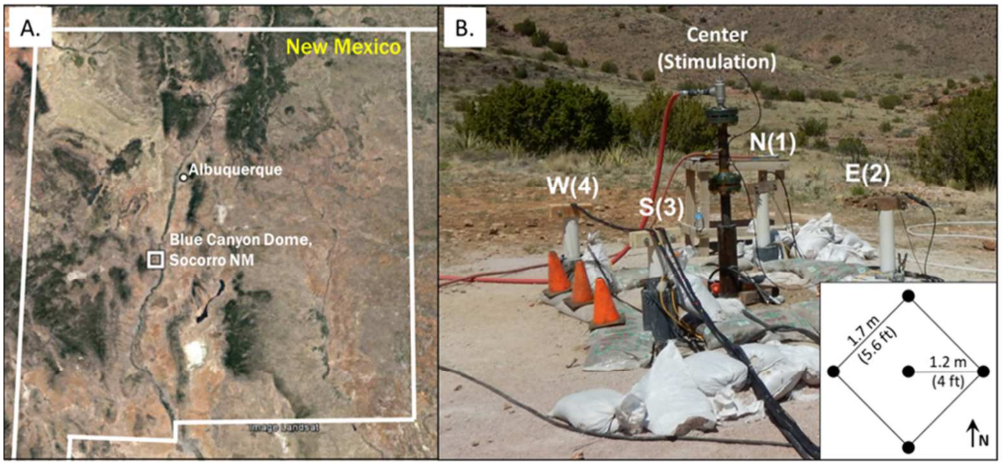

Figure 1. A) This study was conducted at Blue Canyon Dome, approximately 120 km south of Albuquerque, New Mexico. B) The monitoring boreholes were configured in a five-spot borehole pattern oriented North-South and East-West, with a stimulation borehole located in the center.

80x36mm (300 x 300 DPI)

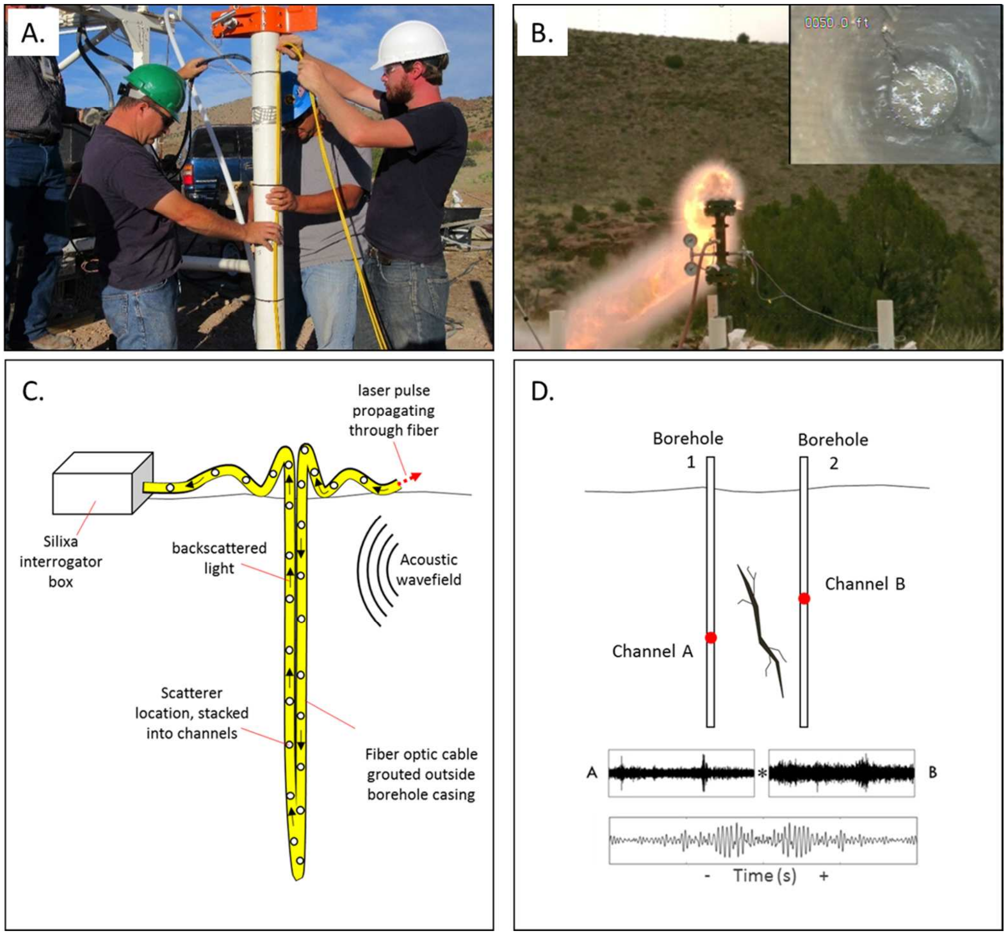

Figure 2. A) The downgoing and upgoing portions of the fiber optic cable were grouped and attached to the outside of the borehole casings. B) An example image of the second stimulation is shown along with an inset photo from the downhole camera at 15 m of the near-vertical fracture generated. C) Conceptual model of the DAS collection scheme: The Silixa iDAS interrogator box sends a laser pulse through the fiber every 100 µs. Post-processing results in scatterer locations (seismic channels) every ~1 m. D) Conceptual model of the cross-correlation analysis: 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. Channel pairs spanning the generated fracture should experience a stronger velocity change than pairs that do not intercept the fracture, thereby allowing for detection and possible delineation of the fracture location.

