

## Phase 2 Update for the Fallon FORGE Site, Nevada, USA

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**Keywords:** FORGE, geothermal energy, Fallon, Nevada, EGS

### ABSTRACT

The Department of Energy (DOE) Frontier Observatory for Research in Geothermal Energy (FORGE) is to be a dedicated field laboratory where the scientific and engineering community can develop, test, and improve sub-surface 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 an understanding of the key mechanisms controlling a successful EGS. The Fallon FORGE site in Nevada is one of two sites that are still being evaluated as potential candidates for hosting the final FORGE laboratory. In Phase 1 of the FORGE initiative, the Fallon team reviewed extensive, pre-existing data including lithological, well log and flow test results from deep wells within the Fallon FORGE footprint that penetrate the target reservoir, as well as a suite of geophysical, geochemical, geological and hydrological data on and adjacent to the site. Such evaluation confirmed that the Fallon site is ideally positioned to host a sub-surface EGS laboratory, with low permeability, appropriate temperatures and depths (175-225°C, 1-4 km), no hydrothermal system, appropriate lithologies, and a favorable stress regime. In Phase 2, key activities included:

- securing additional environmental permits and initiating an EA;
- extensive outreach with key local, regional and state stakeholders;
- preparing our induced seismicity mitigation plan (ISMP);
- acquisition of seismic and geodetic baseline datasets (MEQ, GPS and InSAR);
- reprocessing and reinterpretation of preexisting seismic reflection profiles;
- acquisition of new, detailed gravity and magnetic data;
- refining our detailed 3D model of the site (originally constructed in Phase 1) based on the new geophysical data and reinterpreted seismic reflection profiles;
- geomechanical and reservoir modelling, and
- siting and drilling a deep well to provide additional certainty that the target reservoir has low permeability.

This paper provides an overview of these Phase 2 activities at the Fallon FORGE site, and how these activities have further improved our knowledge of site characteristics.

### 1. INTRODUCTION

The Frontier Observatory for Research in Geothermal Energy (FORGE) is a Department of Energy (DOE) Geothermal Technologies Office (GTO) initiative 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 research 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, Nevada, in the Carson sink within the Basin and Range 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 GTO 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 Energy and Geoscience Institute at the University of Utah.

The selection of the Fallon site was based on existing geologic, geophysical, and subsurface data and well test results acquired during geothermal exploration conducted by the U.S. Navy Geothermal Program Office (GPO) and Ormat Nevada Inc. The DOE GTO required specific characteristics of potential sites to be met in order to be considered as a viable FORGE site. These site criteria 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 lacking an existing hydrothermal system. The satisfaction of these criteria along with extensive existing infrastructure (Naval Air Station Fallon, Ormat Nevada Inc. lease-land, and the cities of Fallon and nearby Reno, NV) proximal to the site and partnerships with all community stakeholders (including the U.S. Navy and Ormat Nevada Inc.) makes Fallon an ideal location for FORGE. In total, an area of ~4.5 km<sup>2</sup> is available for development of infrastructure on the FORGE site and another ~40 km<sup>2</sup> for monitoring and instrumentation on the surrounding lands.

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 and Henry, 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 and fault kinematic 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 compiled in Phase 1 of the Fallon FORGE project included 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, geochemical data, alteration data, gravity surveys, magnetotelluric data, and 270 km of interpreted seismic reflection profiles. These data were compiled and integrated into a 3D geologic model of the Fallon FORGE site (Hinz et al., 2016; Siler et al., 2016). This paper reports on the key activities for Phase 2 of the Fallon FORGE project.

## **2. PHASE 2 ACTIVITIES**

Phase 2A was 4 months in duration, from November 2016 to February 2017. Phase 2B was a one-year operation and commenced in March 2017. The following discussion outlines the combined Phase 2A and Phase 2B activities. Activities in Phase 2A included securing the appropriate environmental clearances for Phase 2B activities on site, developing an Environmental Information Volume (EIV), local and regional outreach, and an assessment of the existing supporting infrastructure. Phase 2B included collection of baseline data, additional geophysical data acquisition and processing (e.g., gravity, magnetic, geodetic, and InSAR data), reprocessing and reinterpretation of seismic reflection profiles, updating the geological and geochemical evaluation, reservoir modelling, and drilling a deep confirmation well at the site.

### **2.1 Permitting activities**

#### 2.1.1 NEPA Compliance

Any work contemplated on military land or on Bureau of Land Management (BLM) geothermal leases, requires NEPA compliance and any necessary permits and/or approvals. The Fallon team has and continues to conduct all necessary environmental and permitting work to allow FORGE to move toward full implementation. To enable activities onsite during Phase 2B, environmental reviews were completed and applicable permits for the planned activities were obtained. All FORGE activities performed within military/Navy lands required necessary approvals from Navy Command that included securing a CATEX (categorical exclusion) through Phase 2C (CATEX was acquired on 12-12-2016 for all Phase 2B and 2C work). All FORGE Phase 2B activities performed within BLM-leased land by Ormat Nevada Inc. fall under the existing Environmental Impact Statement (EIS) approved in 2011, and are conducted under a Determination of NEPA Adequacy.

#### 2.1.2 Phase 3 Environmental Assessment

Phase 3 activities at the Fallon site require additional permitting, specifically those related to reservoir stimulation. Preparation of an Environmental Assessment (EA) is currently in progress in collaboration with the Navy, BLM and the DOE. EMPSi has been contracted to support the development of the EA. As of early February 2018, EMPSi is reviewing comments received from the Navy Public Works environmental office and the Carson City BLM office and compiling them into the draft EA document. After all stakeholders approve, the next step is to release the draft document to the public for comment, with a final decision on the EA anticipated by April 2018.

## 2.2 Revising the 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. The preliminary ISMP is being updated using seismic monitoring and regional historical data acquired during initial Phase 2A and 2B. The hazard from natural and induced seismicity is being quantified using probabilistic seismic hazard analyses (PSHA). The results from the PSHA are being used to characterize the risk to existing structures and to develop a mitigation plan in accordance with standard protocol outlined in Majer et al. (2016), and following the DOE best practices for addressing induced seismicity associated with EGS (refer to [http://esd1.lbl.gov/research/projects/induced\\_seismicity/egs/fallonforge.html](http://esd1.lbl.gov/research/projects/induced_seismicity/egs/fallonforge.html) for further information). The most current ISMP will be available as part of the Final Phase 2B report for the Fallon site.

## 2.3 Outreach

Conducting outreach is a critical component of the FORGE initiative, involving stakeholder engagement, education, and promotion of the aims, rationale and expected outcomes of the project. Detailed information about our outreach efforts are presented in a companion paper by Robertson-Tait et al. (this volume). In Phase 2, the Fallon FORGE team used a tiered approach to outreach that relied on local officials and civic leaders to identify key stakeholders and facilitate meetings with them: this led to positive feedback from nearly all parties we contacted or met with during the course of our outreach. We found that ordinary citizens, business leaders, local and State officials, and the Nevada congressional delegation all appreciated simple and honest discussions about complex technical subjects and potentially thorny issues. Our participation in local events engendered genuine interest, showing that it can be possible to develop EGS in populated areas if communications and outreach efforts clearly demonstrate local support, whether resulting from economic interest, a desire to be part of a project that develops new technology, support for clean energy, or some combination of these elements.

