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Surface Seismic Monitoring of a Geothermal Stimulation

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Summary

The Cape Modern project near Milford, Utah was stimulated as a plug-and-perf hydraulic fracture completion in granitic host rock. The project was monitored for seismicity by a network of seismometers on the surface, shallow-borehole-deployed sensors, 3C passive sensors deployed closer to stimulation depth, and DAS fiber-optic cables deployed in multiple wells. Dadi et al. (2024) showed how induced seismicity traffic light protocols, stimulation of a pre-existing fracture network, and the distribution of moment tensors can all be inferred from analyses on these different data streams. In this publication, we focus on the surface/shallow-borehole network, and the subset of conclusions that may be drawn on the fracture geometry with reference to the image provided by the multi-well DAS, which we take as "ground truth". We observe that near-realtime post-processing of a relative relocation technique obtains a very good match with the image of the DAS microseismic, excepting for a static shift, mostly in depth.

Cape Modern Project

The Cape Modern project is a commercially operated Enhanced Geothermal System (EGS) located in Southwest Utah, adjacent to the Utah FORGE (Frontier Observatory for Research in Geothermal Energy) site in Milford Valley. The project involved stimulation of three horizontal wells (1-I, 2-P and 3-I) in February and March 2023, drilled from the Frisco pad (Figure 1). A fourth horizontal (4-P) was not stimulated and kept as a test well. Another eight horizontal wells were completed in November/December 2024 from the Bearskin pad 1.5 km further north. The three Frisco wells were drilled horizontally at a depth of ~2500 m TVD in the granitic basement rock and completed using plug-and-perf hydraulic stimulation technique. In addition to the horizontal wells, the project also involves the Delano vertical monitoring well, and the 16B-78-32 monitoring well from the FORGE site.

Extensive seismic monitoring was performed during the stimulation of the Frisco wells. This included a network of shallow-borehole and surface stations, equipped with 3-component broadband seismometers and/or accelerometers, a surface nodal array, multi-well deep borehole fiber-optic (installed in the Delano and 16B-78-32 wells) and a downhole 3-component geophone.

