PROCEEDINGS, 46th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 15-17, 2021
SGP-TR-218

Numerical Modeling of Microseismic Monitoring at the Second EGS Collab Testbed

Jiaxuan Li[1], Lianjie Huang[1], Yu Chen[1], Joseph Morris[2], Jonathan Ajo-Franklin[3], Timothy Kneafsey[4], and The EGS Collab Team[1]

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

[2]Lawrence Livermore National Laboratory, Livermore, CA 94551, USA

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

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

[5]The EGS Collab Team

Keywords: EGS Collab experiment II, event location, fracture stimulation, moment tensor inversion, numerical modeling, microseismicity.

ABSTRACT

The EGS Collab project will continuously monitor microseismicity during shear stimulation of fractures at the second EGS Collab testbed at the depth of 4100 ft at the Sanford Underground Research Facility in South Dakota. The microseismic monitoring will use multiple wells surrounding the stimulation region with four accelerometers in each well, centered at the stimulation region. We conduct numerical modeling of the microseismic monitoring to understand the optimal well separation distances/angles. We perform location error analysis and moment-tensor inversion error analysis for four well setups with different geometries, controlled by parameters including wellhead locations of monitoring wells and the opening angle between two wells. We add Gaussian noise to synthetic traveltime picks and waveforms for event location and moment-tensor inversion analyses, to account for errors in the velocity models and traveltime picks. We determine the optimal well design by selecting a well geometry that provides balanced minimal errors in both event locations and moment tensors.

1. INTRODUCTION

The first Enhanced Geothermal System (EGS) Collab testbed is located at the depth of 4850 ft at the Sanford Underground Research Facility (SURF) in Lead, South Dakota, USA (Kneafsey *et al.*, 2020). The project team conducted a comprehensive meso-scale (10~20 m) monitoring to advance our understanding of hydraulic stimulations in enhanced geothermal production. In the first experiment, continuous microseismic monitoring was performed and used to infer the hydraulic fracture stimulation (Chen *et al.*, 2019; Chen, 2019; Chai *et al.*, 2020; Fu *et al.*, 2020; Schoenball *et al.*, 2020) For the first EGS Collab testbed, Chen et al. (2019) perform numerical modeling to determine an optimal number of geophones needed in multiple monitoring wells to achieve cost-effective monitoring for the planned configuration of multiple monitoring wells.

The second EGS Collab testbed is located at the depth of 4100 ft at SURF to study shear stimulation of fractures (Kneafsey *et al.*, 2021). In this experiment, the project decides to deploy 4 geophones in each monitoring well. The project also considers four different configurations of multiple monitoring wells. We perform numerical modeling to evaluate the efficacy of these four different borehole configurations for microseismic monitoring. We determine the optimal well design by selecting a well setup with balanced minimum errors of event location and moment tensor inversion.

2. NUMERICAL MODEL SETUP

We design four well setups to evaluate the efficacy of location and moment tensor inversion of microseismic events using numerical modeling (Figure 1). We assume the injection well is drilled from Site B (Figure 1) and the well length is 265 ft. Three production wells are drilled at the same location with the same length. We assume the notch cut for shear stimulation is located at a depth of about 201 feet

---

[1] J. Ajo-Franklin, T. Baumgartner, K. Beckers, D. Blankenship, A. Bonneville, L. Boyd, S. Brown, J.A. Burghardt, C. Chai, T. Chen, Y. Chen, K. Condon, P.J. Cook, D. Crandall, P.F. Dobson, T. Doe, C.A. Doughty, D. Elsworth, J. Feldman, A. Foris, L.P. Frash, Z. Frone, P. Fu, K. Gao, A. Ghassemi, Y. Guglielmi, B. Haimson, A. Hawkins, J. Heise, M. Horn, R.N. Horne, J. Horner, M. Hu, H. Huang, L. Huang, K.J. Im, M. Ingraham, R.S. Jayne, T.C. Johnson, B. Johnston, S. Karra, K. Kim, D.K. King, T. Kneafsey, H. Knox, J. Knox, D. Kumar, K. Kutun, M. Lee, D. Li, J. Li, K. Li, Z. Li, M. Maceira, P. Mackey, N. Makedonska, C.J. Marone, E. Mattson, M.W. McClure, J. McLennan, T. McLing, C. Medler, R.J. Mellors, E. Metcalfe, J. Miskimins, J. Moore, J.P. Morris, 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, B.Q. Roberts, M. Robertson, W. Roggenthen, J. Rutqvist, D. Rynders, M. Schoenball, P. Schwering, V. Sesetty, A. Singh, M.M. Smith, H. Sone, F.A. Soom, P. Sprinkle, C.E. Strickland, J. Su, D. Templeton, J.N. Thomle, C. Ulrich, N. Uzunlar, A. Vachaparampil, C.A. Valladao, W. Vandermeer, G. Vandine, D. Vardiman, V.R. Vermeul, H.F. Wang, J. Weers, N. Welch, 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

