

# Imaging Fractures Through Relative Velocity Change Using Ambient Seismic Noise And Distributed Acoustic Sensing (DAS): A SubTER Pilot Study At Blue Canyon Dome, Socorro NM

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## 1. Introduction

- Imaging fracture systems is critical for groundwater and energy applications (i.e. contaminant transport, geothermal energy, carbon sequestration).
- We applied seismic interferometry using ambient seismic noise recorded on fiber optic cables through Distributed Acoustic Sensing (DAS) to evaluate its potential for fracture detection and imaging.
- This work was conducted as part of the Department of Energy SubTER crosscut at Blue Canyon Dome, Socorro NM (Figure 1).

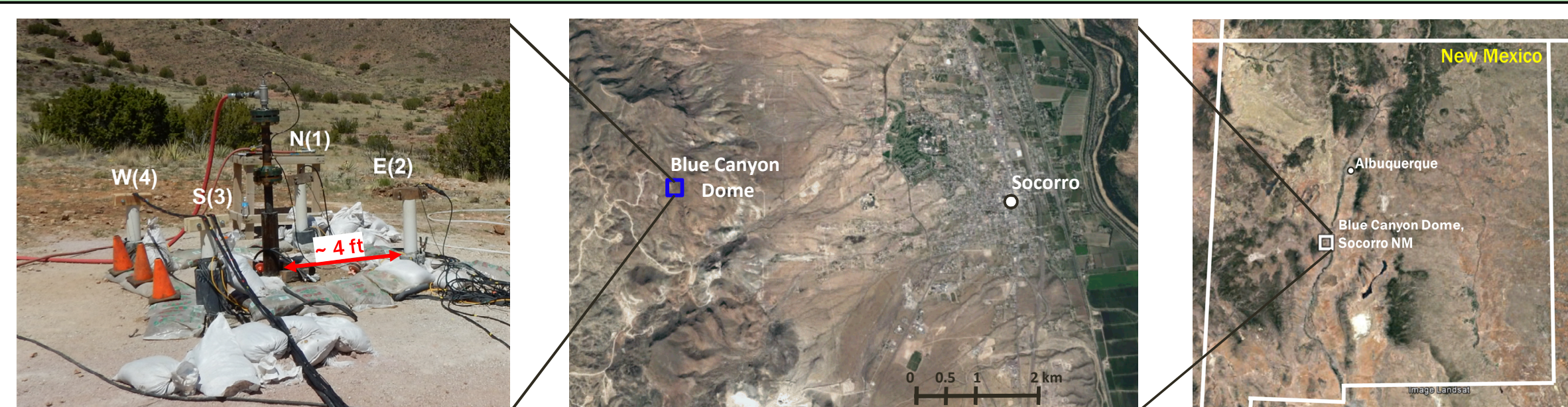


Figure 1. The study site was located atop Blue Canyon Dome, Socorro, New Mexico. Four monitoring boreholes (North(1), East(2), South(3), West(4)) were drilled to 22 meters depth and surround the center stimulation borehole.

## 2. Installation

- Four cased monitoring boreholes were installed around a center stimulation borehole at a radius of 4 feet and to 22 meters depth (Figure 1).
- Fiber optic cables were grouted in the outer annulus of the monitoring boreholes (Figure 2a,b).
- Fractures were generated by an innovative energetic material that was detonated in two separate shots (Shot-1, Shot-2) at 19 m depth.

