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# Good Agreement of Fracture Sets Detected by Acoustic Televiewer with Fracture Clusters Revealed by Microseismicity Within the Basel EGS Reservoir

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## ABSTRACT

The high precision hypocenter locations and focal mechanism solutions of the micro-seismicity during the Basel EGS stimulation were compared to the fracture sets and high fracture frequency zones observed with the acoustic televiewer at the borehole. The focal mechanisms provide orientations for all micro-seismic clusters that match one of the three most common fracture sets determined by borehole televiewer data within the stimulated depth between 4 km and 5 km. Additionally, these sets share the same rake. Clusters in set 2 are characterized by a strong normal component, while set 1 and set 3 are pure strike-slip (right lateral and left lateral respectively). The calculated intersection of each cluster with the borehole also show a match with the observed areas of high fracture frequency at the borehole and coincide with the dominant fracture orientation at that interval. The arrangement of the three sets is concordant with the theoretical Reidel shear fractures where set 1 and set 3 would correspond to the antithetic R' and synthetic R components, while set 2 would be the T component (extension) parallel to the maximum regional horizontal stress. The consistency of the two independent data sets adds confidence on their good representation and understanding of the main geo-mechanical characteristics of the Basel EGS stimulation. Furthermore, we conjecture that good acoustic televiewer data could be utilized for other projects to predict EGS reservoir creation before stimulation.

## 1. INTRODUCTION

The Basel Enhanced Geothermal System (EGS) was drilled to a total depth of 5 km with the open hole section located at the last 391 m. The reservoir was stimulated by injecting 11570 $m^3$ of water for 6 days, after which a short shut-in phase and a prolonged bleed-off of 3400 $m^3$ was done (Häring et al., 2008). During the bleed-off, a 3.4 magnitude seismic event associated with the injection was felt in the city of Basel, which finally led to the permanent suspension of the geothermal project.

The seismic array installed for this project produced data of exceptional quality which was used to calculate a precise focal mechanism catalog of 185 events, which are grouped into clusters that share the same solution (Deichmann et al., 2014). Additionally, acoustic televiewer rendering produced a detailed catalog of the fracture sets present at the stimulated area, which are set 1, set 2 and set 3, and coincide with the regional fault orientation (NW-SE) attributed to Hercynian deformation. During drilling operations, two zones of mud loss were identified and interpreted as cataclastite zones (Haring, 2008).

The comparison of sheared fracture planes within the reservoir with the fractures observed at the borehole can reveal new information on the general stimulation mechanism. In this paper we will compare both the focal mechanism catalogue and the observed fracture sets. We will test if these methodologies are adequate to characterize EGS reservoirs and if new information on the stimulation mechanisms can be revealed.

## 2. METHODOLOGY

The similarities between both datasets was assessed with a simple decision tree. Any of the two nodal planes of the focal mechanism solutions could be the fracture plane, but only the most probable one is given (Deichmann et. al, 2014), therefore the conjugate plane was calculated. First, the rakes of each nodal plane were clustered by dominant fracture mode. Then, the strike of each nodal plane for all 186 events, and of the three fracture sets (Set 1, 2, and 3) mean vectors were transformed to directional cosine form.

The Euclidian distance between the clustered nodal planes and each of the three sets was calculated, and the minimum value taken as the most probable fracture set belonging to a given event. The results were plotted with Stereonet to assess the goodness of the fit. Assuming that each fracture plane has an infinite extent, the intersections of each event with the borehole were calculated. The effects of the hypocenter location uncertainty of ± 5 m on borehole intersections was taken into account by calculating the maximum and minimum possible intersection depth. The features within uncertainty range are considered as probable intersects.

The catalogue of the Swiss seismological survey (SED) was used to assess the plausibility of clustered orientations, by calculating the best fit plane (154N 83N) of the whole catalogue (Figure 1).