The outreach and communications activities conducted to date led to the conclusion that people in the Fallon area are genuinely interested in geothermal development, including projects that aim to develop leading-edge technology, as is intended for FORGE. The local community is welcoming the project for reasons that both include and transcend the local benefits that would accrue from such a project. We are grateful for this support, and have developed a new appreciation of why public acceptance is so important for the widespread development of EGS.

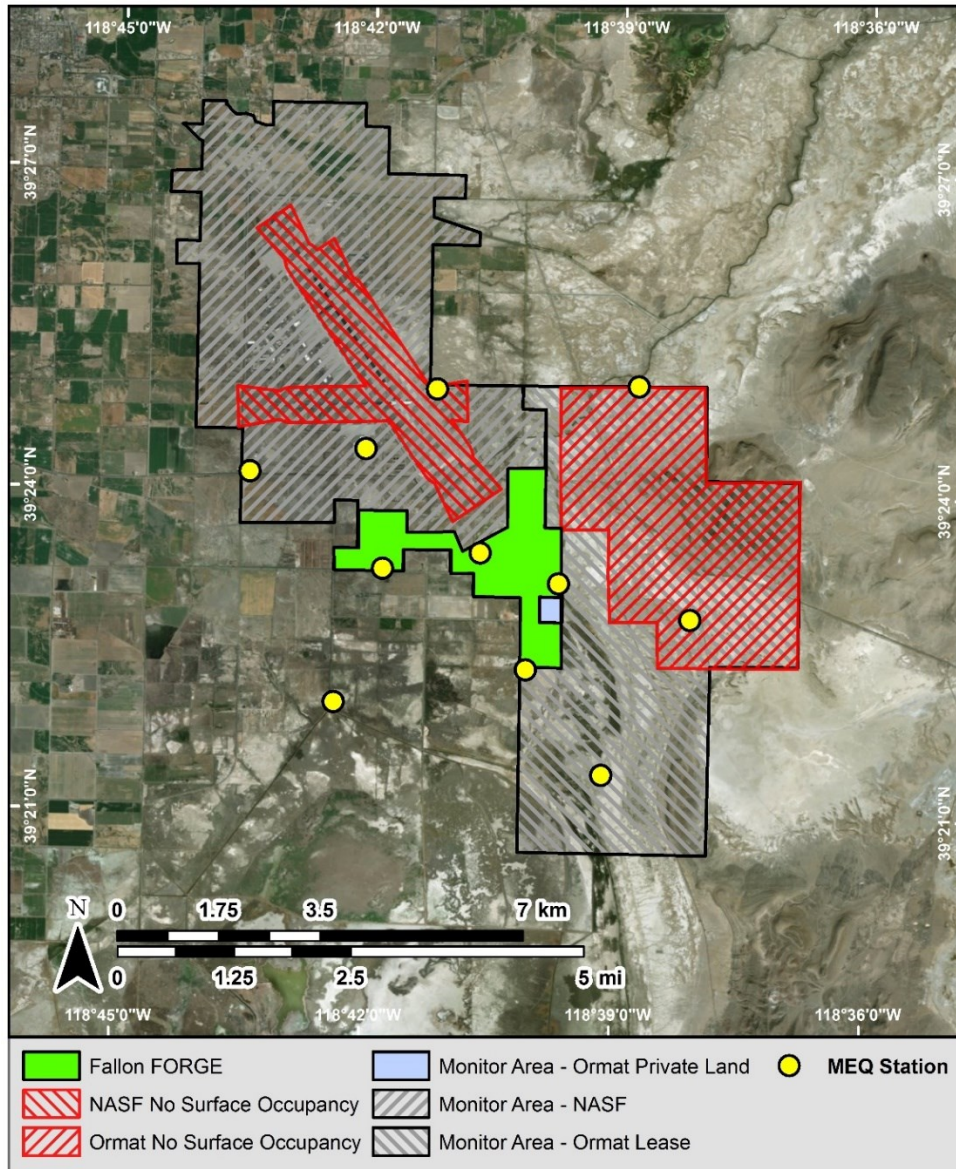
## 2.4 Additional site characterization

Although substantial geologic, geochemical, and geophysical data have previously been collected for the Fallon area, Phase 2B efforts were directed at further reducing the geological uncertainty in several key areas: (1) delineating the precise location of EGS targets such that all FORGE criteria are fully 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.

To address these needs, new microseismic, geodetic, and InSAR baseline data collections were initiated during Phase 2A and 2B. In addition, geochemical data were further reviewed, new gravity and magnetics data were acquired, and seismic reflection data were reprocessed and reinterpreted. These new data sets have permitted enhancement of the original geological model for the site.

### 2.4.1 Microseismicity

The preliminary seismic monitoring of the Fallon FORGE site officially began on November 1, 2016. The borehole micro-earthquake (MEQ) array (Figure 1) installed by the U.S. Navy GPO prior to the FORGE project was upgraded during Phase 2A (November 2016-February 2017). The data gathered to date indicates a very low risk of any significant impact related to induced seismicity that would occur during operations at the Fallon FORGE site. Monitoring of MEQ activity (magnitude -0.5 detection threshold) at the Fallon site with this 10 station, 3C - 4.5 Hz borehole (300 ft (90 m) deep) geophone array since November 2016 has not detected any seismicity within the proposed FORGE footprint; these data are available on the LBNL induced seismicity website – [http://esd1.lbl.gov/research/projects/induced\\_seismicity/egs/fallonforge.html](http://esd1.lbl.gov/research/projects/induced_seismicity/egs/fallonforge.html). Historical seismicity records for the past 100 years have shown that there has been no seismicity of magnitude 1 or greater within at least a 10 km radius of the proposed Fallon FORGE site. Expected micro-seismicity associated with EGS stimulations and other operations is anticipated to be at a level well below that required to cause possible damage or other risk at NAS Fallon, the local community, or in the City of Fallon. Our examination of induced micro-seismicity at nearby EGS projects is consistent with the preliminary predictions of magnitudes for induced seismicity at Fallon. Should a higher level of induced seismicity occur, pre-determined mitigation measures can be implemented, based on accurate, real-time monitoring of seismicity during site operations and the ISMP.



**Figure 1. Seismic monitoring array installed on and adjacent to the Fallon FORGE site.**

#### 2.4.2 Geodetic studies: GPS and InSAR

High-precision GPS and SAR (synthetic aperture radar) satellite data have been collected to establish a geodetic baseline for monitoring surface deformation in the FORGE area associated with EGS stimulation experiments in Phase 3. The SAR data were processed using the InSAR (interferometric SAR) method, making it possible to identify deformation time series and rates at numerous points. GPS and InSAR complement one another, as GPS can record mm-scale three-component deformation on a regional scale within a global reference frame, whereas space-based InSAR data provide blanket coverage and can thus locate deformation without the need for ground stations.

