Solid Earth Discuss.,
https://doi.org/10.5194/se-2019-72-AC2, 2019

Solid Earth
Discussions

Interactive comment on "Stress Characterization and Temporal Evolution of Borehole Failure at the Rittershoffen Geothermal Project" *by* Jérôme Azzola et al.

Jérôme Azzola et al.

jerome.azzola@gmail.com

Received and published: 4 June 2019

We thank the referee for his comments and review. We appreciate his recognition of the importance of our contribution. Please find below a point by point response to the comments. A pdf file including in black the comments and in blue, our response, is provided as supplement.

Sincerely, on behalf of the authors Jérôme AZZOLA

The authors present a detailed study in orientation and magnitude of the local stress field at the geothermal site of Rittershoffen in France, near the well-known site Soultz-

Printer-friendly version

Discussion paper

sous-Forêts. The manuscript focuses on the temporal evolution of borehole breakouts and drilling induced tension fractures using acoustic images of two boreholes acquired by Ultrasonic Borehole Imager in 2012, 2013 and 2105. The manuscript is interesting and provides an important contribution for the understanding of the time-dependent deformation. In this form the manuscript is not ready for publication. Please see my comments.

Major comments: 1. The author mentioned in the abstract that they used for their investigation image datasets from two boreholes GRT-1 and GRT-2. In the manuscript the analysis as well as the description and the discussion of the results are mainly focused only on GRT-1. I suggest the authors to show only the analysis on GRT-1 well. In case the author wants to continue keep also the GRT-2, a detailed analysis of the datasets of this borehole is requested. The analysis must be related to the inclined borehole taking into account the orientation of the principal stresses in an inclined borehole.

We acknowledge that the description and the discussion of the results are mainly focused on the data of the GRT-1 well, as the quality of data from GRT-2 is generally lower than for GRT-1 (line 240). The image quality problems with GRT-2 are detailed in section 6.1 of the manuscript and illustrated in figure 3.c. It shows in particular the significant stick-slip effect inducing alternative compression and stretching of the UBI images. Figure 3.d. is an example of an erroneous borehole radius record. Given the extent of the artefacts highlighted in GRT-2, the measurements of the breakout parameters in this borehole are more uncertain than in GRT-1 and no DIFTS have been measured in GRT-2 (line 247). We still analysed the stress tensor in GRT-2 using a proper deviated well approach, which has been clarified in appendix A of the revised manuscript. We feel that it is worth adding the GRT-2 data in the manuscript as the expression of the measurements in TVD enables to compare the results with the measurements performed in GRT-1, even if the data quality doesn't enable to propose an extended analysis of the stress tensor as in GRT-1.

2. The authors show in Figure 15 the magnitude of Sv, Sh and SH from 2000 m to 2500 m of GRT-1. To calculate the Sv magnitude the authors used equation (6). The Sv curve is presented as if it were made using a fixed value of 2440 kg/m3 for the entire well. Can you explain why? At 2300 m using equation (6) as the author wrote the value Sv is 54.37 MPa but using the value of 2570 kg/m3 (Table 3) corresponding to the granite rock at a depth of 2200 m Sv is 58.28 MPa.

The magnitude of the vertical stress Sv is obtained from the weight of the overburden. The density profile provided in Table 3, is integrated from surface to maximum depth. The trend provided in equation (6) is obtained from a linear fit to the measurements in the range of depths considered in our study. We apologize for the typo in Eq. (6), which should read 0.0248 z – 0.83. This misleading rounding is corrected in the revised manuscript, which leads to a trend in line with density value 2570 kg/m3 chosen for the granitic layer.

3. I suggest redrawing figure 15 showing the entire section of the GRT-1 between 0 and 2562 m (TVD).

We acknowledge and tested this advice, but by redrawing figure 15 from 0 to 2562 m, we considerably deteriorate the readability of the measurements presented in the figure 15 for greater depths, from 1950 to 2550m, while showing a long wellbore section (from 0 to 1950 m) without data. After careful consideration, we decided thus not to extend the vertical scale to the entire GRT-1 section.

4. Furthermore, in line 387 the authors should specify that the density value shown in equation (6) is related to the Jurassic rocks between 1172 and 1447 m of GRT-1 as an example, but that the Sv was calculated taking into account the density values of the different rocks at different depths. No Figure for GRT-2. If the authors want to include this well, they have to show the data and results.

We added details about the procedure followed (after line 402). We measure Sv as a function of TVD in order to apply the same measurements in both wells. Figure 17 and

18 are showing results for GRT-2.