in the injection well. We evenly placed 125 virtual microseismic events within a 12*12*12 m^3 cube centered around the shear stimulation region. Each event source has a Ricker source time function with a central frequency of 15 kHz. Following the instrumental setup in the EGS Collab Experiment I, the temporal sampling rate of all receivers are 100 kHz.

In Scenario 1 (Figure 1a), two monitoring wells (E2-SMU and E2-SML) are drilled from the entrance of the battery alcove (Site A) and the other two monitoring wells (E2-AMU and E2-AML) are drilled from the end of the battery alcove. Here, "SM" means south monitoring in the drift. "AM" stands for alcove monitoring. "U" means upper and "L" denotes lower. Each well has a length of 185 ft. Four receivers are evenly placed from the endpoint of the well with an interval of 37 ft, such that the receiver span area is centered around the monitoring/stimulation region. We use two parameters: the monitoring distance (monDistance) and the monitoring injection depth distance (monInjDepth) to control the opening angle between two wells drilled from the same location and the opening angle between two sets of wells drilled from different locations. The monDistance represents the shortest distance between points on the injection well and points on the monitoring well. For the point that achieves the shortest distance on the monitoring well, the monInjDepth measures its distance from the shear stimulation fracturing point. In our numerical modeling for Scenario 1, the monDistance ranges from 10 to 90 feet, with an increment of 10 feet, and the monInjDepth ranges from 50 to 90 feet, with an increment of 10 feet.

In Scenario 2, two monitoring wells are drilled from the entrance of the battery alcove (E2-SMU and E2-SML). Both of them have a length of 185 ft. Another two monitoring wells are drilled from the north side in the drift with a length of 295 ft (E2-NMU and E2-NML) such that they are almost parallel to the other two monitoring wells. The NM means north monitoring on the drift. We use the same two parameters monDistance and monInjDepth as those in Scenario 1 to control the wells' orientations.

In Scenario 3, two monitoring wells are drilled from the entry of the battery alcove (length=180 ft) (E2-AMU and E2-AML), two monitoring wells are drilled from the 2020 small niche (Site A) (length=195 ft) (E2-DMU and E2-DMD), and another well drilled from Site B (length=265 ft) (E2-TS). Here, "DM" means drift monitoring. "T" means test. Well E2-TS has a declination angle of 16.5 degree and azimuth of 57.7 degree. Four receivers are evenly deployed in wells E2-AMU, E2-AML, E2-DMU, and E2-DML. We use the same two parameters monDistance and monInjDepth as those in Scenario 1 to control the wells' orientations.

In Scenario 4, four monitoring wells (E2-MU, E2-MD, E2-MN, and E2-MS) are drilled from Site B (length=265 ft). E2-MU and E2-ML are in the same vertical plane (UD plane). E2-MN and E2-MS are in the plane that is perpendicular to the UD plane. We use the opening angle between the monitoring well and the injection well to control the well layout geometry. The opening angel ranges from 5 to 45 degrees with an increment of 5 degrees in our numerical modeling

