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The geologic framework of the Fallon FORGE site

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ABSTRACT

The proposed Fallon FORGE site is located south of Fallon, NV. Data confirm that the Fallon site consists of predominantly crystalline metamorphic and granitic rocks, with low permeability, and temperatures in excess of 175°C at ~1.7 km beneath the surface. Well testing data confirm that the Fallon site is not within an existing hydrothermal field. Stress data suggest that the natural fracture system is well oriented for reactivation during EGS stimulation. The 3D geologic framework model for Fallon confirms that these characteristics are present in the subsurface throughout the site, and indicate that a minimum volume of ~3.2 km^3 rock satisfy FORGE criteria within ~4 km of the surface. As such the proposed Fallon site represents an ideal environment for development, testing, and validation of EGS technologies under the FORGE initiative.

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 eligible to develop, test, and improve new technologies and techniques in a well characterized environment that is ideal for EGS. This will allow the geothermal and other subsurface communities to gain a fundamental understanding of the key mechanisms controlling EGS success, in

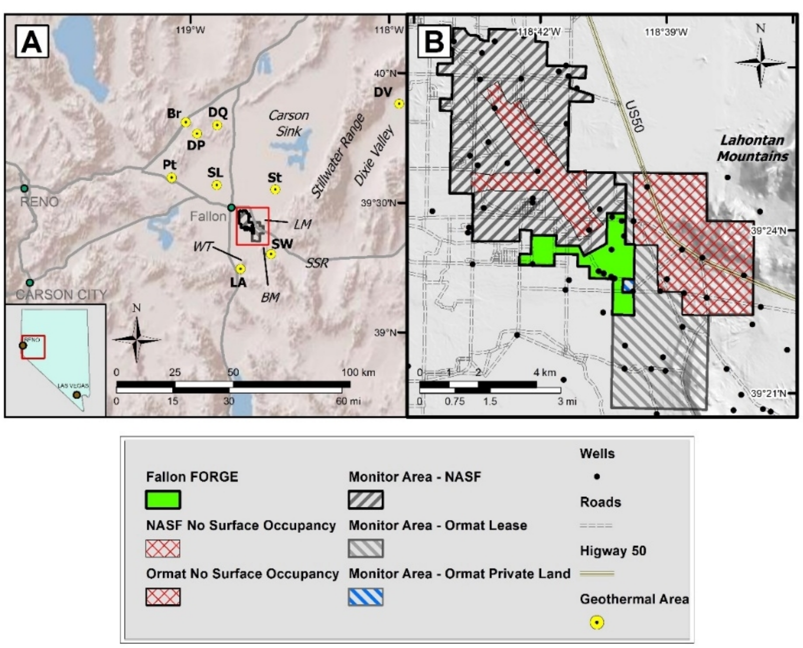

Figure 1. A. General location map of the proposed Fallon FORGE site in west-central Nevada. B. More detailed location map showing land status and major access roads. Abbreviations for physiographic features shown in italics: BM, Bunejug Moutains; LM, Lahontan Mountains; SSR, Sand Springs Range; WT, White Throne Mountains. Abbreviations for geothermal fields in the Carson Sink area shown in bold: Br, Bradys; DP, Desert Peak; DQ, Desert Queen; DV, Dixie Valley; LA, Lee-Allen; Pt, Patua; SL, Soda Lake; St, Stillwater; SW, Salt Wells.

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particular how to generate and sustain fracture networks in basement rock formations using different stimulation technologies and techniques.

Here, we present the geologic framework of the proposed Fallon FORGE site as interpreted through synthesis of a wide variety of data from previously completed geologic, geophysical, and geochemical studies. Key data available at Fallon include detailed geologic mapping, downhole 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 integrated into a 3D geologic model of the Fallon FORGE site.

The above data and the 3D analyses clearly indicate that Fallon satisfies all the requisite characteristics for FORGE; i.e. 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 proximal to the site and partnerships with all community stakeholders makes Fallon an ideal location for FORGE.

The proposed Fallon FORGE 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 that include land owned by the NASF (Naval Air Station Fallon) and Ormat Nevada, Inc. (Figure 1B and Figure 2). The site is bound by NASF on the northwest, parts of the Fallon agricultural district to the north, west, and south, Carson Lake wetlands at the base of the White Throne Mountains to the south, and Ormat lease lands to the east, which include parts of the Lahontan and Bunejug Mountains. Ormat has both privately held land and geothermal leases. The Ormat lease area includes portions of 12 sections (7426 acres) used in part for seasonal cattle grazing. A project Environmental Assessment (EA) covering geothermal exploration and development was completed in 2008 for the Ormat lease area. Most of the surrounding lands in the Ormat lease area and NASF are open to monitoring and instrumentation activities. 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.

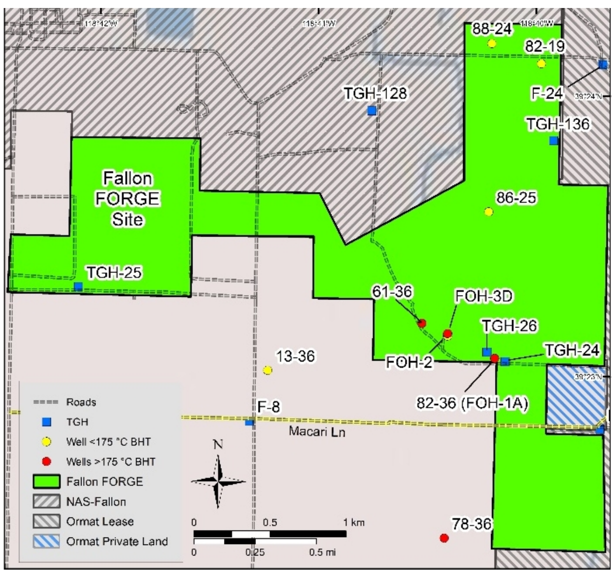


Figure 2. Map of Fallon FORGE site, showing geothermal wells, temperature gradient holes, and accessible roads. Approximately 4.5 km^2 has been cleared for research experiments and development.

