Minor revisions to the manuscript are suggested and pertain mainly to providing more details and discussion with respect to the modelling parameters and the significance of the results in a geological context, as well as with revising minor items.

Overall, the authors do well to address most of the related subjects at a sufficient detail. Among others, these include considerations of regional stress orientation variability, timing of travertine deposition and leakage, and the lack of in situ stress measurements. However, several shortcomings were noted, but not limited to:

- Outcrop information (travertine mounds) provides a critical link between the geomechanical modeling and the observed leakage phenomena. What is lacking is the presentation of field observations to build and strengthen the validity of the author's models with respect to the fault parameters. Based on the text, it does not appear that the authors contributed or incorporated any new or direct field data. For instance, fault orientation measurements and fault rock observations from outcrop were not mentioned, but would bring confidence in the modeling parameters chosen by the authors. Perhaps this could be a possible avenue of future research.

- The parameters used to build the fault model heavily influence the results shown in figures 4, 5, and 6. Fault geometry (strike and dip) can have a dramatic impact on geomechanical modelling results, and at no point do the authors state them or describe why those values were used for building the fault. Also, no details about the fault mesh or grid were given to the reader. In most modeling programs, points on stereo plots or Mohr diagrams are derived from orientations either extracted from the 3D surface of the fault at each of its unit faces (mesh or grid) or unit vertices. Along with the number of points shown in figures 4 and 5, the authors could provide details about the modeled surface (mesh or cell size) and method of value extraction from the fault surface in Figure 6. This would provide the reader and future workers some idea of how to repeat the workflow and obtain similar results.

- Fault rock type is discussed and taken into consideration in the geomechanical modeling. Despite this effort, the authors do not provide an explanation as to why they interpreted the primary fault rock type to be either phyllosilicate (PFFR's, i.e., Fig. 2 from Yielding et al., 2010) or clay smears rather than other possible fault rock or fracture corridor types (such as some sort of deformation bands). The authors go on to assign values to geomechanical properties used in the fault model based on the interpretation of the possible fault rocks. The authors again fail to provide reasoning behind their decisions. To resolve this, the authors could provide reasoning behind their interpretation of the fault rock types (perhaps based on calculated burial depth and throw or outcrop observations) and associated modeling parameters (maybe with references).

- The stratigraphic section contains both siliciclastic and carbonate units, which have been displaced by the Coyote Wash Fault where the CO2 column is interpreted to be trapped along. Siliciclastic fault rocks were discussed in detail by the authors, while carbonate fault rocks could also be discussed or at least mentioned in the manuscript.

- The authors state that they have generated a 3D geomodel based on several sources of outcrop and subsurface data, and it is evident that the model has guided many of their interpretations and discussion points throughout the length of the manuscript. Aside from the 3D fault model in Figure 6, however, there is no presentation of the 3D model by the authors to aid the reader while reviewing their descriptions and discussion points. Aside from simply assisting the reader and showcasing the model, providing visuals from the 3D geomodel could be used to support arguments made by the authors. For instance, the authors mention several significant structural levels inside the closure of the Cedar Mesa Anticline with no visual aid, such as with the maximum clo-

sure height (300 m) or the additional fault-limited capacity based on the geomechanical model results (up to 160 m of additional CO2 than its current state). The authors go on to suggest that travertine deposits outside the current areal extent of the CO2 accumulation may have once been located with it when the structure contained more CO2 before leakage. This is stated without demonstrating this to the reader visually. A suggestion is to include more of the 3D model in the current array of figures. This could be in the form of structural contours for the top of the reservoir overlain in Figure 2 or a new map or 3D view of the model.

- With respect to the history of the faults in the area, it is perplexing that shortening in the Laramide created a normal fault. Reverse sense of movement would be exhibited in that case. Seems that this is more of a Basin and Range or Rio Grande Rift type structure, where extension lead to normal faulting and a footwall rebound anticline. Interpretations from the cited literature suggest inversion of a Laramide reverse fault into a normal fault later in the Tertiary during Basin and Range/Rio Grande Rift events. With that in mind, this detail should be reflected in the text.

- SHmax measurement locations were cross-checked with their mapped pattern in Figure 2. The pattern for the set of 8 points appears to agree with what is shown in Figure 2 except for point ID 4 (SHmax=61 deg, Connor et al., 1992), which plots much further south than what is indicated in Figure 2. This means that either the mapped location in Figure 2 is correct or the location form Table 1 is correct. Point coordinates were then checked based on their sources. WSM points from Heidbach et al. (2016) were validated, but those from Connor et al. (1992) were not. It was not clear from Connor et al. (1992) where the authors of se-2020-12 obtained both their SHmax azimuths and coordinate locations in Table 1. Could it be that the data was sourced from an alternative data repository? Two suggestions to the authors here include addressing the discrepancy between Table 1 and Figure 2 locations for point ID 4, and describing the origin/location of the measurements derived from Connor et al. (1992) in greater detail.