102x95mm (300 x 300 DPI)

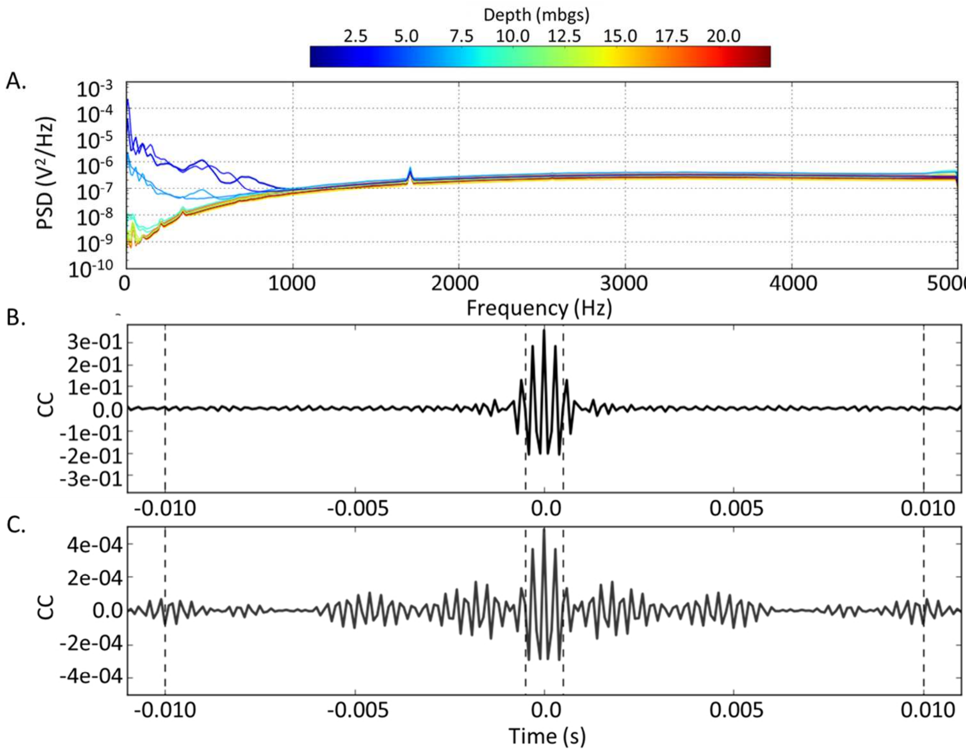

Figure 3. A) The mean power spectral density (PSD) of raw Post-stimulation 1 DAS data from channels in the East hole as a function of depth. B) Cross correlations (CC) are shown for channels 35 (20.262 m, West-4) and 100 (20.614 m, South-3) for the full 3-hour stack of cross correlations from Pre-stimulation 1, and C) an example 120-minute individual cross correlation from Post-stimulation 1. Measurements of δv/v were made by comparing the delay time of the scattered phases as a function of lag time in a series of windows between the minimum and maximum lag times (dashed black lines), ±0.0005 s and ±0.01 s, respectively.

123x95mm (300 x 300 DPI)

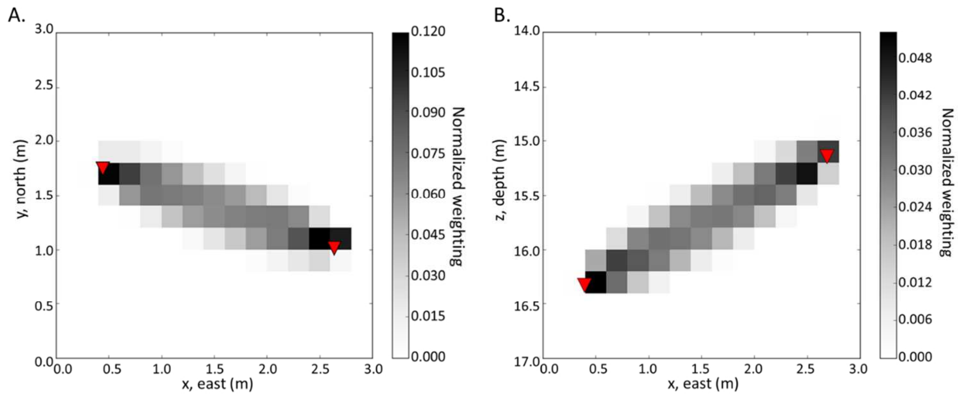

Figure 4. An example normalized weighting function for channel pair 26-167 between the West and East holes. The weighting functions defined the zones of sensitivity for each channel pair in the δv/v tomographic inversion.

121x50mm (300 x 300 DPI)

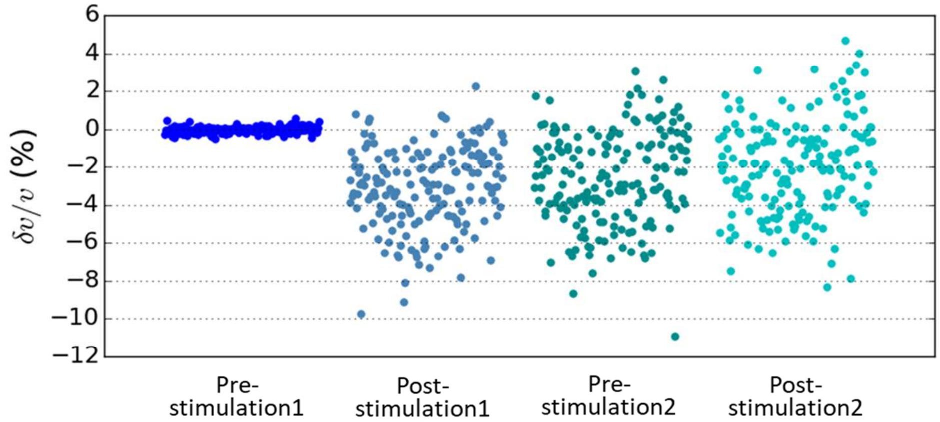

Figure 5. Average percent velocity changes (δv/v) are shown as a function of channel pair and categorized by time period. All velocity changes are relative to the full 3-hour stack of Pre-stimulation 1 cross correlations.

