PROCEEDINGS, 45th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2020
SGP-TR-216

Anisotropic Imaging of Created Fractures in EGS Collab Experiments Using CASSM Data

Benxin Chi[1], Lianjie Huang[1], Kai Gao[1], Jonathan Ajo-Franklin[2,3], Timothy J. Kneafsey[2], and EGS Collab Team[4]

[1]Los Alamos National Laboratory, Los Alamos, NM 87545, USA

[2]Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

[3]Rice University, Houston, TX 77005, USA

[4]The EGS Collab Team

benxin.chi@gmail.com; ljh@lanl.gov

Keywords: EGS Collab, anisotropic, fracture imaging, seismic monitoring, elastic-waveform inversion

ABSTRACT

A multi-level continuous active source seismic monitoring (ML-CASSM) system is used to monitor the fracture creation at the EGS Collab project testbeds located at the Sanford Underground Research Facility (SURF). Four fracture-parallel and two orthogonal wells with 24 hydrophones, 18 accelerometers and 17 dipole sources are used to acquire CASSM data during the stimulations in the first testbed. We recently obtained fracture images using elastic-waveform inversion and least-squares reverse-time migration in isotropic media. However, both core sample analyses and traveltime tomography of the campaign cross-borehole seismic data acquired from the site indicate that the host rock is anisotropic. To improve fracture imaging using CASSM data, we employ elastic-waveform inversion and least-squares reverse-time migration methods in anisotropic media instead of isotropic media. We first apply 3D anisotropic traveltime tomography and anisotropic elastic-waveform inversion to the CASSM data to obtain high-resolution elastic parameters within the stimulation region. To improve the robustness of elastic parameters inversion, we use the traveltime tomography results of the campaign cross-borehole seismic data as the initial models, and employ a multi-scale strategy during anisotropic elastic-waveform inversion. We analyze time-lapse CASSM data to detect waveform variations caused by the fracture creation during the stimulations. We finally apply 3D least-squares anisotropic elastic reverse-time migration to the time-lapse waveform differences to produce high-resolution fracture images. Our results of elastic parameters inversion indicate that the rock within the stimulation region is anisotropic and heterogeneous. Our least-squares reverse-time migration images reveal the shape and the location of the fractures created by hydraulic stimulations. Our results demonstrate that using ML-CASSM, anisotropic elastic-waveform inversion and least-squares anisotropic elastic reverse-time migration has great potential for imaging stimulation-created fractures.

1. INTRODUCTION

The EGS (enhanced geothermal systems) Collab project, supported by the United States Department of Energy's (DOE's) Geothermal Technologies Office (GTO), utilizes readily accessible underground facilities to refine the understanding of rock mass response to stimulation at the intermediate scale (on the order of 10 m) for the validation of thermal-hydrological-mechanical-chemical (THMC) modeling approaches (Kneafsey et al., 2019). The first phase (Experiment 1) of the project is performed at the Sanford Underground Research Facility (SURF) in South Dakota on the level of 4850 ft (1478 m) below ground. The purpose of the Experiment 1 is to establish a fracture network that connects an injection well and a production well using hydraulic fracturing.

The project uses a range of geophysical and hydraulic measurements to monitor the hydraulic fracturing, such as microseismic monitoring (Chen et al., 2019), multi-level continuous active-source seismic monitoring (ML-CASSM), electrical resistance tomography, step-pressure and tracer tests, distributed temperature sensing (DTS), etc. Four fracture-parallel boreholes and two fracture-orthogonal boreholes are used to acquire active and passive seismic data during the experiment. Two cemented hydrophone strings with 12 sensors