2. GEOLOGIC SETTING

2.1 Regional setting

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., 2005). 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). Major tectonic events affecting this region that are relevant to the FORGE site include: (1) Mesozoic contractional tectonism, involving arc volcanism, back arc sedimentation and volcanism, and east-directed folding and thrusting; (2) early Tertiary erosion, which beveled the preexisting arc and related thrust sheets, producing an erosional surface with considerable relief by the Oligocene; (3) the ignimbrite flare-up in late Oligocene time, involving eruption of voluminous ash-flows from calderas in central Nevada and deposition of the ash-flow tuffs in deep paleovalleys across western Nevada; (4) mafic to intermediate composition volcanism in Miocene time related to the ancestral Cascade arc; (5) regional east-west to west-northwest extension from early Miocene time to present; and (6) dextral shear from the late Miocene to present associated with Pacific-North American plate motion, northwestward propagation of the Walker Lane into the region, and concomitant retreat of the ancestral Cascade arc to the northwest. Regional studies constrain the onset of regional extension to ~17-15 Ma to the northeast of Fallon (Fosdick and Colgan, 2008) and ~15-12 Ma in the Wassuk Range area to the south (Stockli et al., 2002). 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., 2014; Jolie et al., 2015).

The northern Walker Lane directly west and to the northwest of Fallon is one of the youngest parts of the Pacific-North American plate boundary, having developed in the past ~5 Ma (Faulds et al., 2005). 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).

2.2 Local Geologic Setting

The proposed Fallon FORGE site lies in the southeastern part of the Carson Sink in west-central Nevada (Figure 1). High temperatures (>175° C) have been encountered at depths of 1.5 to 3.0 km beneath the site, but the demonstrated lack of permeability in these wells makes it an ideal test site for EGS research and development. It is also important to note that no surface hot springs or fumaroles are present at the surface. In addition, no indications of paleo-hot spring activity, such as sinter or travertine, have been observed on the surface in the area. Thus, there is no evidence for a recent, conventional hydrothermal system at Fallon.

No bedrock units crop out at the proposed site. However, four wells (61-36, FOH-3D, 82-36, and 84-31) penetrate the entire Neogene section and the Mesozoic basement, and many additional wells penetrate the basin-fill sediments and Miocene volcanic section (Figure 3). The structural framework of the Carson Sink local to Fallon is dominated by Miocene to recent north- to north-northeast-striking normal faults. Seismic reflection data reveal that the region area is composed of a series of half graben, including a west-tilted half graben in the Fallon area (Faulds et al., 2015; Hinz et al., 2016). These half graben constitute a series of extensional anticlines and synclines (i.e., extensional accommodation zones; Faulds and Varga, 1998), resulting from flips in the predominant dip direction of the normal fault systems which control the half graben. The west-tilted half graben at the Fallon site is the western limb of a northerly trending extensional anticline (Faulds and Varga, 1998) that lies directly east of the FORGE site beneath the Ormat lease area (Hinz et al., 2014; Hinz et al., 2016).

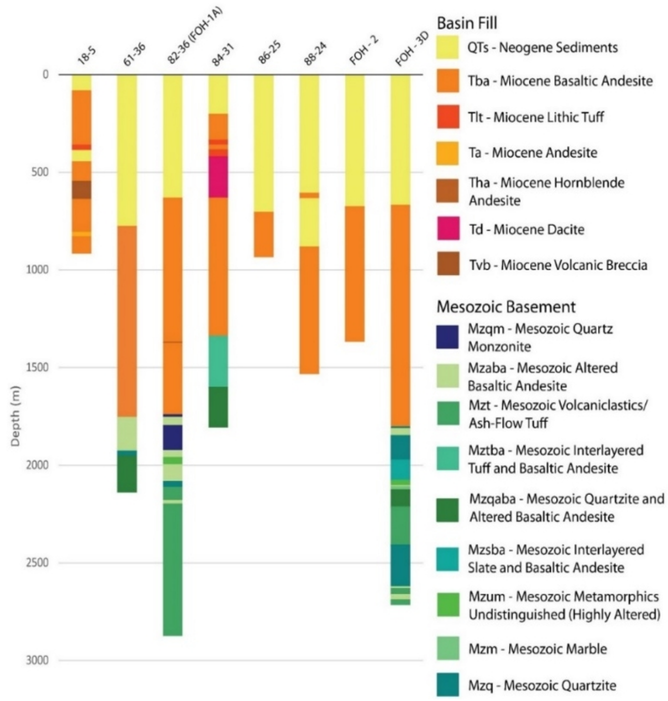
Quaternary faults have not been observed within the proposed FORGE site, and no significant historic seismicity has occurred at the site. The nearest Quaternary scarp lies ~5 km southeast of the southeastern corner of the FORGE site and cuts late Pleistocene lacustrine sediments (Hinz et al., 2011). The USGS Quaternary fault and fold database (USGS, 2006) does show a Quaternary fault 2.5 km east of the FORGE site, but recent analysis indicates that this scarp is probably a late Pleistocene shoreline rather than a fault (Bell and Hinz, unpublished data).

3. SYNTHESIS OF EXISTING DATA

A wide variety of data were synthesized for interpretation of the geologic framework of the Fallon FORGE site, construction of the 3D geologic model, and confirmation of the suitability of the Fallon site for FORGE activities. These data include surface lithologic data, downhole lithologic data, structural data, stress data, thermal data, fluid geochemical data, alteration data, well flow test data, gravity and magnetic data, magnetotelluric data, seismicity and micro-earthquake data, and seismic reflection data. The lithologic data, structural data, stress data, thermal data, and geophysical data will be discussed here, as they directly relate to the geologic framework of the Fallon FORGE site. The fluid geochemistry data, alteration data, and well flow test data, which provide evidence for low permeability, conductive geothermal gradients, and temperature that meet or exceed requisite FORGE parameters, were presented in detail in Hinz et al. (2016) will not be discussed in detail here.