- The authors propose three potential stress fields for their model (A most-likely, B least-likely, and C-intermediate likely cases). To main a logical order, perhaps cases B and C could be switched throughout the manuscript so that B is the intermediate case and C is the least-likely case?

- The location of travertine deposits is clearly provided in Figure 2. However, the authors make mention to individual deposits with not enough details for the reader to understand which deposit(s) the authors are referring to exactly. Moreover, no attempt is made to communicate the different age of the travertine deposits on the map, which is important for discussing the logic behind interpreting the timing and mechanisms of the CO2 leakage events. It is suggested that the authors either provide a way to distinguish between individual travertine deposits (by location and possibly age) within the text or the figures.

- Although the authors make a logical case for leakage in the northern parts of the study area being related to the stress field acting on the unfavorably oriented Coyote Wash Fault, the possibility exists that CO2 point sources could have been located towards the northern half of the study area and influenced the pattern of travertines observed today? Some discussion on this could be fruitful.

- The figures in the manuscript are generally of good quality. While some minor adjustments could be made to Figure 2, several mapping errors were recognized after trying to georeferenced the map using the coordinate grid along its border. This was evident after plotting the SHmax points provided in Table 1 (aside from point ID 4 mentioned above), as the points on the map did not line up with the plotted points using the coordinates (see attached images for this review). WSM SHmax coordinates in Table 1 were verified with Heidbach et al. (2016), while points from Connor et al. (1992) could not be verified by reviewing the cited publication. If the Figure 2 map is georeferenced based on the WSM points, the map is distorted and the location of features (like Lyman Lake) do not align with satellite imagery. The same can be said if the Figure 2 map is georeferenced based on the Connor et al. (1992) points. The geographic features do

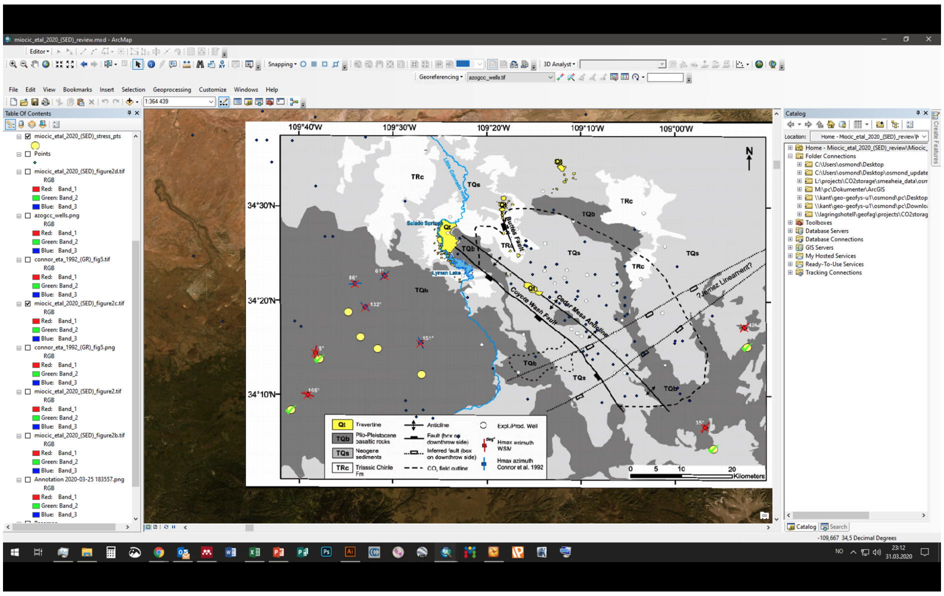
align with satellite imagery if the map is georeferenced to the well locations (I obtained the well locations using ArcMap online data searching Arizona oil and gas wells). However, even though Lyman Lake and other features are aligned, the SHmax points on the map still don't match the points plotted using Table 1 coordinates. Since all the data should agree, it is suggested that the coordinates along the outside of the Figure 2 map and the Table 1 SHmax coordinates are reviewed compared to the geography from the satellite imagery and the well locations. Any errors or reference system discrepancies should be corrected in the manuscript. Furthermore, it is suggested that additional culture data, such as state boundaries or highways, are added to the map.

All comments, suggestions, and corrections are compiled in the PDF document accompanying this review. Aside from the issues described above, most comments and suggested corrections were rather minor and are deemed easily addressed. Spelling mistakes and typographical errors were noted, but did not distract from the flow of the text. Time was put into correcting the format of the items in the reference list to match the SE style. On occasion, suggestions were made as an attempt to improve clarity or flow of the text. Minor suggestions of a similar nature were also made for figures.