[4] J. Ajo-Franklin, T. Baumgartner, K. Beckers, D. Blankenship, A. Bonneville, L. Boyd, S. Brown, J.A. Burghardt, C. Chai, Y. Chen, B. Chi, K. Condon, P.J. Cook, D. Crandall, P.F. Dobson, T. Doe, C.A. Doughty, D. Elsworth, J. Feldman, Z. Feng, A. Foris, L.P. Frash, Z. Frone, P. Fu, K. Gao, A. Ghassemi, Y. Guglielmi, B. Haimson, A. Hawkins, J. Heise, C. Hopp, M. Horn, R.N. Horne, J. Horner, M. Hu, H. Huang, L. Huang, K.J. Im, M. Ingraham, E. Jafarov, R.S. Jayne, S.E. Johnson, T.C. Johnson, B. Johnston, K. Kim, D.K. King, T. Kneafsey, H. Knox, J. Knox, D. Kumar, M. Lee, K. Li, Z. Li, M. Maceira, P. Mackey, N. Makedonska, E. Mattson, M.W. McClure, J. McLennan, C. Medler, R.J. Mellors, E. Metcalfe, J. Moore, C.E. Morency, J.P. Morris, T. Myers, S. Nakagawa, G. Neupane, G. Newman, A. Nieto, C.M. Oldenburg, T. Paronish, R. Pawar, P. Petrov, B. Pietzyk, R. Podgorney, Y. Polsky, J. Pope, S. Porse, J.C. Primo, C. Reimers, B.Q. Roberts, M. Robertson, W. Roggenthen, J. Rutqvist, D. Rynders, M. Schoenball, P. Schwering, V. Sesetty, C.S. Sherman, A. Singh, M.M. Smith, H. Sone, E.L. Sonnenthal, F.A. Soom, P. Sprinkle, C.E. Strickland, J. Su, D. Templeton, J.N. Thomle, V.R. Tribaldos, C. Ulrich, N. Uzunlar, A. Vachaparampil, C.A. Valladao, W. Vandermeer, G. Vandine, D. Vardiman, V.R. Vermeul, J.L. Wagoner, H.F. Wang, J. Weers, N. Welch, J. White, M.D. White, P. Winterfeld, T. Wood, S. Workman, H. Wu, Y.S. Wu, E.C. Yildirim, Y. Zhang, Y.Q. Zhang, Q. Zhou, M.D. Zoback

at 1.75 m spacing accompanied by 18 3-C accelerometers were deployed in the six monitoring boreholes. A ML-CASSM system (Ajo-Franklin et al., 2011) is used to record data continuously for several months using a novel dual recording system.

We apply the anisotropic first-arrival traveltime tomography, anisotropic elastic-waveform inversion to the CASSM data recorded before the stimulations to obtain accurate P and S wave velocity models and anisotropic parameters. Using the inverted elastic parameters, we apply least-squares anisotropic elastic reverse-time migration (LS-AERTM) to the scattered data caused by the five times of stimulation activities, to obtain high-resolution migration images. From the LS-AERTM images, we can clearly identify the created facture, which intersects the injection well E1-I and matches the location of the notch at 164.4 ft depth.

2. DATA ACQUISITION SYSTEM AND DADA ANALYSIS

2.1 ML-CASSM acquisition system

The multi-level continuous active-source seismic monitoring system used in EGS experiment 1 is shown in Figure 1. One production well (E1-P) and one injection well (E1-I) are indicated by red and blue lines. Six monitoring boreholes including two shallow fracture-parallel boreholes (E1-PSB and E1-PST), two deep fracture-parallel boreholes (E1-PDB and E1-PDT) and two fracture-orthogonal boreholes (E1-OT and E1-OB), are displayed using black lines. The CASSM experiment involves the repeated activation 17 sources (green stars), and the data are recorded by the permanent 24 hydrophones (red triangles) and 18 accelerometers (blue triangles), to allow monitoring the seismic property changes within the stimulated regions (black circles).