3.1 Lithologic data

The Carson Sink in the vicinity of the Fallon site is covered by Quaternary deposits, including alluvial and lacustrine sediments (Morrison, 1964). No bedrock units crop out in the proposed Fallon site. However, bedrock is exposed in the Lahontan Mountains to the east, Bunejug Mountains to the southeast, and White Throne Mountains/Lee-Allen geothermal area to the south. The stratigraphic section exposed in these ranges consists of ~16 to 12 Ma basaltic andesite, dacite, and rhyolite domes and lava flows interfingering with or overlain by fluvial-lacustrine sediments spanning ~12 to 5 Ma. The Miocene section locally rests on Oligocene ash-flow tuffs and Mesozoic basement rocks, although this deeper part of the section is exposed only in the Lee Allen area.



Lithologic interpretations from ~14,000 m of core, well cuttings, and thin sections of core and cuttings from 26 wells within and local to the Fallon FORGE site are consistent with the surficial data and further constrain the suitability of the Fallon site for FORGE (Hinz et al., 2016). These data indicate that the Quaternary-Tertiary sedimentary section is ~100-900 m thick and overlies ~2 km of Miocene basaltic-andesite, andesite, dacite lava flows, ash-flow tuffs, and volcanic breccias. The four wells that penetrate through the Neogene section (61-36, FOH-3D, 82-36, and 84-31) indicate that the Mesozoic basement consists of, in order of decreasing abundance: (1) metamorphosed felsic ash-flow tuff, (2) meta-basaltic andesite, (3) quartzite, (4) granite, (5) slate, and (6) marble (Figure 3).

Figure 3. Lithologic logs of the 8 deepest wells on the Fallon FORGE site and the surrounding monitor area (Figure 2). In this figure, depth corresponds well path distance, not true vertical depth. All available cuttings, core, petrographic thin sections of cuttings and core, and down-hole logs for these wells were reviewed in Phase 1 of this project.

3.2 Structural data

The structural framework within and surrounding the proposed Fallon FORGE site, including the Carson Sink and bounding mountain ranges to the northwest, north, and east, is characterized by northerly striking normal faults and gently to moderately tilted fault blocks. The structural setting of the southeastern Carson Sink in the vicinity of the Fallon FORGE site appears to be relatively simple, with no major basin-bounding faults and a paucity of mapped faults. The apparent lack of structural complexity, lack of Quaternary faults, and absence of a favorable structural setting for geothermal activity (e.g. Faulds et al., 2011), in this area indicate that a hydrothermal system is unlikely, thus satisfying an important criteria for the FORGE site. Downhole image logs from wells 88-24, 86-25, 61-36, and FOH-D at Fallon reveal primarily north to northeast striking natural fractures (Figure 4; Blake and Davatzes, 2012; Blake et al., 2015), consistent with the overall structural setting of the Carson Sink, where the predominant strike of normal faults is ~N-S to NNE.

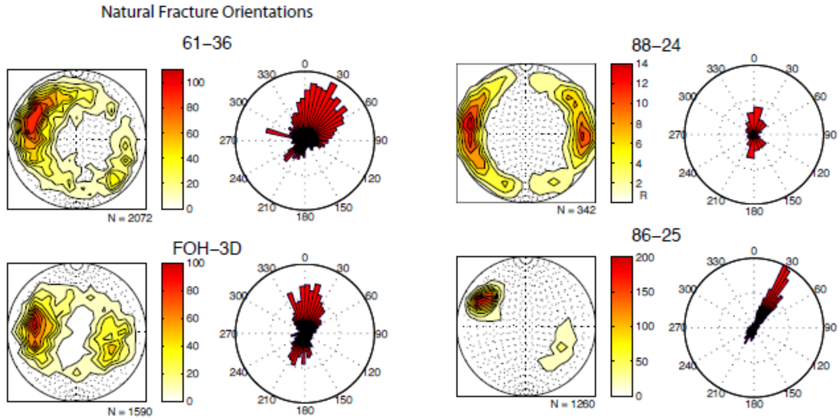


Figure 4. Contoured poles to planes and rose diagrams of the fractures mapped based on the image logs of the four wells analyzed.

3.3 Stress data

Drilling induced structures (e.g. Li and Schmitt, 1998; Zoback et al., 2003) in the downhole image logs from wells 88-24, 86-25, 61-36, and FOH-D (Blake and Davatzes, 2012; Blake et al., 2015) indicate that the maximum horizontal principle stress ranges between 005-026 (~N-NNE). These results are consistent with both regional tectonic data and models (e.g. Faulds et al., 2005; Kreemer et al., 2012; Hammond et al., 2014), and inversion of fault-slip data from the nearby Bunejug Mountains and Salt Wells geothermal field (Hinz et al., 2014, unpublished data).

3.4 Thermal data

Temperature data in the Carson sink area surrounding the Fallon FORGE site are available from 136 temperature gradient holes and geothermal wells. These data identify a shallow thermal anomaly ~5 km long, elongated north-northeast, transecting the southeast part of the Ormat lease area, which became known as the Carson Lake geothermal prospect. The locus of this anomaly lies ~3 km southeast of the southeast corner of the FORGE site. Downhole temperature logs are available from wells 61-36, 88-24, 82-36, FOH-3D, 82-25, 86-19, 84-31, and temperature gradient wells FDU-1 and FDU-2 from within and within ~3 km of the Fallon FORGE site. The equilibrated temperature log from FOH-3D indicate that 175°C, the requisite minimum temperature for FORGE, is reached at ~1700-1800 m bgs. 175°C is reached just above and within the Mesozoic basement in FOH-3D. These data clearly confirm that a conductive thermal regime is present in the Mesozoic basement and that measured temperatures are above the required 175°C at the necessary FORGE depths (Figure 5).