Minor comments: 1. I suggest that the figures and tables have the same MD or TVD depths, or that both are reported. For example, Table 3 shows lithologies and densities relative to TVD depths, while if I look at the stratigraphy in Figure 8, the lithologies refer to MD depths.

TVD is the most relevant depth scale to present stress estimate and to compare results across both wells, with GRT-1 almost vertical (TVD and MD are not very different) and GRT-2 being deviated. We follow thus the advice of the reviewer and made sure to add a TVD depth scale on all our figures and tables.

2. Please include also the fractures distribution (number, dip, dip azimuth) highlighting the main faults or fracture zone to better understand the borehole breakout rotation and/or deviation from the mean of Sh.

The major fracture network was observed from acoustic wall imagery in the open-hole sections of GRT-1 and GRT-2 by Vidal (2017). Major continuous fractures (thickness measured on acoustic images higher than 1 cm) are analyzed in both wells. The detailed structural survey is available in Appendix 2 of Vidal's thesis. The fractures are oriented globally in GRT-1 N 15° E to N 20° E with a dip of 80° W. In GRT-2, the main fracture family is oriented N 155° E to N 175° E with a dip of 80° E to 90° E. Fracture density is highest on the roof of the granitic basement. These summary elements are added in section 2 of the revised manuscript, which details the context of the Rittershoffen project. Our analysis doesn't consist in the measurement / discussion of the distribution and orientation of the natural fractures highlighted through the GRT-1 and GRT-2 wells, which has been extensively studied by Jeanne Vidal in her thesis. We believe thus that adding data regarding the fracture distribution and orientation in the figures doesn't contribute to the discussion of the proposed measurements but would necessitate to analyse data that are not in the focus of our paper.

3. The value from hydraulic test at GRT-1 differs from the data from the boreholes

GPK1. Could you explain better the reason? Please add also this Sh- value from GRT-1 in Figure 15

The approach followed has certainly not been sufficiently clearly explained, and we added details in the section 8.3 to carefully describe the steps in the estimation of the Sh profile proposed in the GRT-1 and GRT-2 wells.

The profile of the minimum horizontal stress Sh is estimated from pressure limiting behavior during hydraulic injections. Since we did not have enough information related to the Rittershoffen project to compute a complete Sh stress profile, we used measurements carried out at the nearby Soultz-sous-Forêts project. The trend is evaluated after Cornet et al. (2007). To complete our analysis, we analyzed the wellhead pressure measured during the hydraulic stimulation of GRT-1 and derived an "estimate at best" of the Sh magnitude at depth from the pressure reached at maximum flow rate. The wellhead pressure measured at 1913m in GRT-1 during the hydraulic stimulation (data provided in figure fig. 12) shows a gradual but not definitive stabilization at flow rates up to 80 L.s-1. Even if the pressure limiting behavior, related to the creation or reactivation of faults, is not reached, we discuss the measurement as a lower bound for the minimum horizontal stress Sh at 1913m. By comparing our measurement in Rittershoffen at 1913m with the trend considered in the stress analysis and measured originally in Soultz-sous-Forêts, we show that both measurements are consistent and that the Rittershoffen measurement is indeed a realistic lower bound for the chosen trend.

4. The caption of figure 13 refers to figure 12. Whereas the caption of figure 12 refers to figure 13. Please modify.

The caption of figure 13 has been inverted with caption of figure 12, as mentioned by both referees. We fixed this issue in the revised manuscript.

5. Line 16 GRT-2 instead of GRT2 6. Line 16 2500 m instead of 2500m 7. Line 40 provide an indirect information instead of provide a indirect in-

formation 8. Line 90 WSM released in 2016 no in 2008. Please update the reference and cite as: Heidbach, Oliver; Rajabi, Mojtaba; Reiter, Karsten; Ziegler, Moritz; WSM Team (2016): World Stress MapDatabase Release 2016. GFZ Data Services. http://doi.org/10.5880/WSM.2016.001 (http://dataservices.gfz-potsdam.de/wsm/showshort.php?id=escidoc:1680890) 9. Line 120 GRT-1 instead of GRT 1

We corrected the typographical errors referenced in comment n° 5, 6, 7 and 9 in the revised manuscript. We updated the reference to the WSM (comment n° 8).

10. Lines 142-143: please specify which failure condition

Details have been added to the manuscript regarding the failure criterion used to the above-mentioned lines.