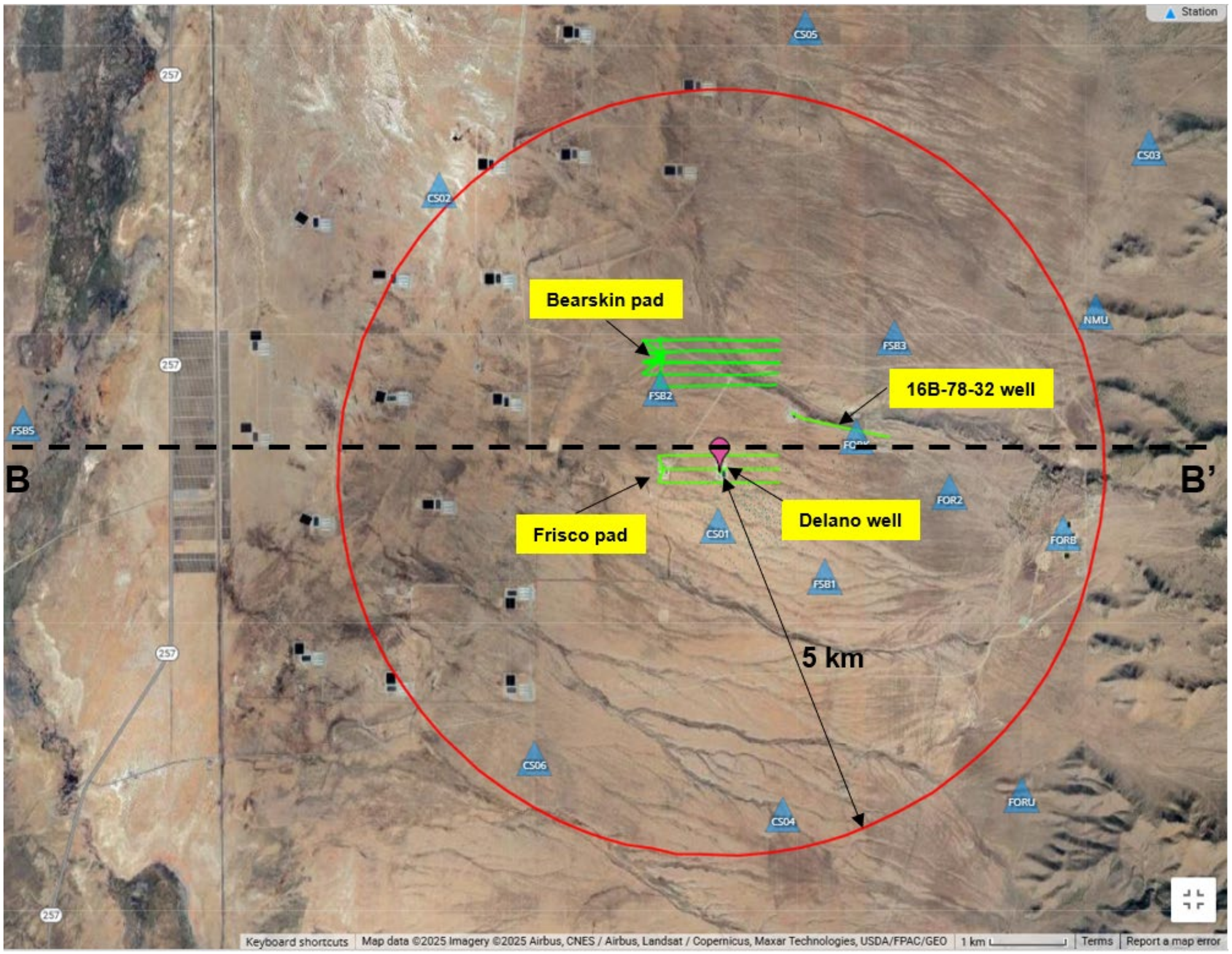

Figure 1. Overview of the Cape Modern Project site. The velocity model cross-section B-B' is shown in Figure 2.

Surface / Shallow-borehole Seismic Event Catalog

Data from a total of 23 surface and shallow-borehole stations were processed to obtain a catalog of seismic events in realtime. The blue triangles in Figure 1 show the subset of stations closest to the project site. Event locations were determined by minimizing the residuals between observed and theoretical arrival times of P and S wave phases. A grid search algorithm was used in a 3D subsurface velocity model to solve the non-linear location problem.

To properly capture the complexity of subsurface geology, a 3D velocity model was built based on all available sonic logs from Fervo and Utah FORGE wells, along with top of basement measurements from 3D seismic and gravity data. The basement P- and S-wave velocities were estimated from travel time observations from more than 800 seismic events using a regression analysis of hypocentral distance versus travel times. Figure 2 shows an E-W cross-section through the P-wave velocity model at the Frisco well pad (section B-B' in Figure 1).

An automated, AI-enhanced event detection and location algorithm was used to pick P and S arrival times and generate initial automatic event solutions in real time. These solutions were later reviewed by a human analyst to remove potential false positives and adjust picks (if needed), providing updated manual solutions.

A high-precision post-processing algorithm was running quasi-continuously in the background during the entire duration of the stimulation. This algorithm is based on the double-difference relocation method described in Waldhauser and Ellsworth (2000) and is taking into account the entire available historic event catalog. The result is a high-precision event catalog, available in near realtime. These high-precision locations were used in a Traffic Light System for managing induced seismicity during the stimulation phase (Dadi et al., 2024).