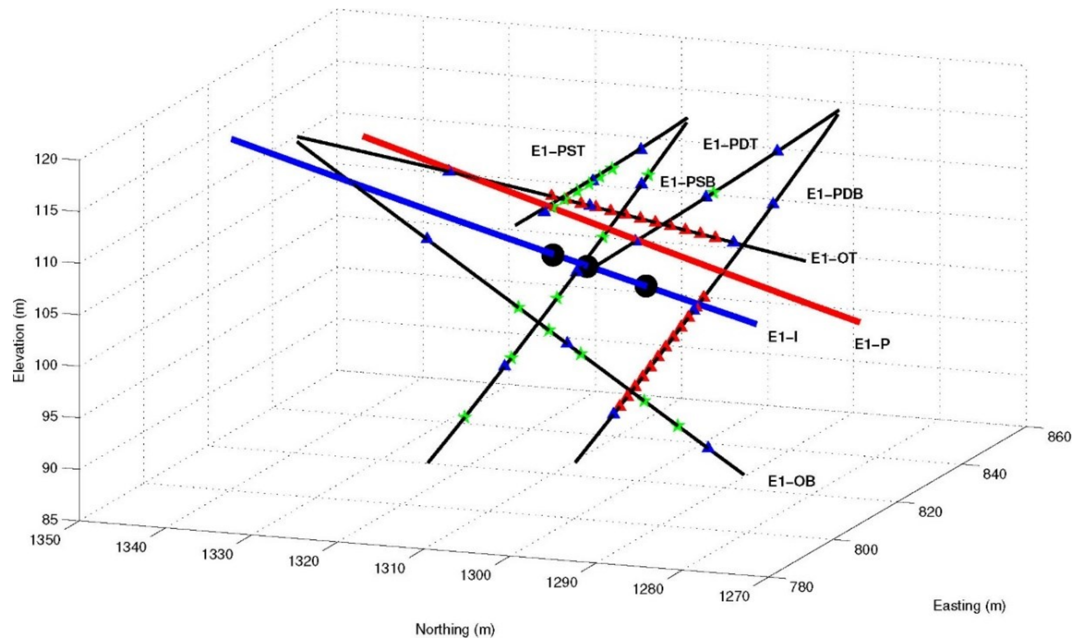

Figure 1: The ML-CASSM acquisition system at EGS Collab Experiment 1. The red line represents the production well. The blue line represents the injection well. The black lines represent the six monitoring wells. The green stars indicate the 17 CASSM sources. The red triangles represent the 24 hydrophones. The blue triangles represent the 18 accelerometers. The black circles represent the notch positions cut in the injection well.

2.2 CASSM data analysis

The CASSM data were recorded with a maximum time of 0.5 s and a sampling interval of 20.8 μs. Useful data lie in the frequency band of [5 kHz, 25 kHz]. We use five days of data recorded from 05/21/2018 to 05/26/2018 for seismic inversion and imaging to detect the fracture created by the stimulations. During the five days, stimulations were performed five times and parameters of stimulations are summarized in Table 1. From Table 1, we can find that the injection volume of the first and second stimulations are low. The significant flow was observed after the third stimulation and an about 5m size fracture was created to connect injection and production wells.

The CASSM data can be used to monitor the creation of the fracture. Figure 2a shows one source-receiver CASSM data set that cross the potential fracture. We find that, in the first two days, the CASSM data are repeatable, which means no obvious fractures were created. However, we observe significant changes in the CASSM data recorded after 05/23/2018. The scattering waveform difference caused by the stimulation activities (Figure 2b) are obtained by subtracting the waveform before the first stimulation. The energy of the scattering waveform (Figure 2c) increases with stimulation activities. Using the CASSM data, we detect 5 times of stimulations. In the first two stimulations, the scattering energy caused by the created fracture is weak because the size of the created fracture is small. In the last three stimulations, a larger fracture was created to connect the injection and the production wells, leading to very strong scattering energy detected in the CASSM data. The analysis indicates that the temporal evolution of scattering energy in the CASSM data can be used to monitor the stimulation process of hydraulic fractures in the EGS-Collab testbed.

Table 1: Summary of the stimulation activities concerned in the current work (Fu et al., 2019).

Label	Date, in 2018	Duration (min) at rate > 0.05 L/min	Max. flow rate (L/min)	Total Inj. Vol. (L)
522	May 22	10.5	0.2	2.1
523	May 23	65.2	0.4	23.3
524	May 24	31.7	5.0	79.6
525A	May 25	31.5	4.6	77.8
525B	May 25	32	4.6	119.3