92x43mm (300 x 300 DPI)

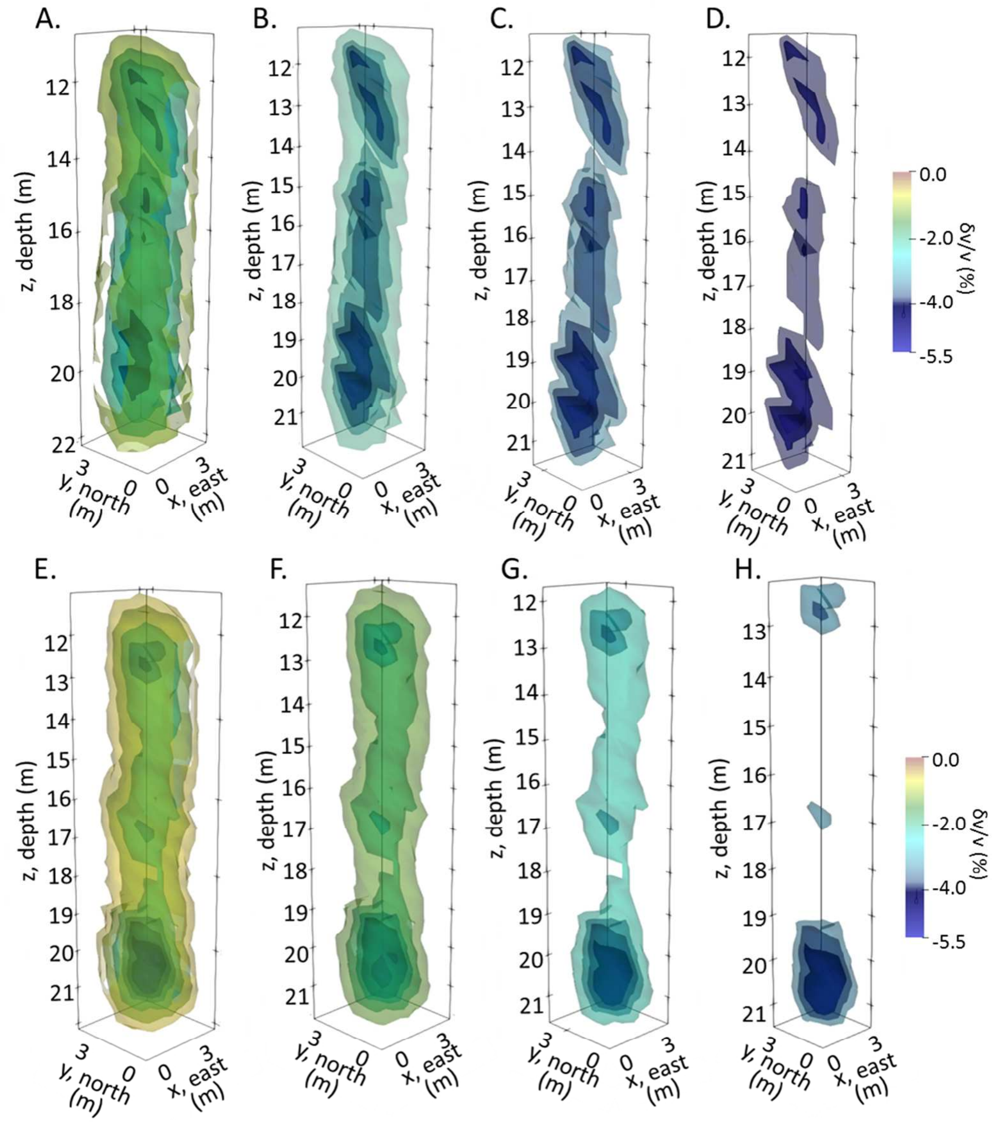

Figure 6. δv/v tomography results. Volumetric contours (isosurfaces) for Post-stimulation 1 are shown for the intervals (A) -1, -2, -3, -3.5, -4, -4.5 %, (B) -2, -3, -3.5, -4 %, (C) -3, -3.5, -4 %, and (D) -3.5, -4 %. Post-stimulation 2 isosurfaces are shown for the intervals (E) -1, -1.5, -2.25, -3, -3.5, -4 %, (F) -1.5, -2.25, -3, -3.5, -4 %, (G) -2.25, -3, -3.5, -4 %, and (H) -3, -3.5, -4 %.

99x114mm (300 x 300 DPI)