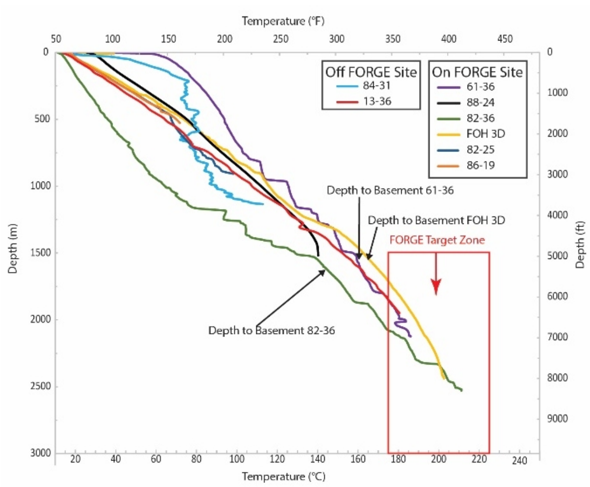


Figure 5. Well temperature profiles for Fallon FORGE. Profiles from wells 61-36 and 82-36 are not equilibrated temperature (collected under flowing or injection conditions). All other wells are equilibrated profiles. Depth is true vertical depth, adjusted for well path deviation from vertical. Depth to basement noted for the three wells that intersect the FORGE target zone. The target zone for FORGE is designated as 1.5 to 4 km depth and 175 to 225°C per DOE-GTO FOA guidelines.

3.5. Gravity data

A database of nearly 8000 gravity stations spanning ~130 x 130 km and centered on the Carson Sink was compiled from databases developed by Zonge International and Ormat Technologies, Inc. for the University of Nevada, Reno (UNR). Data were compiled from 15 sources, consisting of both public domain and privately contracted datasets held under the care of UNR and made available for this study. These data provide regional coverage of the Carson Sink and allow us to infer the location of major faults, as well as the thickness of basin-fill sediments and depth to Mesozoic basement throughout the Carson Sink.

3.6. Magnetic data

Aeromagnetic data were derived from a statewide compilation of Nevada (Kucks et al., 2006). The compilation spanning the study area and most of the regional surroundings consists of a single survey flown at 2743 m barometric elevation (nominally 1524 m above terrain in the immediate area around the FORGE site) with flight lines oriented east-west and spaced 3218 m apart. The contrast in density and magnetic properties between pre-Cenozoic crystalline basement, overlying Tertiary volcanic rocks, and unconsolidated alluvium produces a distinctive pattern of magnetic anomalies at contacts or across faults that juxtapose contrasting units. Distinct changes in character (amplitude and wavelength) can also result from alteration along faults and fracture zones due to the circulation of hydrothermal fluids in the near-surface.

3.7 Magnetotelluric data

A magnetotelluric (MT) study was conducted over the proposed Fallon FORGE site by Fugro Gravity and Magnetics Services under contract to CH2M Hill for the Navy Geothermal Program Office. The survey included 181 soundings of full component tensor broadband MT and produced an average of 9.5 MT soundings per day throughout the field session. Analysis and interpretation of the MT survey were carried out by CGG and Chinook Geoconsulting, Inc. The resistivity patterns in the MT data generally follow stratigraphy across the modeled FORGE area. The Miocene to present basin-fill sediments (QTs) in well logs correspond to the upper, westward thickening low-resistivity zone in the profiles. Lithologic logs and alteration data indicate substantial clay in the basin-fill sediments, consistent with the observed low resistivity. The Miocene volcanic rocks (Tvs) generally correspond to intermediate resistivity values, and the Mesozoic basement corresponds to high resistivity (Figure 6).

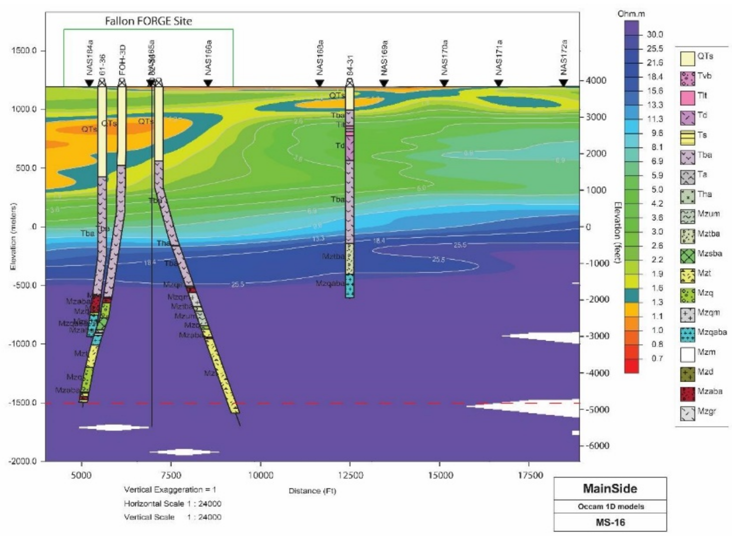


Figure 6. East-west MT profile MS-16 with projected well paths for 61-35, FOH-3D, 82-36, and 84-31 (west to east). View in this profile is looking north, west to the left, and east to the right. This line runs across wells 61-36, FOH-3D, and 82-36. 84-31 is projected a short distance from the north. The local boundaries of the intersection with the FORGE site are bracketed by the green lines above the profile. Lithologic units correspond to units described in the well lithology section of this report. Scale is 1:1 with no vertical exaggeration; meters are shown on vertical scale and feet on horizontal scale.

3.8 Seismic reflection data

A total of 270 km of seismic reflection profiles were interpreted for the southern Carson Sink within and near the Fallon FORGE site. Interpreted profiles constrained the general structural framework of the area, including basin architecture, thickness of major stratigraphic units, and location and spacing of faults. The profiles were also used as the basis for constructing cross sections across the project area, which in turn were used as the primary building blocks of the 3D geologic model. The seismic reflection data indicate that the proposed Fallon FORGE site is underlain by a gently west-tilted half graben cut by widely spaced generally east-dipping normal faults (Figure 7). Faults generally dip moderately to steeply and accommodate relatively minor offset, typically ranging from ~100-200 m. The largest faults generally strike north to north-northeast, but several minor faults (generally <100 m offset) strike ~east-west. Typical spacing of the northerly striking normal faults ranges from ~0.4 to 3.5 km in the vicinity of the Fallon site.