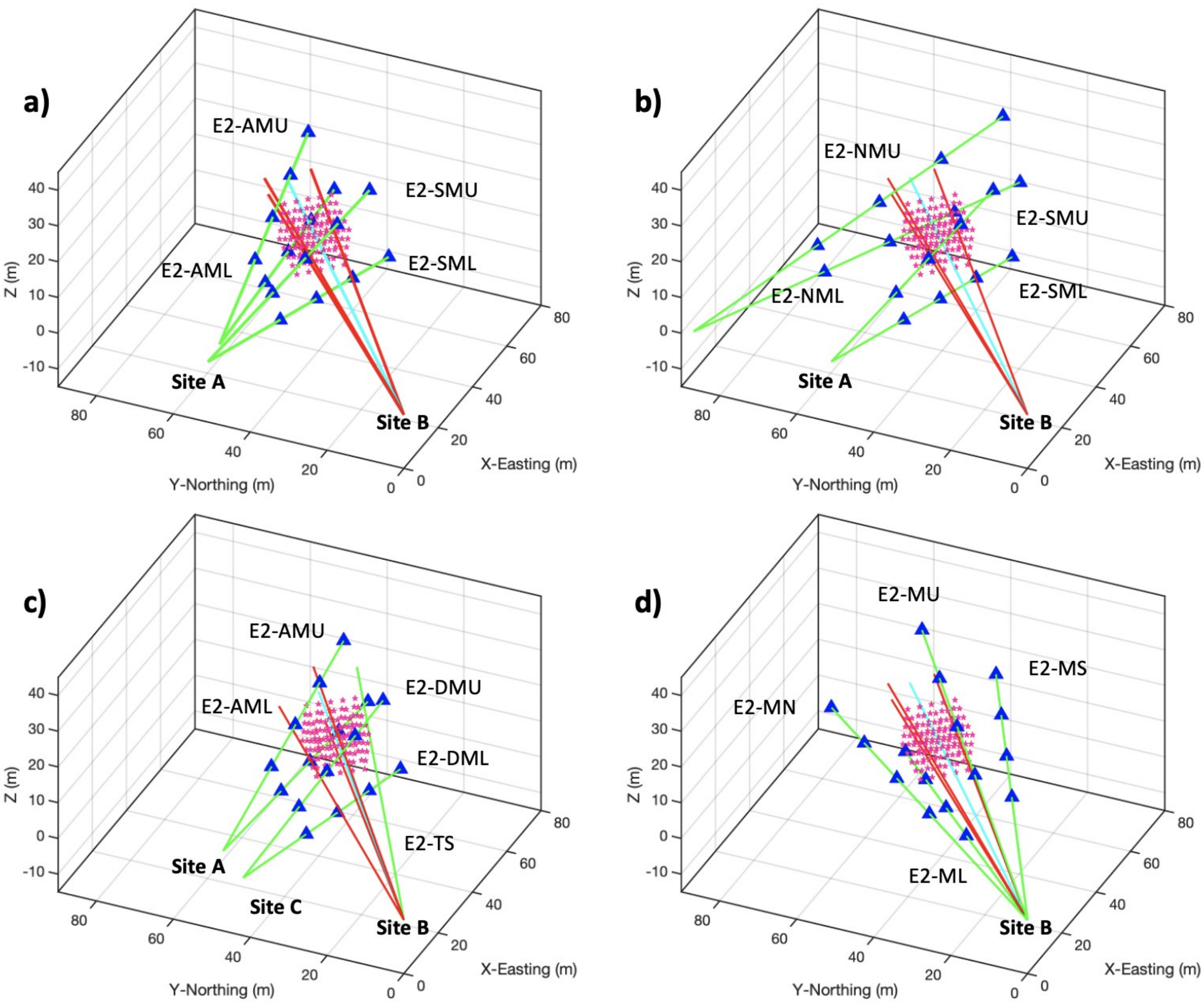

Figure 1: Four different scenarios of well setup to consider for the second EGS Collab testbed. The cyan line presents the injection well and the three red lines represent the production wells. The injection wells and monitoring wells are drilled from Site B (2020 excavation). The magenta stars are virtual sources evenly placed in a cube centered around the fracturing notch cut. In each scenario, we assume 4 receivers (blue triangles) are evenly distributed in four monitoring wells (green lines) and centered around the fracturing region. The monitoring wells are drilled from different locations. a) Two sets of monitoring wells are drilled from the start and end of the Site A (Battery Alcove). b) Two monitoring wells are drilled from Site A and the other two are drilled at the north side of the drift. c) Two monitoring wells are drilled from Site A, two from Site C (2020 small niche), and one from site B. d) Four monitoring wells drilled from Site B. For Scenarios a-c, the well orientation are controlled by two parameters: the monitoring distance (monDistance) and the monitoring injection depth difference (monInjDepth). The monDistance measures the smallest distance between the points on a monitoring well and the injection well. For the point on the injection well that achieves the shortest distance, parameter monInjDepth measures its distance from the shear stimulation fracture point. In order words, parameter monDistance controls the opening angle for two wells drilled from the same site. Parameter monInjDepth controls the opening angle for wells drilled from difference sites. For Scenario d), we have only one controlling parameter: the angle between the monitoring well and the injection well.