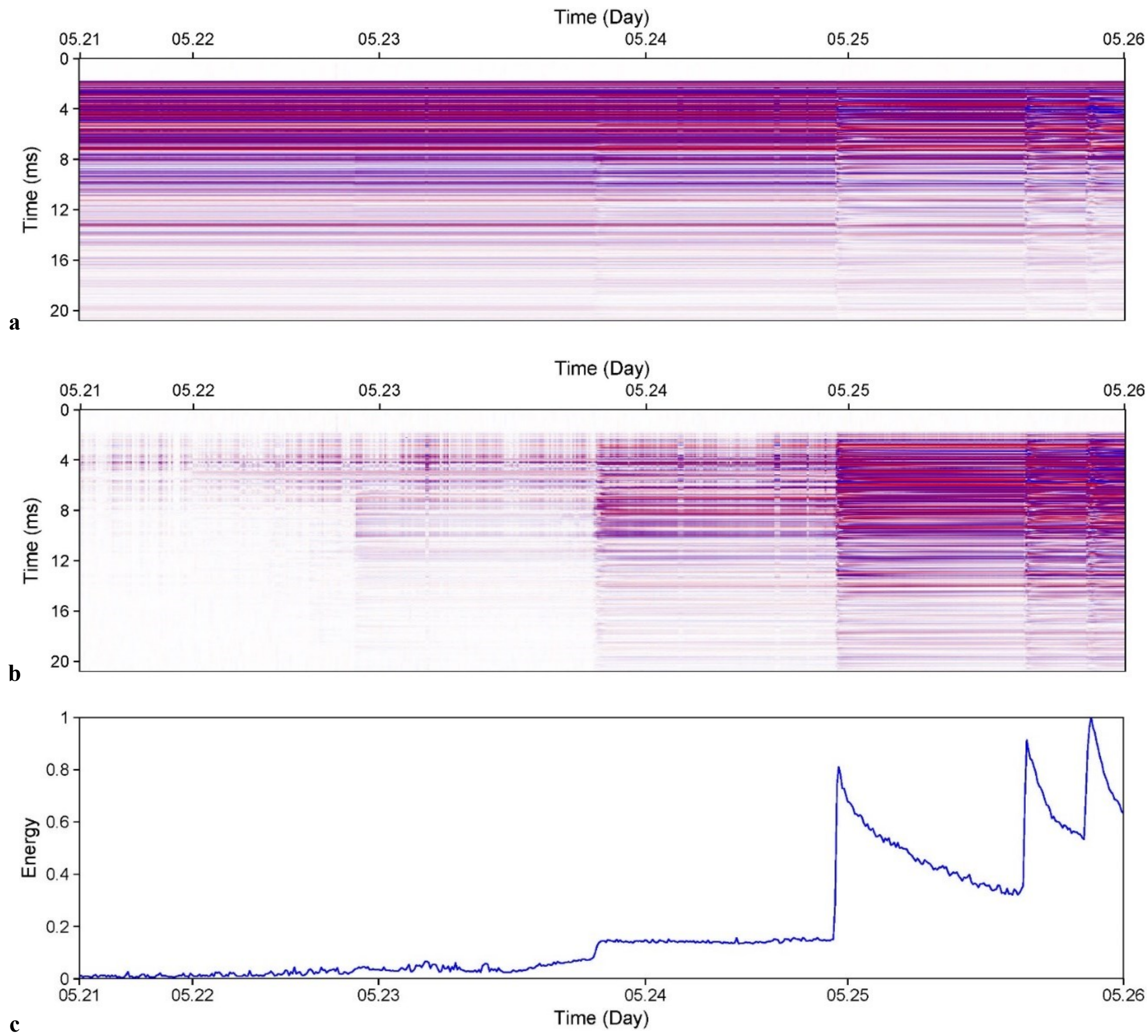

Figure 2: One recorded CASSM data set from 05/21/2018 to 05/26/2018 (a), the scattering data caused by the hydraulic fracture (b) and the energy of scattering data (c).

3. RESULTS

3.1 Building elastic velocity models

To account for lateral variations and anisotropic properties in the velocity model, we conduct 3D anisotropic first-arrival traveltime tomography using a homogeneous velocity model provided by LBNL as the initial model. Figure 3a shows one recorded data of CASSM system and the corresponding picked first-arrival traveltime indicated by the red line. Figure 3b-f show the inverted velocity models and anisotropic parameters. From the inverted models, we find that the host rock in EGS Collab Experiment 1 is heterogeneous and anisotropic (Johnson et al., 2019).