11. Lines 307-309 Please insert one or more figures to confirm what has been said.

The request of the referee is not very clear, as the lines referred to do not highlight an obvious lack in information. If the referee refers to the deviation of the wells in the open-hole section, this is shown in Figure 1: the trajectories of GRT-1 and GRT-2 show that the deviations are constant in the section of interest and that GRT-1 is quasi-vertical.

12. Line 183: why the authors grouped the Triassic sandstone in a single category? Please add in the manuscript the reason: no alteration, homogeneous lithology, no fractures, etc

The sandstones crossed by the open section of the well are all from the Buntsandstein (section 5 of the manuscript). Heap et al, (2019) studied in detail the strength evolution with depth of the Buntsandstein mechanical properties. As suggested by the referee, they evidenced significant variations of the compressive strength together with elastic modulus changes. They also pointed out the role of the fluid content on the UCS. However, these variations are limited compared to the statistical fluctuations of our measurement. Accordingly, we gathered the Buntsandstein sandstones as a single unit. As stated in the manuscript (line 210), only very few tests have been performed on the sandstones. We used typical strength parameters from Hoek and Brown (1997) to characterize the geological unit.

13. Line 387 Sv [MPa] = 0,024 * z [m] – 0,83 or Sv [MPa] = 0.024 * z [m] – 0.83 but no one value as dot and the other a comma. In order not to confuse the reader, I suggest using the asterisk (or an x) as a multiplication sign instead of the point.

To avoid any confusion for the reader about the punctuation used in the equations, we followed the referee suggestions and replaced the dot by an asterisk in the equations proposed in the manuscript.

14. Line 533 please 50 m instead of 50m 15. Line 573 please add a dot after correlation technique 16. Line 579 please add the year of the reservoir stimulation

We modified typographical errors previously referenced (comment #14 and #15) and added details to the manuscript regarding the year of the stimulation to the above-mentioned lines (comment #16).

17. Figure 1: legend: the reference is WSM 2016 not 2006 Helmholtz-Centre Potsdam GFZ. Inset with the sketch of GRT-1 and GRT-2 boreholes: the lithology is not clear, some writings overlap. It would be good if the stratigraphy had the same colours as the geological profile. Highlight the trajectory of the wells on the geological profile. Caption: Heidbach et al., 2016. Cite as: Heidbach, Oliver; Rajabi, Mojtaba; Reiter, Karsten; Ziegler, Moritz; WSM Team (2016): World Stress Map Database Release 2016. GFZ Data Services.

The legend has been updated as well as the caption with the reference proposed by the referee. The writings in the lithology and in the legend have been made clearer. The lithological profile has been set in agreement with the stratigraphy (bottom and left inserts). The geological profile includes the trajectory of the wells even if its scale doesn't enable to distinguish the direction of GRT-1 and GRT-2.

18. Figure 2: Please add two separated scales for radius (mm) and for width (_)

Figure 2 has been updated accordingly to the referee's suggestions.

19. Figure 3: show directly in the figure a, b, c, d, the artefacts (signal loss, stick slip).

In order not to load unnecessarily the figure, we added details in the figure caption regarding to the artefacts. We feel that the mentioned artefacts are now easily recognizable in the images of Fig. 3.

20. Figure 14: please add the fractures as Tadpole related to this section.

In our analysis, we didn't study the distribution and orientation of the fractures, which has been done by Jeanne Vidal in her thesis (Vidal, 2017). We believe that adding data regarding the fracture distribution and orientation in our figures doesn't contribute to the discussion of the proposed measurements but would necessitate to analyze data that are not in the focus of our paper.

21. Figure 15: Please remove the lithology from inside the figure but add it as litho column to the side of the figure. Please add the fractures as Tadpole related to this section. Is the deviation of the stress values between 2250 and 2380 m, more or less, due to the presence of fractures?

We removed the lithology from the inside of the figure and added it to the side of the figure. The deviation of the stress values is correlated to the increase in the breakout width at the mentioned depths.

22. Figure 18: Please remove the lithology from inside the figure but add it as litho column to the side of the figure. The symbols of Sh and Sv of GRT-2 are not very clear in the figure. Please change the symbol.

We removed the lithology from the inside of the figure and added it to the side of the figure. We modified the symbols related to the stress state estimates in GRT-2 to improve readability.

Please also note the supplement to this comment:
https://www.solid-earth-discuss.net/se-2019-72/se-2019-72-AC2-supplement.pdf

Interactive comment on Solid Earth Discuss., https://doi.org/10.5194/se-2019-72, 2019.