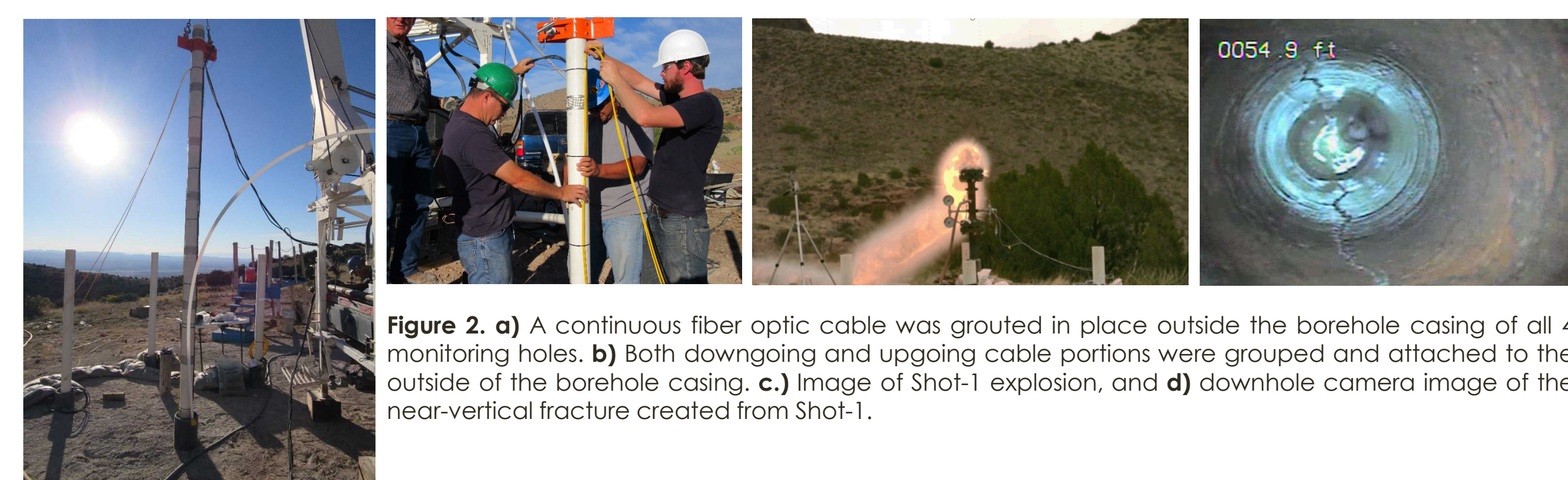


Figure 2. a) A continuous fiber optic cable was grouted in place outside the borehole casing of all 4 monitoring holes. b) Both downgoing and upgoing cable portions were grouted and attached to the outside of the borehole casing. c.) Image of Shot-1 explosion, and d) downhole camera image of the near-vertical fracture created from Shot-1.

## 3. Method

- In DAS, laser pulses are sent through a fiber optic cable and a portion of the light is backscattered along the full length of the cable (Figure 3a). [Daley et al. 2013]
- Propagating seismic waves stretch and compress the cable, altering the light travel times. Therefore, seismic waves are recorded in the arrivals of the continuously backscattered light.
- Ambient seismic noise was recorded on the fiber optic cables at a sampling rate of 10 kHz, before and after each stimulation for 12-hour time periods.
- We used the Python package MSNoise to find cross-correlations (CC) of all near-horizontal (less than 60°) channel pairs between boreholes (Figure 3b).

- To reduce computation time, only the first 3 hours of each time period were analyzed in this preliminary investigation.
- 120-minute moving CC stacks from each time period were compared to the full stack of preshot-1 to find the relative velocity change ( $\delta v/v$ ).
- Greater velocity reduction was expected for channel pairs that perpendicularly span the fracture.