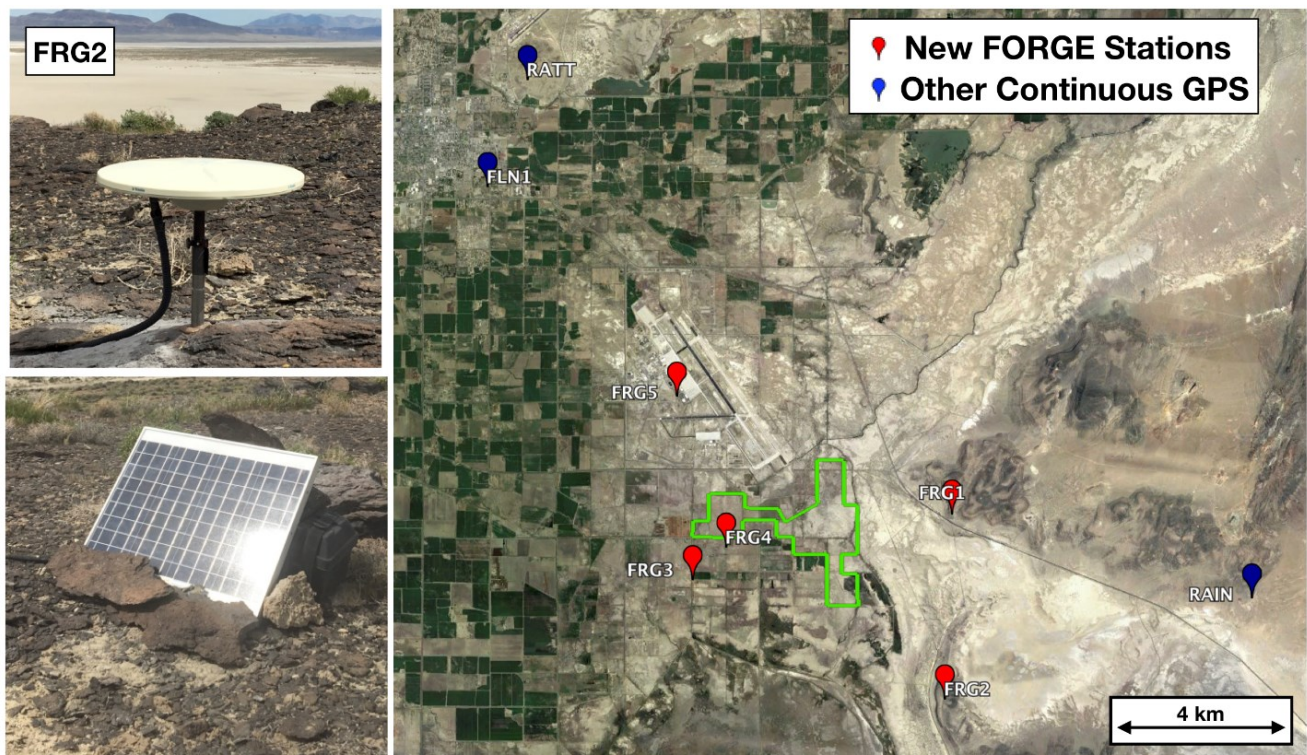
In April-May 2017, five GPS stations were sited, permitted and installed at stable locations within 3 to 5 km surrounding the FORGE wells (Figure 2). These stations are integrated with the UNR MAGNET Network, which measures crustal deformation in the western Great Basin. Data have been collected continuously and processed with the JPL GIPSY/OASIS software to obtain time series of daily positions over the 8-9 months since installation (available online at <http://geodesy.unr.edu>). The data show that for all five stations the chosen locations are stable, with residual RMS horizontal positions of ~2 mm (5 mm) in the horizontal (vertical) direction. This indicates the size of surface displacements to which these stations will be sensitive during FORGE Phase 3 operations. At least one additional GPS station will be added in the near field during Phase 3 operations to capture the maximum vertical deformation associated with stimulation.

The satellite radar data were collected by the Sentinel satellites. The specific InSAR technique used was SqueeSAR, introduced by TRE Altamira. It identifies deformation time series at permanent and distributed scatterers (PS and DS) that can be systematically identified

in consecutive radar scenes (Ferretti et al., 2011). Results are first obtained in the line-of-sight (LOS) to the satellite, in two configurations, descending and ascending, where the satellite moves north to south and south to north, respectively. From these two LOS data sets, it is possible to calculate vertical and east/west horizontal movements. InSAR cannot provide information on the north/south horizontal component of deformation. A set of 56 descending scenes was collected during the period 4/1/2015 – 12/10/2017. Another set of 56 ascending scenes was collected during the period 11/3/2014 – 12/11/2017. More than half of these scenes were collected in 2017, after the addition of a second Sentinel satellite. While the revisit time of the first Sentinel satellite was 24 days, when the second satellite was launched, the revisit time dropped to 6 days for several collections and then settled on 12 days.

The InSAR study area is of size ~860 km<sup>2</sup>. The number of descending PS/DS points is over 340,000, and the number of ascending PS/DS points is over 360,000. Deformation time series and annual rates are established at each of these points. The vertical and east horizontal components are calculated in more than 97,000 pixels of linear size 30 m, using the average descending and ascending LOS values from the PS/DS points within these pixels. The SqueeSAR technique requires a reference point. We chose the GPS station RAIN for the purpose, so all measurements are in reference to this station, which moves at a rate of  $-4.63 \pm 0.15$  mm/year to the west, and at an insignificant rate of  $+0.26 \pm 0.44$  mm/year upward, compared to a fixed North America reference frame. These annual rates are very similar to the average rates from 17 GPS stations in the greater vicinity. Therefore, it is expected that the InSAR measurements, as referred to RAIN, should not show significant tectonic strain across the relatively small area of the Fallon project. Figure 3 shows an example of the average east horizontal time series calculated from the time series at the PS/DS points within a 100-m radius from station FRG1 (7.5 km WNW from RAIN). This time series indicates no significant displacements relative to RAIN, as could be expected. This is representative for the remaining four Fallon stations (FRG2 to FRG5), as well as for the vertical movements. However, the figure shows significant vertical movements elsewhere. They are not tectonic, and are likely due to soil compaction (subsidence) or expansion (uplift). The uplift example is from an area ~2 km south of RAIN in the northern part of the Salt Wells geothermal area, showing a relative uplift of  $+7.5 \pm 0.6$  mm/year, as well as apparent seasonal variations. The subsidence example is from the Carson Lake area, ~20 km SW of RAIN, showing relative subsidence of  $-12 \pm 1$  mm/year.

During Phase EGS stimulation, we will use the Phase 2 geodetic and InSAR data to constrain models of the distribution of volume changes at depth associated with stimulation, testing simple geometries including spherical (Mogi, 1958), ellipsoidal (Yang et al., 1988), and planar intrusions (Okada, 1985).



**Figure 2.** Left: Example of GPS equipment used to collect baseline geodetic data (FRG2 shown). White disk in upper panel is Zephyr Geodetic antenna sitting atop 11” steel pin inserted into outcrop. Lower panel shows solar panel that provides power to system. Right: Map of new MAGNET stations established for FORGE. FRG1 and FRG2 consist of steel pins in natural outcrops; FRG3 and FRG4 consist of steel pins in concrete forms constructed for water diversion; FRG5 is installed on the rooftop of the old air traffic control tower on the Fallon Naval Air Station. Blue pins show locations of other nearby GPS stations that have long position time series.