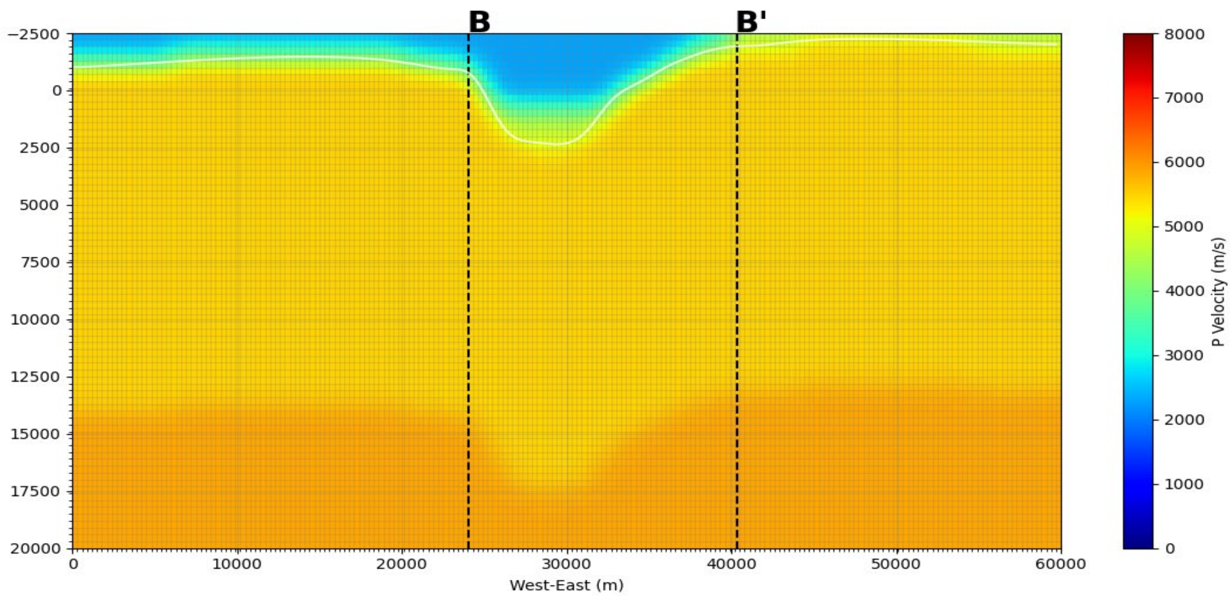

Figure 2. E-W cross-section through the P-wave velocity model at the Cape Modern site.

Comparison to Fiberoptic Catalog

A separate microseismic event catalog was produced from the DAS data from the high-resolution deep borehole fiber-optic cables installed in the Delano and 16B-78-32 observations wells. Due to the geometry and proximity to the stimulation, these event locations are expected to be both precise and accurate, and are therefore considered “ground truth”. In Figure 3 we compare the location of corresponding events between the surface/shallow-borehole (purple) and the DAS catalog (green). The figure shows 2104 events matched by origin time within +/- 1 second. Panels A and B show the manual event locations from the surface/shallow borehole catalog, while panels C and D show the corresponding high-precision locations.