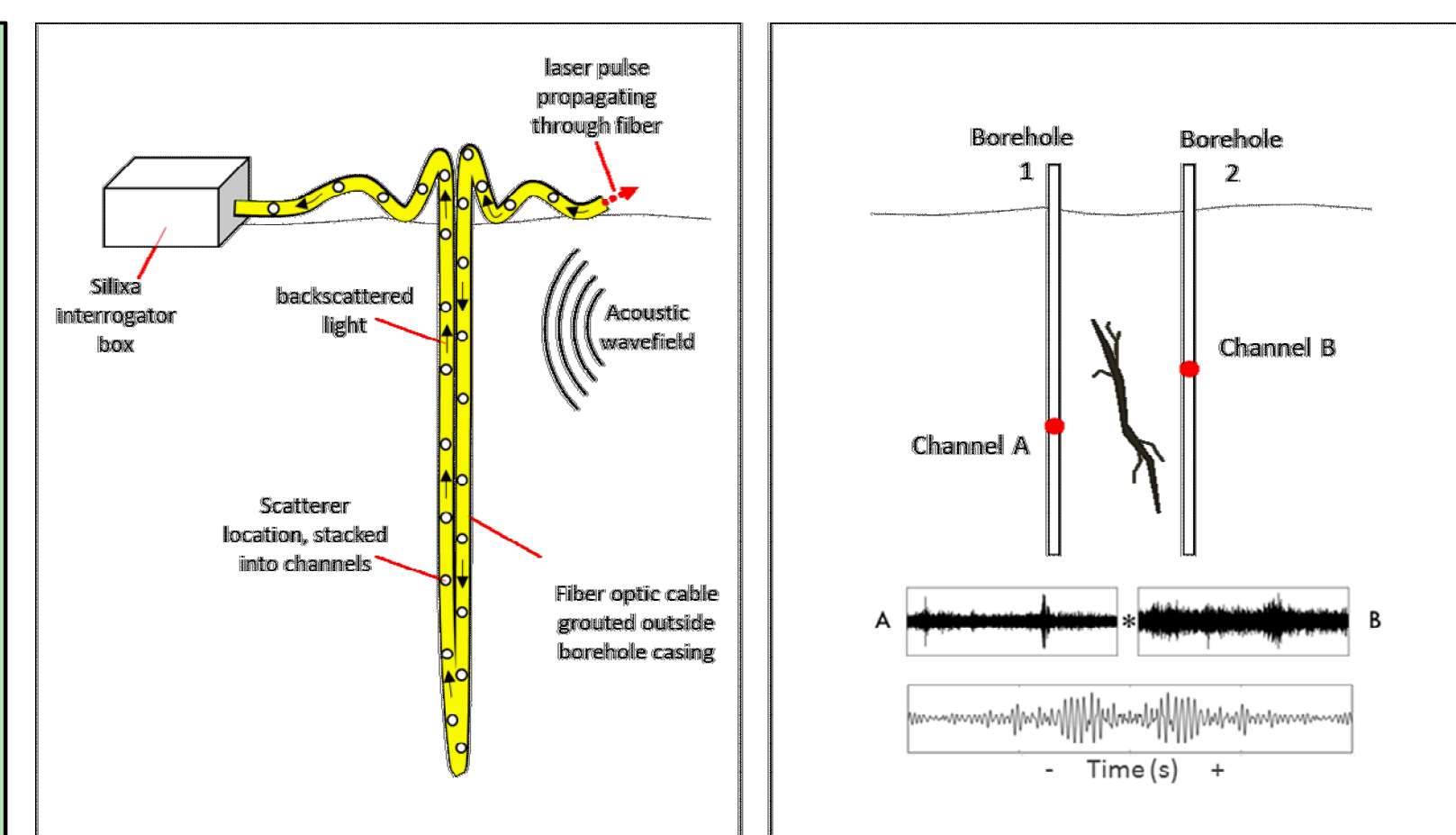


Figure 3. a) The interrogator box sends a laser pulse through the fiber every 100  $\mu$ s. Post-processing results in scatterer locations (seismic channels) every ~1 m b) Recordings from channels within separate boreholes, and less than 60° vertical offset, were cross-correlated to return the impulse response of the subsurface between the two channels. Figure 3a based on image from: <http://silixa.com/resources/what-is-distributed-sensing/>

## 4. Velocity Change Results

- The velocity change relative to the full CC stack for preshot1 was found for each 120-minute moving stack and averaged for each channel pair (Figure 4).
- Preshot1 results returned a near-zero velocity change which was to be expected.
- The remaining time periods had highly scattered results, largely negative reflecting a velocity reduction, consistent with the expected impact of fracture emplacement.

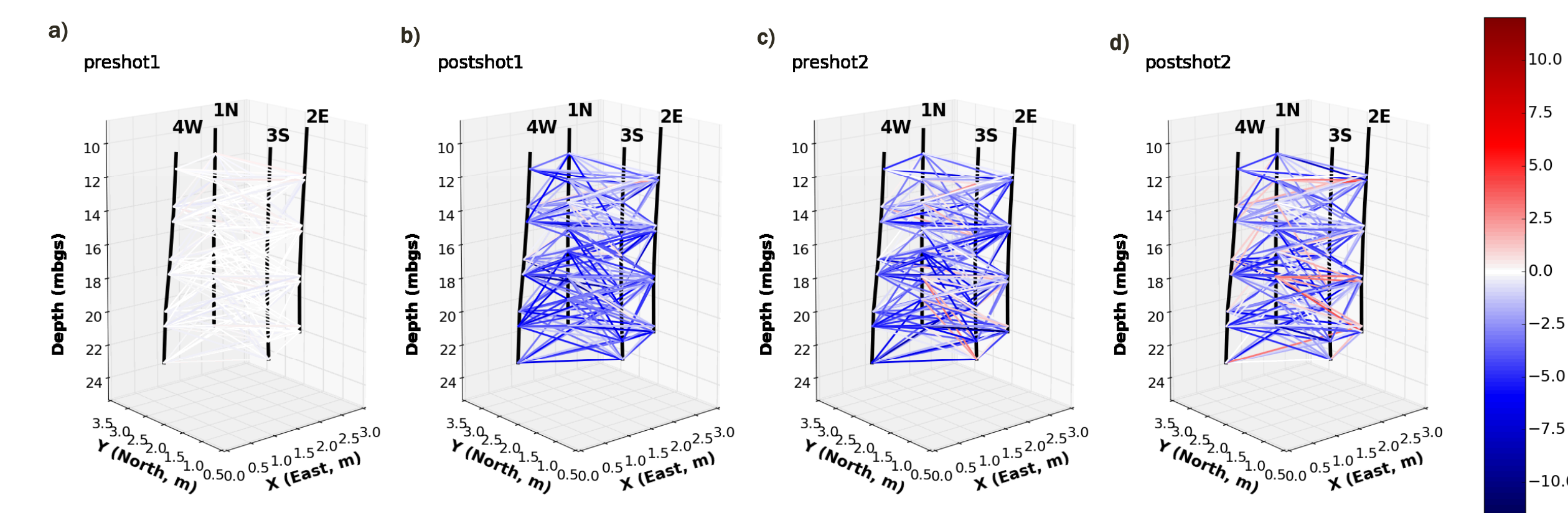


Figure 5. Straight-line paths connecting each channel pair colored by  $\delta v/v$  are shown to visualize spatial variability in relative velocity changes a) preshot1, b) postshot1, c) preshot2, and d) postshot2.

- Cross-well seismic surveys were also collected before and after each shot. 3D P-wave tomography was done for each time and the difference used to find velocity change.
- $\delta v/v$  results were compared to the cross-well tomography and showed good agreement in the areas of velocity change (Figure 6).
- These results, plus other geophysical methods (e.g. electrical resistivity tomography (ERT)) support the presence of a near-vertical fracture oriented NE-SW.