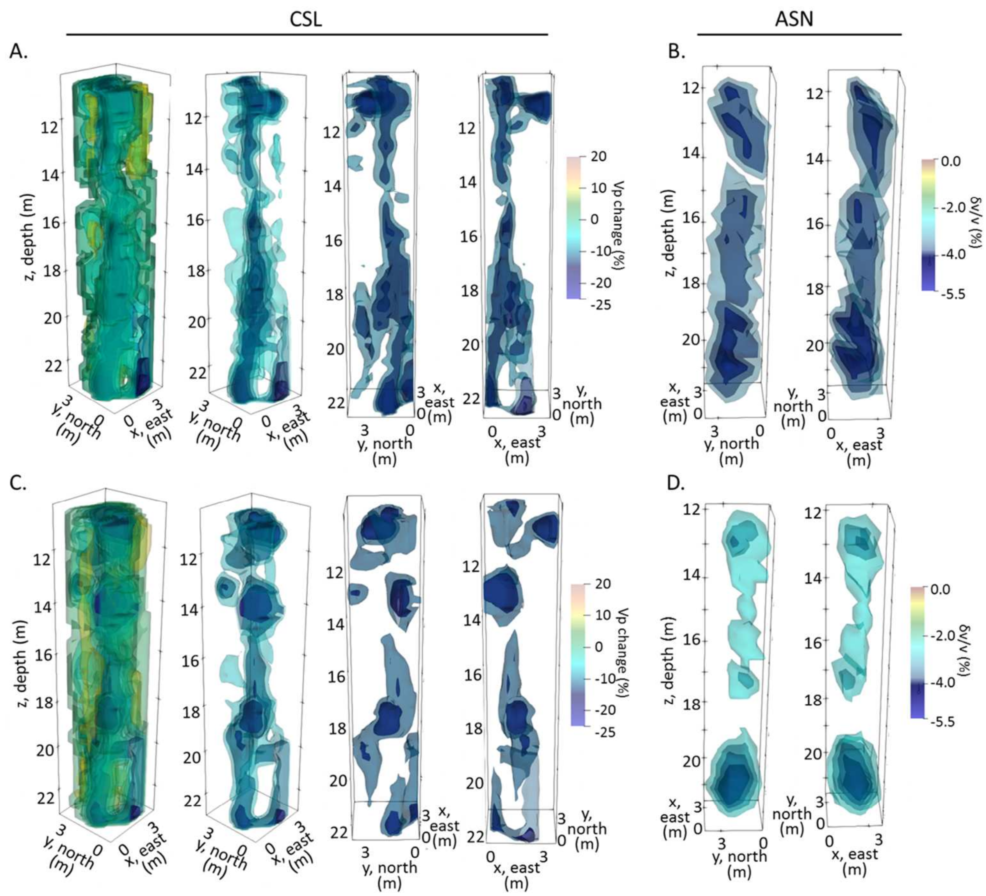

Figure 7. Comparison of tomographic results from cross-hole seismic logging (CSL) and ambient seismic noise δv/v (ASN). (A) The CSL Post-stimulation 1 volumetric contours (isosurfaces) are shown for progressively fewer intervals from left to right: (10, 0, -10, -15, -20, -25 %), (-10, -15, -20, -25 %), and (-15, -20, -25 %). The last interval range is shown looking west to east and then south to north. (B) ASN Posts-stimulation 1 results for the -3, -3.5, and -4 % isosurfaces, looking west to east and then south to north. (C) CSL Post-stimulation 2 isosurfaces for the intervals: (10, 0, -10, -15, -20, -25 %), (-10, -15, -25 %), and (-15, -25 %), with the last interval range shown looking west to east and then south to north. (D) ASN Posts-stimulation 2 results for -2.5, -3, -3.5, and -4 % isosurfaces, looking west to east and then south to north.

113x102mm (300 x 300 DPI)

Fracture Detection and Imaging Through Relative Seismic Velocity Changes Using Distributed Acoustic Sensing (DAS) and Ambient Seismic Noise

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Abstract

Fracture systems are important pathways for fluid and solute transport and exert a critical influence on the hydraulic properties of aquifers and reservoirs. Therefore, detailed knowledge of fracture locations, connections, and evolution is crucial for both groundwater and energy applications (e.g. enhanced geothermal, oil and gas recovery, carbon sequestration, and wastewater injection). The innovative combination of Distributed Acoustic Sensing (DAS) and ambient seismic noise techniques has the potential to detect and characterize fracture systems at high spatial and temporal resolution without an active source. To test this, we conducted a multi-physics field experiment at Blue Canyon Dome, NM. A novel energetic material developed by Sandia National Laboratories was used to generate fractures in two separate stimulations. Ambient noise was recorded before and after each stimulation using fiber optic cables installed in the outer annulus of 4 boreholes surrounding the stimulation hole at a radius of 1.2 m. The Python package MSNoise was used to compute cross correlations and measure changes in velocity between each time period relative to the initial (pre-stimulation) time period. The majority of channel pairs showed a velocity reduction (average -3% relative velocity change) following both stimulations. We used a 3D Bayesian tomography approach to resolve spatial variations by utilizing differences between channel pairs. Results showed the greatest velocity reduction was concentrated near the center of the test area, and suggested the presence of a near-vertical fracture, oriented NE-SW for depths > 19 meters below ground surface, and extending slightly to the SW corner. These results were generally consistent with cross-hole seismic tomography time-lapse images. DAS technology provides valuable sensing capability and – when used with a passive seismic approach – shows great promise for monitoring and characterization of fractured-rock systems.

1. Introduction

While it is well known that fracture networks provide essential pathways for fluid and solute transport, the complexity of their generation, evolution, and morphology continues to be a challenge for characterization and monitoring (National Research Council, 1996; Berkowitz, 2002; Neuman, 2005). The intricate heterogeneity and anisotropy of fractured systems remains an important obstacle for hydrogeologic studies and energy extraction (e.g. enhanced geothermal systems, tight shale gas reservoirs). Accurate characterization of fracture extent, orientation, and communication is needed for assessing hydraulic properties, and subsequently provide direction to decision makers concerning safe and sustainable extraction and injection efforts.

Borehole and surficial geophysical methods have been used successfully for characterization (e.g. Verdon et al., 2009; Day-Lewis et al., 2017), but encounter limitations in efficiency and spatial resolution due to the multi-scale nature of fracture networks. Fracture apertures are typically small (microns to centimeters) but extend over large areas (meters to tens of meters) (Geertsma and De Klerk, 1969; Johns et al., 1993; Hakami and Larsson, 1996). Fracture systems with small apertures and density are typically unresolvable without a drill-back or mine-back study (Warpinski and Teufel, 1987). Borehole logging and cross-hole methods allow for detailed interrogation of the subsurface at very fine scales and up to four dimensions (e.g. Tsvankin et al., 2010). However, this level of detail requires lengthy campaign-style surveying and re-occupation, and great expense with construction of additional boreholes and possibly permanent installation of geophysical sensors. Ideally, a compromise can be reached where geophysical monitoring could be performed with a suite of inexpensive sensors in a cross-hole geometry within nominally uncompleted boreholes (i.e. open below surface casing). This would allow targeting a zone of interest from multiple azimuths and close offsets, which would improve both spatial and temporal resolution (i.e. multi-physics with large numbers of sensors ("large N") approaches such as in Neal and Krohn (2012) and Bergmann et al. (2013)).