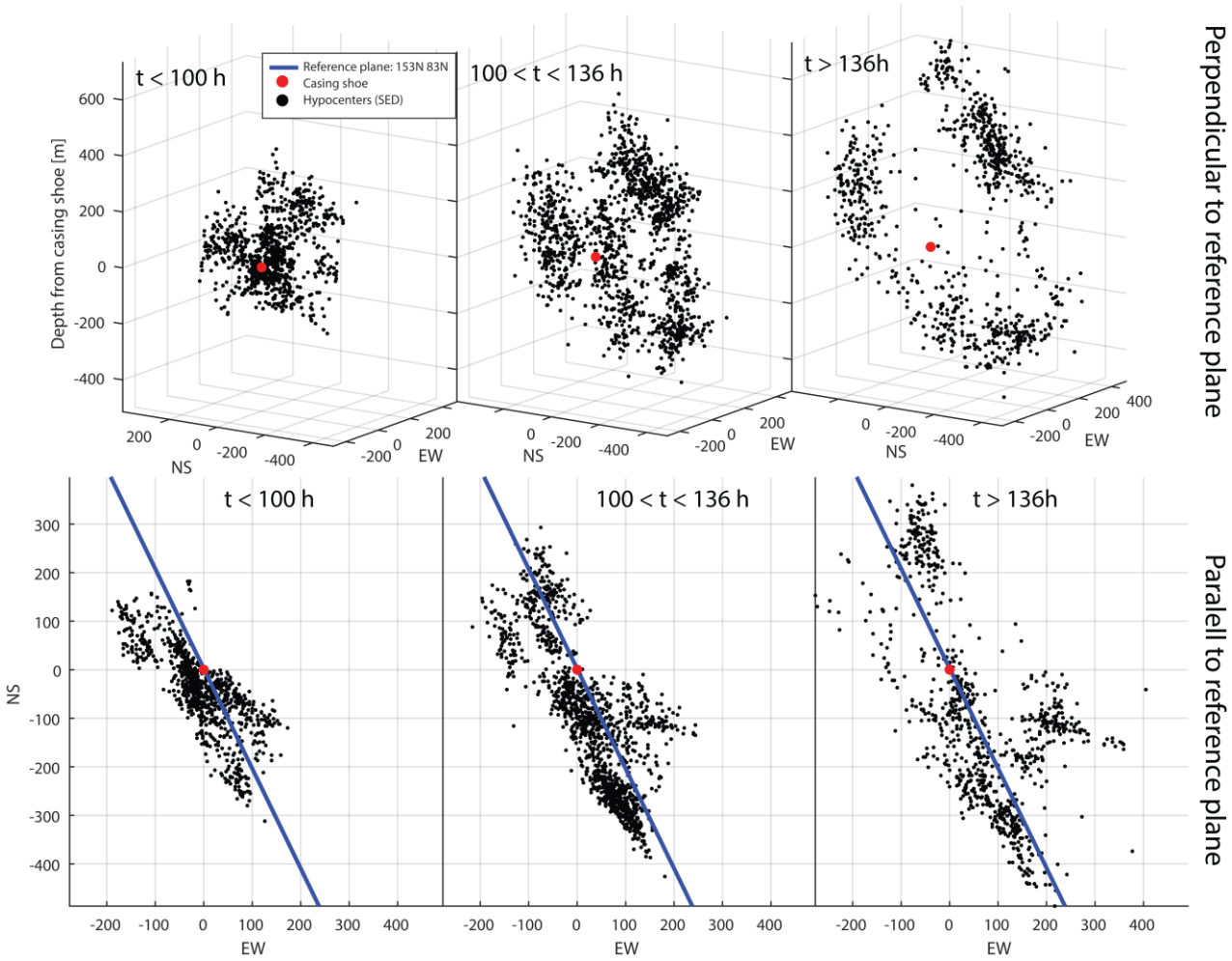


**Figure 1: Extent of seismic cloud superimposed to the best fit reference plane. Top: Perpendicular to 154N 83N. Bottom: Parallel to plane (154N 83N).**

## 3. RESULTS AND DISCUSSION

The classification of the shear planes matches the observed fracture sets (Figure 2) and all are consistent with the general seismic cloud orientation of 153N 83N. Each classified cluster is grouped by focal mechanisms where events from set 1 are left lateral, set 2 are normal, and set 3 are right lateral. Additionally, the mean dip for each classified cluster set is similar for the strike-slip sets (set 1 and set 3, dip of 70 and 83 degrees respectively) while set 2 clusters have a different mean dip of 53 degrees.

For all events, it was expected that the shear plane was the nodal plane that best matched the spatial distribution of the events assuming that it was the same fracture plane activated multiple times. This assumption is valid for events classified as set 1 or set 3, but not for set 2. In this case, the best match was the conjugate plane which aligns the seismic events on an en-echelon configuration with respect to the seismic cloud.

