Solid Earth Discuss.,
https://doi.org/10.5194/se-2019-113-AC1, 2019

Solid Earth Discussions
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EGU

Interactive comment on "Fault reactivation by gas injection at an underground gas storage off the east coast of Spain" *by* Antonio Villaseñor et al.

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Received and published: 9 October 2019

First of all we would like to thank the helpful and constructive comments made by both reviewers on the manuscript. While the comments are generally favorable, the reviewers raise a number of issues that we would like to respond in this rebuttal letter.

A common criticism of both reviewers is the size of the figures and their labels and symbols. While the original figures had a reasonable symbol and font size, when combining them into multi-panel figures, the size was reduced. To compensate for this deficiency we have redone most of the figures to increase the visibility of symbols and labels, and also to include some of the suggestions by the reviewers.

Moreover, in order to address some of the comments, and to facilitate the re-

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Discussion paper

producibility of the results presented here, we have created a data repository where all the data used and modeling results are available. The link to the repository (https://digital.csic.es/handle/10261/192082) and the DOI of the dataset (10.20350/digitalCSIC/8966) have been included in the “Data availability” and References sections of the manuscript.

Now we provide detailed responses to the reviewers comments (in italics), followed by our responses (in normal font).

Referee #1, Dr. Heather DeShon

General Comment: The manuscript “Fault reactivation by gas injection at an underground gas storage off the east coast of Spain” by A. Villasenor, R. Hermann, B. Gaite and A. Ugalde presents improved moment tensor solution for moderate magnitude earthquakes associated with induced earthquakes occurring offshore Spain in 2013. The motivation was to resolve a depth discrepancy for the earthquakes, which currently exists in the literature regarding the event sequence, in order to better understand the causal link between the gas storage facility, faults, and triggered seismicity. The study provides a careful analysis of moment tensors constrained using surface wave data and crustal reverberations to conclude that earthquake depths were between 6-9 km below the surface, in line with reactivation of presumed pre-existing NW-SE trending basement faults, rather than the 2 km depth in other papers consistent with injection levels. The study hypothesizes that to pore fluid pressure diffusion away from injection changes stress on the pre-existing fault structure enough to induce primarily strike-slip earthquakes consistent with the modern stress regime, in line with current research on induced earthquakes in Oklahoma, USA, for example. The paper requires minor changes to the text and figures to ensure consistency.

We are glad to see that we were able to convey the main objective of the manuscript, which is the discrepancy between the injection depth and the focal depths of the largest earthquakes of the sequence.

Specific Comments/Questions: The authors favor pore fluid pressure diffusion to link injection at <2 km to faulting at >6 km. The authors establish that there is a lack of geologic information for the crystalline basement in the study area publicly available. Is there any indication in the literature that faults in the basement offset the overlying units or that there is an extensive fault or fracture network that could serve to rapidly transmit fluid pressure?

The main faults in the region are extensional faults formed during the formation of the Valencia Trough. These faults are known to cut to the basement and could allow pore-fluid migration. We have added a reference about these faults.

Lines 384-385 hypothesize that faults in the basement have a different orientation than faults in the shallow geologic formations. Is there any evidence from the regional data that this could be the case?

We have also added a sentence with a reference about these basement faults.

Are there any faults that could be added to the figures to aid the reader in understanding the overall geologic setting? On lines 341-344 the authors reference faults as plotted in other studies but could these be added to the figures here for clarity?

According to the suggestion, we have plotted in Figure 1 the active faults included in the Quaternary Faults Database of Iberia (QAFI), which is the most complete and authoritative dataset of active faults in the region.

Is triggering via poroelastic stress change necessary?

Poro-elastic stress change is not the only mechanism for earthquake triggering. In fact a recent publication in Science (Bhattacharya and Viesca, 2019) suggests that aseismic fault slip could propagate faster and to larger distances that pore-fluid migration, which might be relevant for this case. Therefore we have added this reference and a small discussion to the manuscript.

Supplementary Material: It was not clear to me why the information in the supplement

(1 paragraph essentially and 1 figure) was not included in the main text. It seemed a valid question worth addressing in the main text. I leave it to the authors' decision however.

We agree with this suggestion. To incorporate it, we have eliminated panel b in Figure 4, and created a new Figure 5 with the comparison of goodness of fit versus focal depths for different frequency bands. However we have kept the Supplementary Material and increased it with another figure.

Citations: In addition to Yeck et al. and McNamara et al., this paper could cite a review paper such as Keranen and Wiengarten (2018), Induced Seismicity, Annual Review of Earth and Planetary Sciences, Vol. 46:149-174, https://doi.org/10.1146/annurev-earth-082517-010054

We agree with the suggestion and we have added this reference to the manuscript.

Figures: In general, the graphics clearly illustrate the points made in the main text. The fonts on the legends are very small, however. There is also a change in color scheme for data vs modeled waveforms in the main text and supplemental figure; red should be consistently used for modeled waveforms with blue/black used for observed data.

We have increased the size of the fonts in most figures, and used a consistent color scheme (red for data and blue for synthetics) in Figures 4, 7, and S1.

In Figure 2, the size of the circles make it difficult to tell the difference between EGF phase and group velocity (though of course the offset in c/U makes this clear).

We have made this figure in color to make it easier to distinguish the different symbols.

In Figure 5, the color bar is marked incorrectly. For example, red is 4 but having the 4 on the far left such that both 4 and 5 bound the red in the color box is not correct. This ends up making 9 and 10 km depth the same color, though there are at least 2 earthquakes at 10 km depth. Most importantly, what are the grey anastomosing lines? They are not referenced in the text or the caption for the figure.

To avoid confusion we have eliminated the triangles at the extremes of the color palette and added one more color for 10-11 km depth. This way earthquakes with different depths are represented with different colors.

The grey lines in Figures 5a,b represent the traces of faults at 1700 m depth obtained by Geostock (2010) from the more detailed 3D seismic studies carried out to delineate the reservoir size. This information should have been included, and we have fixed it in the revised version.

In Figure 6, the open circles and font sizes associated with the cross-correlation column are too small. The open circles can just be made solid, which may solve the small line width issue.

We have modified this figure (now Figure 7) to make labels and symbols clearly visible

Please also note the supplement to this comment:
https://www.solid-earth-discuss.net/se-2019-113/se-2019-113-AC1-supplement.pdf

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