PROCEEDINGS, 42nd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 13-15, 2017
SGP-TR-212

Proposed Fallon FORGE Site: Phase 2 Update

Douglas Blankenship[1], Mack Kennedy[2], Ernest L. Majer[2], Nicholas Hinz[3], James Faulds[3], Bridget Ayling[3], Kelly Blake[4], Andrew Tiedeman[4], Andrew Sabin[4], Mike Lazaro[4], John Akerley[5], Drew Siler[6], J. Ole Kaven[6], Geoffrey Phelps[6], Stephen Hickman[6], Jonathan Glen[6], Colin Williams[6], Ann Robertson-Tait[7], Logan Hackett[7], Will Pettitt[8]

[1]Sandia National Laboratories, Albuquerque, New Mexico
[2]Lawrence Berkeley National Laboratory, Berkeley, California
[3]Nevada Bureau of Mines and Geology, University of Nevada, Reno, Nevada
[4]U.S. Navy Geothermal Program Office
[5]Ormat Nevada, Inc.
[6]U.S. Geological Survey, Menlo Park, California
[7]GeothermEx/Schlumberger[8]Itasca Consulting Group, Inc.

Sandia National Laboratories, NM P.O. Box 5800, Albuquerque, NM 87185-1033

dablank@sandia.gov

Keywords: FORGE, geothermal energy, Fallon, NV

ABSTRACT

The Department of Energy (DOE) Frontier Observatory for Research in Geothermal Energy (FORGE) is to be a dedicated site where the scientific and engineering community conducting subsurface research can develop, test, and improve technologies and techniques for the creation of cost-effective and sustainable enhanced geothermal systems (EGS) in a controlled environment. The establishment of FORGE will facilitate development of an understanding of the key mechanisms controlling a successful EGS. As part of a detailed down-select process, DOE has selected two sites to move forward for further evaluation; Fallon FORGE near Fallon, NV, and Utah FORGE near Milford, Utah. This paper will provide an overview of the candidate Fallon FORGE project and current efforts related to readying the site for full FORGE implementation.

1. INTRODUCTION

The Frontier Observatory for Research in Geothermal Energy (FORGE) is a Department of Energy (DOE) Geothermal Technologies Office (GTO) concept to advance and develop the technologies, techniques, and knowledge needed to make Enhanced Geothermal Systems (EGS) a commercially viable electricity generation option for the United States. The objective of the FORGE project is to establish and manage a dedicated field site, where the subsurface scientific and engineering communities will be eligible to develop, test, and improve new technologies and techniques in a well-characterized environment that is ideal for EGS. After an extensive search and evaluation, our team proposed a site near Fallon, NV, in the Carson sink within the Basin and Range tectonic province. The DOE FORGE project is divided into three general phases. In all, four groups proposed five sites that were selected to participate in Phase 1 planning activities. Two were ultimately down-selected by the DOE GTP to move forward into Phases 2A and 2B (the initial portion of Phase 2) of the program—the Fallon site and a site near Milford, Utah, proposed by the University of Utah and Energy Geoscience Institute. This paper presents an update of the Fallon Phase 2A and 2B activities underway or planned.

The selection of this site was based on existing geologic, geophysical, and subsurface data and well testing acquired during geothermal exploration most recently by the U.S. Navy GPO and Ormat Inc. The DOE GPO required specific characteristics of potential sites to be met in order to be considered as viable FORGE site. These requisite characteristics for FORGE are (1) temperatures of 175-225°C, at (2) depths of 1.5-4.0 km, in (3) crystalline rocks, with (4) low permeability, in (5) a favorable stress regime for permeability generation through well stimulation, and in (6) a location where there is not an existing hydrothermal system. The satisfaction of these criteria along with extensive existing infrastructure (Fallon Naval Air Station and the cities of Fallon and nearby Reno, NV) proximal to the site and partnerships with all community stakeholders (U.S. Navy and Ormat Nevada Inc.) makes Fallon an ideal location for FORGE.