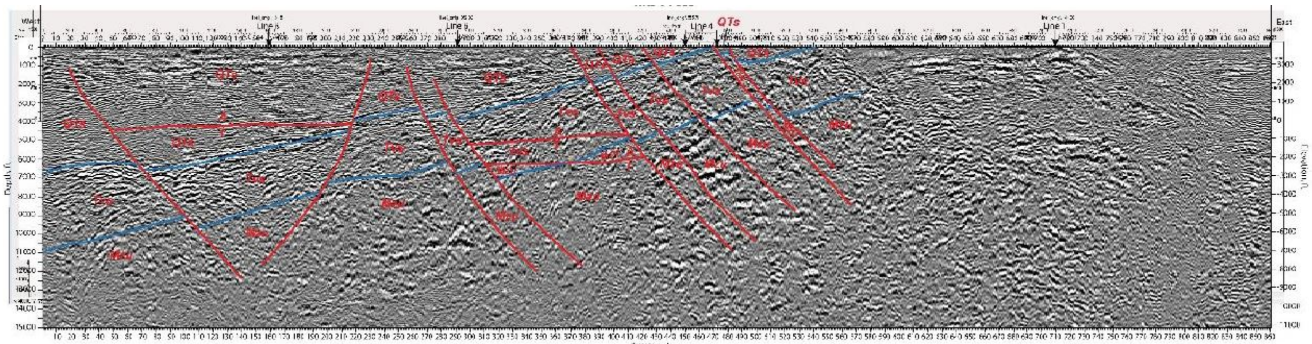


Figure 7. Interpreted profile N-2 from the southern Carson Sink (looking north). Normal faults are shown in red, and lithologic contacts are blue. QTs, Late Miocene to Quaternary basin-fill sediments; Tvs, Miocene volcanic and sedimentary rocks; Mzu, Mesozoic basement undivided.

4. THE GEOLOGIC FRAMEWORK OF THE FALLON FORGE SITE

Despite relatively high regional strain rates, no Quaternary faults have been observed within or proximal to the Fallon FORGE site. This may account for the lack of hydrothermal activity at Fallon, as most geothermal systems in the region are associated with Quaternary faults (Bell and Ramelli, 2007). It is also important to note that favorable structural settings for geothermal activity, such as step-overs, major fault terminations, and accommodation zones (e.g. Faulds and Hinz, 2015), appear to be absent at the Fallon site, which also suggests a low probability of the presence of an active hydrothermal system.

In order to assess the distribution and character of potential EGS reservoirs at Fallon, the above data were synthesized into a 3D geologic model encompassing the area within and around the Fallon FORGE site. The model spans 100 km^2 and is centered on the Fallon site, extending 10 km in the north-south direction and 10 km in the east-west direction (Figure 1B). The geologic model extends from the surface, which ranges between ~1200 to 1350 m above sea level, to a depth of 2500 m below sea level, spanning ~3.8 km.

4.1 Stratigraphic framework

The 3D geologic model consists of four lithologic units, as constrained by geologic mapping local to the Fallon site and the downhole lithologic data. These units are; Late Miocene to Quaternary basin-fill sediments (QTs), Middle to late Miocene volcanic and lesser sedimentary rocks (Tvs), Oligocene ash-flow tuff (Ttr), and Mesozoic crystalline basement (Mzu) (Figure 8).

The Late Miocene to Quaternary basin-fill sediments (QTs), consists predominantly of alluvial and lacustrine deposits (up to 1.5 km thick), with sparse lenses of mafic volcanic rock. A sequence of 2.5 to 0.7 Ma basalt flows intercalated in the upper part of the basin-fill 8 km northwest of the FORGE site indicates that most of the basin fill is late Miocene to Pliocene in age. QTs thickens from < 100 m to > 1.4 km thick from east to west in the area consistent with the presence of a west-tilted half graben. QTs is characterized by good reflectivity in the seismic reflection profiles (Figure 7), allowing for imaging of faults, and relatively low-resistivity (Figure 6) probably due to substantial clay, as supported by the analysis of cuttings. The base of the QTs is constrained by prominent reflectors in the seismic profiles and by well data (Figure 7). The underlying middle to late Miocene volcanic and lesser sedimentary rocks (Tvs), is dominated by basaltic andesite lavas with lesser volcanic breccia, tuff, dacite, and andesite. The Miocene rocks are well exposed in the nearby Bunejug and Lahontan Mountains, with similar lithologies and thicknesses found in cuttings and core at the FORGE site. The thickness of the Miocene volcanic rocks appears to be relatively consistent across the region, ranging from ~0.7 to 1.1 km. The base of the Miocene section (i.e., nonconformity at the top of the Mesozoic basement) is difficult to discern on the reflection profiles but was constrained by four wells and by regional gravity modeling.