- Straight-path rays are drawn to connect each channel pair and colored by their respective  $\delta v/v$  value in Figure 5 to show spatial variations.
- Stronger velocity reduction is observed for deeper channel pairs (< 16 m).
- Results are increasing scattered postshot2 suggesting a possible decrease in quality from further fracturing.
- Some paths, mostly paired with channels in the North(1) hole, show a velocity increase postshot2.

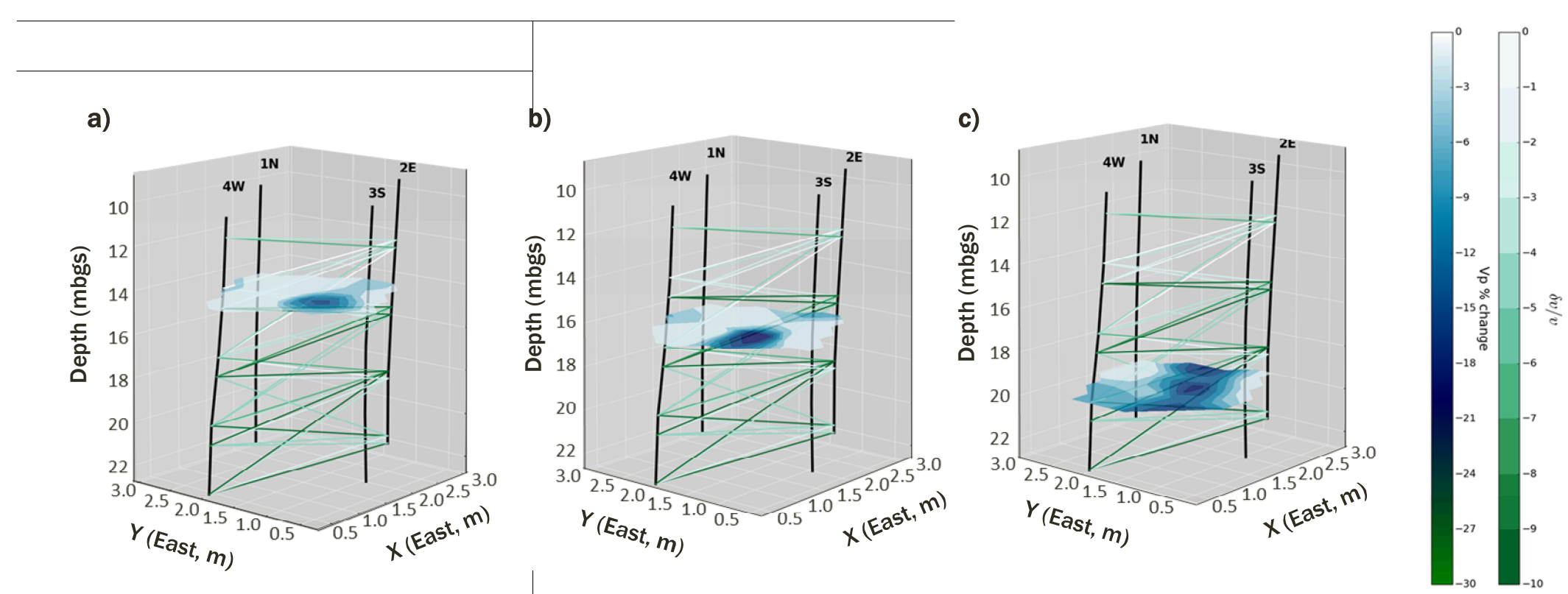


Figure 6. Comparison of relative velocity changes between preshot1 and postshot1 for DAS channel pairs between West(4) and East(2) holes and slices through cross-well seismic tomography P-wave velocity change matrix at a) 15 m, b) 17 m, and c) 20 m depth.

## 5. Pressure Injection

- Molenaar et al. (2012) showed that DAS recorded an increase in amplitude only in channels near perforations at specific frequencies concurrent with high pressure hydraulic-fracturing treatment (Figure 7).
- We tested if a similar response was recorded during a pressure test at Blue Canyon Dome.
- A migration in peak amplitudes is observed at two frequency ranges (near 220 Hz and 350 Hz) and a rise in amplitude during the height of injection is seen at ~50 Hz (Figure 8).