The Fallon FORGE site lies in the Carson Sink within the Basin and Range province, directly northeast of the Walker Lane belt (Stewart, 1988; Faulds et al., 2008). The Walker Lane is a system of strike-slip faults that accommodates ~20% of the dextral motion (~1 cm/yr) between the North American and Pacific plates (Hammond and Thatcher, 2004). As such, the southeastern Carson Sink has some of the higher strain rates in the Great Basin region, as evidenced by GPS geodetic data (Kreemer et al., 2012; Hammond et al., 2014). High strain rates and rocks that are critically stressed (or near critically stressed) for frictional failure in the current stress field favors EGS research and development, because the ability to increase permeability through reactivation of shear fractures during hydraulic stimulation is more readily accomplished under such conditions (Hickman and Davatzes, 2010; Chabora et al., 2012; Dempsey et al., 2013). Quaternary faults are common in the region but are scarce in the southeastern Carson Sink. Well-bore data indicate that a west-northwest-trending extension direction has dominated the Carson Sink region from the late Miocene to present (Faulds et al., 2010; Hickman and Davatzes, 2010; Blake and Davatzes, 2012; Kreemer et al., 2012; Hammond et al., 2014; Hinz et al., 2013; Jolie et al., 2015).

Key data available specific to the Fallon site include detailed geologic mapping, down-hole lithologic data from ~14,000 m of core and well cuttings from numerous bore-holes within and around the site, stress data, thermal data, well-test data, geochemistry data, alteration data, detailed gravity surveys, magnetotelluric data, and 270 km of interpreted seismic reflection profiles. These data were coalesced and integrated into a 3D geologic model of the Fallon FORGE site (Hinz et al., 2016; Siler et al, 2016). In total, an area of ~4.5 km^2 is available for development of infrastructure on the FORGE site and another ~40 km^2 for monitoring and instrumentation on the surrounding lands.

2. PHASE 2A ACTIVITIES

During the four-month Phase 2A segment the focus is on providing an environmental information volume (EVI), an assessment of existing infrastructure available in support of FORGE operations and R&D technology testing and evaluation, implementation of public communication, outreach and stakeholder engagement, and deployment of a telemetered seismic monitoring array.

The EIV describes and summarizes the proposed actions to be conducted while preparing and operating the field site and the existing site environment, potential impacts on the environment, and any necessary plans for resolution of potential environmental impacts. The EIV will also provide an assessment of the team's ability to meet all compliance requirements at the site. The EIV and infrastructure assessment is being compiled and will be presented to DOE by mid-February for review.

The communication, outreach, and stakeholder engagement was initiated during Phase 1 and will continue throughout the duration of the Fallon project. We have focused principally on providing appropriate stakeholders with an introduction to our team, the FORGE concept and its relevance to the national energy sector, the potential local economic (and social) benefits of the project, a description of site development and operation, and an introduction to the type of R&D technology development and research that will likely be conducted at the site.

The preliminary seismic monitoring of the Fallon FORGE site began officially on November 1, 2016. The ten-station borehole array (Figure 1) installed by the U.S. Navy Geothermal Program Office prior to the FORGE project was upgraded during Phase 2A. The existing array had 10 shallow boreholes (nominally 300-foot depth) with three component geophones that had been sanded in at the bottom of each hole. The geophones at each site were connected to a Nanometrics MEQ acquisition system (Janus and first generation Taurus, using one-way spread-spectrum radios with a GPS antenna). All sites were powered with solar panels and a pair of deep-charge 12-V batteries. The data were sent to a central acquisition site for recording by the radios. Initial assessment found that seven of the stations were operational. After further assessment and restarting the array, the following upgrades were performed in order to meet the DOE GTO requirements for sensitivity and telemetry:

- Five of the sites needed new geophones.
- The central computer had to be reprogrammed to focus on local events. Prior to this it was detecting mainly regional events.
- All sites were upgraded with 2 way radios.
- Firmware/software upgrades were performed at all sites.
- The central site was connected to an independent internet connection outside of the Navy internet site, so that the data could be sent in real time to Lawrence Berkeley Lab (prior to this the data were recorded at the central site only).
- New batteries were installed at four of the sites.