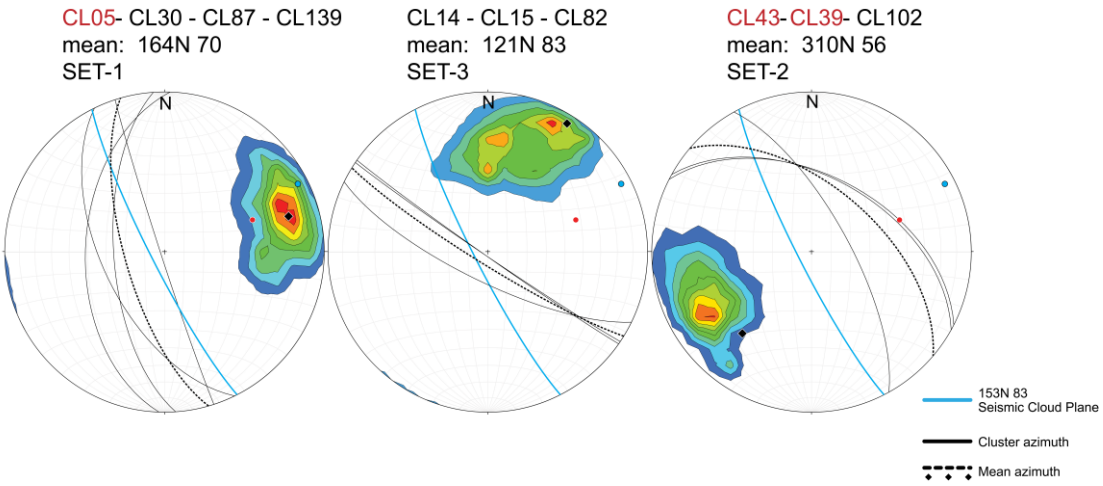


**Figure 2: Stereogram of fracture sets and nodal planes. Color-coded areas represent the pole cloud of sets observed within the stimulated area of the wellbore (4000 m to 5000 m depth), and the clusters assigned to them. The clusters colored in red are the opposite nodal plane to the one suggested by Deichmann (2014).**

The classified sets also correspond with Riedel shear orientations. Riedel shear structures form during the early stages of fault formation. They are a scale invariant set of orientations, commonly observed on the field, of which 3 are the most visible: Synthetic (R), having the same strike-slip direction as the regional stress field, and conjugate asynthetic (R') having the inverse strike-slip direction, and tension gashes (T) formed parallel to $\sigma_1$ as a result of Mode I (extension) fracturing. R fractures occur more commonly than the R' fracture or the tension gashes (T), and together form a network of interconnected en-echelon structures. Set 2 clusters are parallel to $\sigma_1$ corresponding with T fractures, while set 1 and set 3 correspond to R and the R' fractures. The lack of agreement in the dip between set 2 and sets 1 and 3 could be explained by rupture propagation through pre-existing features.

The intersection to the borehole of distant seismic events did not have a clear match. However, set 1 events closest to the borehole (Figure 3c, cluster 5) coincide with areas of high fracture frequency identified by Ziegler (2015), but not with the observed cataclastite zones. Set 3 (Figure 3d, clusters 14, 15) coincide with isolated fractures observed at the borehole and events pertaining to set 2 (cluster 43) are near one of the identified cataclastite zones (Figure 3b).

The borehole intersections did not produce precise results, however, the concordance between the Riedel shears and the nodal plane clusters calculated previously strongly confirm the hypothesis that the Basel stimulation propagated in an en-echelon mode through preexisting fractures (Häring et al 2008).