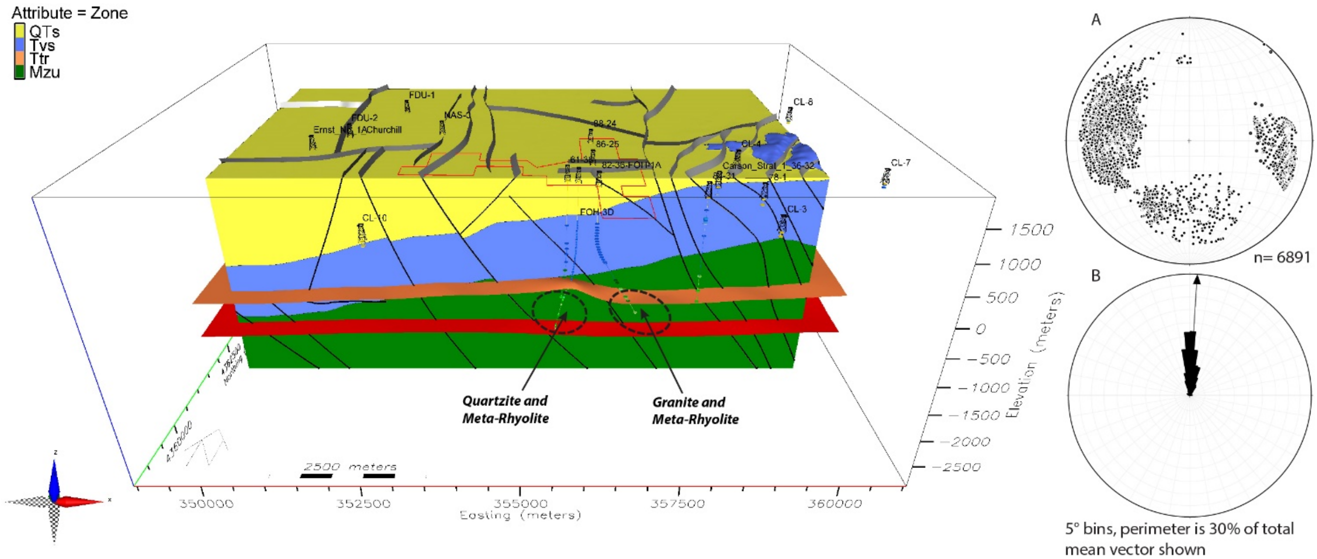


Figure 8. 3D geologic model the proposed Fallon FORGE site. The model is sliced in the east-west direction through the FORGE site. Potential EGS reservoirs in Mesozoic crystalline basement rock, include meta-rhyolite, quartzite, and granite in the central to eastern parts of the proposed FORGE site at Fallon. Several deep wells in this area provide lithologic, thermal, and permeability data for these volumes. These reservoirs lie between the 175°C and 225°C isotherms, as shown by the orange and red planes projecting out of the model, respectively. Left side A) Poles to 3D modeled fault planes at Fallon, and B) rose diagram of the strike of modeled faults. Fault planes were measured for strike and dip at 50 m spacing. Poles (A) indicate that north-striking and steeply- to moderately-east-dipping faults dominate the area. Rose diagram (B) shows the mean plane strikes 003o, both consistent with downhole natural fracture data and regional trends.

The volcanic section images poorly on the seismic reflection profiles and yields intermediate resistivity values (Figures 6 and 7). The total thickness of the Neogene section (basin-fill sediments plus Miocene volcanic rocks) ranges from ~1.7 to 2.8 km in the project area. Oligocene ash-flow tuffs (Ttr), were not observed in the cuttings or core from the Fallon site, however they are present throughout the Carson sink region, and ~100-m-thick section of Ttr was evident on several seismic reflection profiles in the northeast corner of the 3D geologic model area. Though Ttr is present in the northeastern part of 3D geologic model, it pinches out to the south, and is not present within proposed Fallon FORGE site.

The Mesozoic crystalline basement (Mzu) consists of Triassic-Jurassic metavolcanic and metasedimentary rocks, including rhyolitic tuff, quartzite, marble, and mafic lavas, all locally intruded by Jurassic-Cretaceous granite. The basement rocks consistently yield high resistivity values (Figure 6), consistent with low permeability, as supported by the well tests. The Mesozoic basement was penetrated by four wells (Figure 3). Available data suggest that meta-rhyolite and quartzite are two dominant lithologies in the area, attaining thicknesses of ~500 m and 200 m, respectively. It is important to note that, similar to Fallon, metamorphic rocks dominate over granite in much of the Great Basin region east of the Sierra Nevada. Thus, the basement rocks at Fallon are broadly representative of the region. As discussed below, the Mesozoic basement at Fallon contains several potential reservoirs of sufficient volume for research and development of EGS technologies (Figure 8 and Table 1). Additionally, excellent analogues of the basement lithologies are exposed in nearby mountain ranges, including the Lee-Allen area ~20 km south of the FORGE site and the Stillwater Range ~30 km to the northeast.

4.2 Structural framework

The proposed Fallon FORGE site lies on the western limb of an extensional anticline, whose axis lies ~4 km east of the FORGE site, and just east of the eastern edge of the 3D geologic model. Two major fault systems cut the four modeled geologic units, QTs, Tvs, Ttr, and Mzu, a primary north-striking set and a secondary east-striking set (Figure 8). The north-striking faults dip both east and west, though the east-dipping faults dominate, and control the gently west-tilted stratigraphy on the western limb of the extensional anticline (Figure 8). The dominant east-dipping faults are relatively widely spaced (~1.5 km) and all have displacement of less than ~200 m. This geometry of widely-spaced subparallel faults at Fallon, contrasts with significantly more complex structural settings at similarly modeled conventional hydrothermal systems in the region. For example, the Brady's geothermal system, which is ~50 km NW of the Fallon site, was modeled with identical methods and very similar input data density. Brady's contains dozens of closely spaced and intersecting fault strands within an ~1.5 km-wide step-over in a normal fault system (Siler and Faulds, 2013; Siler et al., 2016). Such comparisons suggest that the fault structure at the Fallon FORGE site is not conducive to hosting a conventional geothermal system (Figure 9).

