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STRATIGRAPHIC AND STRUCTURAL FRAMEWORK OF THE PROPOSED FALLON FORGE SITE, NEVADA

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ABSTRACT

The proposed Frontier Observatory for Research in Geothermal Energy (FORGE) at Fallon site lies within and adjacent to the Naval Air Station Fallon (NASF) directly southeast of the town of Fallon, Nevada, within the broad Carson Sink basin in west-central Nevada. The site is located on two parcels that include land owned by the NASF and leased and owned by Ormat Nevada, Inc. The Carson Sink in the vicinity of the Fallon site is covered by Quaternary deposits, including alluvial fan, eolian, and lacustrine sediments. Within the primary FORGE footprint, three wells penetrate the entire Neogene section and terminate in Mesozoic basement. Review of ~14,500 meters of core, cuttings, thin sections of core and cuttings, and well logs have refined earlier summary studies on the stratigraphic and structural framework. Late Miocene to Quaternary basin-fill sediments are 0.5 to 1 km thick and overlie Miocene volcanic and lesser sedimentary rocks. The volcanic section is 0.7 to 1.1 km thick and dominated by Miocene mafic lavas. The Neogene section rests nonconformably on heterogeneous Mesozoic basement, which consists of Triassic-Jurassic metamorphic rocks intruded by Cretaceous granitic plutons. These Mesozoic units are widespread across western Nevada and were formed in the back arc of the Sierran arc. Review of more than 250 km of seismic reflection profiles and gravity models indicate that the FORGE footprint occupies a broad, gently west-tilted block between a synclinal accommodation zone to the west and an anticlinal accommodation zone to the east. Quaternary faults have not been observed within the proposed FORGE site.

The documented temperatures, permeability, and lithologic composition of potential reservoirs fall well within the ranges specified by DOE for FORGE. The well data indicate that a sizeable area (~4.5 km^2) has adequate temperatures in crystalline basement but lacks sufficient permeability within the proposed FORGE site. There are at least three possible, competent target formations in Mesozoic basement for stimulation in the FORGE project area: 1) Triassic to Jurassic felsic metavolcanic rocks, 2) Jurassic metaquartzite, and 3) Jurassic to Cretaceous granitic intrusions. These units make up at least 3 km^3 in the project area and have target temperatures of ~175 to 215° C. The documented temperatures, low permeability, and basement lithologies place Fallon in the target range of FORGE.

1. INTRODUCTION AND GEOLOGIC SETTING

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 community will be eligible to develop, test, and improve new technologies and techniques in an ideal EGS environment. This will allow the geothermal and other subsurface communities to gain a fundamental understanding of the key mechanisms controlling EGS success, in particular how to generate and sustain fracture networks in the spectrum of basement rock formations using different stimulation technologies and techniques. This critical knowledge will be used to design and test methodologies for developing large-scale, economically sustainable heat exchange systems, thereby paving the way for a rigorous and reproducible approach that will reduce industry development risk. Essential to this process is a comprehensive site for characterization, monitoring instrumentation, and data collection effort that will capture a higher-fidelity picture of EGS creation and evolution processes than any prior demonstration. A dedicated FORGE allows for the highly integrated comparison of technologies and tools in a controlled and well-characterized environment, as well as the rapid dissemination of technical data to the research community, developers, and other interested parties.

The proposed Fallon FORGE site lies within and adjacent to the Naval Air Station Fallon (NASF) directly southeast of the town of Fallon, Nevada, within the broad Carson Sink basin in west-central Nevada (Figs. 1 and 2). The Carson Sink lies directly northeast of the Walker Lane shear zone (Stewart, 1988; Faulds and Henry, 2008), a system of strike-slip faults that accommodates ~20% of the dextral motion between the North American and Pacific plates (Hammond and Thatcher, 2004). As the Walker Lane terminates progressively northwestward in this region, dextral shear is transferred to northwest-trending extension in the northwestern part of the Great Basin (Faulds et al., 2004). This region has a greater density of known hydrothermal systems than other parts of the Basin and Range province and currently hosts about a dozen geothermal power plants (Fig. 1B; Faulds et al., 2012). Most of the geothermal activity in this region is considered to be amagmatic (i.e., no middle to upper crustal magmatic heat sources), as volcanism generally ceased 3-10 Ma.