Finally, I would like to take the time to thank the subject editor and authors for the opportunity to review this manuscript. This concludes my frist review of the se-2020-12 SED manuscript.

Please also note the supplement to this comment:
https://www.solid-earth-discuss.net/se-2020-12/se-2020-12-RC2-supplement.pdf

Interactive comment on Solid Earth Discuss., https://doi.org/10.5194/se-2020-12, 2020.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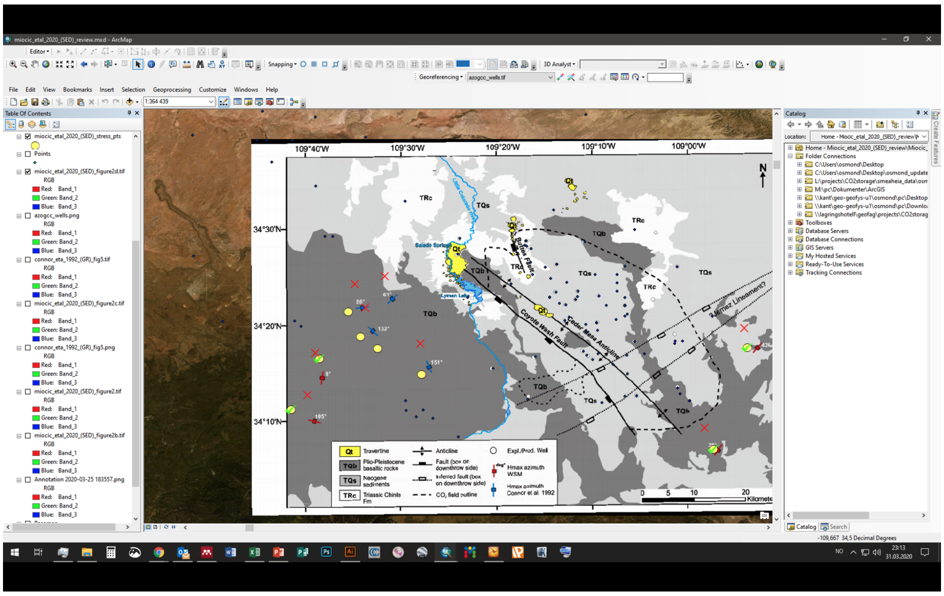
Travertine
Plio-Pleistocene basaltic rocks
Neogene sediments
Triassic Chinle Fm
Anticline
Expl./Prod. Well
Kilometers

Fig. 1.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Travertine
Plio-Pleistocene basaltic rocks
Neogene sediments
Triassic Chinle Fm
Anticline
Expl./Prod. Well

Fig. 2.

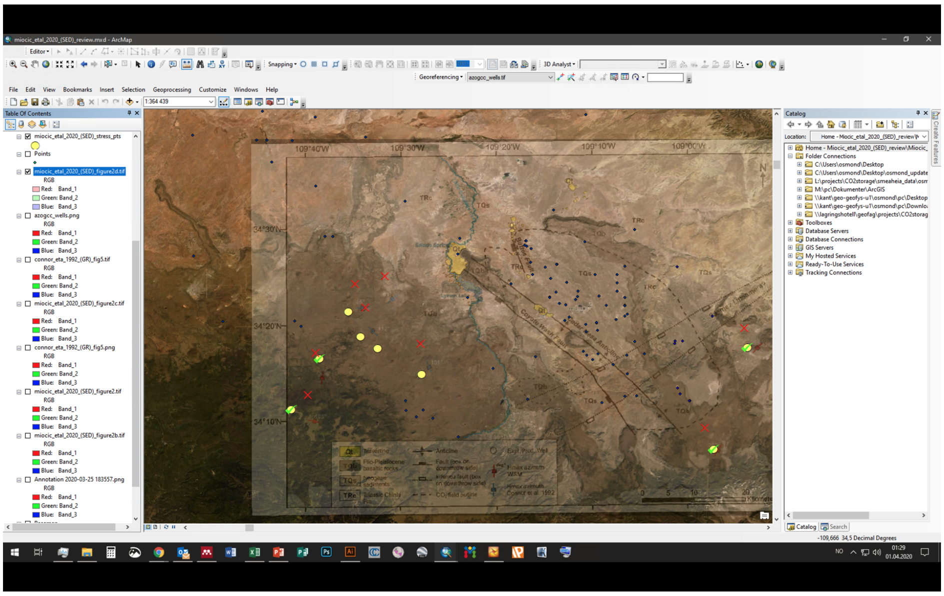

Fig. 3.