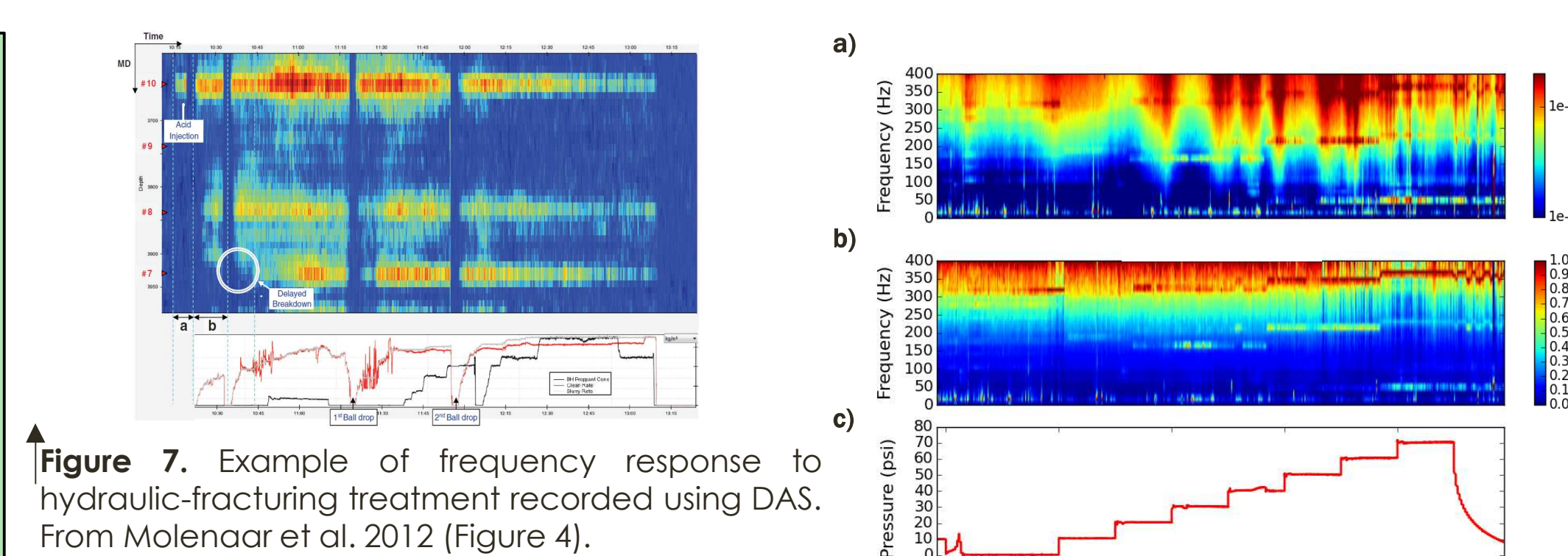


Figure 7. Example of frequency response to hydraulic-fracturing treatment recorded using DAS. From Molenaar et al. 2012 (Figure 4).