Although there is relatively high heat flow (Blackwell and Richards, 2004) across much of the Great Basin, development of conventional hydrothermal systems in this region is still challenging. Favorable structural settings for sufficient permeability and fluid flow (e.g., Faulds et al., 2006, 2011, 2013; Faulds and Hinz, 2015) comprise a small fraction of the region and involve limited volumes of hot rock. In fact, most production well fields in the Great Basin fit within a few square kilometers. The aerial extent of hot, impermeable rock far exceeds the aerial extent of hot permeable rock. Thus, finding sufficient permeability for geothermal production is clearly more of an impediment for exploration and development of convention hydrothermal resources than temperature in this region, and there is a large potential for successful EGS in the this region.

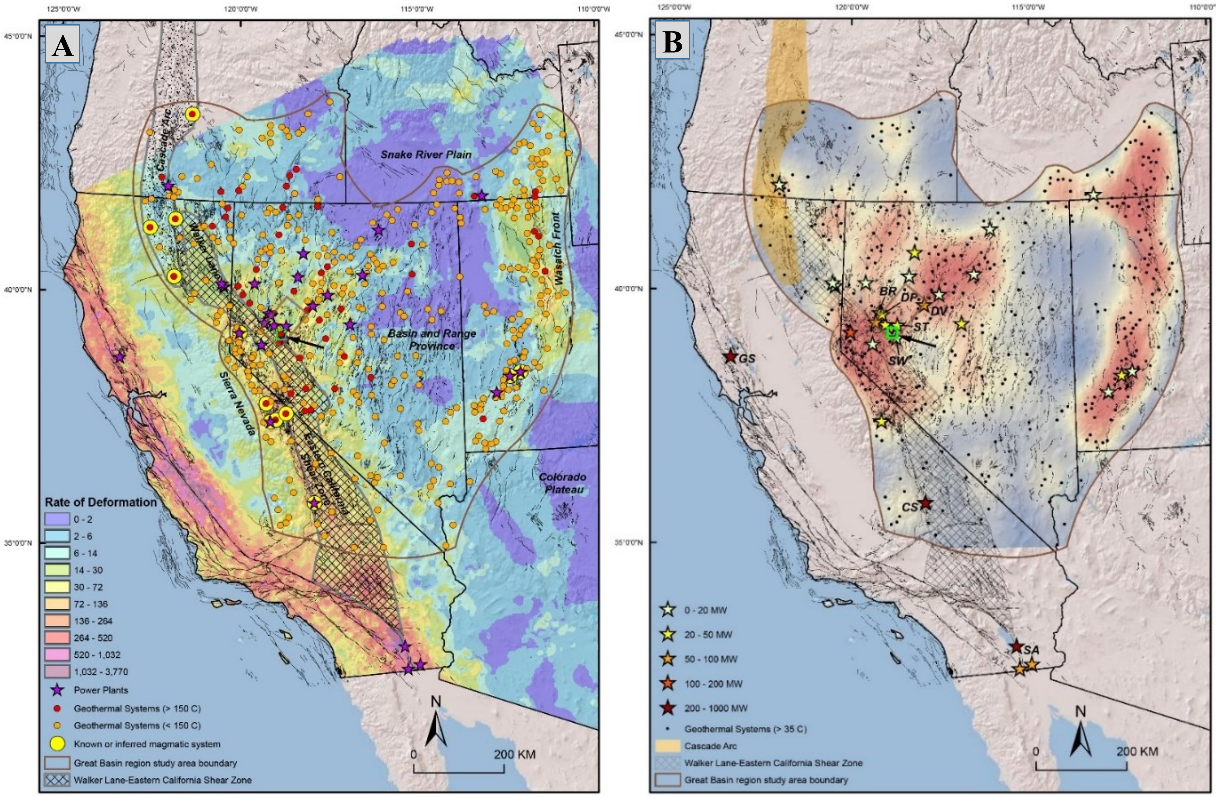
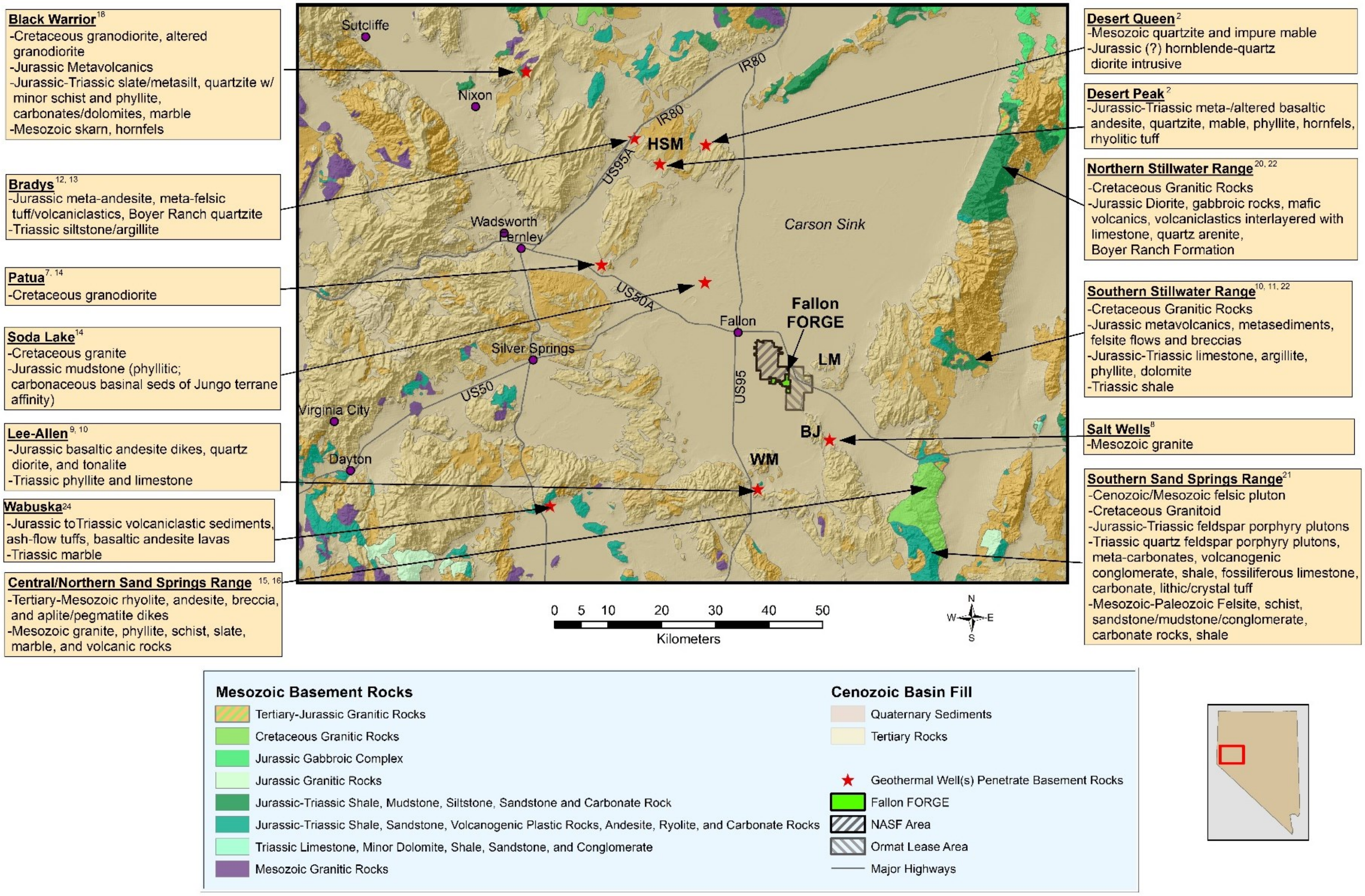