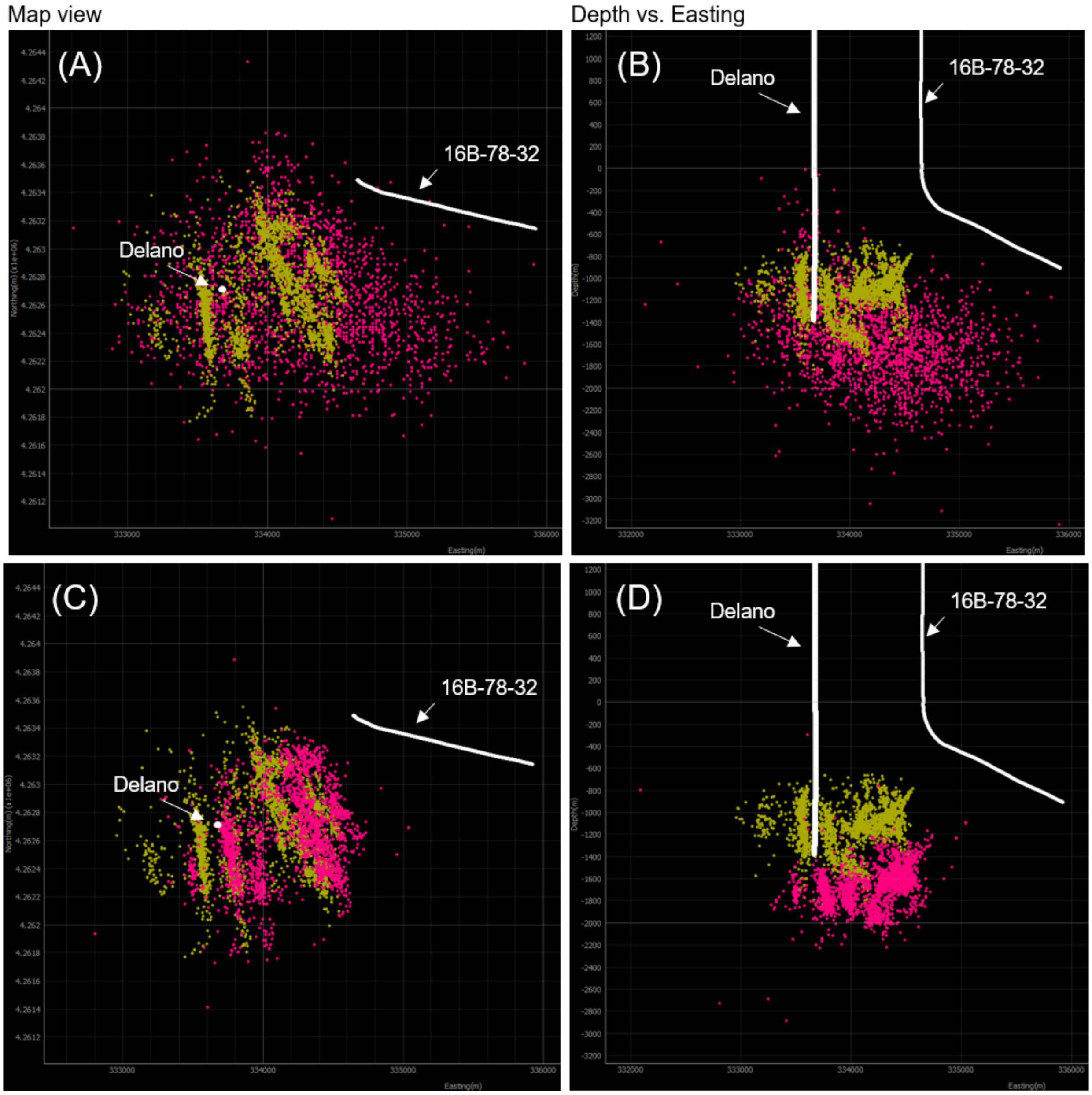

Figure 3. Comparison between the “ground-truth” fiberoptic catalog (green) and the surface/shallow borehole catalog (pink). Panels A and B show the manual locations while panels C and D show the high-precision locations from the surface/shallow borehole catalog.

Observations and Conclusions

Figures 3C and 3D show that high-precision locations from the sparse surface/shallow-borehole network offer spatial resolution that is comparable to the catalog derived from the high-resolution DAS cables. The purple event cloud in Figures 3A and 3B collapses to individual clusters and linear features, highlighting fractures with orientations in close agreement with the "ground truth" DAS dataset. Most of these fractures are trending 10-15 degrees NNW-SSE. This points to reactivated pre-existing natural faults and fractures as they are not aligned with the orientation of maximum horizontal stress (SHmax) at 10-35 degrees NNE-SSW, but are optimally oriented for strike-slip failure under the known regional stress regime (Dadi et al., 2024).

While the relative event locations are matching very well, we observe a systematic location offset between the two catalogs. The median offset is 216 meters in E-W, 25 meters in N-S and 546 meters in depth. This is owed to the nature of the double-difference algorithm, which calculates small event location shifts for improving location precision, but leaves the center of mass of clusters unchanged. In other words, a systematic location offset will be preserved in double-difference locations, even though the location precision is improved significantly. The largest offset is observed in depth, which is little surprising for a sparse (near-) surface network. Lateral offset mostly occurs in E-W direction, which we anticipate is caused by the asymmetric station coverage. Note in Figure 1 how the region East of the Frisco pad has denser coverage compared to the West.

Overall, this dataset demonstrates how a relatively sparse surface and/or shallow borehole seismic array can be a simple and cost-effective approach for monitoring seismicity associated with hydraulic stimulation in the context of enhanced geothermal systems. If combined with relative location post-processing techniques (such as double-difference relocation), it allows for near realtime monitoring with event location precisions comparable to high-resolution downhole arrays (such as fiber-optic DAS) and enables traffic light systems for effective management of induced seismicity.

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References

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