Distributed sensing technologies represent a promising tool for multi-phenomenological investigations, especially for fracture-flow systems where measuring acoustic, strain, and temperature signals is important. These sensing technologies offer the opportunity for large N permanent installations (i.e. either grouted behind casing or direct buried) at lower economic burdens since the fiber cost is relatively low. Further, fiber-based methods provide distributed measurements with offsets tailored to the scale of the project, typically on the order of a few meters. The three primary challenges for this type of monitoring are 1) the large volumes of data that are recorded with these extensive arrays, 2) the differences in sensitivity and directionality of fibers in contrast with conventional point sensors, and 3) the cost of the interrogator systems. The first challenge is addressed through the ever increasing availability of computational power and data storage, while the latter two will only be addressed as fiber-based measurements become more commonplace and well-characterized. For the remainder of the paper, we will focus only on Distributed Acoustic Sensing (DAS) and an application that could further reduce the economic burden of long term monitoring by eliminating active sources as a requirement for change detection imaging.

DAS is a new and rapidly advancing technology that uses fiber optic cables to detect the transmission of acoustic waves through the subsurface (Molenaar et al., 2012; Daley et al., 2013; Parker et al., 2014). An interrogator box sends a laser pulse through the cable and records as minor imperfections cause a portion of the light to be backscattered through Rayleigh scattering. Passing acoustic waves stretch and compress the cable, thereby altering the optical path length and subsequent travel time of the backscattered light. Scattering occurs along the entire length of cable, allowing for a distributed network of individual channels (or sensors). However, only the scatterers in the perturbed portion of fiber will show a change in transit time thereby allowing for their spatial isolation. Application of this method within boreholes has the potential to provide detailed information on fracture geometries and characteristics by monitoring changes in seismic velocity. This could be particularly valuable for providing actionable feedback during injection and extraction operations, assuming adequate inversion algorithms exist.

Seismic interferometry using ambient seismic noise is another burgeoning field that has great potential for passive monitoring applications. Cross correlation of records from two stations is effective at estimating the impulse response, or empirical Greens Function, of the media between the two stations (Campillo and Paul, 2003; Shapiro and Campillo, 2004). The first station becomes a virtual source for the waves recorded on the second. This technique has been applied successfully for a variety of applications from crustal to near-surface scales (e.g. Moschetti et al., 2007; Picozzi et al., 2009; James et al., 2017). However, ambient noise studies are limited in their depth of investigation and spatial resolution by the sensor spacing. Therefore, DAS technology could be a boon for seismic interferometry studies since it transforms a continuous line of fiber optic cable (m to km in length) into a distributed network of sensors at very close spacing (~1 m). Here, we present results from a unique field experiment in which we used DAS installed in the annulus of four monitoring boreholes to record the ambient noise wavefield before and after fracture emplacement from a novel energetic material. Specifically, DAS was examined for its potential in fracture generation detection and fracture imaging, as well as to provide a unique dataset for examining the ambient wavefield as recorded by DAS within boreholes.

2. SubTER Field Test

We conducted this field experiment as part of the Department of Energy (DOE) Subsurface Science, Technology, Engineering, and R&D (SubTER) crosscut with the goal of developing efficient and economic systems for imaging and monitoring fractures. While multiple geophysical characterization and change detection techniques were applied (Knox et al., 2016), this paper focuses on the utilization of DAS, ambient noise interferometry, and seismic change detection techniques for fracture imaging. We present tomographic results from the more established cross-hole seismic logging (CSL) active source survey for comparison. Even though these two seismic methods were sensitive to different feature scales and the inversion approaches differed, a first-order comparison for determining successful fracture detection and delineation was valuable. The experimental design consisted of five boreholes drilled to 23 meters below ground surface configured in a five-spot borehole pattern. A center stimulation hole (C, Center) was surrounded by four cased monitoring holes at a radius of 1.2 m (4ft) and oriented along the cardinal directions (N1, North-1; E2, East-2; S3, South-3; and W4, West-4) (Figure 1). These monitoring holes were instrumented with electrodes and fiber optic cables attached to the outside of the casing and grouted in place (Figure 2A). We used a single continuous fiber optic cable for all four monitoring holes, starting in the West hole and ending in the North, with each hole containing a down-going and up-going segment.

Upon completion of the boreholes, the field campaign began with geophysical characterization of the site using seismic and electrical methods, which established the initial conditions of the test bed. The next step was to emplace a fracture network using a novel energetic material developed by Sandia National Labs, which allowed us to eliminate near-field wellbore damage by tailoring the initial pressure while creating an extended pressure pulse to drive the multiple energetically initiated fractures. This energetic stimulation technique bridges the gap between a propellant and a conventional high explosive stimulation. Minimal damage was caused to the stimulation hole thereby allowing re-entry for repeated tests. The energetic material was emplaced between 18 and 22 m depth in the open hole section of the center stimulation borehole. Afterward, another comprehensive characterization effort was undertaken using hydrologic tests, geophysical tracers, seismic, and electrical methods. The stimulation borehole was then re-fractured using the same novel energetic material to test the efficacy of secondary stimulation. The test bed underwent a final comprehensive hydrologic and geophysical characterization. These series of measurements afforded detailed investigations into fracturing, re-fracturing, and flow phenomenology (Knox et al., 2016). DAS and cross-hole seismic measurements were taken throughout at targeted intervals.

2.1. Study Site

The field test was conducted at Blue Canyon Dome, which is located ~6 km west of Socorro, NM on a ridge shared with Socorro Peak (Figure 1). The site is managed by the Energetic Materials Research and Testing Center (EMRTC), an affiliation of the New Mexico Institute of Mining and Technology. The ridge is unbounded on three sides and free of background stress that might generate preferential fracture orientations. The shallow configuration of the wells also precludes the site from having strong preferential stress directions. The site geology consists dominantly of Miocene-age rhyolite (Chamberlin, 1981).

Borehole logging provided details on the lithology, texture, pre-existing fractures, and borehole construction. A weathering contact occurs at ~9 m depth separating weathered and highly fractured rhyolite above from comparatively un-weathered rhyolite below. Sparse near-vertical and re-mineralized fractures were observed at deeper depths (> 9 m). A zone of larger clast sizes was observed in the optical televiewer logs near the bottom of the boreholes. Gamma-gamma logs indicated a single lithology throughout with little clay. Caliper logs showed the boreholes were consistently sized (13 cm) with no or minimal drilling-induced fractures (Knox et al., 2016). Deviation logs indicated the boreholes had minor titling (< 2°) and deviation (< 0.2 m). However, the close hole spacing made the x-y deviations significant so all measurement locations were corrected to account for this deviation.

