

The Geologic and Structural Framework of the Fallon FORGE site

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ABSTRACT

The working geologic framework model of the Fallon Frontier Observatory for Research in Geothermal Energy (FORGE) site has been updated with new data. These new data have been collected in order to fill gaps in an already robust data set, and contribute significantly to our evolving understanding of the geologic framework at the Fallon site. Our previous analyses has confirmed that the Fallon FORGE site consists of Mesozoic crystalline metamorphic and plutonic basement rocks, with low permeability, and conductive temperatures in excess of 175°C at ~1.7 km depth. Data from multiple deep wells within the FORGE site confirm that the target reservoir for EGS experiments has sub-commercial fluid productivity and injectivity and does not support a convective hydrothermal system. Image log data show that the natural fracture system is appropriately oriented with respect to local tectonic stresses for reactivation and propagation of fractures during EGS stimulation. Gravity and magnetic data, along with 2D and 3D modeling and inversion of these data, re-processed and re-interpreted seismic reflection data, geologic data from analogous Mesozoic basement units, and temperature data have been integrated with the existing data. The combined data set has been used to build the working geologic framework model of the Fallon FORGE site. This updated geologic framework represents a significant step forward in the characterization of the Fallon site, especially the crystalline basement. These data and analyses demonstrate that the Mesozoic crystalline basement units are well-suited to serve as EGS stimulation targets and are representative of many potential EGS localities throughout the United States.

1. INTRODUCTION

The Frontier Observatory for Research in Geothermal Energy (FORGE) project offers a unique opportunity to develop the technologies, techniques, and knowledge needed to make enhanced geothermal systems (EGS) a commercially viable electricity generation option for the USA. The objective of this project is to establish and manage FORGE as a dedicated site, where the subsurface scientific and engineering communities will be able to develop, test, and improve EGS-related technologies and techniques in a well-characterized environment. A crucial aspect of FORGE is the ability to apply the new technologies and techniques developed at FORGE to EGS development throughout the country. It is crucial, therefore, that the FORGE site be geologically analogous to a wide range of prospective EGS sites. The geology and structure of Fallon site is well-suited for this important criteria.

In this paper, we present an updated geologic framework of the proposed Fallon site. Pre-existing iterations of the Fallon geological model (e.g., Faulds et al., 2015; Siler et al., 2016, 2017; Hinz et al., 2017) have been refined and integrated with results from newly collected gravity and magnetic data, geologic and structural data from analogous lithologic sections proximal to Fallon, and interpretation of re-processed seismic reflection data. Existing data include detailed geologic mapping in the adjacent ranges, downhole lithologic data from ~14,000 m of core and well cuttings from numerous previously drilled boreholes within and around the Fallon site, stress data based on analyses of drilling induced fractures in boreholes on-site, natural fracture data from the existing boreholes, subsurface temperature data, well-test data, geochemical data, secondary alteration data, and magnetotelluric data. Our synthesis of these new and existing data adds greater detail to our characterization of the subsurface

geologic structure at Fallon and further indicates that the crystalline basement section at the Fallon site. Fallon represents the both the ideal location for FORGE activities and is analogous to a variety of sites where newly developed EGS technologies can be applied in the future.

The Fallon site is situated in the southeastern part of the Carson Sink basin in west-central Nevada, ~12 km southeast of the city of Fallon (Figure 1). The site is located on two parcels including land owned by the NASF (Naval Air Station Fallon) and adjacent geothermal production leases held by Ormat Nevada, Inc. (Figure 1). NASF has been the focus of geothermal exploration conducted by the Navy Geothermal Program Office (GPO) and its contractors for several decades. In total, an area of ~4.5 km² are available for development of infrastructure on the FORGE site and another ~40 km² for monitoring and instrumentation on the surrounding lands.