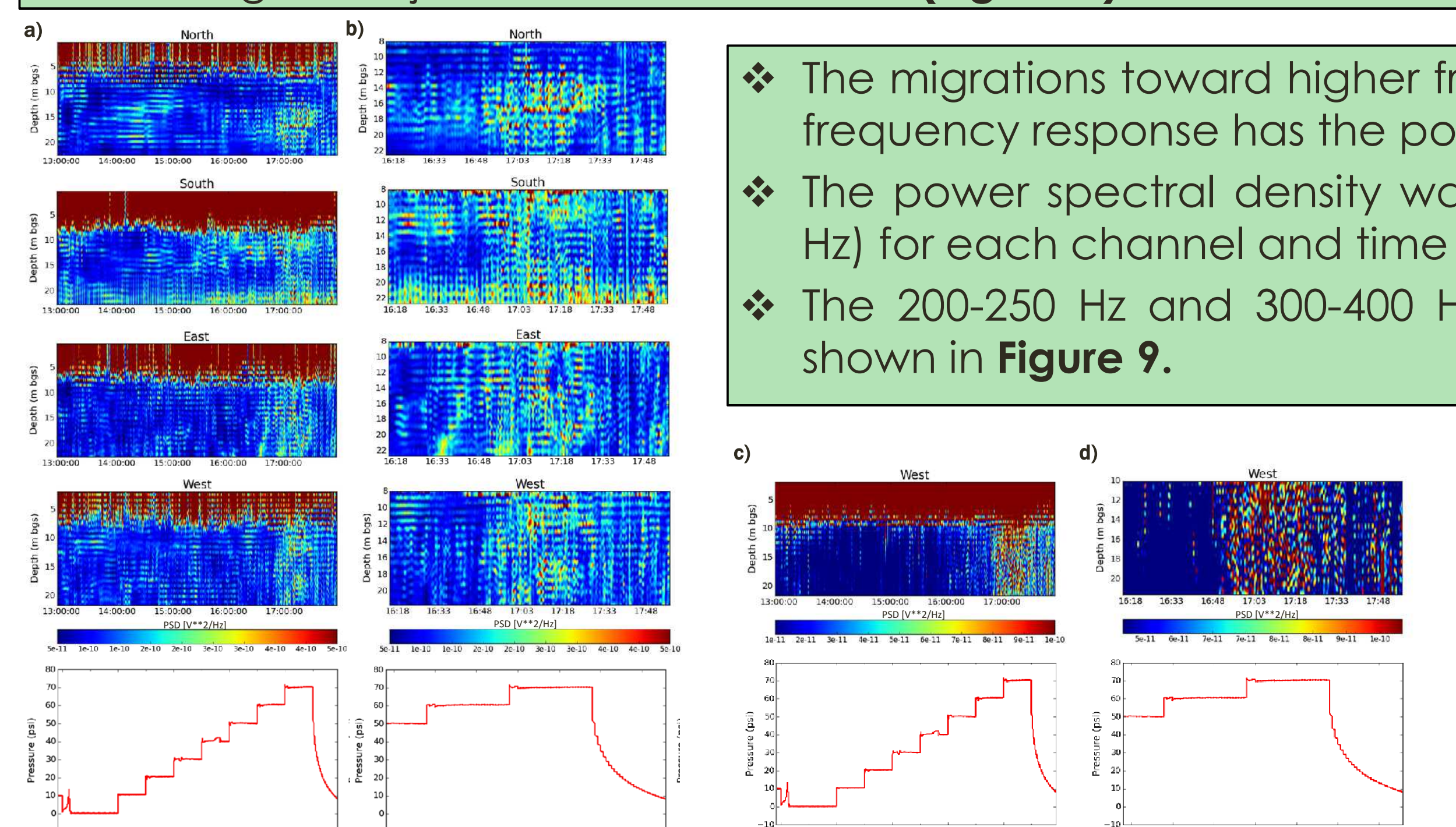


Figure 9. a) Average power in 300-400 Hz frequency range for each DAS channel during injection, separated by borehole b) a close up view of deeper channels (> 8 m) during peak injection. c) Average power in 0-100 Hz frequency range for only the West(4) borehole, and d) deeper channels (> 10 m) during peak injection.

- The migrations toward higher frequencies within the damage zone (Figure 8) suggested a frequency response has the potential to locate fractures by channel.
- The power spectral density was averaged in three ranges (0-100 Hz, 200-250 Hz, 300-400 Hz) for each channel and time during injection.
- The 200-250 Hz and 300-400 Hz ranges showed similar results, so only the 300-400 Hz is shown in Figure 9.
- Both frequency ranges show high amplitudes at shallow depths (< 8 m) that decrease with depth.
- The 300-400 Hz range show differences with location, but all contain an increase during peak injection.
- The 0-100 Hz range showed no relationship with location, only the West(4) channels are shown.
- A close view during peak injection (Figure 9b,d) show no clear depth relationship.

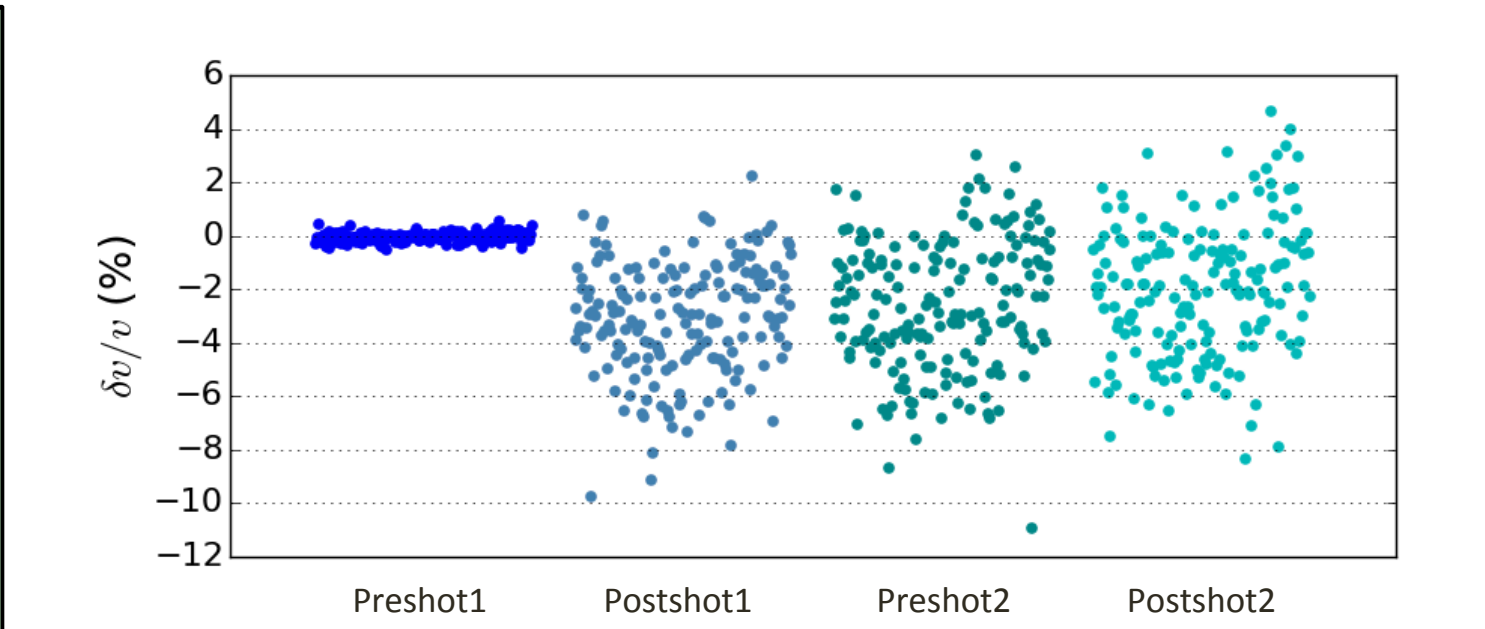


Figure 4. Velocity change relative to preshot1 conditions for each channel pair at each of the four time periods. All 120-minute stacks for each channel pair were averaged.