3. Methods

3.1. DAS & Ambient Seismic Noise

Cross correlations of ambient seismic noise are useful for measuring subtle changes in seismic velocity in the subsurface between two stations (e.g. Sens-Schönfelder and Wegler, 2006; Brenguier et al., 2011). Comparison of the scattered arrivals within cross correlations between two time periods allows for measurement of the change in velocity relative to the earlier time. The presence of fractures typically reduces bulk seismic velocity (Moos and Zoback, 1983). Therefore, the emplacement of fractures at Blue Canyon Dome was expected to result in a measurable reduction in seismic velocity as recorded in the ambient noise wavefield. Fractures should also alter travel times through increased scattering. Seismic waves traveling perpendicular to fractures were expected to experience stronger velocity reductions than waves that intercept only a small portion or none of the fracture (Figure 2). Therefore, variations between different channel pairs should be useful for detecting the fracture location and orientation.

We installed a continuous length of fiber optic cable (tactical single-mode/multi-mode cable with polyurethane sheathing) behind casing in the monitoring boreholes (Figure 2). The fiber was grouted in place, which allowed for repeat collection of both passive and active seismic data throughout the study. Silixa was contracted to collect the DAS recordings using their iDAS system and a 10 m gauge length. Approximately 13 hours of ambient seismic noise were recorded before and after each energetic stimulation creating four distinct time periods for comparison: Pre- and Post-stimulation 1 and Pre- and Post-stimulation 2. Post-stimulation 1 and Pre-stimulation 2 data were treated as distinct because large volumes of fluid (water and tracers) were injected into the system at low pressures (≤ 70 psi) between the two stimulations. Ambient recordings occurred approximately between 6:30 PM and 7:30 AM to minimize potentially dominant influences from on-site activities. Environmental and anthropogenic noise sources were expected, though the specific sources were not known, nor was knowledge of their origin required for the cross-correlation procedure. Silixa completed the de-noising and pre-processing stacking of scatterers to create ~1 m channel spacing.

Processed data consisted of HDF5 files containing 30 s records, at 10 kHz sampling rate, for all 263 channels. Each ~13-hour time period resulted in ~500 Gb of data, totaling nearly 2 Tb of continuous data. Once the data was compiled, we determined the channel depths and locations corresponding to each borehole, removed all above-ground channels, and corrected locations using the deviation logs. To make the large dataset more manageable, and analysis computationally feasible, we focused only on channels located within the unweathered rhyolite zone (> 9 m depth) and further down sampled by a factor of 3. This resulted in a final 60 channels, with ~3 m spacing, whose records we converted to miniseed format for the next analysis stage.

We used the Python package MSNoise (Lecocq et al., 2014) to compute the cross correlations and measure the relative velocity changes. Only channel pairs with < 60° vertical offset between boreholes were computed to encourage coherence of horizontally propagating waves. Records were bandpass filtered between 3000 and 4000 Hz to target high frequency waves due to the close station offsets (< 2 m). Power spectral density plots of the raw DAS data revealed a depth dependence only for frequencies <1000 Hz, suggesting surface waves were only recorded at these lower frequencies and the higher frequency arrivals were direct or scattered body waves (Figure 3A). The vertical orientation of the fiber optic cable would have resulted in decreased sensitivity to horizontally propagating compressional waves (P-waves). Therefore, we suspect scattered vertically polarized shear waves (S-waves) as the primary phases in the cross correlations, and acoustic emissions as a likely source at this frequency range. We computed 1-minute cross correlations using the preprocessed records. Despite initial data reduction efforts, the cross-correlation procedure was still computationally intensive so we focused on measurements in the first 3 hours of each recording periods. We recognize omitting viable data is not desirable but needed to weigh the cost of computation time against correlation and measurement quality. The goal of this preliminary analysis was to determine if this methodological approach (DAS + ambient noise) has potential for this application and warrants further study, for which 3 hours proved sufficient. A more in-depth study of the influence of stacking time and frequency is needed in the future.

We stacked the 1-minute correlations into moving 120-minute stacks for each time-period (Pre-stimulation 1, Post-stimulation 1, Pre-stimulation 2, Post-stimulation 2). Since this dataset encompassed such small timescales and a unique time-period assessment compared to typical interferometry studies, the MSNoise source codes required significant alteration. We adjusted the MSNoise procedure to calculate velocity changes ($\delta v/v$) in sliding 120-minute stacks for each time-period relative to the complete stack for Pre-stimulation 1 (all 3 hours). Then, we averaged the individual $\delta v/v$ values for each channel pair in each time-period. Figure 3 shows an example channel pair's full stack from Pre-stimulation 1 and a representative Post-stimulation 1 individual 120-minute cross correlation. The $\delta v/v$ measurements were done by calculating the phase delay (δt) between the two cross correlations in a series of overlapping windows (0.004 s wide) between minimum and maximum lag boundaries (±0.0005 s and ±0.01 s, respectively). The slope of the delay times as a function of lag time ($\delta t/t$) is equal to $-\delta v/v$ (Ratdomopurbo and Poupinet, 1995; Snieder et al., 2002; Clarke et al., 2011). This relationship contains the simplifying assumption that the velocity perturbation is homogeneous along the ray path.