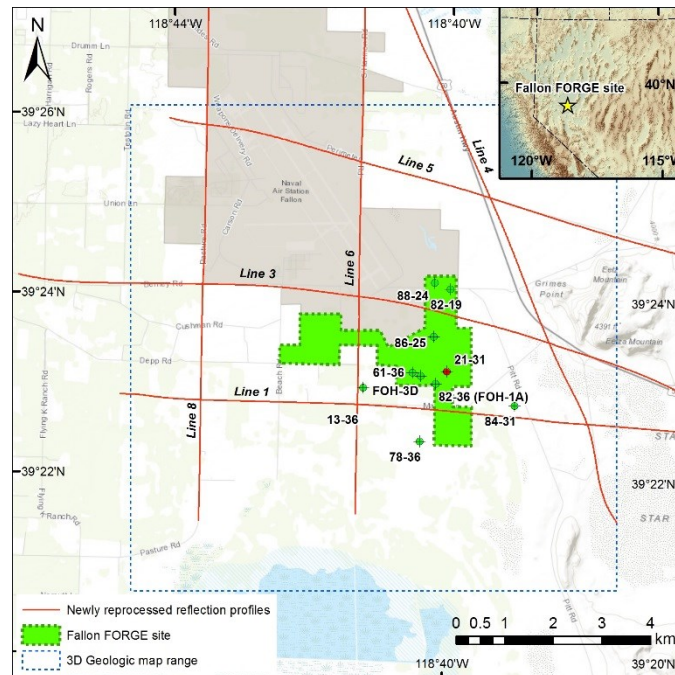


Figure 1. Map of the Fallon FORGE site. Inset shows the location of the Fallon site in western Nevada. The re-processed seismic reflection profiles are shown in red. The 3D geologic map extent is shown as the blue dotted line. The Fallon FORGE site is shown in green with locations of FORGE wells, including the well drilled in early 2018 (21-31).

2. GEOLOGIC SETTING

The Fallon FORGE site lies in the Carson Sink within the Basin and Range province, adjacent and directly northeast of the Walker Lane belt (Stewart, 1988; Faulds and Henry, 2008). Major tectonic events affecting this region that are relevant to the geology and structure at the Fallon site include: 1) Mesozoic contractional tectonism, arc volcanism, back-arc sedimentation, and volcanism, 2) Oligocene to Miocene mafic to felsic composition volcanism, and east-west to west-northwest extension, and 3) west-northwest extension and dextral shear from late Miocene time to present. Though no bedrock geologic units are exposed at the surface at Fallon, all of the geologic units present in the subsurface are exposed in ranges adjacent to the Carson Sink. Though situated in a seismically active region, no significant historic seismicity has occurred at the site, nor do any Quaternary faults cut surficial units on site.

Equilibrated temperature measurements reveal high temperatures (>175° C) along conductive geothermal gradients at depths of 1.5 to 3.0 km beneath the site. The lack of active or paleo-geothermal features present at the surface along with the demonstrated lack of permeability in several wells with high temperatures, indicates there is no natural hydrothermal system at the Fallon site.

3. DATA

3.1 Existing data

Data collected and analyzed during preceding phases of our analysis of the Fallon site have been presented in several recent papers (e.g., Faulds et al., 2015; Siler et al., 2016, 2017; Blankenship et al., 2017; Hinz et al., 2017; Majer et al., 2017). These

data include lithologic data from ~14,000 m of core and well cuttings from eight boreholes in-site and adjacent to the site, including cuttings from four boreholes that penetrate the Mesozoic crystalline basement. Image log data interpretations from two of these deep boreholes define the orientation of the natural fracture systems at depth at Fallon, as well as the orientation of drilling induced fractures. The latter were used to constrain that the orientation of the local tectonic stresses at Fallon are such that $S_{Hmax} = N15^{\circ}E$ (Blake and Davatzes, 2012). Based on these data, the natural fractures (mean strike $N13^{\circ}E$), relative to the orientation of the maximum horizontal stress, are well-oriented with respect to the ambient stress field for reactivation and propagation of fractures associated with EGS stimulation.