3. ERROR ANALYSES OF EVENT LOCATION AND MOMENT TENSOR INVERSION

3.1 Error analysis of event locations

We assume the host rock is homogeneous and isotropic with P wave velocity of 5900 m/s, S wave velocity of 3315 m/s, and density of 2717 kg/m3 estimated using Gardner's equation. We calculate synthetic P wave and S wave arrival times and add random Gaussian traveltime perturbation with a standard deviation of 5 msec to account for the traveltime pick error and velocity heterogeneities in the real monitoring. We use the simulated annealing method to search for the events' starting time and 3D spatial locations. The average standard deviation of the event location errors for 125 synthetic microseismic events are shown in Panel a) of Figure 2-5 for four different scenarios. In Figure 2-4, each line represents the variation of event location error with respect to parameter monDistance for a specific monInjDepth. For each monInjDepth, the event location error shows a local minimum as we increase parameter monDistance from 10 to 90 feet.

3.2 Error analysis of moment tensor inversion

For each microseismic event location, we randomly generate the same set of 20 moment tensors (Figure 6). Thus, for each well setup, we have 20*125=2500 moment tensors to invert for. All the synthetic moment tensors are normalized such that we are only inverting the radiation pattern and not determining the moment magnitude. We generate the synthetic waveforms using analytical Green's functions with a Ricker source time function having a central frequency of 15 kHz. We then employ the least-squares waveform-based method to invert for moment tensors. The standard deviation of inverted moment tensors is shown in Panel b) of Figure 2-5 for four different Scenarios.

Combining error analysis results of event location and moment-tensor inversion, we determine that the parameter monDistance plays a more important role and its optimal value for Scenarios 1-3 should be ~40 ft, as indicated by the ellipses in Figs. 2-4. For Scenario 4, the optimal opening angle between the injection well and monitoring well should be 15°, as shown in Fig. 5.

The EGS Collab project selects Scenario 3 for the final experimental design for several reasons. First, the orientation of the injection and production wells is selected to increase the likelihood of intersecting natural fractures that are favorably oriented for shear reactivation. Second, given that the locations of fractures are unknown until drilling is completed, it is decided to have multiple production wells surrounding the injection well, such that it can be expected that at least one production well will intersect stimulated fractures. Finally, the monitoring wells are oriented so as to span the volume of interest on as many sides as possible. Consequently, we have two pairs of orthogonal monitoring wells above and below the stimulation zone, as well as one subparallel on the southern size of the stimulation zone.

