8-27-2021
Chet Hopp
Postdoc
Lawrence Berkeley National Lab

se-2021-84 Reviewer comments:

Overall assessment:

In “Seismic monitoring of the STIMTEC hydraulic stimulation experiment in anisotropic metamorphic gneiss”, Boese et al. present an overview of the seismic monitoring network installed at the STIMTEC site in the Reiche Zeche underground lab, as well as a number of analyses focusing on wave propagation and seismic event location in the experiment volume. In particular, the authors focus on deriving a velocity model that accounts for anisotropic propagation speeds of seismic waves and the velocity model’s effect on the location uncertainty of the detected acoustic emission events. The authors also do an excellent job of placing the STIMTEC experiment and results in the context of the growing body of underground lab work and the publication of these results will be a significant help to a number of researchers (myself included). The paper is very well written, logically organized, and worthy of prompt publication.

I’ve made a number of minor comments below, some of which are maybe more conversational than anything else. I do think the paper would benefit from a better illustration of the network geometry and distribution of events, as well as to more complete summary of the entirety of the STIMTEC stimulations. As it is currently, the paper focuses on the calculation of velocity model parameters with some asides to mention the relocation of a broadband sensor or to show the relationship between the rate of seismicity and hydraulic parameters for a couple of intervals. My suggestion would be to either 1) more completely document these tangential parts of the paper, including more clearly relating the broadband data to hydraulic data and documenting all of the intervals (not just the two shown in Figure 6), or 2) refocus the paper on determining the velocity model parameters and their effect on the AE locations. My personal preference would be for option 1) given that this will provide a robust foundation for further STIMTEC publications. I don’t know what the STIMTEC manuscript-in-prep ecosystem looks like, so I, of course, leave that to the authors.

The paper was a pleasure to read and I look forward to seeing the revised version.

Chet

General comments:

The formatting of the equations is a bit hard to follow (D*, for example). I’ll admit that even Thomsen needed two lines for that one.

The citation Renner et al., (2021) isn’t yet available and is cited differently than in the author’s ARMA paper. Is it a special issue to be published at the end of the year? Apart from conference proceedings, Renner is the only other potential publication detailing the STIMTEC experiment. Unless I’m simply missing another overview paper (entirely possible, and apologies if that’s the case), then I think this current work needs to include some additional detail about the seismic network, making it the ‘go-to’ citation for further work (see comment on line 286).

Below, I also mention a need for better visualization of the network, seismicity, or (ideally) both. Something similar to the author's figures in the ARMA paper on the AE hydrophones (Fig 2, specifically) would help show the reader the vertical and map-view distribution of sensors and seismicity and confirm that there are indeed distinct clouds for the two stimulated boreholes.

Specific comments:

Ln 101: We're using Continuous Active Source Seismic Monitoring (CASSM) in our meso-scale experiments at LBL. Admittedly, the publications from URLs (Mont Terri or SURF) are only in conference proceedings so far, or not yet completely analyzed...But there are some cases of CO_2 plume imaging, for example: https://doi.org/10.1002/2017JB014164 Feel free to cite only if you think it's pertinent to the point you're making.

Ln 124: Here's the most recent analysis of the Collab seismic data, hot off the press: https://doi.org/10.1029/2020JB020840

Ln 187: I'm a little confused here. You're trying to maximize the angle between the foliation and injection borehole, correct?

Figure 1: Hard to show on an oblique view, but what's North? I may have missed this, but is the driftway oriented due North?

Ln 269: Previously you mentioned the EDZ is up to 10 m in width. How did you determine you had drilled beyond this with the 1.5 m holes?

Ln 286: Not strictly relevant to the analyses in this work, but since you're setting the stage for future analyses (and there appears to be no other review of STIMTEC published), a little more detail on the installation would help (selfishly, it will also help me with EGS Collab and other future experiments too!)

- How are the GMuG sensors clamped to the borehole wall?
- How are the Wilcoxons installed? Are they potted in some sort of housing? Are they also clamped? If they're potted, has the effect of the potting on the frequency/phase response of the sensor been characterized (these will be used as the ground-truth for the calibration of the AE sensors, correct?).