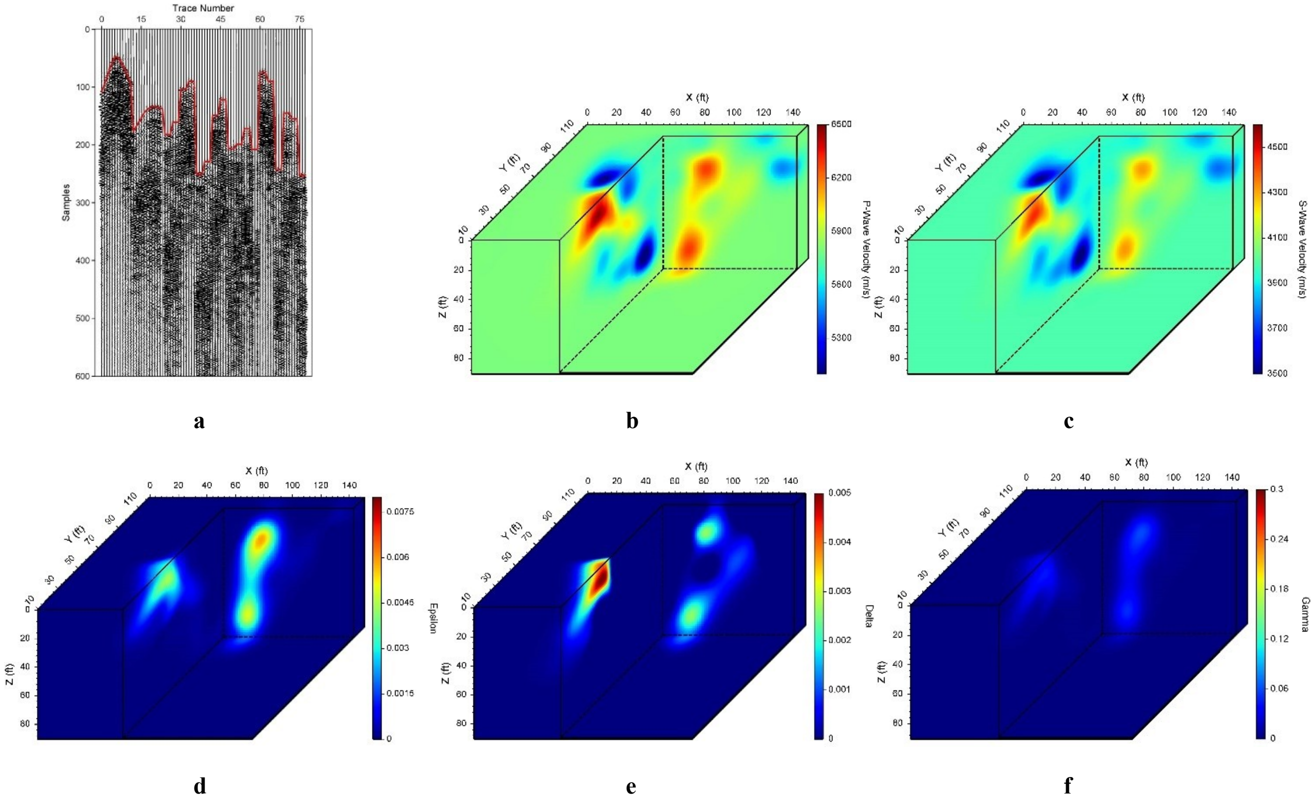

Figure 3: One shot CASSM data and the corresponding picked first-arrival traveltime (a), the inverted Vp (b), Vs (converted from Vp model) (c), Epsilon (d), Delta (e) and Gamma (converted from Vp model) (f) models obtained using 3D anisotropic first-arrival traveltime tomography.