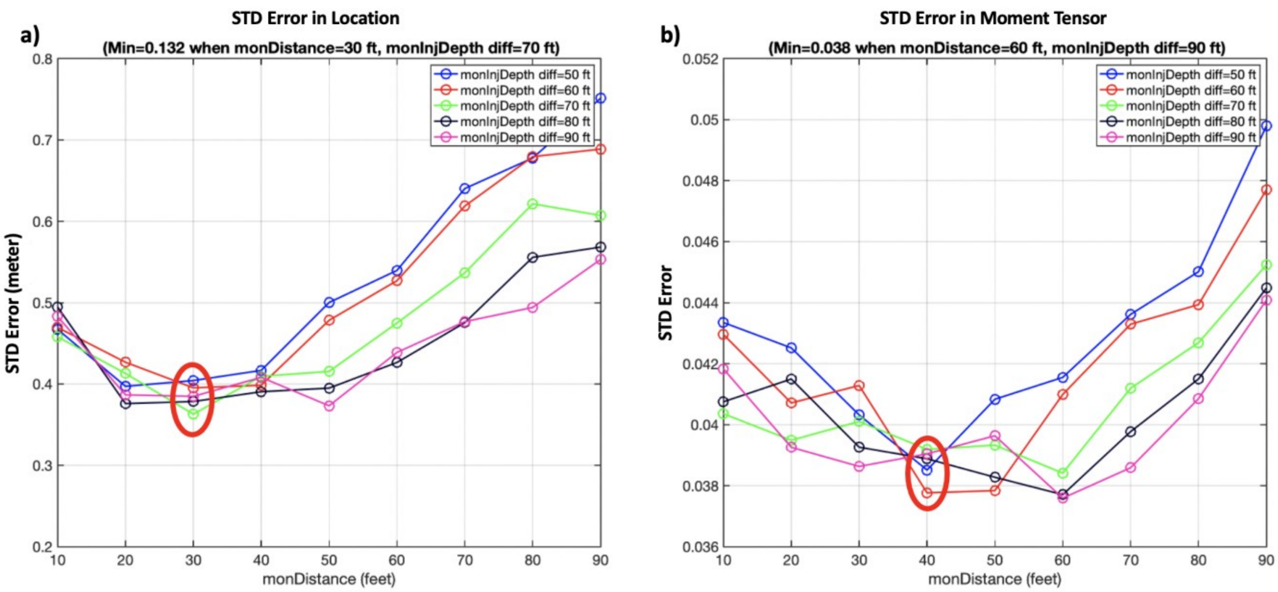

Figure 2. Event location error and moment tensor inversion error vs parameter monDistance for Scenario 1 under different monInjDepth. The red ellipse represents the optimal parameters (monInjDepth, monDistance) that achieves a balanced minimized error for event location and moment tensor inversion.

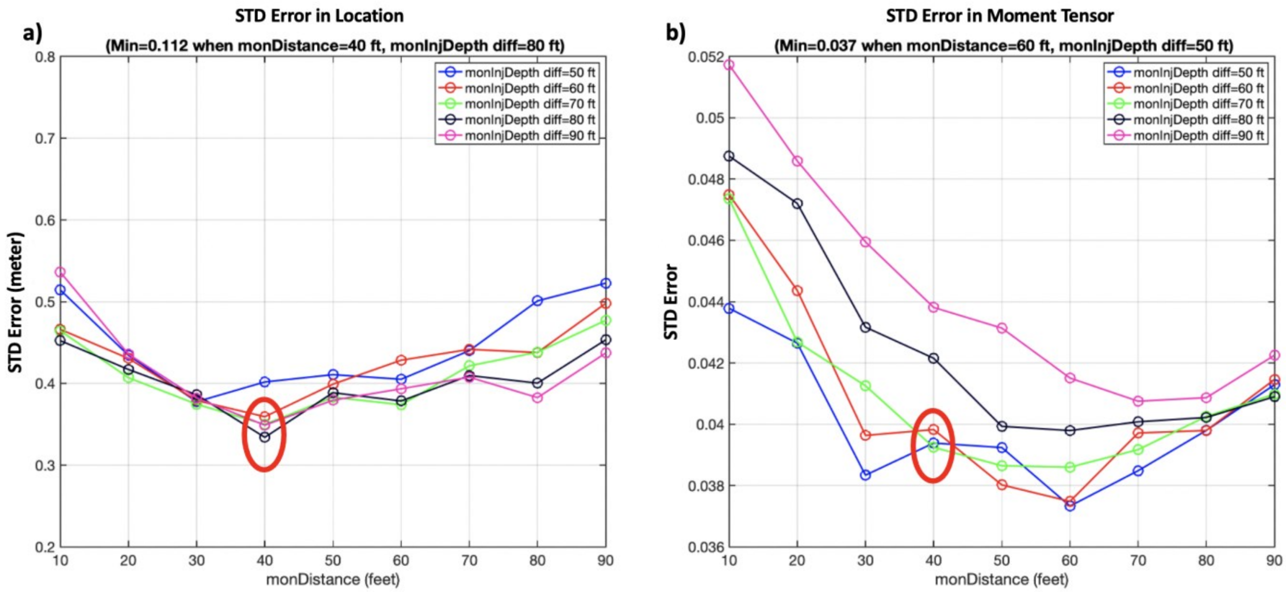

Figure 3. Event location error and moment tensor inversion error vs parameter monDistance for Scenario 2 under different monInjDepth. The red ellipse represents the optimal parameters (monInjDepth, monDistance) that achieves a balanced minimized error for event location and moment tensor inversion.