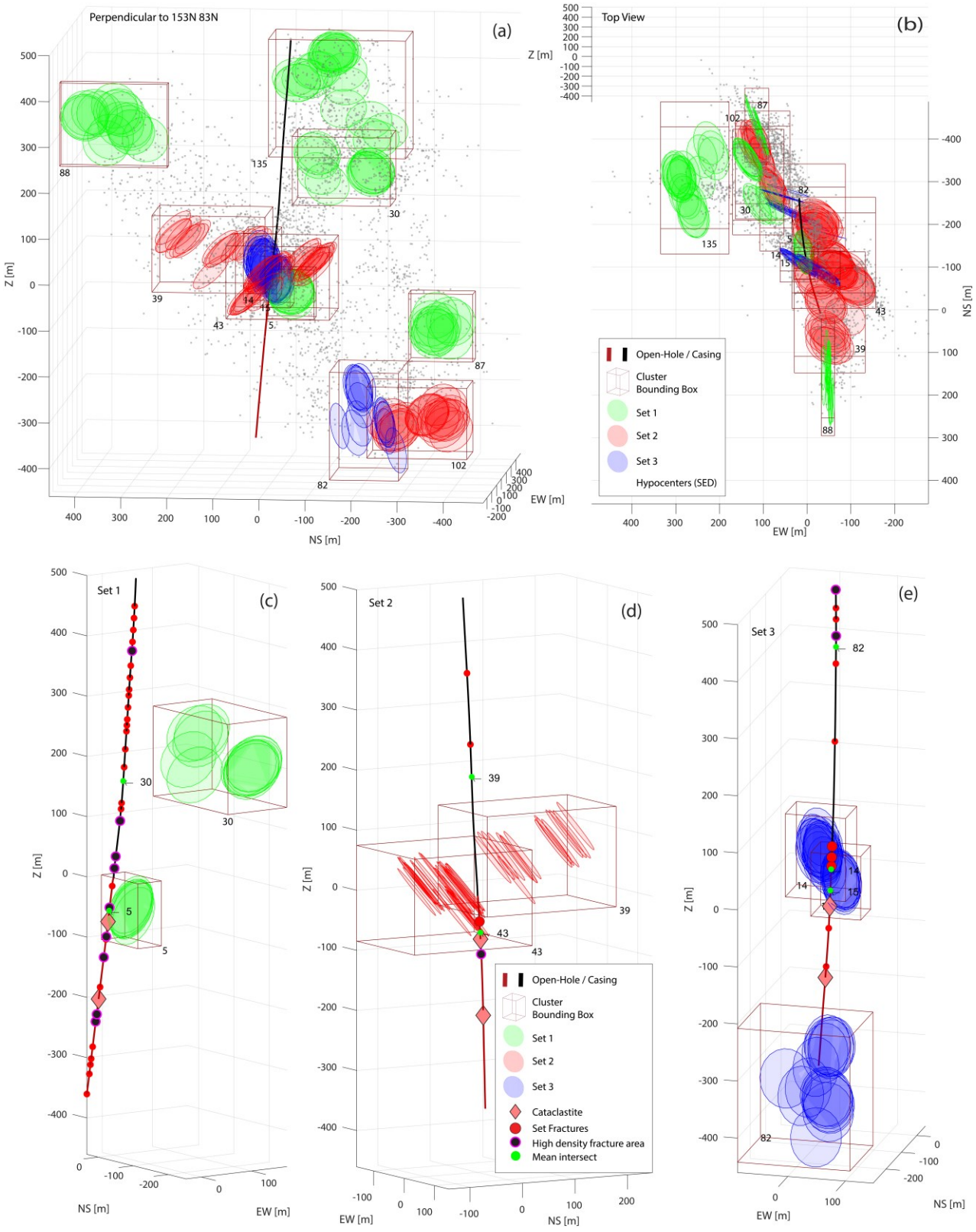


**Figure 3: Hypocenters and focal mechanisms of Deichmann et. al (2014) and their borehole intersections, classified by set: Set 1 green, Set 2 red, Set 3 blue. a) Cluster overview, perpendicular to 153N 83N with SED seismic cloud superimposed for context (grey dots). b) Cluster overview, parallel to 153N 83N, c) Set 1 borehole intersects d) Set 2 borehole intersects, e) Set 3 borehole intersects.**

## 4. CONCLUSION

The nodal plane solutions observed during the stimulation, and borehole acoustic televiewer data show that the seismic events are grouped into the observed fracture sets. These sets each share the same fracture mode and fit the classic Riedel fracture orientations that is concordant with the regional stress field. It suggests that the Basel stimulation propagated in an en-echelon network oriented 154N 83N through preexisting fractures which confirms the rupture mechanism proposed by Häring et al (2008).

It shows how detailed borehole logs, and high precision seismic data can be used successfully to estimate the geomechanical evolution of reservoir stimulation. Therefore, future EGS projects could use borehole logs to predict reservoir creation.

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