## 6. Discussion

- Preliminary results of DAS using ambient noise show promise for fracture imaging, though further analysis is needed.
- The power spectral density of ambient noise during each of the 4 time periods (preshot1, postshot1, preshot2, postshot2) show flat response above 1000 Hz and variations with depth below 1000 Hz (Figure 10).
- Cross-correlations were analyzed in the 3000-4000 Hz range, though subsequent pressure injection work suggested the lower frequencies might more accurately detect true environmental response.
- The fracture location and orientation was best imaged by cross-well seismic tomography and electrical resistivity tomography (Figure 11).
- A similar tomographic inversion is needed of  $\delta v/v$  to assess if detailed fracture imaging is possible.

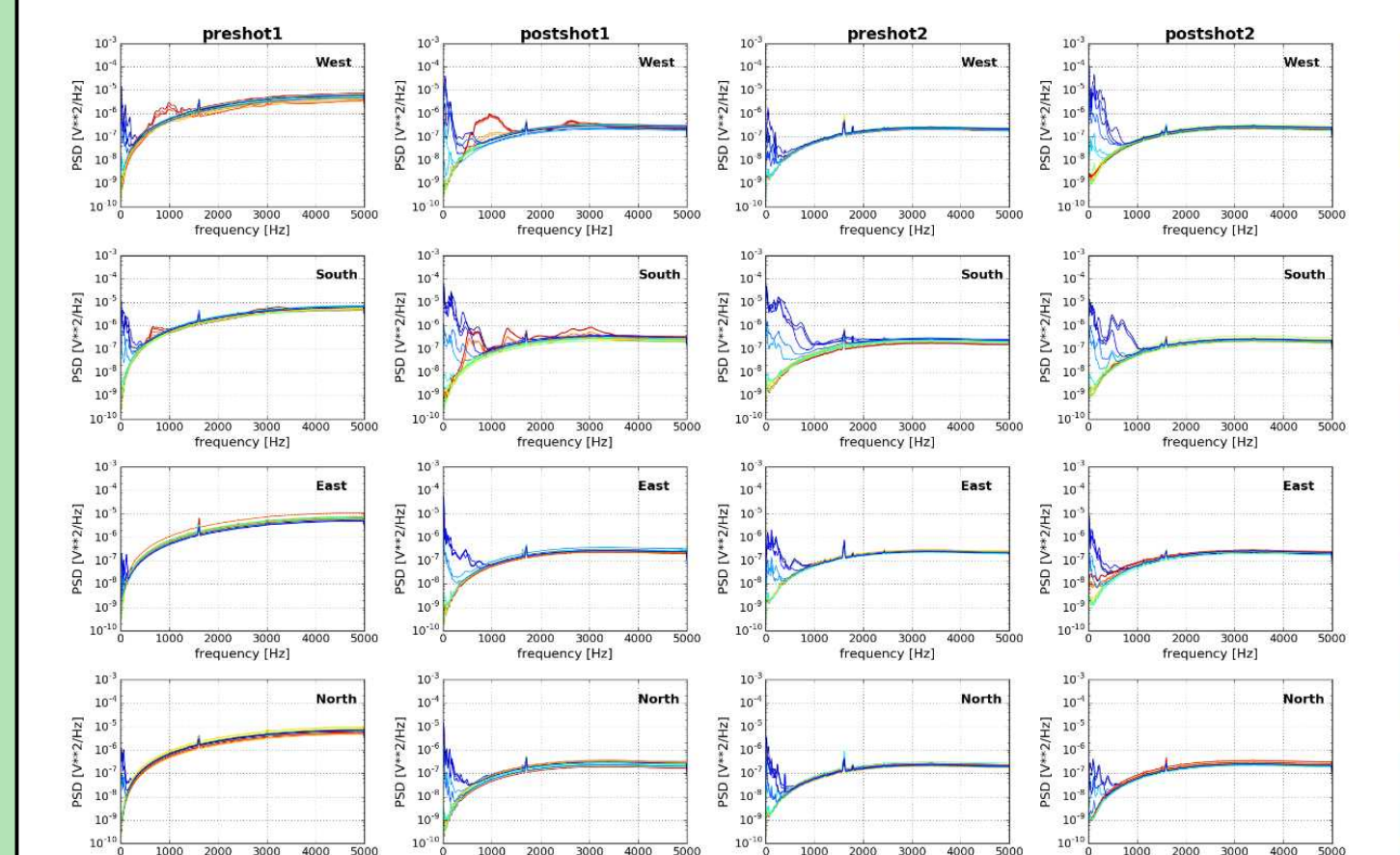


Figure 10. Power spectral density for each borehole (rows) and each time period (columns).