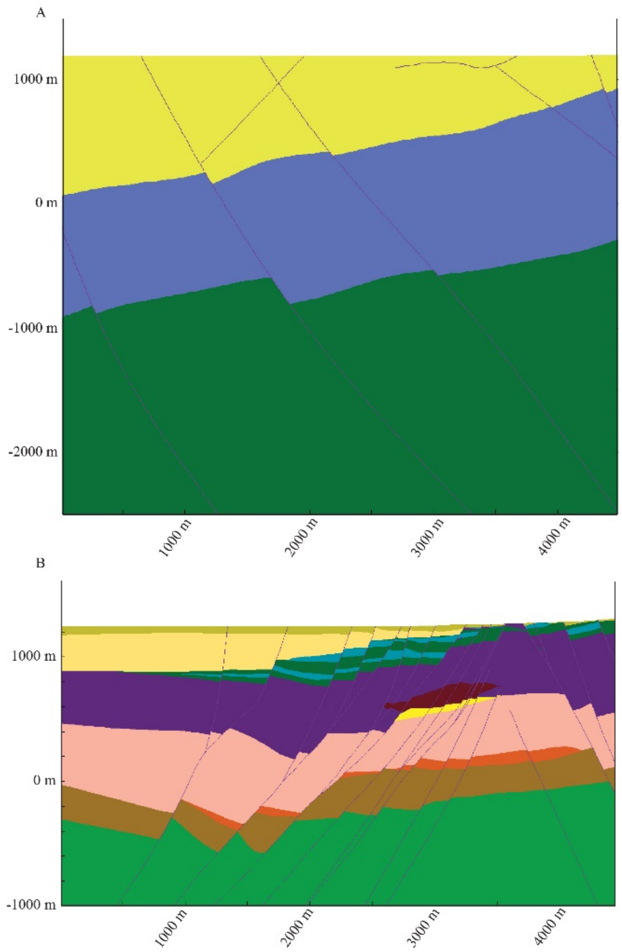


Figure 9. Cross-sections through 3D geologic models at (A) Fallon FORGE site, and (B) Brady's geothermal system (Siler et al., 2016). Both models were built with identical methods, similar data, and similar data density. The dense anastomosing fault system at Brady's hosts natural geothermal fluid flow at several intervals between elevations of ~1000 to -500 m. Faults at Fallon are widely spaced by comparison

It is also important to note that faults within the 3D model volume have an average strike of 003 (Figure 8), which is compatible with the average orientation of natural fractures imaged in four wells at the site (Figure 4). This suggests a strong correspondence between macro- and micro-scale structures at the Fallon FORGE site. Additionally, the predominant orientation of the macro-scale faults and micro-scale fractures is approximately orthogonal to S_{Hmin}, and thus these structures are in a favorable orientation for hydraulic stimulation.

4.3 Uncertainty in 3D geologic interpretations

Uncertainty in the 3D geologic interpretations was calculated based on relative distance from the input datasets. The primary input datasets utilized for constraining the subsurface 3D geologic geometries are the lithologic logs along the well paths and seismic reflection profiles. The distance between the locations of these datasets and all locations within the 3D geologic model were calculated. We also assume that uncertainty increases with depth, so uncertainty with increasing distance from the surface was also calculated. Relative uncertainty was calculated by fitting these distances to logarithmic relative uncertainty curves. Very near to input data, relative uncertainty in the 3D modeled geologic interpretation is very low (i.e. we have high confidence in the geologic interpretation). With increasing distance from each input dataset, relative uncertainty increases progressively. Past a distance of 500 m, the characteristic spacing of the wells used for lithologic analyses, the progressive increase in relative uncertainty with distance lessens. Relative uncertainty between zero and one was calculated for the twenty-four wellbores with lithologic data and the seismic reflection profiles. The relative uncertainty volumes for all the input datasets were summed to produce a cumulative relative uncertainty for the 3D volume for which the 3D geologic model was constructed (Figure 10). This analysis indicates that we have relatively high confidence in the modeled geologic relationships, as a result of a high density of data, within the Fallon

FORGE site. We also have relatively high confidence in the modeled geologic relationships directly to the east of the Fallon site. However, adjacent to the Fallon site to the north, west, and south the density of downhole lithologic data and seismic reflection data are less, relative to the center of the Fallon site, and the uncertainty in the modeled geologic relationships is therefore higher.

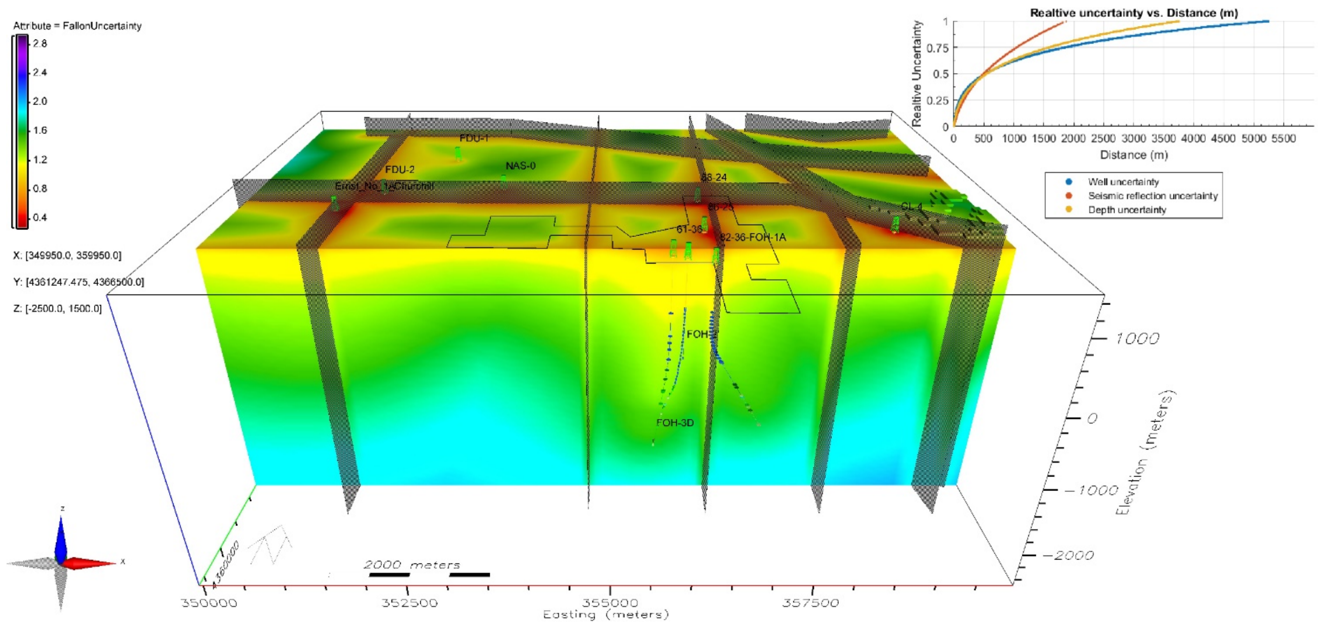


Figure 10. 3D perspective looking north at relative uncertainty in the 3D geologic interpretations at Fallon. The model is sliced in the east-west direction through the FORGE site. Warm colors correspond to low relative uncertainty and cool colors correspond to high relative uncertainty. Green rig symbols denote the surface locations of the 24 wells analyzed for downhole lithologic data. Black planes denote the location of the seismic reflection profiles that pass through the Fallon site. The Fallon site is shown is outlined in black. Inset shows relative uncertainty vs. distance from data for the surface, the 24 well paths, and the 14 seismic reflection profiles used in construction of the 3D geologic model.