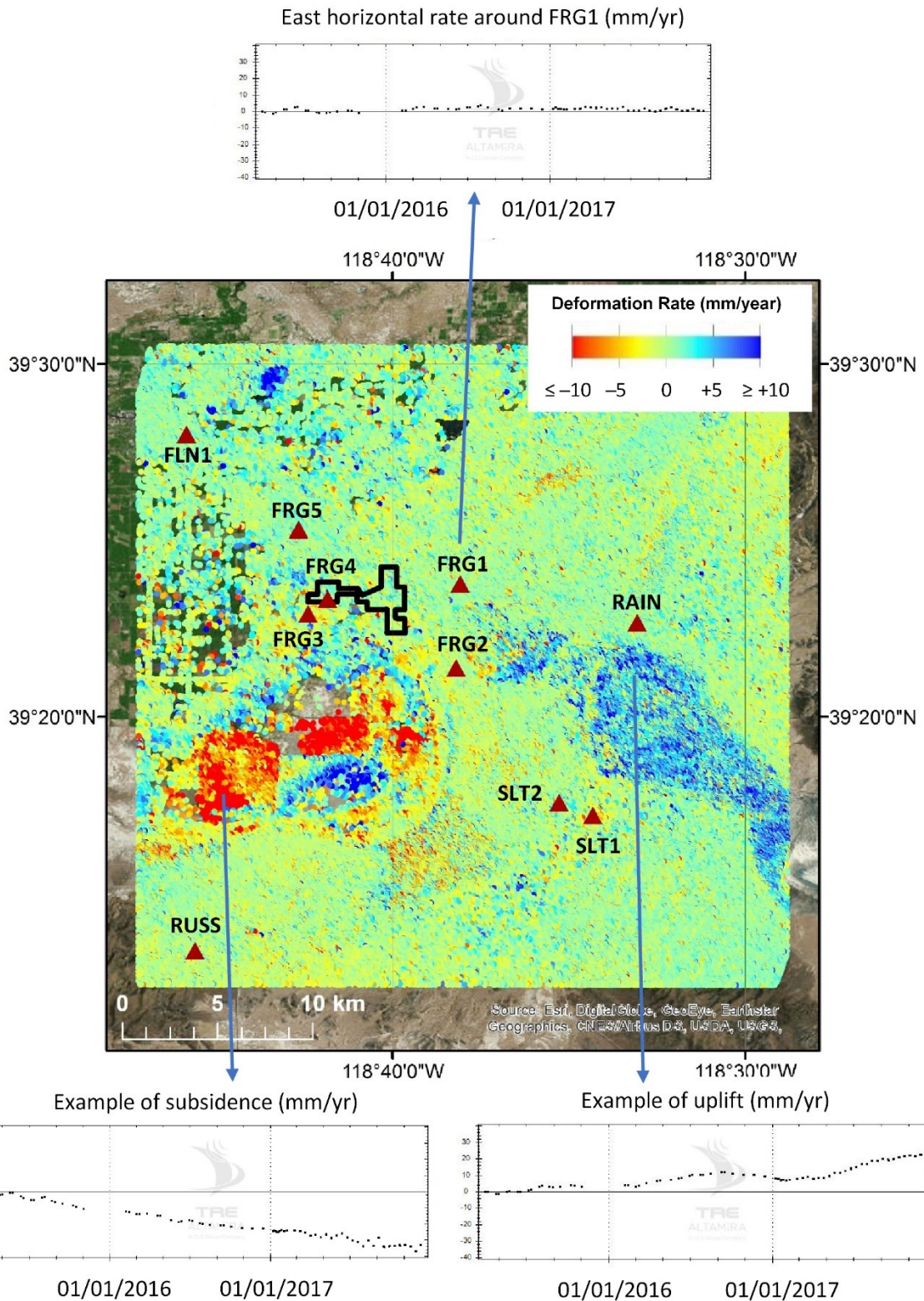
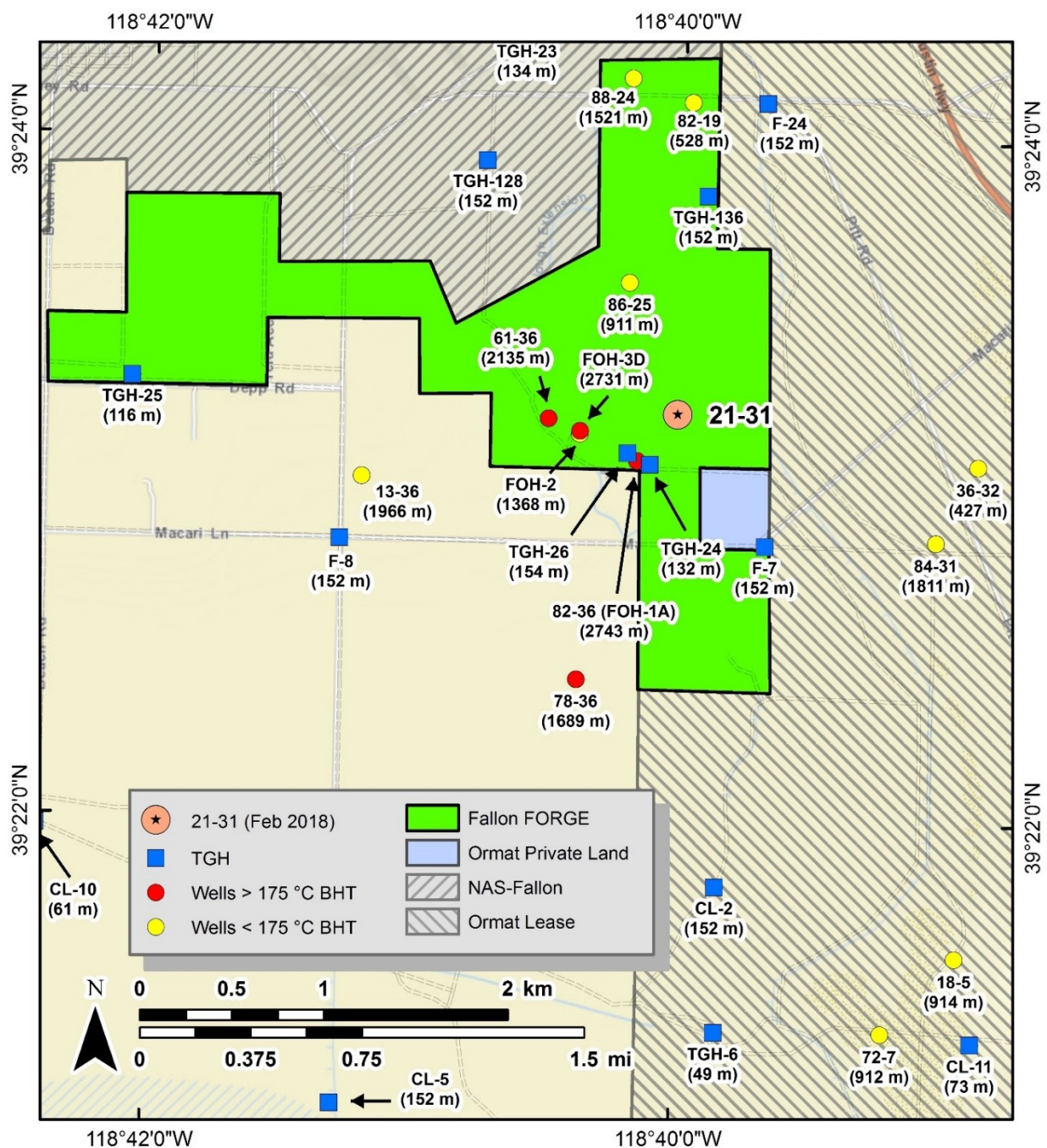


Figure 3. Surface deformation in the Fallon area and surroundings measured with InSAR. Map shows color coded annual deformation rates relative to the GPS RAIN station, at the locations of descending permanent and distributed scatterers (PS/DS) in a ~860 km<sup>2</sup> area including the Fallon project (outlined in black). Red indicates movements away from the satellite, and dark blue indicates movements towards the satellite. Green color indicates no relative movement. Red triangles show GPS stations. The time series plot on top show the average east horizontal annual rate around the FRG1 station, which indicates no significant movements compared to RAIN. The time series plots on the bottom show non-tectonic subsidence (left) and uplift (right).