Equilibrated downhole temperature logs from nine deep (~1000-to-2750 m) boreholes (borehole locations shown on Figure 1) and several shallow boreholes constrain the 3D temperature structure at Fallon. These data indicate a conductive temperature regime with temperatures in excess of ~175°C at ~1.7 km depth. Injection tests in two wells that penetrate the crystalline basement revealed insufficient permeability for production flow rates and very low injectivity (<1 gpm/psi). 3D inversion of magnetotelluric data indicate high resistivity in the crystalline basement section, consistent with low permeability. Furthermore, the resistivity structure mirrors the stratigraphic structure, suggesting no significant fluid convection.

A database of nearly 8000 existing gravity stations spanning a ~130 x 130 km area centered on the Carson Sink was compiled from 15 different sources, consisting of both public domain, and privately contracted datasets that were and made available for this study. In addition, a ground-magnetic survey, consisting of ~130 line km of data collected proximal the study area, was performed in 2013 and provided by Ormat Technologies, Inc.

3.2 New Data

3.2.1 Magnetic data

In April 2017, ~475 line km of ground-magnetic data were collected at Fallon (Figure 2). Data along roads and existing tracks were collected using two ATV driven magnetometer systems, and off-road data were collected using backpack-mounted, walking magnetometer systems. Magnetic susceptibility and remanent magnetization were measured on core samples from wells adjacent to the Fallon site and on paleomagnetic samples and hand samples from the surrounding ranges. The new magnetic data were combined with data from existing surveys. A pseudogravity transformation (Blakely, 1995) was performed on a grid of the merged magnetic data to aid the interpretation of magnetic anomalies and constrain the edges of buried magnetic sources that may reflect structure or geologic contacts. Maximum horizontal gradients, 2D forward modeling of potential field data, and 3D inversion and forward modeling were used in conjunction with interpretation of the re-processed seismic reflection data for interpretation of structural and stratigraphic geometries in the subsurface.

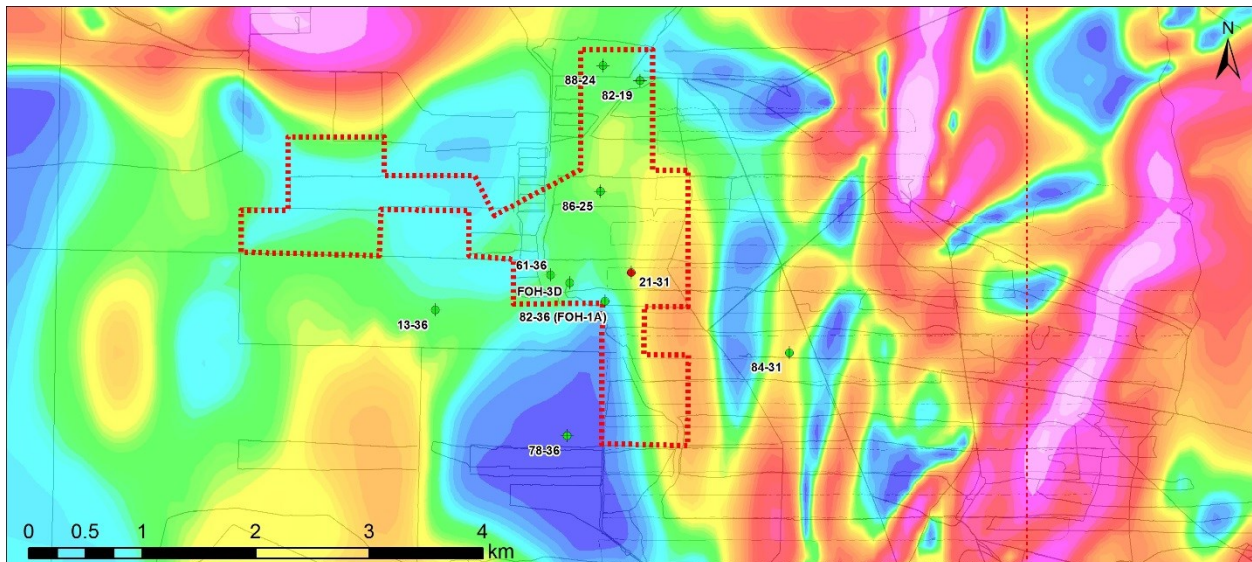


Figure 2. Horizontal gradient of pseudogravity. Magnetic traverses are shown as grey lines. Warm colors correspond to high horizontal magnetic gradient, cool colors to low horizontal magnetic gradient. These data show many, relatively high gradients (interpreted as dense geologic structure) east of the Fallon site and low gradients (a lack or major geologic structure) on site.