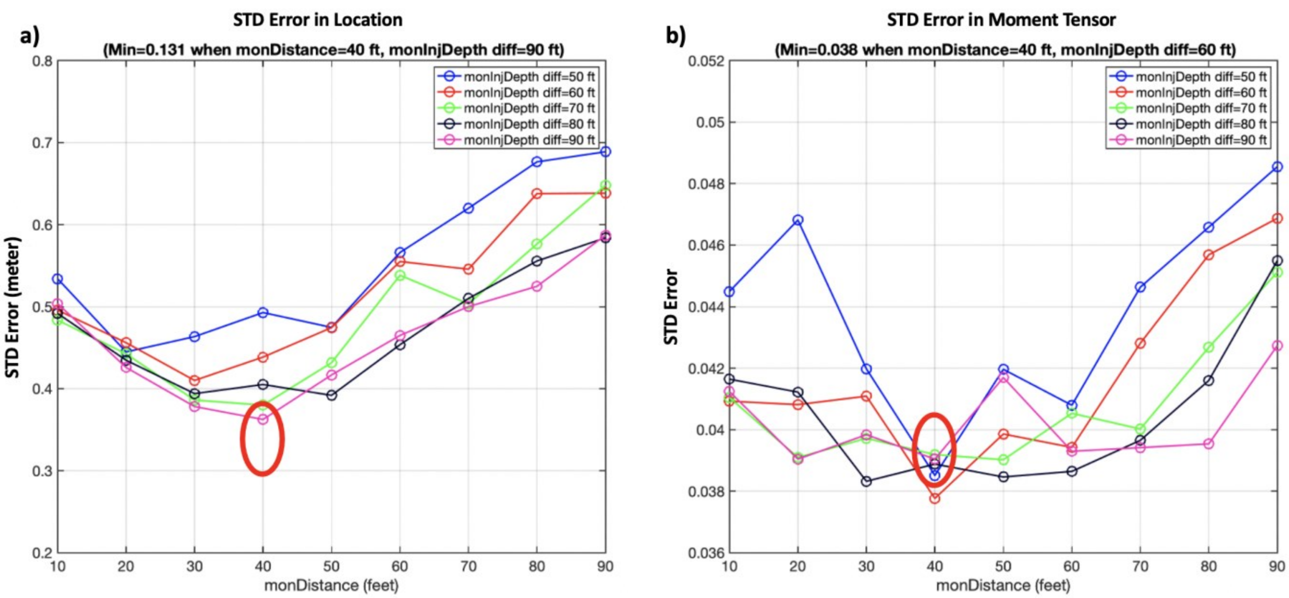

Figure 4. Event location error and moment tensor inversion error vs parameter monDistance for Scenario 3 under different monInjDepth. The red circle represents the optimal parameters (monInjDepth, monDistance) that achieves a balanced minimized error for event location and moment tensor inversion.

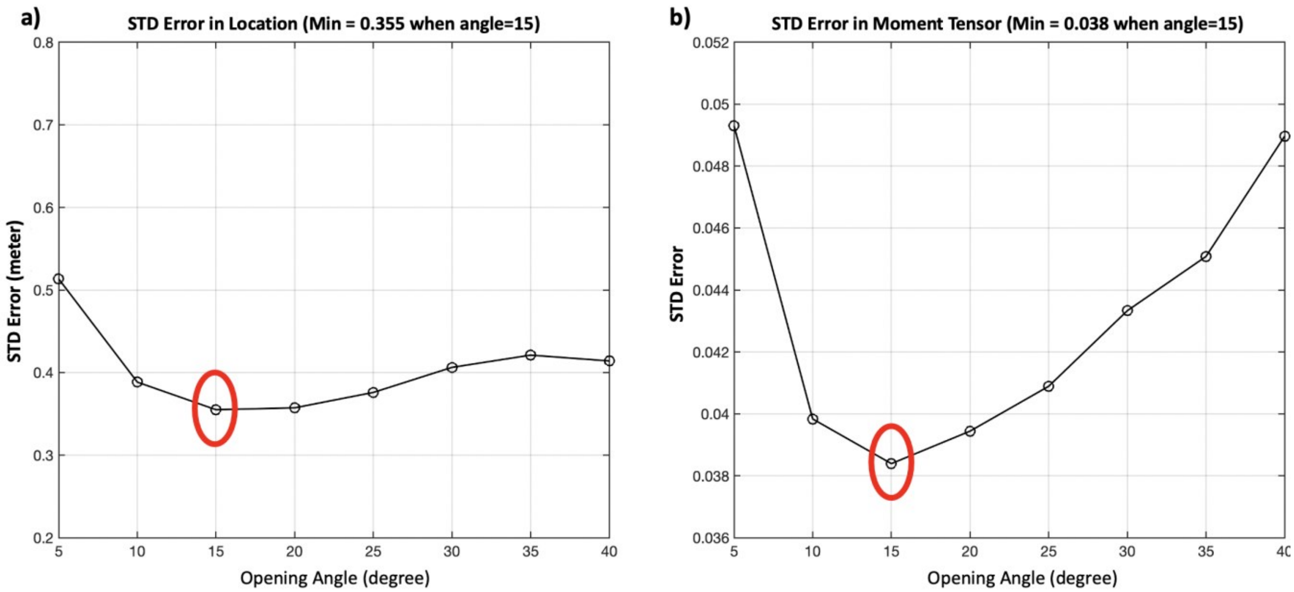

Figure 5. Event location error and moment tensor inversion error vs the opening angle between the injection well and monitoring wells for Scenario 5. The red circle represents the optimal opening angle between the injection well and monitoring wells.