**Figure 4. Map of the key wells drilled on and adjacent to the proposed FORGE site at Fallon. Well depths are shown in brackets beneath the well names. Also shown is the location of the new confirmation well 21-31 to be drilled in Phase 2B (February 2018).**

#### 2.4.3 Aqueous geochemistry

Reliable water chemistry data are available from 5 wells on or adjacent to the FORGE footprint. Wells FOH-3D, 61-36 and 88-24 are located within the central part of the proposed FORGE site, well 84-31 is located to the east of the site on Ormat-leased land, and well TGH-6 is located to the south-east of the FORGE site (Figure 4).

All samples on the FORGE site are classified as alkali-chloride waters, containing relatively low dissolved sulfate and bicarbonate. These fluids are mature fluids, given their low magnesium contents, as elevated magnesium indicates that the fluids have mixed with shallower, non-equilibrated groundwater. A sample from well 84-31 has more intermediate composition with higher sulfate, and is considered an immature fluid (Figure 5). Applying traditional cation geothermometry relationships to the geochemical dataset indicates apparent high temperatures at depth at the Fallon FORGE site. The data suggest two different equilibration temperatures for the various fluids: 1) a higher temperature between 240-260°C from the FOH-3D well (8170 ft (2490 m) depth), and 2) a more moderate temperature between 140-160 °C (wells 61-36, 88-24 and TGH-6) (as indicated by Giggenbach’s Na-K geothermometer (Giggenbach,

1988)) (Figure 5). The cooler temperatures are somewhat consistent with the fact that none of the deep wells are cased to basement, and produced fluids are likely dominated by shallower fluids from the Tertiary section and may have only a small contribution from the Mesozoic basement.

To narrow the possible range of fluid equilibration temperatures in the target EGS reservoir, the multi-component equilibrium geothermometry code iGeoT (Spycher et al., 2014; 2016) was applied to fluid samples from the FOH-3D well, from which the highest temperatures were predicted using the classical solute geothermometers (i.e. Na/K etc.). The iGeoT code allows sampled fluids to be corrected for possible degassing effects and/or mixing with other fluids via numerical optimization, to provide a ‘corrected’ deep water composition. This corrected fluid is then compared with mineral saturation indices for minerals known or presumed to be present in the reservoir, and used to estimate reservoir temperatures. For this study, XRD analyses of cuttings in the FOH-3D well were used to constrain the likely mineral assemblage. Key minerals detected at depth in FOH-3D were quartz, chlorite, illite, plagioclase feldspar, potassium feldspar, calcite, magnetite, and epidote, therefore the iGeoT simulations incorporated these or similar minerals. The results of the simulations suggest that reservoir fluids in the Mesozoic basement are equilibrating around 205-215°C, which is consistent with the measured bottom-hole temperatures in well FOH-3D and 82-36 (200-210 °C) (Figure 6), and suggests that the higher estimates (>240°C) from the solute geothermometers may not be realistic.

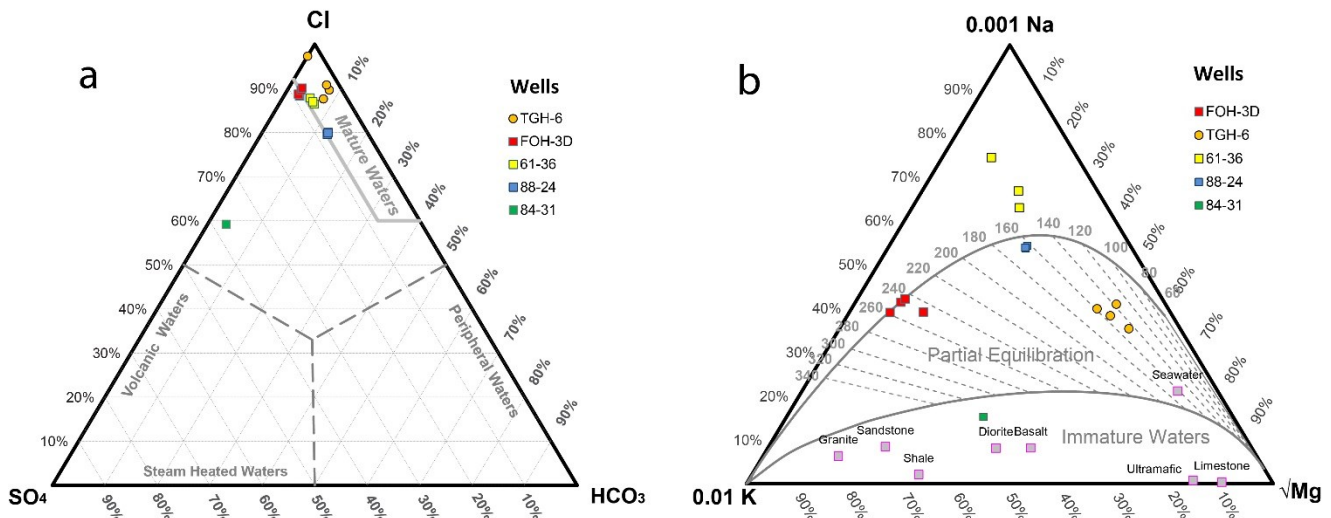


Figure 5. (a) Ternary plot of geochemical data from wells on or adjacent to the Fallon FORGE site. (b) Giggenbach plot illustrating potential equilibration temperatures for the sampled fluids.