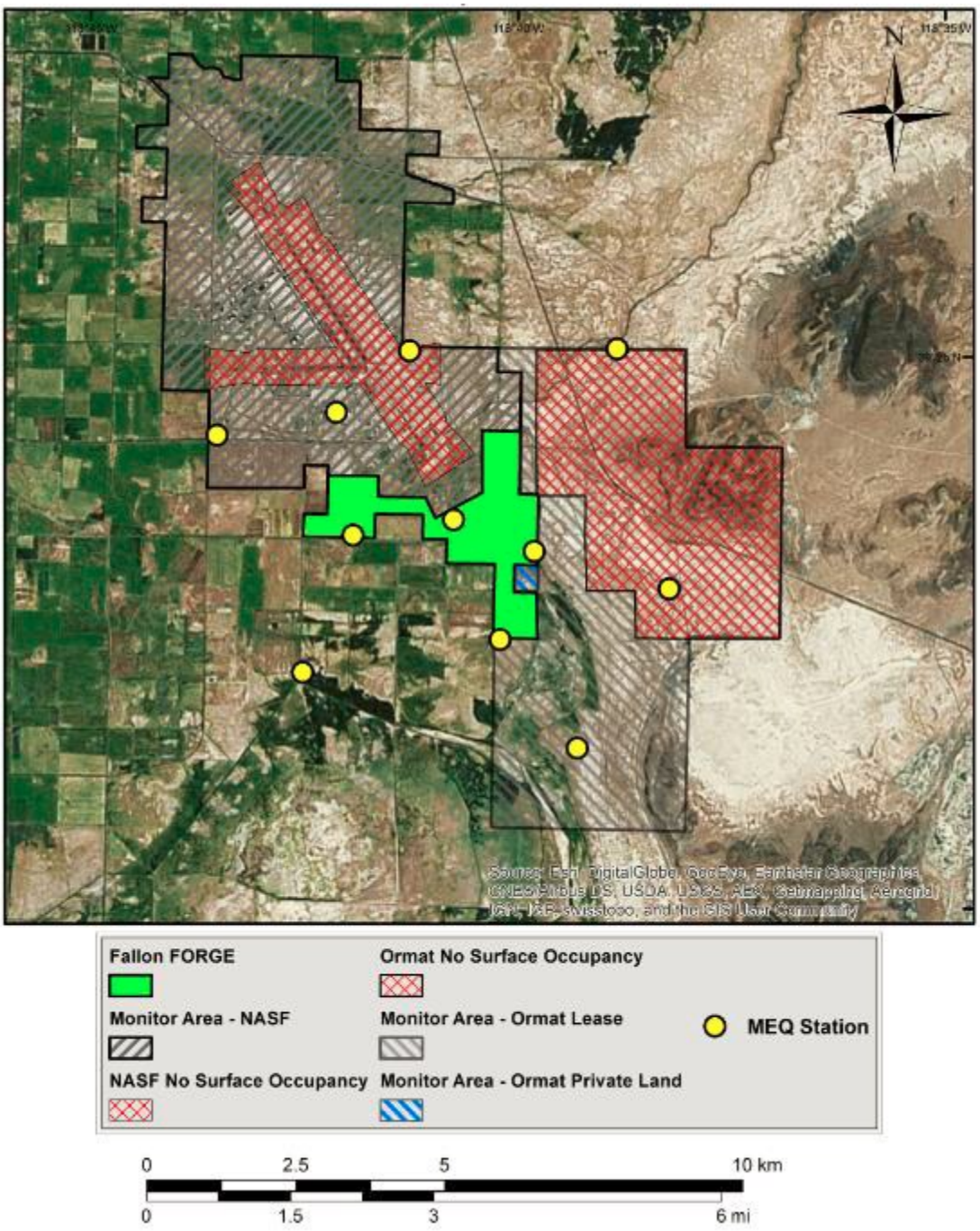

Figure 1: Seismic Monitoring Array.

Data acquisition and processing began on Nov 1, 2016. Since data collection began, approximately 10 to 20 events have been detected daily. Upon "hand picking" it was seen that all of the events are either false triggers (local cultural noise) or regional events. As of January 23, 2017, no local events have been located within the current array. The detection threshold is estimated to be about -1.0 M, consistent with the DOE requirement for the preliminary monitoring task.

A website hosted at LBNL has been developed for monitoring and analyzing the seismicity in real time. This will be a public website for anybody to monitor seismicity, and also a tool to keep track of any injection related seismicity during FORGE operations. An example of a display on the website is shown in Figure 2. Various options are available to the interested users, i.e., station location, maps of the events in plan and 3-D, time slices and magnitude distributions and other useful information.