3.2 δv/v tomography

To better visualize the results and spatial variations, we computed a 3D tomographic inversion using the final $\delta v/v$ measurements for each station pair for Post-stimulation 1 and Post-stimulation 2. We used a Bayesian tomography approach and weighted each mean $\delta v/v$ measurement by its standard deviation. A 7 m x 7 m x 16 m volume was discretized into 0.5 m x 0.5 m x 0.5 m cells, centered on the test pad, and spanned the depth range of 8-24 m. Since the $\delta v/v$ measurements relied on scattered shear waves, we accounted for volumetric sensitivity by calculating the 3D Fresnel zone for each channel pair, assuming a 2000 m/s shear-wave velocity and 3500 Hz center frequency (0.57 m wavelength, λ). The Fresnel zone approximated the volume represented by each $\delta v/v$ measurement, thereby accounting for channels closer together sampling a smaller volume and thus having greater sensitivity to the localized velocity perturbations (i.e. fracture generation) than channels further apart. This approximation also ensured greatest sensitivity near the channel locations (Figure 4) to be suitable for $\delta v/v$ inversion (Margerin et al., 2015).

For each channel pair, the straight-line path (L) between channel locations was found and divided into step segments (l) of 0.1 m. At each step increment (i), the Fresnel zone radius (r) was calculated by the following equation (Spetzler and Snieder, 2004):

$$r_i = \sqrt{\frac{n\lambda d_1 d_2}{L}} \quad (1)$$

where d_1 and d_2 are the distances along the straight-line path to the current step location from the starting and ending channel locations, respectively, and n is a scalar (0.75 in this case). The radius was used to define a circle perpendicular to the straight-line path, then the area of the circle that fell within each intersecting cell (a_c) was calculated. These Fresnel zone areas were then normalized and summed along the entire straight-line path distance to get an integrated final weighting value (μ) for each cell (c) and channel pair (p) (Figure 4):

$$\mu_{c,p} = \sum_{i=0}^{L/l} \frac{\left(\frac{a_c}{\pi r_i^2}\right) * l}{L_p} \quad (2)$$

We used a Markov Chain Monte Carlo (MCMC) algorithm to iteratively propose, accept, and reject models consisting of individual relative velocity variations for all cells ($\mathbf{dv_{cells}}$). Following the sensitivity calculation, only 675 cells (out of 6272) ended up being used (intersected by a Fresnel zone) and active during the inversion. The volumetric sensitivity weights ($\mu_{c,p}$) populated the matrix **A** (Number of pairs x Number of cells) and were used to take the modeled dv values of all cells and calculate predicted velocity variation measurements for each channel pair: $\mathbf{A} \times \mathbf{dv_{cells}} = \mathbf{dv_{pre}}$. The MCMC algorithm ran for 5 chains, each of 1,000,000 iterations and starting with a model proposed at random from the prior dv distribution: $-15\% \leq dv \leq 10\%$. Cells were randomly chosen and perturbed per a Gaussian probability distribution centered at the current dv value with a variance of 0.5%. A proposed model was either accepted or rejected based on an acceptance criterion defined using the misfit between the predicted and observed velocity variations. Preliminary results were very scattered with large differences occurring between adjacent cells which were either near zero or pushed toward the minimum and maximum *dv* boundaries. This suggested smoothing needed to be enforced so we added a roughness calculation and factored the model roughness into the acceptance criterion. Therefore, models that reduced misfit and/or roughness were favored. An ensemble of the 25,0000 best (lowest misfit) models was created and used to find the final solution as the most probable *dv* value for each cell.

3.3. Cross-hole Seismic Survey & Tomography

In addition to the DAS measurements, we conducted angled cross-well seismic surveys before and after each stimulation. A pair of piezoelectric hydrophones (42 kHz center frequency, interchangeable as source and receiver) were lowered and raised incrementally within adjacent boreholes. The source hydrophone emitted compressional waves (P-wave) in the ultrasonic frequency band to be recorded on the receiver hydrophone in the adjacent hole, thereby providing a measurement of the subsurface P-wave velocity (Vp) between the two locations (Olson and Wright, 1989). A depth wheel controlled the hydrophone movements such that a signal was recorded every 1.4 cm along the entire length of the boreholes. The angled cross-hole survey incorporated data from nine vertical offset angles between the source and receiver hydrophone (0°, ±15°, ±30°, ±45°, ±60°) for each borehole pair (6 in total). These exhaustive campaigns resulted in over 25,000 P-wave arrival picks used in a 3D tomographic inversion of each time-period (Knox et al., 2016). The tomographic images for the 2.44 m x 2.44 m x 12.2 m rectangular volume encompassing the experiment area were computed via an iterative least squares inversion of the travel times subject to smoothing constraints. We found the ray path geometry for each time-period using a Vidale-Hole finite-difference 3D eikonal solver (Vidale, 1990; Hole and Zelt, 1995). The vertical resolution was determined to be between approximately 7.5-15.2 cm from checkerboard tests (Knox et al., 2016).

4. Results

4.1 Relative Velocity Changes (δv/v)

All 120-minute cross correlation stacks were compared to the full 3-hour stack from Pre-stimulation 1. Accordingly, the resulting average *δv/v* values for all stations pairs from Pre-stimulation 1 were near zero (Figure 5). Following the first shot, the Post-stimulation 1 cross correlations overwhelmingly returned a relative velocity decrease. More than 90% of station pairs recorded a velocity reduction, with an average reduction of -3% (Figure 5). Eighty-four percent of channel pairs measured a velocity decrease of -1% or more, 10% measured little to no velocity decrease (-1% < *δv/v* ≤ 0%), and the remaining 6% of channel pairs showed a small velocity increase. The Pre-stimulation 2 results were very similar to the Post-stimulation1 results, but individual channel pairs did show some variation. The majority of Post-stimulation 2 cross correlations still showed a velocity reduction. Sixty-four percent of channel pairs measured a velocity decrease of -1% or more. Like Post-stimulation 1, 10% of channel pairs showed little to no velocity reduction compared to Pre-stimulation 1 conditions. However, an increased number showed a relative velocity increase (20% of channel pairs) (Figure 5).