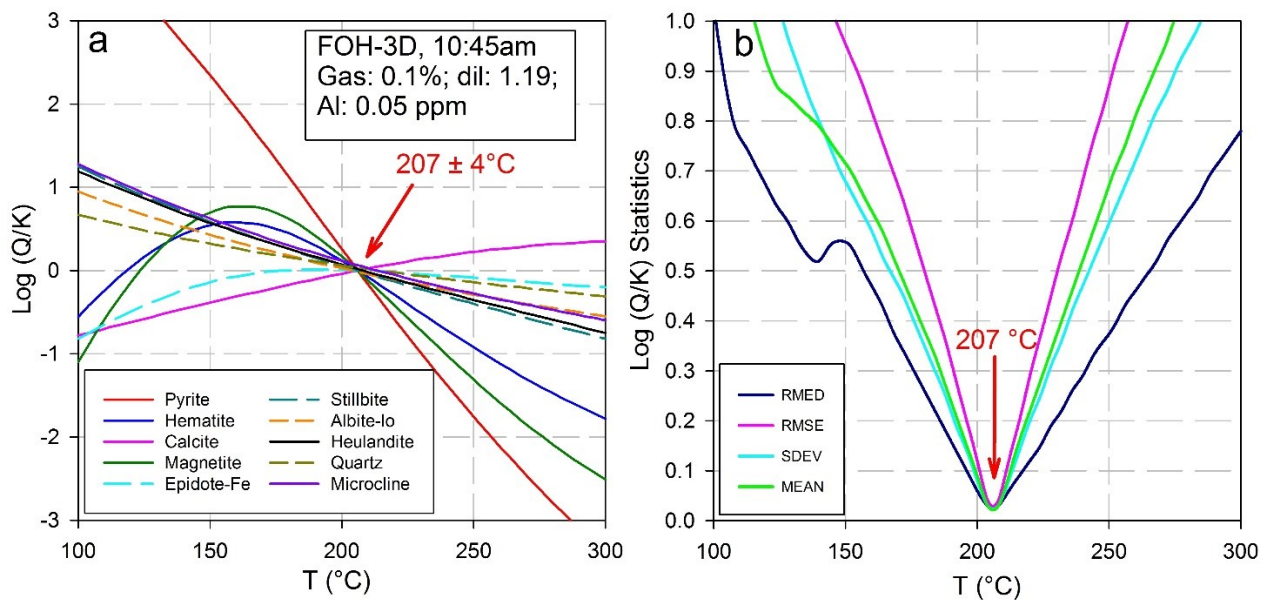


Figure 6. An example of one multi-component equilibrium simulation of a water sample collected from FOH-3D. (a) Results from a run in which minimal CO<sub>2</sub> degassing (0.1%) and some fluid dilution (<20%) were allowed. Given that the FOH-3D is not cased to basement, dilution of the deep reservoir fluid is likely. (b) Statistical parameters for the iGeoT run.

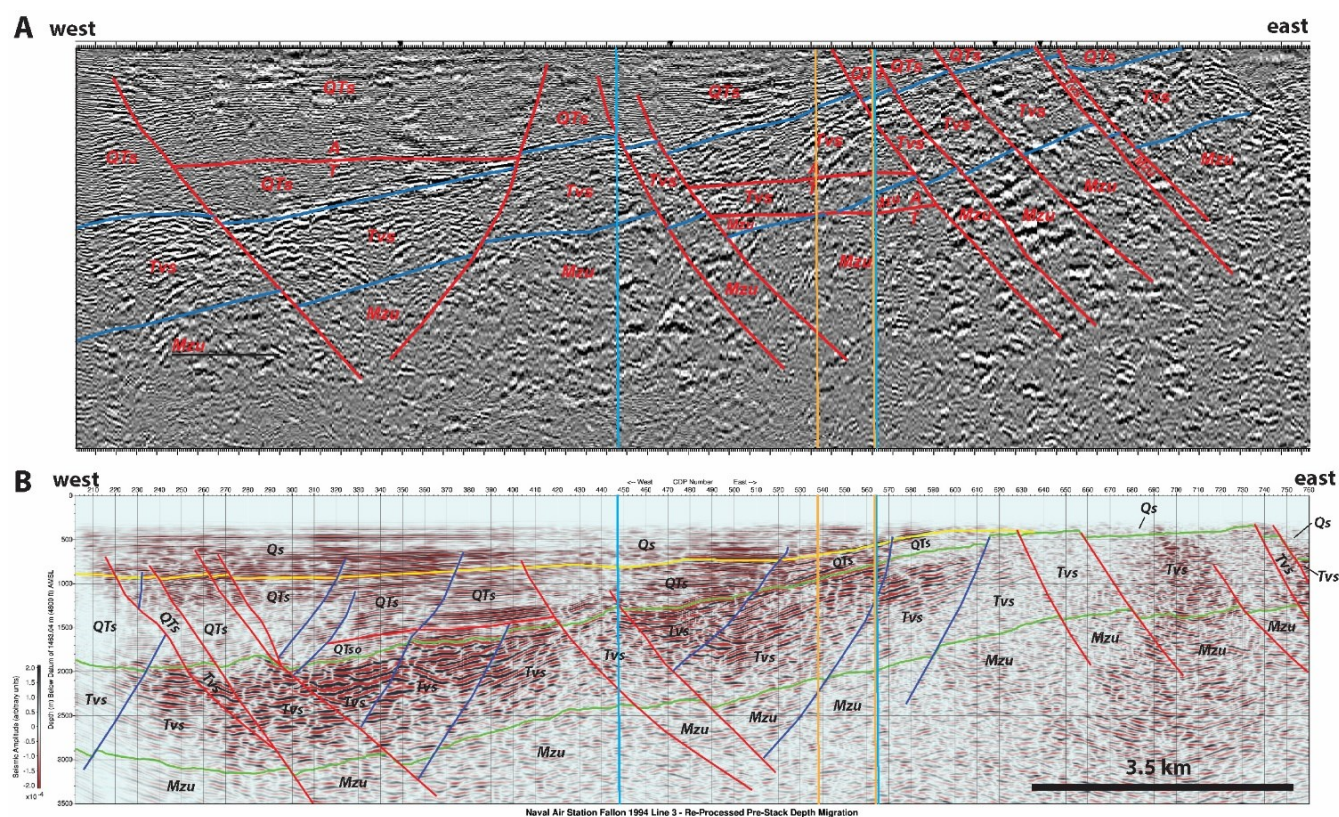


### 2.4.4 Gravity and magnetic surveys, and seismic reprocessing

Only the eastern part of the project area had previously been covered by a detailed gravity survey. Consequently, a new, detailed ground-based survey was conducted in September/October 2017 to complement existing data. This new survey focused on the western part of the site, but also provided coverage with stations spaced every 200–300 m across the majority of the ~100 km<sup>2</sup> surrounding the Fallon site that has been the subject of detailed geological characterization, as well as closer-spaced (100 m) stations along the seismic reflection transects. Additional gravity stations were placed surrounding the project area, to characterize the regional field. The new gravity data were merged with existing local and regional gravity data, which involved extensive quality control and reprocessing of the existing data sets. Further processing was also applied to help determine source depths for gravity signatures and better constrain source geometries. Approximately 475 line-km of new ground magnetic data were also acquired at the Fallon FORGE site in April 2017, using two ATV-driven magnetometer systems and backpack-mounted walking magnetometer systems. Additionally, magnetic susceptibility and remnant magnetization were measured using core samples from wells on and adjacent to the Fallon site, and from bedrock samples from the surrounding ranges. The magnetic data were processed using a variety of methods, included paired gravity and magnetic forward modelling, and 3D inversion, to inform the subsurface conceptual structural model.

An additional activity in Phase 2 included the reprocessing and reinterpretation of a seismic reflection data set that was collected by the Navy Geothermal Program Office in 1994. This provided much improved constraints on subsurface fault geometries and major stratigraphic contacts at Fallon. Data along seven profiles (>100 km of total profile length) through and adjacent to the Fallon site were re-processed. The most up-to-date, industry-tested seismic processing techniques were utilized to improve the signal strength and coherency in the sedimentary, volcanic, and Mesozoic crystalline basement sections, in conjunction with fault diffractions in order to improve the identification and definition of faults within the study area (Figure 7).

The combined gravity and magnetic datasets together with the reprocessed, reinterpreted reflection seismic data were used to assess and enhance the 3D geologic model. Integration of these datasets helped to constrain basin geometry and resolve intra-basin and basin-bounding faults and fracture zones in a more robust manner than the earlier Phase 1 work. Additional detailed information about the geophysical data acquisition and processing is presented in a companion paper by Siler et al. (this volume).