3.2.2 Gravity data

In September and October 2017, 906 gravity stations were collected using a LaCoste and Romberg Model-G gravity meter (Figure 3). Gravity stations were nominally spaced in a 300 x 300 meter grid spanning the study area, with additional stations spaced at 100 m along the seismic reflection profile lines. These new gravity data were combined with existing detailed and regional gravity data. Density measurements were performed on core samples from wells adjacent to the Fallon site and on samples collected from the surrounding ranges. Analogous to the magnetic data, edges of steeply dipping, dense bodies, possibly related to geologic structure or geologic contacts, were located along local lineations in horizontal gradient maxima (Blakely and Simpson, 1986). Maximum horizontal gradients, 2D forward models of potential field data, and 3D forward models and inversion of gravity data were used in conjunction with interpretations of the re-processed seismic reflection data to define structural and stratigraphic geometries in the subsurface.

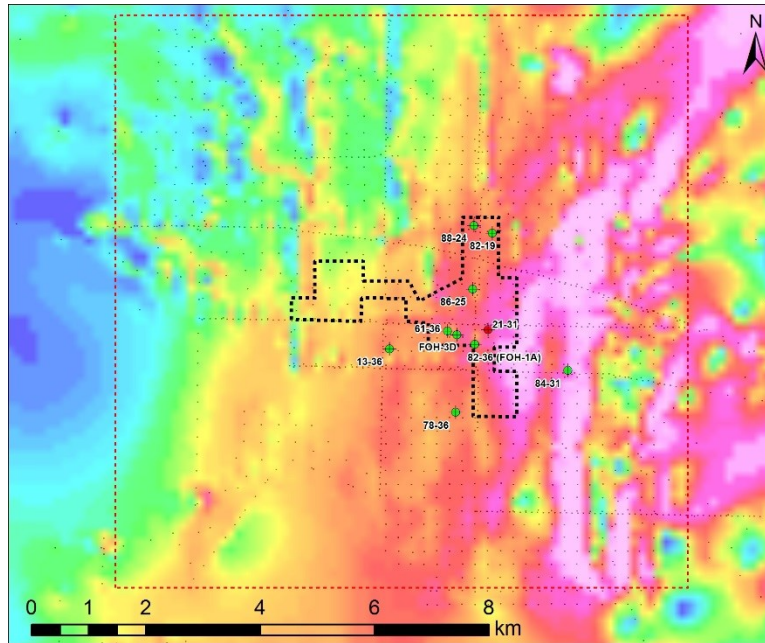


Figure 3. Horizontal gradient grid of isostatic gravity. Gravity station locations are show as grey dots. Warm colors correspond to high horizontal gravity gradient, cool colors to low horizontal gravity gradient. These data show many, relatively high gradients (interpreted as dense geologic structure) east of the Fallon site and generally low gradients (a lack or major geologic structure) on site.