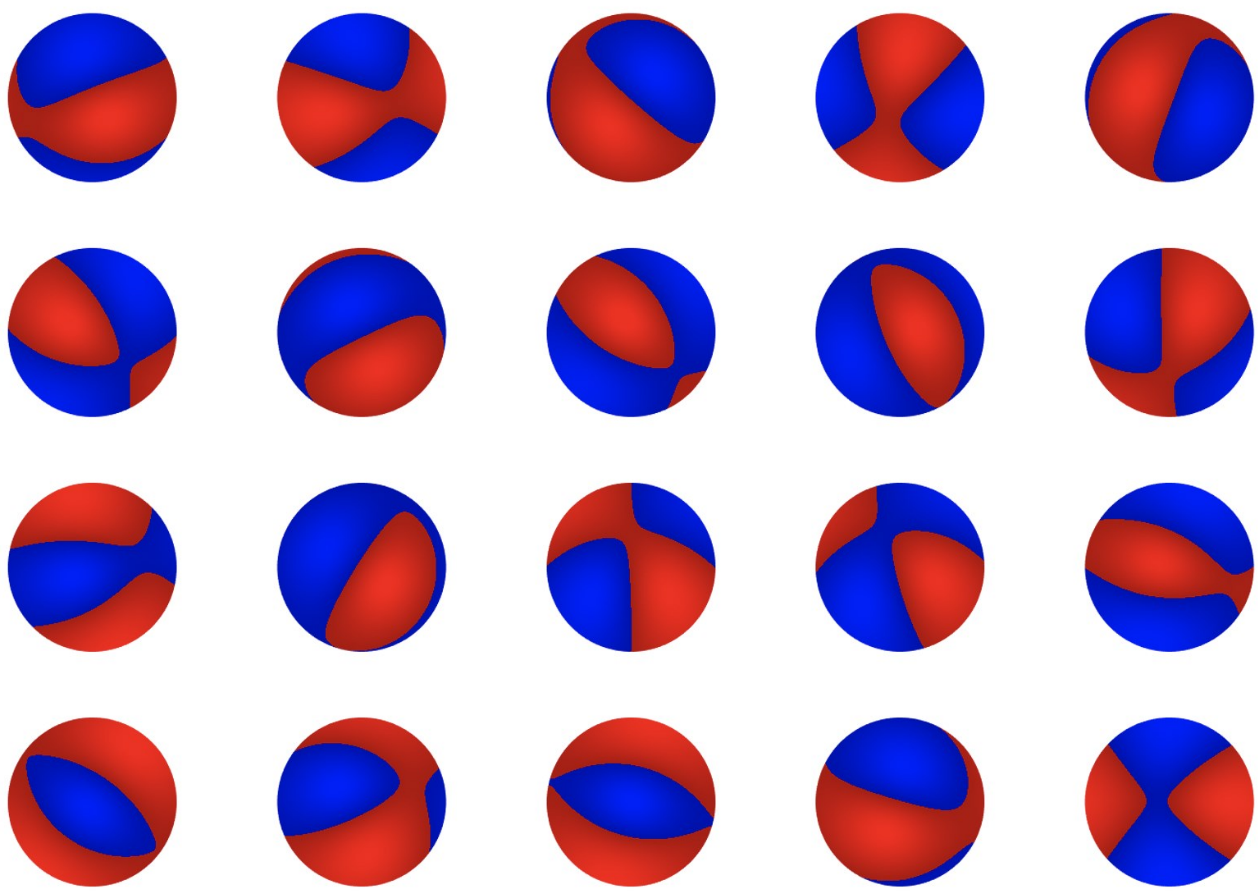

Figure 6. 20 beach balls of randomly generated moment tensors for our numerical modeling study. The red represents the outward motion and the blue represents the inward motion.