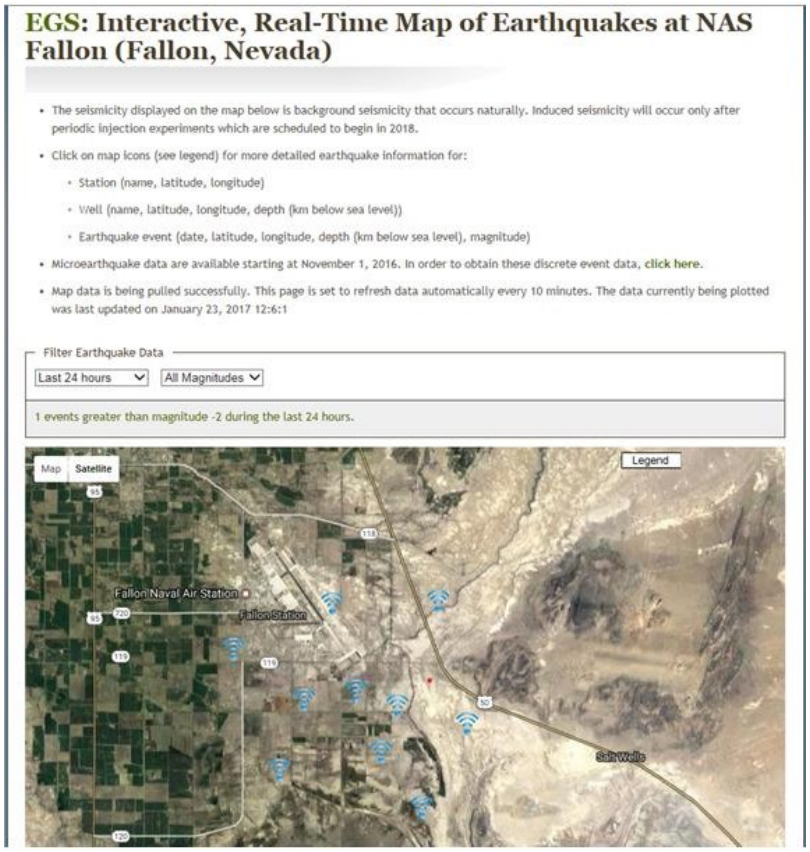

Figure 2: Screen Shot of the LBNL Fallon Web Site for Real-Time Monitoring of Seismicity at the Fallon Site.

3. PHASE 2B ACTIVITIES

Phase 2B is a one-year operation and will commence on approximately March 1, 2017, assuming the Fallon team receives a "Go" from DOE at the end of Phase 2A. The following discussion outlines the Phase 2B requirements and planned site characterization activities. During Phase 2B, for the first time we will have access to the site to collect data to augment existing data and refine the initial Fallon 3D geologic model generated in Phase 1.

3.1 NEPA Compliance

A requirement of any work contemplated on military land as well as on Bureau of Land Management (BLM) geothermal leases is NEPA compliance and any necessary permits and/or approvals. The Fallon team will conduct all necessary environmental and permitting work to allow FORGE to move toward full implementation. As discussed further below, the Fallon FORGE team intends to perform additional site characterization activities in Phase 2B. To enable these activities, environmental reviews will be completed and applicable permits for the planned activities will be obtained early in Phase 2B; this process has been initiated at the Fallon FORGE site. Because of existing permits issued for the prior exploration program conducted by the Navy and Ormat at the Fallon site, the FORGE team is confident that needed approvals and permits will be obtained to allow all Phase 2B planned field activities.

3.2 Final Induced Seismicity Mitigation Plan

The preliminary induced seismicity mitigation plan (ISMP) submitted in Phase 1 was based on the Protocol for Induced Seismicity associated with Geothermal Systems (Majer et al., 2012) with more detail given in Majer et al. (2016). The seven steps identified in the protocol (preliminary screening evaluation, outreach and communication plan, criteria for ground vibration and noise, seismic monitoring, quantify hazard from natural and induced seismic events, characterize risk from induced events, develop mitigation plans) were followed in preparing the preliminary ISMP. To bring the preliminary Induced Seismicity Mitigation Plan (ISMP) into its final form, we will use seismic data acquired during initial Phase 2A seismic monitoring and regional historical data and quantify the hazard from natural and induced seismicity using probabilistic seismic hazard analyses (PSHA). The results from the PSHA will be used to characterize the risk to existing structures and ultimately to develop a mitigation plan in accordance with standard protocol outlined in Majer et al. (2016). A full ISMP, in accordance with the standard protocol, will be written and presented to the DOE and local stakeholders.