Ln 333: So all center punch shots (50, 130, 250N) were recorded on all accelerometers? Another selfish clarification, as I'm hoping to use this technique at EGS Collab.

Ln 335: Are the magnitudes still in the works and intended for a separate paper? I see a hint at relative magnitudes in the ARMA paper.

Ln 348: Just clarifying: The UT surveys comprised 1024 pulses at each meter along the injection borehole, correct? Is this a single transmitter, or a multi-level string of them?

Ln 350: I'm not familiar with UT sources. Can you please give a little more detail on what it is and how it's deployed? Also, what do you mean here by 'different orientations'? Is this because the UT sources have an irregular radiation pattern that you're trying to account for? Or do you mean different orientation as in, 'different position in the borehole'?

Figure 4a: I don’t think you state anywhere what the direction of the black uncertainty vectors signify. Also, is it a coincidence that the more highly fractured zones at the top and bottom of the borehole correspond to the zones of higher uncertainty and also the zones where your array coverage is poorest (i.e. larger azimuthal gaps)? It’s a little difficult to make out the network geometry with this one oblique view. Can you provide a map-view and a cross section along with one of the figures (e.g. Figure 1, 4a, or 5)?

Figure 4a: All of the larger uncertainties point upwards. Is this a product of such a one-sided array with only 1 sensor (AE hydrophone) below the stimulation intervals? Or, as you state, an underestimation of the attenuation in the fractures zones?

Ln 549: What did this reveal about the detection limits?

Ln 569: Can you also show the progressive growth with distance from the injection interval in Figure 6?

Ln 571-572: Figure 5 would be a good place for a map-view and cross-section to show the reader that the seismicity from injection and vertical validation are distinct.

Figure 6: A few comments:

- Text is too small in most cases
- AE and Hammer bars in the histogram are indistinguishable
- Very hard to see the waveforms, so what’s being shown? You say ‘all’ events, so are these all the waveforms superimposed on each other, stacked, something else?
- What about the other seismically-active intervals?

Ln 586: It’s hard to assess the claim of that these signals resemble pressure and not flow without adding the hydraulic parameters to these plots in some way.

Figure 7: The discussion of the broadband sensors seems a little tangential to the rest of the paper which I see as focused on the AE locations and velocity model. It might be better to leave this out or transfer to the supplements?

Ln 601: Plus no (good) S-wave

Ln 607: And destroyed some of the monitoring equipment…

Ln 609-612: Its a difficult trade-off between near-field monitoring and allowing the fracture to grow unimpeded. EGS Collab #2 will have a central injection well with four surrounding open boreholes (all drilled from same wellhead). Seismic instrumentation will be further afield this time in separate grouted wells (in an attempt to avoid what happened last time). Still, we’ll likely intercept the fracture with one of the boreholes surrounding injection. As you mention, this significantly affects the fracture’s behavior but also allows us to monitor the fracture at multiple locations (e.g. with a straddle packer or 3D displacement probe). But I agree that seismic monitoring should stay out of the way, especially when using high-sensitivity AEs.

Ln 648-652: If you choose to leave the broadband recordings in the main body of the paper, it would be nice to see a comparison of the waveforms and the hydraulic parameters. Not necessarily an interpretation of mechanisms, but a clearer view of the pressure-waveform relationship you mention in the text. In addition, half of the waveforms in the Figure 7 helicorders are just noise and not adding a ton to the story.

Technical corrections:

Ln 79: EGS not defined beforehand

Ln 136: ‘focusses’

Ln 195: I have a hard time following this sentence. Maybe one sentence per mine-back borehole?

Ln 220: ‘[the] vein drift’?

Ln 384: suit[e]s?

Ln 446-449: This is hard to follow. Please rephrase or break into smaller chunks.

Ln 523: [the] fault or fault[s]?

Ln 532: resulting → result

Ln 643: obtained or observed/measured?

Ln 725: time times

Ln 781: Should these be a bulleted list?

Ln 785-787: Unclear. “Estimates of the uncertainties related to simplifications...”, maybe?

Ln 790: overprint[s]

Ln 793: protocol[s]