3.2.3 Reprocessed seismic reflection data

A seismic reflection data set collected by the Navy (GPO) in 1994 has been re-processed and re-interpreted in order to provide improved constraints on subsurface geologic geometries at Fallon (Figure 4). Data along seven profiles, (>100 km of total profile length) through and adjacent to the Fallon site were re-processed (Figure 1). 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, and collapsing fault diffractions were employed to improve the identification and definition of faults within the study area. The re-processing utilized crooked line processing, surface-consistent deconvolution and residual reflection statistics, regional velocity and final stacking interval velocity analysis, surface-consistent and residual noise attenuation, Kirchhoff pre-stack time migration, and Kirchhoff pre-stack depth migration. The depth migrated data were interpreted in 3D in OpendTect software. The final interpretation, which was made in conjunction with the acquired gravity and magnetic data, represents a significant improvement to our understanding of stratigraphic and structural geometries in the subsurface at the Fallon site. This includes greatly refined identification of faults, thickness of basin-fill sediments, and in combination with the gravity data, depth to Mesozoic basement. These data demonstrate that the Fallon FORGE site is dominated by a gently west-tilted late Miocene to recent half graben that is cut by widely spaced east- and west-dipping, minor normal faults. This interpretation differs from the initial interpretation of primarily east-dipping normal faults (Figure 4).

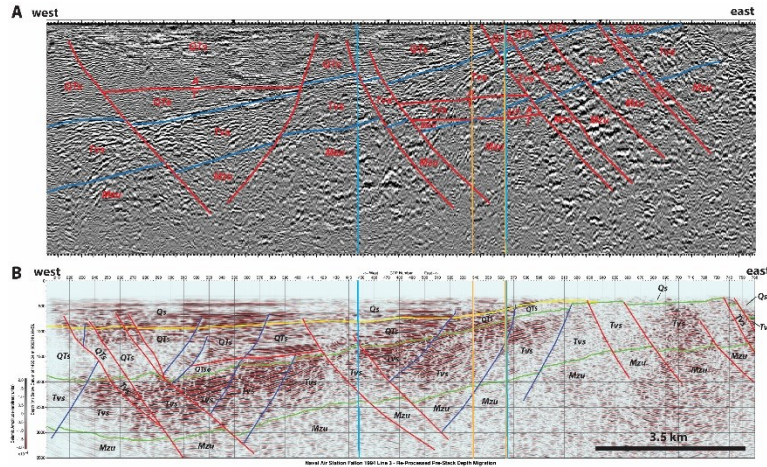


Figure 4. Original processing and seismic interpretation (A) and reprocessed seismic reflection and interpretation (B) of Line 3 (Figure 1). In A, faults are shown by red lines and contacts in blue. In B, east-dipping faults are shown by red lines, west-dipping faults by blue lines, and contacts in yellow 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 (Figure 1). 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.

3.2.4 Analogue geologic studies

Analogue studies of nearby Mesozoic crystalline basement exposures were conducted to supplement compositional and structural data collected from the boreholes at the Fallon site. The Mesozoic crystalline basement rocks (i.e., rock units conducive to EGS experiments) at Fallon include low- to medium-grade Triassic-Jurassic metavolcanic and metasedimentary rocks intruded by Jurassic and/or Cretaceous granitic plutons. These units are part of the Mesozoic Sierran arc and are widespread throughout this region of western Nevada (e.g., Oldow, 1984; Busby-Spera, 1988). Analogous metamorphic and plutonic rocks are ubiquitous throughout the western Cordillera of the United States and at depth beneath the North American craton. The specific Mesozoic units as identified by analysis of well cuttings from four boreholes include plutonic rocks (quartz monzonite), metasedimentary rocks (quartzite, marble, and phyllite) and metavolcanic rocks (felsic ignimbrites and volcanoclastic sediments, basaltic andesite lavas, and mafic volcanoclastic sediments). Corresponding units are well-exposed on the north side of the Carson Sink basin in the West Humboldt Range (phyllite, marble, plutonic rocks), in the Stillwater Range (quartzite, meta-basaltic andesite, and meta-mafic volcanoclastic sediments), and in the Humboldt Range (marble, phyllite, meta-felsic ignimbrites and meta-volcanoclastic sediments). Structural data collected from the units in these localities include: 1) fracture orientation, 2) fracture spacing, 3) fracture length, 4) fracture roughness, and 5) presence and type of mineralization along the fractures. In addition to these properties, the attitudes of overlying Cenozoic strata are recorded and used to correct structural data for tilting associated with Basin and Range extension. These data have been integrated with the on-site borehole data for use in constraining structural trends in the crystalline basement and as boundary conditions for EGS modeling and engineering.