3.3 Site Characterization

Although substantial geologic, geochemical, and geophysical data have previously been amassed for the Fallon area, several key data gaps preclude comprehensive characterization of some important aspects of the site. These data gaps relate to the following major themes: (1) delineating the precise location of EGS targets such that all FORGE criteria are satisfied, (2) establishing the mechanical and hydrologic attributes of these potential targets, (3) obtaining baseline data sets critical for evaluating the effects of stimulation experiments, and (4) minimizing uncertainties in interpretations and decisions. Resolution of these gaps will provide better characterization of the subsurface allowing for (1) targeting competent lithologies for EGS experiments, (2) selecting drilling sites with minimal risk, (3) conducting more comprehensive modeling for EGS experiments, and (4) monitoring the effects of any experiments.

The Fallon team has identified additional data needs including geologic, potential fields, geodesy-InSAR, pressure-temperature logging, geochemical, and slip and dilation tendency. These data, along with data generated by a confirmation well, will contribute to an improved geologic model and reservoir modeling activities. Furthermore, two additional issues were reported by reviewers of the Phase 1 report: (1) Well testing to evaluate reservoir permeability were conducted in an open hole, resulting in an integrated permeability of the open-hole section that included overlying sediments and volcanic and reservoir target basement lithologies, and (2) Structure of measured temperature gradients in the exploration wells suggested the possibility of fluid advection. As discussed below, in Phase 2B a deep well will be drilled to address these questions and provide additional data to further characterize the target reservoir, including core.

3.3.1 Geologic

There are several geologic data gaps at the proposed Fallon FORGE site related primarily to better constraining the stratigraphic and structural framework of the Mesozoic basement in the area, which is the chief target for EGS experiments. The new geologic studies will involve a multidisciplinary approach that includes analogue studies of nearby basement exposures, complementary geochronologic and petrographic analyses of cuttings, and core from previously drilled holes. Collectively, the new geologic studies will place better constraints on the permeability, composition, and depth of potential EGS targets, as well as provide important data for future EGS experiments and monitoring

3.3.2 Potential Fields

Only the eastern part of the project area had previously been covered by a detailed gravity survey; therefore, a new, detailed ground-based survey will be conducted to complement existing data. This new survey of Bouguer gravity measurements will focus on the western part of the site, but will also provide coverage with stations spaced 200–300 m apart for the entire ~100 km^2 project area. Additional gravity stations will be collected surrounding the project area, as needed, to characterize the regional field. The new gravity data will be merged with existing local and regional gravity data. This will include extensive quality control and reprocessing, as necessary, of the existing data sets. Further processing will be applied to help determine source depths for gravity signatures and better constrain source geometries.

High-resolution 2D ground profiles of gravity and magnetics will be carried out along several key transects (4–5 total with ~2 km spacing) across the proposed FORGE. 2D models of subsurface geologic structure based on the gravity and magnetic data will be generated. The combined gravity and magnetic datasets will then be used to assess and enhance the 3D geologic model. High-resolution gravity and magnetic data will enable rigorous 3D modeling of the potential field data, which will help constrain basin geometry and resolve intra-basin and basin-bounding faults and fracture zones.

3.3.3 Geodetic–InSAR Studies

High-precision geodetic data will be integrated with InSAR (interferometric synthetic aperture radar) data to establish a baseline set of measurements for monitoring surface deformation in the Fallon area, thus providing a means of distinguishing any surface deformations associated with EGS stimulation experiments in Phase 3 of this project. The two methods complement one another, as the GPS techniques can record mm-scale deformation in all directions on a regional scale within a global reference frame, whereas the InSAR data can delineate the precise location of the deformation. To establish baseline measurements in preparation for stimulation activities planned for Phase 3, up to six MAGNET GPS stations will be installed that will complement the University of Nevada, Reno (UNR) regional MAGNET GPS network. The latter will provide a very strong geodetic reference for high-precision studies at the FORGE site. InSAR satellite data will be acquired to complement the GPS data. A deformation baseline over a 400-km^2 area encompassing the entire project site and surrounding area will be obtained from publically available (free) Sentinel-1 data that have been collected since 2014. The data will continue to be collected for many years to come. The spatial resolution of the Sentinel-1 data is 20 x 5 m. If this project continues into Phase 3, when EGS stimulation will take place, we will also incorporate TerraSAR-X data, which have 3 m x 3 m spatial resolution. We will integrate the InSAR and GPS measurements during Phase 2, distinguishing to the best extent possible the location of any vertical and horizontal deformation (Hammond et al., 2012).