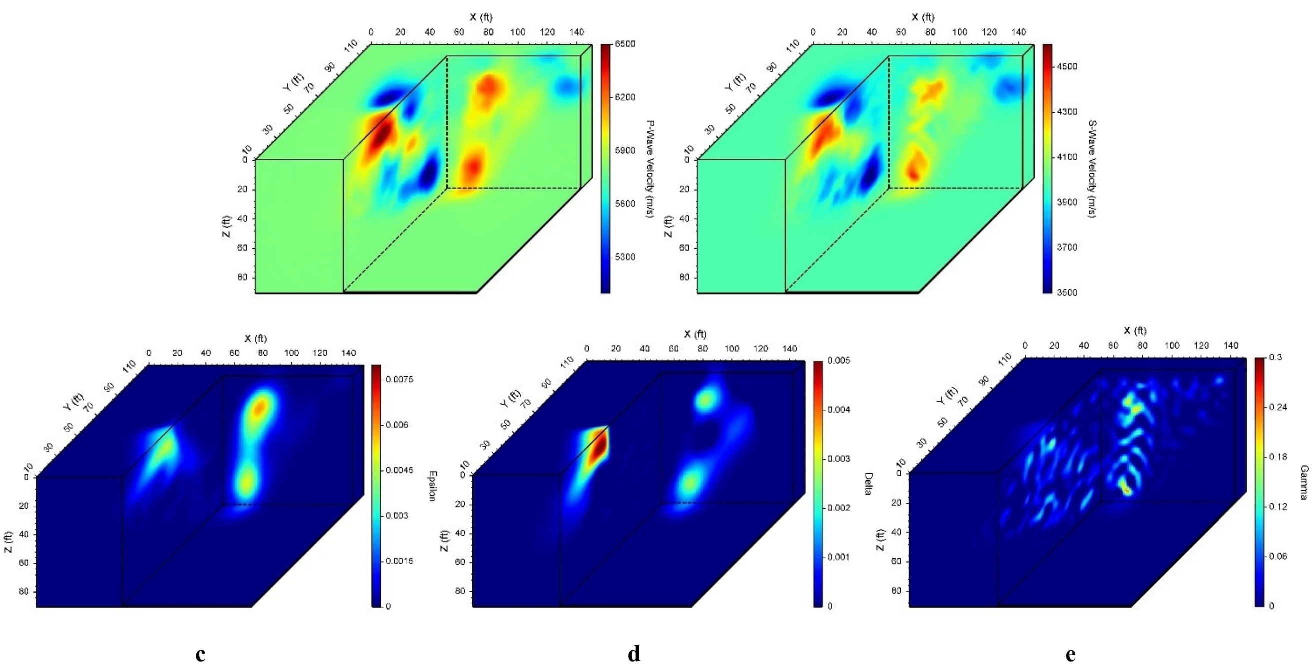

Figure 4: The inverted Vp (a), Vs (b), Epsilon (c), Delta (d) and Gamma (e) models obtained using 3D anisotropic elastic-waveform inversion.

We apply anisotropic elastic-waveform inversion to 3 components data collected at the 3C accelerometers to further improve the velocity and anisotropic models. Our anisotropic elastic-waveform inversion uses the 3D anisotropic first-arrival traveltime tomography velocity and anisotropic models as the initial models. We show our final anisotropic elastic-waveform inversion results of 3D compressional- (P-

), shear-wave (S-wave) velocity models and the anisotropic models in Figure 4 Our anisotropic elastic-waveform inversion results further refine the elastic velocity and anisotropic models.

3.2 Imaging the fractures created by hydraulic stimulations

After we obtain the scattering data caused by five times of stimulations and the inverted velocity and anisotropic models, we use least-squares anisotropic elastic reverse-time migration to produce the high-resolution fracture images. The LS-AERTM images obtained using scattering data caused by the first and second stimulation are blurred and noisy, as depicted in Figure 5a and 5b. It is difficult to identify the created fracture from these images. This is because the size of created fracture is small and the corresponding scattering data is weak. In this situation, no obvious and continuous fracture images can be recognized. The LS-AERTM images of the last 3 times of stimulations (Figure 5c, 5d and 5e) clearly show the created fracture (indicated by the black arrows). The created fracture intersects with the injection well and match the location of the notch at 164.4 ft depth, which is consistent with the measured location of the notch in the experiments. The same conclusion can be obtained using the S-wave images (Figure 6).

4. CONCLUSIONS

We have analyzed the ML-CASSM data for EGS Collab and detected the scattered wavefields caused from the fractures created by the hydraulic stimulations. The results demonstrate that CASSM is suitable for monitoring the fracture stimulation activities. We have conducted 3D anisotropic first-arrival traveltime tomography and 3D anisotropic elastic-waveform inversion of the CASSM data acquired during the Experiment I of the EGS Collab project, and obtained improved elastic velocity and anisotropic models. We have obtained high-resolution image of the created fracture using least-squares anisotropic elastic reverse-time migration of the CASSM data and the inverted models. The image of the created fracture well matches the location of the notch at 164.4ft depth.

5. ACKNOWLEDGEMENTS

This material was based upon work supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Office of Technology Development, Geothermal Technologies Office, under Award Number No. 89233218CNA000001 to Los Alamos National Laboratory (LANL) and Award Number DE-AC02-05CH11231 with Lawrence Berkeley National Laboratory (LBNL). The United States Government retains, and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. This research used resources provided by the Los Alamos National Laboratory Institutional Computing Program, which is supported by the U.S. Department of Energy National Nuclear Security Administration under Contract No. 89233218CNA000001.