**Figure 7. (a) Original processing and seismic interpretation, and (b) newly reprocessed seismic reflection and interpretation of Line 3. In (a), faults are shown by red lines and contacts in blue. In (b), east-dipping faults are shown by red lines, west-dipping faults by blue lines, and contacts in yellow and green. All east- and west-dipping faults are interpreted as normal faults. This profile crosses the northernmost part of the eastern arm of the FORGE footprint and the vertical orange lines denote where line 3 crosses this arm. The approximate boundaries of the widest east-west segment of Fallon site (which is ~500 m south of line 3) are shown by the vertical blue lines. Unit abbreviations in descending order: Qs, Quaternary sediments; QTs, late Miocene to Quaternary sediments; Tvs, Miocene volcanic and lesser sedimentary rocks; Mzu, Mesozoic metamorphic and granitic rocks, undivided. Note the much higher resolution in the reprocessed profile.**

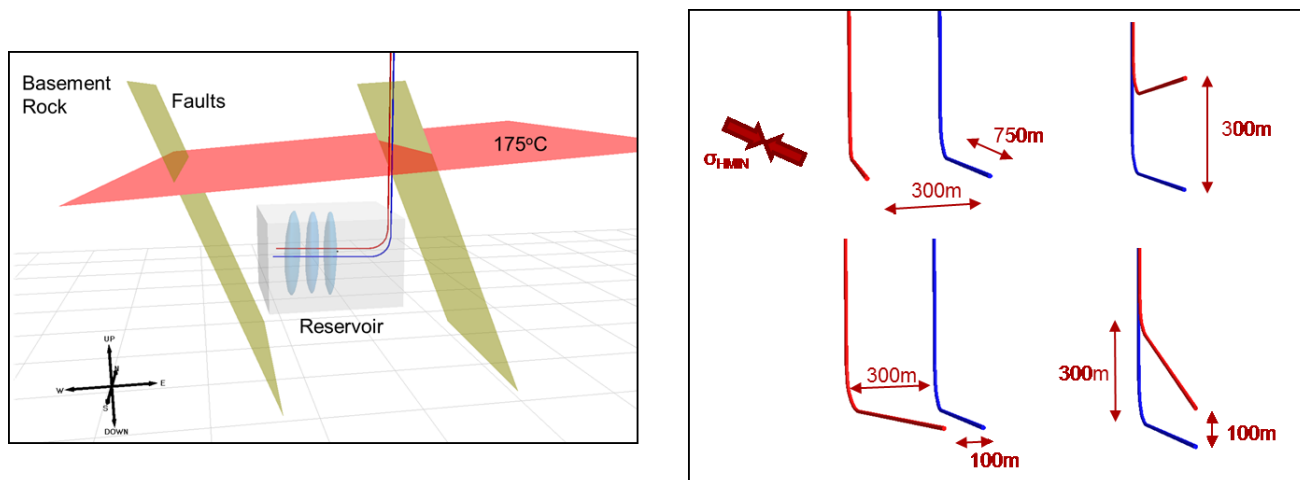
### 2.4.5 Geologic Modeling

In Phase 2, previous iterations of the Fallon 3D geological model are being refined and updated with results from the new gravity and magnetic data, geological and structural data from analogous stratigraphic sections proximal to Fallon, and the re-processed, re-interpreted seismic reflection data (refer to Siler et al., (this volume) for more information). When the Phase 2 geological model is finalized, all available stress data will be assessed 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 higher likelihood of acting as fluid flow conduits. The orientation of the in situ stress field at Fallon is well constrained by imaging of drilling induced fractures in existing wells at the site (Blake and Davatzes, 2012; Blake et al., 2015). Hydraulic fracturing stress measurements in new well 21-31 will constrain the magnitudes of the stress tensors (e.g., Zoback et al., 2003), thus providing the required data to refine the slip and dilation tendency analyses.

### 2.4.6 Reservoir Modeling

The Fallon team members are performing geomechanical modeling to support reservoir design and optimization at the FORGE site. Through simulating reservoir fracturing and fluid flow, this modeling is being used to inform different conceptual designs for well geometries and stimulation strategies in the geological context of the proposed site. Both continuum methods and discrete element approaches are being used. A continuum thermo-hydraulic-mechanical-chemical (THMC) model based on LBNL's TREATMECH code has been developed to evaluate shear and tensile failure, and resulting dynamic fracture permeability changes (mechanical and chemical), for proposed stimulation well designs. In conjunction with this effort, the Distinct Element Method (DEM) using Itasca's 3DEC software is being used to develop a suite of coupled 3D THM models that consider the geological site characteristics, design concepts, and criteria for the FORGE project. Metrics of hypothetical long-term power output are being used to qualify the conceptual designs, and simulated induced microseismicity is also incorporated to inform induced-seismicity mitigation planning and the design of site monitoring needs in future phases. Examples from the DEM modelling efforts are presented in the following section.

A regional geomechanical model has been constructed in 3DEC from the geological model developed during Phase 1 of the project (Siler et al., 2016). The model is 10 km (x) by 10 km (y) by 3.5 km (z) in dimension and consists of the main lithological units and fault network. An accompanying paper by Blanksma et al. (this volume) examines stress magnitudes at the reservoir depth using the regional model, borehole breakout data from acoustic televiewer measurements at the site, and assuming a normal stress regime. The approach illustrates that an ability to simulate the location of a borehole breakout can provide confidence in estimating the magnitude of the principal stresses that support traditional measurements of stress orientations. The results for the Fallon site indicate a minimum horizontal stress that lies in a range of 53% to 79% of the vertical stress and a maximum horizontal stress that lies in a range of 79% to 88% of the vertical stress for reservoir depths. The best estimate of the minimum and maximum horizontal principal stresses at the Fallon FORGE site are 56% and 80% of the vertical stress, respectively.



**Figure 8. Left: Conceptual geometry of an EGS reservoir at Fallon FORGE. Right: Four conceptual well designs being tested as part of geomechanical modeling scenarios for the site. The designs are based on sub-horizontal, multi-stage stimulations.**

The regional geomechanical model has been used to construct a reservoir model in 3DEC that is 1200 m (x) by 800 m (y) by 800 m (z) volume around the positions of conceptual sub-horizontal well designs at the Fallon FORGE site. Figure 8 shows the conceptual design of the reservoir and geometries for different well designs being evaluated. The reservoir is inside the Mesozoic basement between 175 and 225°C, and for our simulations, fluid injection occurred at 2470 m below ground surface. The model (Figure 9) contains relevant geological structure and a joint network constructed using borehole measurements from the reservoir volume (Blake and Davatzes, 2012). Our simulated stimulation is being performed in six stages along the horizontal well using techniques similar to those successfully applied in the unconventional oil and gas industry. Injection pressures above and below the minimum horizontal stress are being used to test both hydraulic fracturing and hydraulic shearing conditions. The exercised joint network from an illustrative model run is shown in Figure 10. Simulated induced microseismicity is being used as a metric for measuring the hydraulic treatment zone in a technique analogous to proposed site measurements. Initial reservoir modeling results indicate that the FORGE site is ideally suited for

hydraulic stimulation of an EGS in sub-horizontal multi-stage wells due to orientations of the natural joint network in the regional principal stress field.