3.3.4 Pressure-Temperature Logging

Existing holes within the Fallon FORGE area will be re-logged with a pressure-temperature (P-T) tool to obtain fully-equilibrated, static thermal and pressure profiles for the wells. We suspect that some of the initial temperature logs collected from wells at Fallon (presented in the Phase 1 report) may not be fully thermally-equilibrated, as they were collected soon after well drilling and flow or injection testing. Re-logging of these existing wells will provide more accurate profiles of temperature as well as measured bottom-hole temperatures, which will further reduce the uncertainty in the geological and reservoir models of the Fallon FORGE site. Wells that have been identified for re-logging include 82-36, 61-36, and 88-24.

3.3.5 Slip and Dilation Tendency

The available stress data will be assessed in order to determine the tendency of faults and fractures at the proposed Fallon site to slip and dilate. It is well established that critically stressed fault segments have a relatively high likelihood of acting as fluid flow conduits. Thus, the tendency of a fracture to slip or to dilate provides a quantitative indication of the likelihood of fractures of particular orientations to dilate or shear under stimulation. Slip and dilation tendency values will therefore be calculated for each set of prominent faults and fracture sets within the project area, based on the 3D geologic model, borehole imaging, analogue studies of nearby exposures, and existing geologic maps of the region. The orientation of the in situ stress field at Fallon is well constrained by imaging of drilling induced fractures (Blake and Davatzes, 2012; Blake et al., 2015). Extended leak-off tests and/or formation integrity tests conducted on the proposed well drilled in Phase 2B will constrain the magnitudes of the stress tensors (e.g., Zoback et al., 2003), thus providing the requisite data with which to carry out the slip and dilation tendency analyses.

3.3.6 Confirmation Well

As noted in a previous section, an exploration well will be constructed to provide data needed to supplement the existing wells on the site. Final casing will be set in basement to allow hydraulic isolation of the proposed candidate reservoir section. Core will be retrieved for selected zones, and logging suites will be run to support the further development of the geologic and reservoir models.

3.3.7 Geologic and Reservoir Modeling

The additional data obtained and synthesized during this phase will used to supplement the existing site data and to further refine the geologic model developed in Phase 1 of this project. In addition, preliminary reservoir models will be developed to inform the plans for the full execution of the FORGE effort.

4. CONCLUSION

The DOE FORGE project represents a unique and important opportunity to develop the technologies, techniques, and knowledge needed to make EGS a commercial reality. Moving forward over the next year, the intent of the Fallon FORGE team is to complete the work needed to demonstrate that the proposed site is well suited for hosting FORGE from a technical, environmental, and societal perspective.

REFERENCES

Blake, K., and Davatzes, N.C., 2012, Borehole image log and statistical analysis of FOH-3D, Fallon Naval Air Station, NV: Proceedings, Thirty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford University, 14 p.

Blake, K., Tiedeman, A., Sabin, A., Lazaro, M., Meade, D., Huang, W-C., 2015, Naval Air Station Fallon Mainside: Update of geothermal exploration: Geothermal Resources Council Transactions, v. 39, p. 407-414.

Chabora, E., Zemach, E., Spielman, P., Drakos, P., Hickman, S., Lutz, S., Boyle, K., Falconer, A., Robertson-Tait, A., Davatzes, N., Rose, P., Majer E., and Jarpe, S., 2012, Hydraulic Stimulation of Well 27-15, Desert Peak Geothermal Field, Nevada, USA, Proceedings, 37th Workshop on Geothermal Reservoir Engineering, Stanford University, SGP-TR-194, 12 p.

Dempsey, D., Kelkar, S., Lewis, K., Hickman, S., Davatzes, N., Moos and Zemach, E., 2013, Modeling Shear Stimulation of the Desert Peak EGS Well 27-15 Using a Coupled Thermal-Hydrological-Mechanical Simulator, 47th US Rock Mechanics/Geomechanics Symposium, San Francisco, CA, June 23-26, 2013, 12 p.