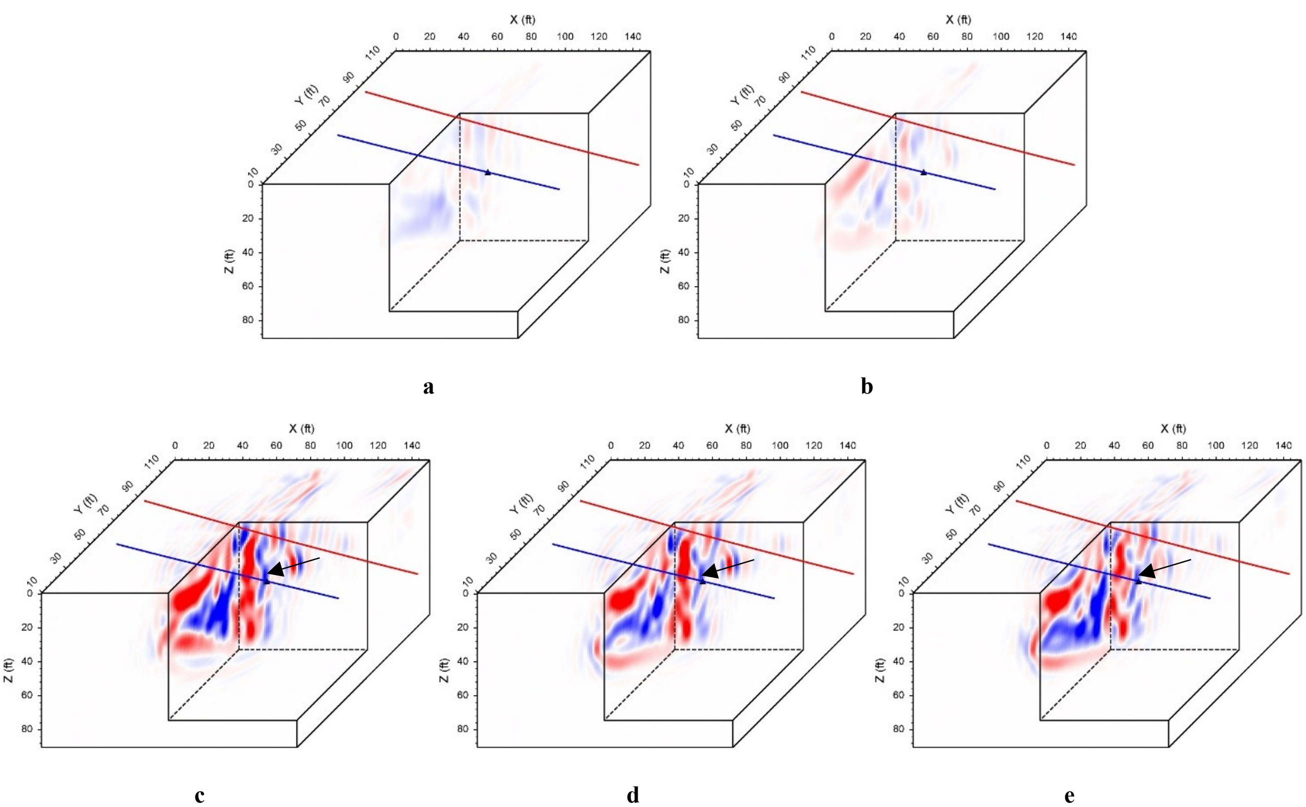

Figure 5: P wave images of the created fracture obtained using least-squares anisotropic elastic reverse-time migration of the 1st (a), 2nd (b), 3rd (c), 4th (d) and 5th (e) stimulation scattering data.