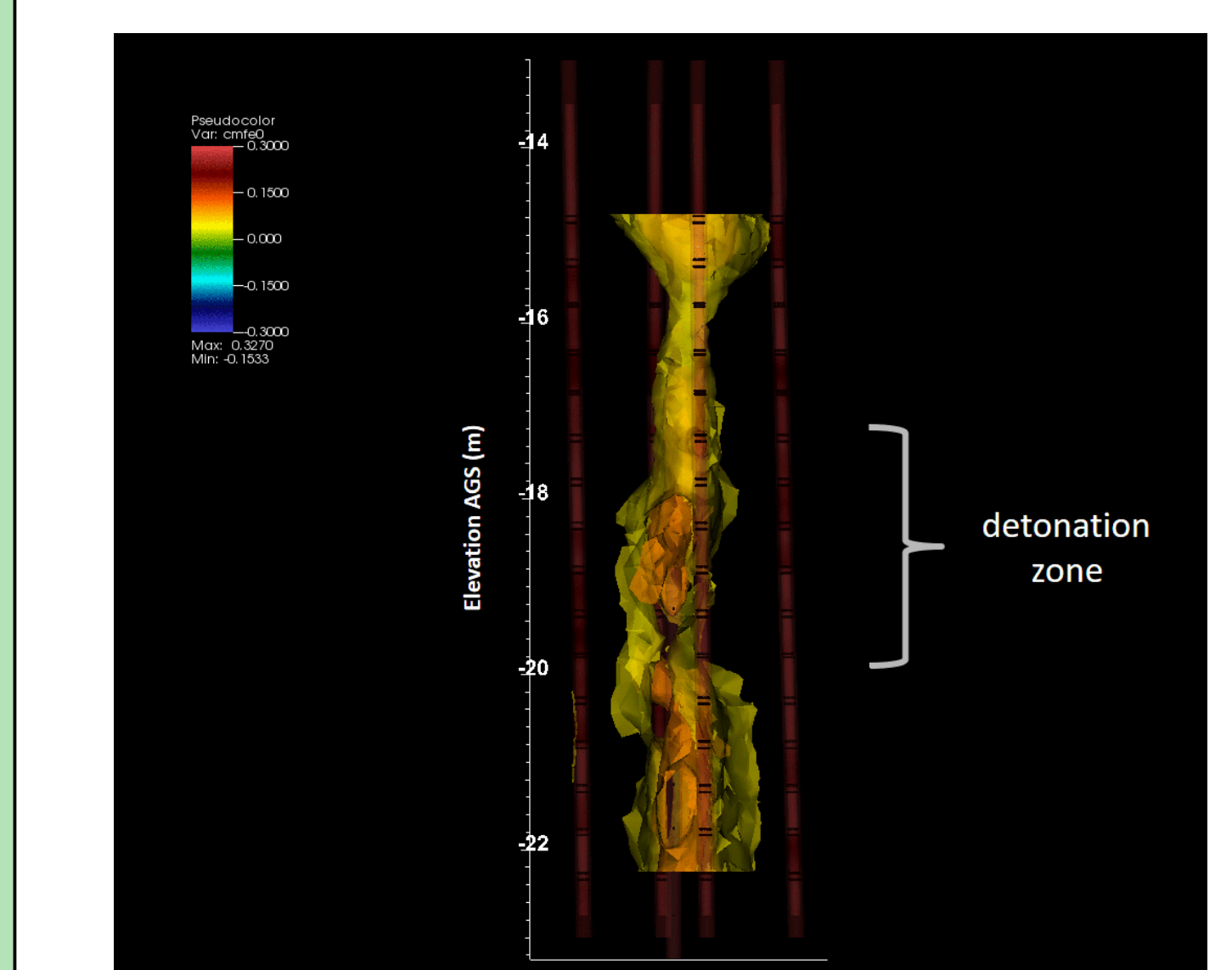


Figure 11. Electrical resistivity tomography (ERT) results during ZVI injection showing the general fracture location and morphology.

## 7. Conclusions

- Distributed Acoustic Sensing using ambient noise within boreholes is a novel approach for fracture imaging. Our work was a preliminary investigation into the viability of this technique.
- Relative velocity change following fracture emplacement showed an average velocity decrease of ~4%.
- Differences between station pairs suggest this method may be useful for locating fractures, though a tomographic approach would be needed.
- Analysis of frequency changes during pressure injection showed a promising increase in power and migration towards higher frequencies, particularly during peak injection. However, the frequency response was not found to be localized in space.
- Overall, this technique shows promising sensitivity to fracture generation and location. While the computation limitations are burdensome, further research is needed to more decisively conclude its viability.

## Acknowledgements

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