4.4 Conditions for reservoir engineering at Fallon FORGE

A 3D subsurface temperature model was interpolated based on downhole temperature measurements in eight wells (FDU-1, FDU-2, 88-24, 82-19, 84-31, 82-36, FOH-3D, and 61-36) within and proximal to the Fallon FORGE site. A minimum tension gridding algorithm was used to interpolate temperatures into data-sparse areas. The subsurface temperature model is well constrained within the Fallon FORGE site proper, with temperature logs from 88-24, 82-19, 82-36, FOH-3D, and 61-36, all within the FORGE site. Three of these wells, 61-36, FOH-3D and 82-36, extend to ~2200-2600 m below ground surface (bgs), so the 3D temperature model is well constrained to at least 2600 m bgs. Based on this temperature model, the 175°C isotherm lies at ~1700-1900 m bgs, whereas the 225°C isotherm lies at ~2400-2800 m bgs (Figure 8).

Within the 366.5 km^3 total modeled volume, 65 km^3 of crystalline basement rock (consisting of metamorphosed felsic ash-flow tuff, meta-basaltic andesite, quartzite, granite, slate, and marble) lie between the 175°C and the 225°C isotherms (Table 1). Within the boundaries of the Fallon FORGE site, ~3.2 km^3 of crystalline Mesozoic basement rock and ~4.7 km of crystalline Tertiary volcanic rocks lie between the 175°C and the 225°C isotherms (Table 11). All of this volume lies within the depths of 1.5 to 4.0 km required for FORGE.

	Total volume modeled (km^3)	Total modeled volume 175-225 °C (km^3)	Total volume within FORGE area (km^3)	Total volume 175-225 °C within FORGE area (km^3)

All Units	366.5	65	16.6	8
QTs	122	0.2	3.2	0.1
Tvs	111	18	4.8	4.7
Ttr	3.5	1.8	0	0
Mzu	130	45	8.6	3.2

Table 1. Volume for each of the 4 modeled lithologic units. Column 1, total modeled volume (100 km² areal extent). Column 2 modeled volumes falling within 175-225°C. Column 3 modeled volumes within the Fallon FORGE site (4.6 km² areal extent). Column 4 modeled volumes within the Fallon FORGE site and falling within 175-225°C. All volumes calculated to a depth of -2500 m bsl or ~3800 m bgs.

5. Conclusions

Evaluation and synthesis of the multiple geologic and geophysical data sets have facilitated the development of a 3D geologic framework model of the proposed Fallon FORGE site. These data and the 3D analyses permit confirmation that the Fallon site satisfies each major qualifying criteria for FORGE and represents and ideal candidate for future FORGE activities.

1) Temperature (175-225°C): Temperature log data from numerous wells, petrographic data, fluid geochemistry data, alteration data, and well testing data all individual and collectively confirm that FORGE temperature window of 175-225°C occurs between ~1.7-1.9 km and 2.4-2.8 km (Figures 5 and 8), which is well within the 1.5-4.0 km required for FORGE. Sufficiently high temperatures at these relatively shallow depths will facilitate FORGE drilling activities without the need to drill any wells deeper than ~2.0-2.5 km. 3D geologic modeling reveals the location(s) and extent of discrete rock volumes in which the requisite temperatures occur (Figure 8).

2) Low Permeability: Well testing data (Hinz et al., 2016), structural data, fault kinematic data, stress data, alteration data, magnetotelluric data, and seismic reflection data individual and collectively confirm that the Fallon FORGE site consists of low permeability crystalline basement rocks at FORGE depths (1.5-4.0 km).

3) Crystalline rock: Regional stratigraphic data, well lithology data, petrographic data, gravity and magnetic data, magnetotelluric data, and seismic reflection data individual and collectively constrain the upper contact of the Mesozoic crystalline basement rocks. These data confirm that metavolcanic rocks, metasedimentary rocks, and granitic rocks constitute the crystalline basement at FORGE depths in the Fallon site. 3D geologic modeling reveals the location(s) and extent of discrete rock volumes, and the locations where these volumes fall within the 175-225°C temperatures required for FORGE (Figure 8).

4) Depth (1.5-4.0 km): Well lithology data, petrographic data, thermal data, well testing data (Hinz et al., 2016), gravity and magnetic data, magnetotelluric data, and seismic reflection data individual and collectively confirm that all FORGE parameters (temperature, low permeability, lithology, stress, and lack of existing hydrothermal system) all occur within 1.5-4.0 km bgs, as required for FORGE. In fact all FORGE parameters are met in the upper ~1 km of this depth window (Figure 8).

5) Favorable stress regime for stimulation: Stress data, structural data, fault kinematic data, and seismicity data individual and collectively confirm that the Fallon FORGE site is characterized by extensional stress conditions that are conducive to for EGS success. These data indicate that the existing natural fracture system is well oriented with respect to the ambient stress field for EGS stimulation.

6) Not in and active hydrothermal system: Well test data (Hinz et al., 2016), thermal data, structural data, alteration data, magnetotelluric data, seismicity data, and seismic reflection data all individual and collectively confirm that no hydrothermal system exists at the proposed Fallon FORGE site.

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