4.2 δv/v Tomography

The 3D Bayesian tomography results for both Post-stimulation 1 and Post-stimulation 2 showed a velocity reduction throughout most of the experiment area. Contoured isosurface volumes revealed the greatest reductions (~5%) were concentrated toward the center (Figure 6). The magnitude of velocity reduction increased toward the center stimulation hole and decreased towards the edges of the model area. Focusing on the largest magnitude velocity reductions, distinct zones were observed along the center, with variable morphology and orientations. Following Post-stimulation 1, zones of reduced velocity occurred from ~11-14 m, 15-18 m, and ~18-21 m depth. The shallow and deep zones appeared to strike approximately NE-SW, though the surfaces were fairly irregular (Figure 6). The greatest velocity reductions were near the center, from ~18-21 m depth, and slightly toward the SW corner. Post-stimulation 2 results were similar to Post-stimulation 1, where the magnitude of velocity reduction increased toward the center and distinct zones could be observed (Figure 6E-H). The greatest velocity reduction (>4%) following the second stimulation was concentrated at the greatest depths (~19-21 m). Smaller, secondary zones also occurred at ~17 m and at shallow depths (~12-13 m). Compared to Post-stimulation 1, the zones of reduced velocity become more spherical and less planar following the second stimulation.

4.3 P-wave Tomography

We used the resulting P-wave velocity models from the CSL tomography to find the percent velocity change following each stimulation, relative to the first time period (Pre-stimulation 1). Results showed both strong increases and decreases in P-wave velocity (Vp). Apart from some anomalies near the model edges, the greatest velocity reductions occurred near the center of the model area and slightly to the SW (Figure 7A,C). Some heterogeneity in velocity variations was observed, with zones of large velocity increases present toward the model edges and in scattered zones between 10 and 15 m depth toward the eastern side. Contoured volumes showed variations with depth. Following stimulation 1, a semi-continuous zone of velocity reduction was seen throughout the model area concentrated toward the center and roughly oriented NE-SW. Velocity reductions appeared concentrated to the south and west at depths greater than ~18 m. Post-stimulation 2 results were similar, except the zones of greatest velocity reduction were more segmented and spherical (Figure 7C). The magnitude of velocity changes also increased, in both positive and negative directions, following the second stimulation. Distinct shallow zones were observed in the center and slightly east above ~11 m, and in the SW from 12-14 m. Velocity reduction was also concentrated in the center from 17-18 m with arms that extended and thinned to the south up to ~15 m and to the north down to ~21 m (Figure 7C). A second deep zone of great (>10%) velocity reduction was also observed near the south and west edges of the model, in a similar location as in Post-stimulation 1.

5. Discussion

The greatest velocity reductions from the $\delta v/v$ tomography were concentrated around the center stimulation hole and generally supported the presence of a near-vertical fracture, as observed in downhole camera images (Figure 2B inset). Comparison of $\delta v/v$ tomography results with CSL tomography images revealed important similarities and differences, which were expected. First, both seismic methods returned velocity reductions near the stimulation borehole and emplaced fracture (center). Post-stimulation 1 results for both methods showed reductions concentrated at depths greater than ~18 m and slightly toward the SW corner of the array. This suggested fracturing was primarily at the depths corresponding to the energetic material emplacement, and dominant propagation was to the SW. Second, both results showed a linear zone of velocity reduction that indicated the fracture was oriented roughly NE-SW and extended vertically throughout the model domain. However, the orientation was more clear in the cross-hole results. The *δv/v* results consistently showed the velocity reduction in the center while the cross-hole results showed much more heterogeneity, including significant zones of velocity increases. Third, both methods revealed distinct zones of velocity reduction, including at shallow (12-14 m), intermediate (15-18 m), and deep (18-21 m) depths. For example, a discontinuity in the zones of greatest velocity reduction was observed around 14.5-15 m depth in both Post-stimulation 1 results (Figure 7A,B). Post-stimulation 2 *δv/v* images suggested the second stimulation primarily fractured around the center hole at deeper depths (~19-21 m) and to a lesser extent from 12-18 m (Figure 7D). The CSL results showed velocity reductions occurred separately at shallow (< 14 m) and deep (> 17 m) depths, but both zones were less concentrated toward the center compared to the *δv/v* results. In addition, the CSL results indicated greater fracturing between 17 and 18 m depth, with possible fracture limbs extending to shallower depths northward and deeper depths southward (Figure 7C). The *δv/v* results did reveal a zone at 17-18 m depth that extended to shallower depths on the south side of the model. However, no northward extension below this volume was recovered and the feature was secondary in terms of magnitude and size to the zone from 19-21 m depth. These differences could be the result of multiple factors including: 1) the CSL campaign used much higher frequencies than the *δv/v* measurements meaning they were sensitive to features at different scales, 2) the *δv/v* measurements used scattered waves and assumed a homogeneous velocity perturbation which may in effect dampen or smear the velocity changes to a greater degree than can be accounted for with the inversion's volumetric sensitivity, 3) the tomography in each case contained different smoothing parameters.

6. Conclusions

Preliminary results of relative velocity variations in seismic noise cross correlations from DAS show great promise for fracture detection and imaging. By using 3D Bayesian tomography that accounted for volumetric sensitivity, we were able to model spatial variations in *δv/v* related to fracture emplacement. Velocity variations accurately located the emplaced fracture and characterized distinct zones in fracture morphology and orientation. Although cross-hole seismic tomography should be examined at similar frequencies – so the wavefield is sensitive to similarly sized structures – the comparison supported the major *δv/*v findings and helped validate this methodological approach. Three hours of ambient noise proved sufficient for obtaining meaningful measurements of velocity changes and spatial variations. The quality of these measurements is expected to improve with stacking time so further analysis is needed to identify the full potential of this method. Furthermore, the influence of frequency and wave type (body vs. surface) should be explored to fully characterize the ambient wavefield. If lower frequencies prove useful in this type of imaging, lower sampling rates (<10 kHz) would greatly reduce the size of the dataset and ease computation and memory requirements. The combination of DAS with ambient noise techniques has great potential for large scale characterization and monitoring studies with high spatial and temporal resolution and relatively efficient and inexpensive data collection. We have showed that DAS can be used in conjunction with passive seismic interferometry techniques to detect and characterize fractured systems and this methodological approach warrants further attention.

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