Faulds, J.E., and Henry, C.D., 2008, Tectonic influences on the spatial and temporal evolution of the Walker Lane: An incipient transform fault along the evolving Pacific-North American plate boundary, in Spencer, J.E., and Titley, S.R., eds., Ores and orogenesis: Circum-Pacific tectonics, geologic evolution, and ore deposits: Arizona Geological Society Digest 22, p. 437-470.

Faulds, J.E., Coolbaugh, M.F., Benoit, D., Oppliger, G., Perkins, M., Moeck, I., and Drakos, P., 2010, Structural controls of geothermal activity in the northern Hot Springs Mountains, western Nevada: The tale of three geothermal systems (Brady's, Desert Perk, and Desert Queen): Geothermal Resources Council Transactions, v. 34, p. 675-683.

Hammond, W.C., and Thatcher, W., 2004, Contemporary tectonic deformation of the Basin and Range province, western United States: 10 years of observation with the Global Positioning System: Journal of Geophysical Research, v. 109, B08403.

Hammond, W.C., Blewitt, G., Li, Z., Kreemer, C., and Plag, H.-P., 2012, Contemporary uplift of the Sierra Nevada, western United States, from GPS and InSAR measurements: Geology, v. 40, p. 667-670, doi:10.1130/G32968.1.

Hammond, W.C., Blewitt, G., and Kreemer, C., 2014, Steady contemporary deformation of the central Basin and Range Province, western United States. J. Geophys. Res. Solid Earth 119, doi:10.1002/2014JB011145.

Hickman, S.H., and Davatzes, N.C., 2010, In-situ stress and fracture characterization for planning of an EGS stimulation in the Desert Peak geothermal field, Nevada: Proceedings, 35th Workshop on Geothermal Reservoir Engineering, Stanford University, February 1-3, 2010, SGP-TR-188.

Hinz, N.H., Ramelli, A.R., and Faulds, J.E., 2013, Preliminary geologic map of the Wabuska Quadrangle, Lyon County, Nevada: Nevada Bureau of Mines and Geology Open-File Report 13-08, 1 sheet, 1:24,000 scale.

Hinz, N.H., Faulds, J.E., Siler, D.L., Tobin, B., Blake, K., Tiedeman, A., Sabin, A., Blankenship, D., Kennedy, M., Rhodes, G., Nordquist, J., Hickman, S., Glen, J., Williams, C., Robertson-Tait, A., and Calvin, W., 2016, Stratigraphic and structural

framework of the proposed Fallon FORGE site, Nevada: 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, Feb. 22-24, 12 p.

Jolie, E., Moeck, I., and Faulds, J.E., 2015, Quantitative structural-geological exploration of fault-controlled geothermal systems: A case study from the Basin and Range Province, Nevada (USA). Geothermics 54, p.54-67.

Kreemer, C., Hammond, W.C., Blewitt, G., Holland, A.A., and Bennett, R.A., 2012, A geodetic strain rate model for the Pacific-North American plate boundary, western USA: NBMG Map 178, scale 1:1.500,000, 1 sheet

Majer, E., Nelson, J. Robertson-Tait, A. Savy, J. and Wong, I., 2012, Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems. DOE Geothermal Technology Program, DOE/EE0662, 52p., and reprint: http://esd1.lbl.gov/files/research/projects/induced_seismicity/egs/Best_Practices_EGS_Induced_Seismicity_8-APR-2016.pdf

Siler, D.L., Hinz, N.H., Faulds, J.E.,Tobin, B., Blake, K., Tiedeman, A., Sabin, A., Lazaro, M., Blankenship, D., Kennedy, M., Rodes, G., Nordquist, J., Hickman, S., Glen, J., Williams, C., Robertson-Tait, A., Calvin, W. and Pettitt, W., 2016, The geologic framework of the Fallon FORGE site. Geothermal Resources Council Transactions, v., p.

Stewart, J.H., 1988, Tectonics of the Walker Lane belt, western Great Basin: Mesozoic and Cenozoic deformation in a zone of shear, *in* Ernst, W. G., ed., The Geotectonic development of California: Prentice Hall, Englewood Cliffs, New Jersey, p. 683-713.

Zoback, M.D., Barton, C.A., Brudy, M., Castillo, D.A., and Finkbeiner, T., 2003, Determination of stress orientation and magnitude in deep wells: International Journal of Rock Mechanics and Mining Sciences, v. 40, p. 1049–1076, doi: 10.1016/j.ijrmms.2003.07.001.

Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.