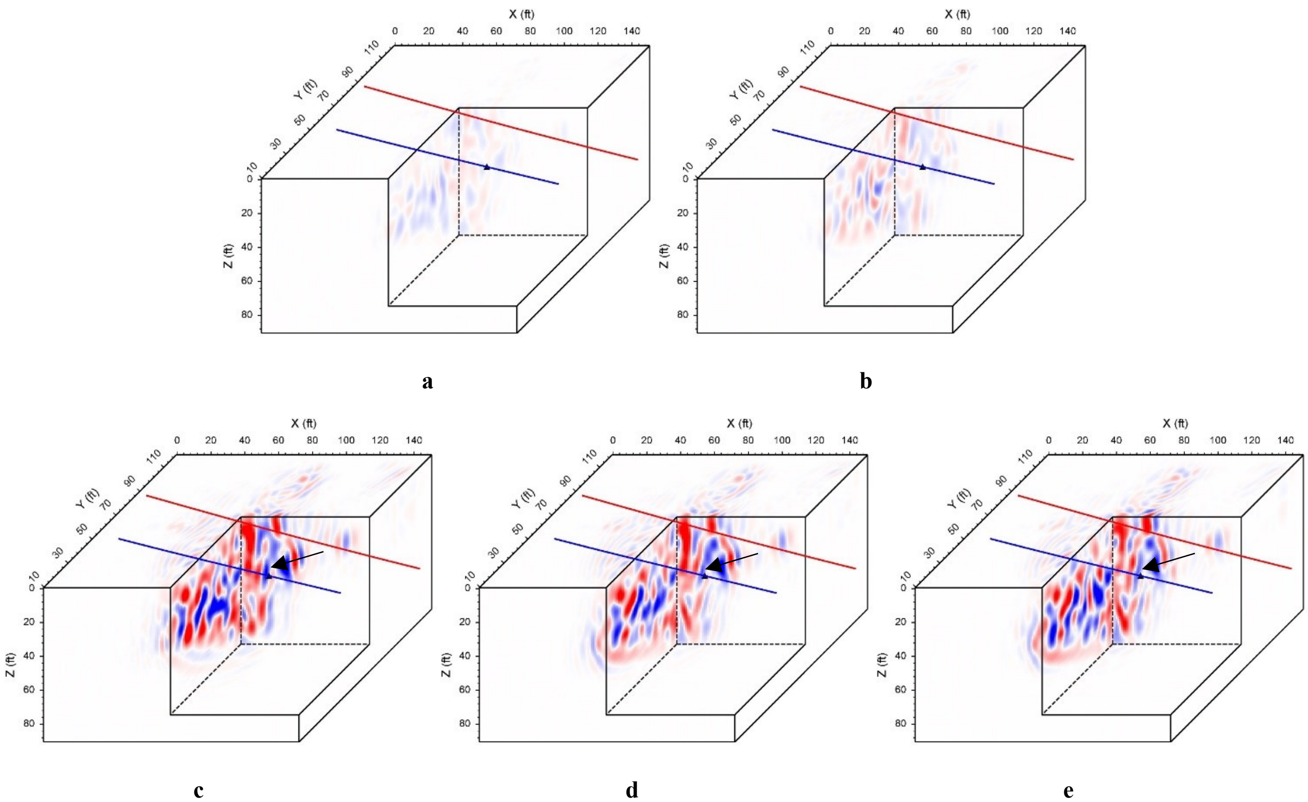

Figure 6: S wave images of the created fracture obtained using least-squares anisotropic elastic reverse-time migration of the 1st (a), 2nd (b), 3rd (c), 4th (d) and 5th (e) stimulation scattering data.

REFERENCES

Ajo-Franklin, J.B., Daley, T.M., Butler-Veytia, B., Peterson, J., Wu, Y., Kelley, B., and Hubbard, S.: Multi-level continuous active source seismic monitoring (ML-CASSM): Mapping shallow hydrofracture evolution at a TCE contaminated site, Extended Abstracts of Society of Exploration Geophysicists Annual Meeting, (2011).

Chen, Y., L. Huang, M. Schoenball, J. Ajo-Franklin, T. Kneafsey, and EGS Collab Team: Real-Time Microearthquake Event Detection and Location in Anisotropic Media Using a Multiscale Scanning Approach for EGS Collab Experiments, 44th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California (2019).

Fu, P., M. White, J. Morris, T. Kneafsey, and EGS Collab Team: Predicting Hydraulic Fracture Trajectory Under the Influence of a Mine Drift in EGS Collab Experiment I, in PROCEEDINGS, 44th Workshop on Geothermal Reservoir Engineering, edited, Stanford University, Stanford, California, (2018).

Johnson, T., C. Strickland, H. Knox, J. Thomle, V. Vermuel, C. Ulrich, T. Kneafsey, D. Blankenship, and EGS Collab Team: EGS Collab Project Electrical Resistivity Tomography Characterization and Monitoring Status, 44th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, (2019).

Kneafsey, T. J., Blankenship, D., Knox, H. A., Johnson, T. C., Ajo-Franklin, J., Schwering, P. C., … EGS Collab Team: EGS Collab Project: Status and Progress, 44th Workshop on Geothermal Reservoir Engineering, Stanford University California, (2019).