CONCLUSIONS

We have conducted numerical modeling to analyze the event location errors and moment-tensor inversion errors for four different well setup scenarios to consider for the second EGS Collab testbed. For each scenario, we perform numerical modeling for different values of the borehole controlling parameters and determine the optimal design that minimizes both the event location and moment-tensor inversion errors. We find that the monitoring distance between the monitoring well and the injection well plays a important role. In general, a monitoring distance between 30 to 40 feet achieves the optimal resolution of microseismic events' location and moment tensor inversion for Scenarios 1 to 3. For Scenario 4, an opening angle of 15 degree between the injection well and monitoring wells is optimal.

ACKNOWLEDGMENTS

This material was based upon work supported by the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), Office of Technology Development, Geothermal Technologies Office, under Contract No. 89233218CNA000001 to Los Alamos National Laboratory (LANL). LANL is operated by Triad National Security, LLC, for the National Nuclear Security Administration (NNSA) of U.S. DOE. This research used resources provided by the LANL Institutional Computing Program, which is supported by the U.S. DOE NNSA under Contract No. 89233218CNA000001. 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, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The research supporting this work took place in whole or in part at the Sanford Underground Research Facility in Lead, South Dakota. The assistance of the Sanford Underground Research Facility and its personnel in providing physical access and general logistical and technical support is acknowledged.

REFERENCES

Chai, C., M. Maceira, H. J. Santos-Villalobos, S. V. Venkatakrishnan, M. Schoenball, W. Zhu, G. C. Beroza, C. Thurber, and the EGS Collab Team (2020), Using a Deep Neural Network and Transfer Learning to Bridge Scales for Seismic Phase Picking, *Geophysical Research Letters*, ***47***(16), e2020GL088651.

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

Chen, Y. H., Lianjie; and the EGS Collab Team (2019), Optimal design of 3D borehole seismic arrays for microearthquake monitoring in anisotropic media during stimulations in the EGS collab project, *Geothermics*, ***79***, 61-66.

Fu, P., M. Schoenball, J. B. Ajo-Franklin, C. Chai, M. Maceira, o. P. Morris, H. Wu, H. Knox, P. C. Schwering, M. D. White, J. A. Burghardt, C. E. Strickland, T. C. Johnson, V. R. Vermeul, P. Sprinkle, B. Roberts, C. Ulrich, Y. Guglielmi, P. J. Cook, P. F. Dobson, T. Wood, L. P. Frash, L. Huang, M. D. Ingraham, J. S. Pope, M. M. Smith, G. Neupane8, T. W. Doe, W. M. Roggenthen, R. Horne, A. Singh, M. D. Zoback, H. Wang, K. Condon, A. Ghassemi, H. Chen, M. W. McClure, G. Vandine, D. Blankenship, T. J. Kneafsey, and the EGS Collab Team (2020), Close Observation of Hydraulic Fracturing at EGS Collab Experiment 1: Fracture Trajectory, Microseismic Interpretations, and the Role of Natural Fractures, unpublished.

Kneafsey, T., D. Blankenship, P. Dobson, M. White, J. P. Morris, P. Fu, P. C. Schwering, J. B. Ajo-Franklin, L. Huang, H. A. Knox, G. Neupane, J. Weers, R. Horne, W. Roggenthen, T. Doe, E. Mattson, and the EGS Collab Team (2021), Fracture Stimulation and Chilled-water Circulation Though Deep Crystalline Rock: Characterization, Modeling, Monitoring, and Heat-transfer Assessment, *ROCEEDINGS, 46th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California

Kneafsey, T. J., D. Blankenship, P. F. Dobson, J. P. Morris, M. D. White, P. Fu, P. C. Schwering, J. B. Ajo-Franklin, L. Huang, M. Schoenball, T. C. Johnson, H. A. Knox, G. Neupane, J. Weers, R. Horne, Y. Zhang, W. Roggenthen, T. Doe, E. Mattson, C. Valladao, and the EGS Collab team (2020), The EGS Collab Project: Learnings from Experiment 1, *PROCEEDINGS, 45th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California

Schoenball, M., J. B. Ajo-Franklin, D. Blankenship, C. Chai, A. Chakravarty, P. Dobson, C. Hopp, T. Kneafsey, H. A. Knox, M. Maceira, M. C. Robertson, P. Sprinkle, C. Strickland, D. Templeton, P. C. Schwering, C. Ulrich, T. Wood, and the EGS Collab Team (2020), Creation of a Mixed-Mode Fracture Network at Mesoscale Through Hydraulic Fracturing and Shear Stimulation, *Journal of Geophysical Research: Solid Earth*, ***125***(12), e2020JB019807.