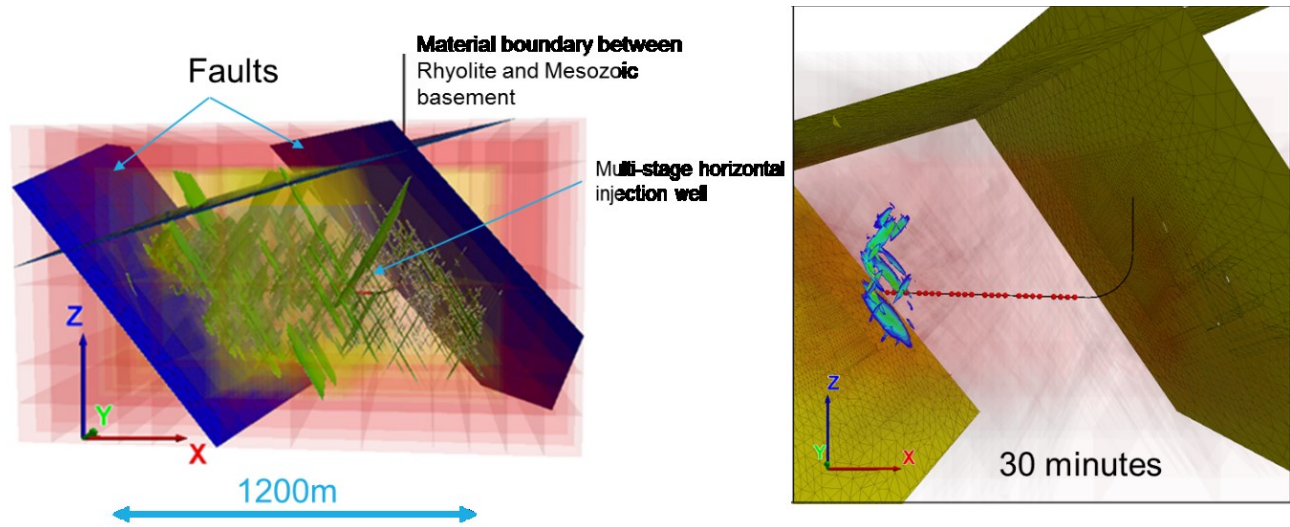


Figure 9. Left: Geometry of the initial reservoir model. Green joints are the input Discrete Fracture Network (DFN) determined from borehole measurements at the site. Right: Stimulated zone of joints after 30 minutes of modelled fluid injection in Stage 1 at the toe of a sub-horizontal well.

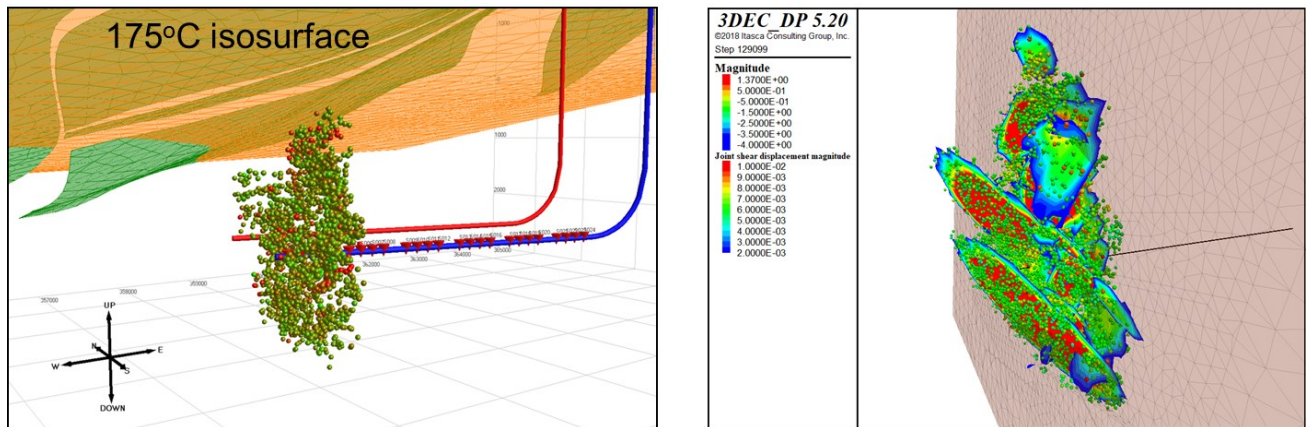


Figure 10. Left: Simulated (synthetic) microseismicity from Stage 1 of hydraulic treatment. Blue is injection well showing six stages along the sub-horizontal section, with four injection positions per stage. Red is production well for the side-by-side conceptual design. Microseismicity is color scaled to moment magnitude, green to red, in the range -3 to 1. Right: Stimulated joint network in Stage 1 overlain by simulated microseismicity. Joints are color scaled blue to red according to shear displacements induced by the hydraulic pressures.

#### 2.4.7 New drilling

The last major field activity during Phase 2 is the drilling of a deep well to intersect the target rock units (the Mesozoic basement) for EGS experiments and provide additional confirmation that the site meets the criteria to host FORGE. The well will be drilled to around 2440 m (~8000 ft) and is expected to intersect the Mesozoic basement at approximately 1685 m (~5530 ft). The final casing stage will be set in basement to (1) allow hydraulic isolation of the proposed candidate reservoir section, and, (2) injectivity testing to confirm that the Mesozoic basement has low permeability. The well will be completed as follows: 26" hole at surface, with a 20" conductor to 100 ft (30 m); a 17.5" hole with 13-3/8" casing to 900 ft (274 m); a 12.5" hole with 9-5/8" casing into basement (expected at around ~5530 ft (~1685 m); and a 8.5" hole to ~8000 ft (2440 m).

The drilling plan involves use of NOV Reed Hycalog Polycrystalline Diamond Compact (PDC) bits below the conductor, as well as FuseTek trials (a hybrid PDC bit). Roller bits will also be on site. The mechanical specific energy (a measure of drilling efficiency – input energy required to remove a unit volume of rock) and vibrations in the bottom-hole assembly (BHA) will be monitored in real time.

Tests that are planned for the well include injectivity testing during drilling and mini-frac stress measurements at several locations in the target reservoir. Wireline logs will be run for density, resistivity, porosity, sonic, temperature, and pressure for the whole borehole

length, and an acoustic televiwer will be run for the basement section (8.5' borehole). Up to 180 m (600 ft) of spot core will be collected in the basement section for geomechanical testing, and between 50-100 sidewall cores will also be collected. Due to the anticipated lithological variability in the Mesozoic basement, the decisions about which sections to spot core will be made onsite in real time, depending on the drilling results.

### 3. CONCLUSION

The DOE FORGE initiative represents an unparalleled and important opportunity to develop the technologies, techniques, and knowledge needed to make EGS a commercial reality. The Fallon FORGE site is demonstrated to be an ideal candidate to host the FORGE laboratory. The injectivity tests from the confirmation well 21-31 are the final dataset to be acquired to confirm that the Fallon site unequivocally meets all site criteria for FORGE as specified by the DOE. Having made substantial progress in both defining a site development strategy through the geological and reservoir modelling efforts in Phase 2B, and in developing an Environmental Assessment, the Fallon team is well placed to take the project into Phase 2C and 3 should we be selected.

### ACKNOWLEDGEMENTS

This project is funded by a Department of Energy grant EE0007160 awarded to the FORGE team, with Sandia National Laboratory as lead on the project. The team wishes to thank the NAS Fallon staff and leadership as well as Navy senior leadership for their cooperation and fruitful discussions, especially Commanding Officer CAPT David B Halloran, and Public Works Officer CDR Scott Beyer. We also thank the Nevada Governor's Office of Energy for their support of additional data collection during drilling activities at the Fallon FORGE site. The SqueeSAR processing of the Sentinel data was provided by TRE Altamira, Inc. Also we thank N. Spycher at Lawrence Berkeley National Laboratory for assistance with the iGeoT software.

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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