4. THE FALLON STRUCTURAL FRAMEWORK

The newly collected data have been integrated with existing data (e.g., Faulds et al., 2015; Siler et al., 2016, 2017; Hinz et al., 2017) to construct a refined 3D geologic map of the Fallon site. The 3D geologic map consists of four stratigraphic units, younger and older Neogene basin-fill sedimentary units, Miocene predominantly basaltic andesite lava flows, and Mesozoic crystalline basement consisting of the rock units above. Within the Fallon site, the total thickness of the Neogene section (basin-fill sediments plus Miocene mafic volcanic rocks) ranges from ~1.5 to 2.2 km. The Neogene section nonconformably overlies the Mesozoic crystalline basement rocks. Though a wide variety of Mesozoic crystalline basement units are present, data from boreholes suggest that meta-rhyolite and quartzite are the two dominant lithologies in the area, attaining thicknesses of ~500 m and 200 m respectively, and comprising greater than half of the total vertical thickness penetrated in the boreholes.

The Fallon site lies in a gently west-tilted half graben on the western limb of an extensional anticline, with the axis situated ~4 km east of the site and just east of the eastern margin of the 3D geologic map (Figure 4). The geologic contact between the

Neogene volcanic section and the Mesozoic crystalline basement within the graben dips $\sim 20\text{--}25^\circ$ west. This westward dip, rather than significant vertical separation across faults, accommodates the majority of the east-to-west deepening (from ~ 1.5 to 2.2 km) of the crystalline basement beneath the Fallon site.

The geologic section at Fallon is cut by one primary fault system, which strikes north-to-north-northeast. The northerly striking faults dip steeply ($\sim 50\text{--}70^\circ$) to the east and west. To the east of the Fallon site, near the hinge of the anticline, fault density is greater (i.e., there are several faults per km in the east-west direction). This is evidenced by high horizontal gradients in both the magnetic and gravity data (Figures 2 and 3). To the west within the half graben, and beneath the Fallon site, west-dipping and east-dipping faults are more widely spaced, ($\sim 0.5\text{--}2.0$ km in the across-strike direction). As evidenced by seismic reflection data, faults cutting through the Fallon site have relatively minor offset, on the order of 10s to 200 m. In total >3.2 km³ of crystalline basement has the appropriate characteristics for FORGE activities, including conductive temperatures between $175\text{--}225^\circ\text{C}$, between 1.5 and 4 km depth, demonstrated low permeability, no convective hydrothermal circulation, and a favorable stress regime for reactivation and propagation of fractures.

5. CONCLUSIONS

Evaluation and synthesis of geologic and geophysical data with variety of existing data sets has facilitated the development of a refined 3D geologic framework of the proposed Fallon FORGE site. These data help to constrain key geologic parameters and the suitability of the Fallon site for FORGE activities. The relatively widely-spaced east-dipping and west-dipping faults cutting through the Fallon site have relatively minor offset, on the order of a few 10s to 200 m, and none of these faults have ruptured surficial Quaternary deposits at or proximal to the site. Additionally, none of the modeled faults intersected by existing deep boreholes have shown any evidence for commercially viable permeability or fluid transmission. The existing natural fracture system is well-oriented, with respect to the measured stress field for reactivation and propagation of fractures associated with EGS stimulation. The top of the Mesozoic crystalline basement section occurs at ~ 1.7 km depth in the center of the Fallon site. The majority of this section has measured temperatures in excess of 175°C along conductive geothermal gradients. There is a total of >3.2 km³ of crystalline basement rock with the appropriate characteristics for FORGE activities. Igneous, metasedimentary, and metavolcanic lithologies are all present in the Mesozoic crystalline basement section at the Fallon site. This wide range of lithologies ensures that new EGS insights gained from future FORGE activities at Fallon will be directly applicable to a variety of analogous basement sections throughout the United States for future EGS development.

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