Figure 1: (A) Map showing strain rates and geothermal systems in the Great Basin and adjacent regions (from Faulds et al., 2012). Strain rates reflect the second invariant strain rate tensor (10^{-9}/yr; from Kreemer et al., 2012). Light brown box encompasses the Carson Sink. Small bright green box surrounds the Fallon FORGE site (see black arrow). (B) Spatial density of all known geothermal systems in the Great Basin region (from Faulds et al., 2012). Density values were calculated using a kernel density plot in which the number of geothermal systems within a radius of ~30 km was calculated for each 3 km cell in a grid. Warmer colors represent progressively greater geothermal system densities. Power plants and their relative capacities are shown by stars. Light brown box encompasses the Carson Sink. Small bright green box surrounds the Fallon FORGE site (see black arrow). Labeled geothermal systems: BR, Bradys; DP, Desert Peak; DV, Dixie Valley; CS, Coso; GS, The Geysers; SA, Salton Trough; ST, Stillwater; SW, Salt Wells.

Figure 2: Next Page. Regional geologic map of the Carson Sink area highlighting the distribution of known Mesozoic basement lithologies exposed in ranges and intersected by deep geothermal wells. The base map is simplified from Stewart and Carlson (1978). Red stars correspond to known geothermal areas with Characterized basement from outcrops and/or deep wells. Labels: BJ, Bunejug Mountains; HSM, Hot Springs Mountains; LM Lahontan Mountains; WM, White Throne Mountains. References noted in this figure: [1]Barton et al., 2000; [2]Benoit et al., 1982; [3]Buer and Miller, 2010; [4]Dilek and Moores, 1995; 2000; [5]Hinz et al., 2013; [6]Ernst et al., 2008; [7]Garg et al., 2015; [8]Hinz et al., 2014; [9]Hinz et al., 2008; [10]Hinz et al., 2010; [11]John, 1995; [12]John and Silberling, 1994; [13]Lutz and Hulen, 2002; [14]Lutz et al., 2010; [15]McLachlan, personal communication; [16]UNR, 1962; [17]Oldow, 1984; [18]Sadowski, personal communication; [19]Speed, 1974; [20]Speed and Jones, 1969; [21]Satterfield, 2002; [22]Willden and Speed, 1974; [23]Wyld, 2002.



Black Warrior[18]
-Cretaceous granodiorite, altered granodiorite
-Jurassic Metavolcanics
-Jurassic-Triassic slate/metasilt, quartzite w/ minor schist and phyllite, carbonates/dolomites, marble
-Mesozoic skarn, hornfels

Bradys[12, 13]
-Jurassic meta-andesite, meta-felsic tuff/volcaniclastics, Boyer Ranch quartzite
-Triassic siltstone/argillite

Patua[7, 14]
-Cretaceous granodiorite

Soda Lake[14]
-Cretaceous granite
-Jurassic mudstone (phyllitic; carbonaceous basinal seds of Jungo terrane affinity)

Lee-Allen[9, 10]
-Jurassic basaltic andesite dikes, quartz diorite, and tonalite
-Triassic phyllite and limestone

Wabuska[24]
-Jurassic toTriassic volcaniclastic sediments, ash-flow tuffs, basaltic andesite lavas
-Triassic marble

Central/Northern Sand Springs Range[15, 16]
-Tertiary-Mesozoic rhyolite, andesite, breccia, and aplite/pegmatite dikes
-Mesozoic granite, phyllite, schist, slate, marble, and volcanic rocks

Desert Queen[2]
-Mesozoic quartzite and impure mable
-Jurassic (?) hornblende-quartz diorite intrusive

Desert Peak[2]
-Jurassic-Triassic meta-/altered basaltic andesite, quartzite, mable, phyllite, hornfels, rhyolitic tuff

Northern Stillwater Range[20, 22]
-Cretaceous Granitic Rocks
-Jurassic Diorite, gabbroic rocks, mafic volcanics, volcaniclastics interlayered with limestone, quartz arenite, Boyer Ranch Formation

Southern Stillwater Range[10, 11, 22]
-Cretaceous Granitic Rocks
-Jurassic metavolcanics, metasediments, felsite flows and breccias
-Jurassic-Triassic limestone, argillite, phyllite, dolomite
-Triassic shale

Salt Wells[8]
-Mesozoic granite

Southern Sand Springs Range[21]
-Cenozoic/Mesozoic felsic pluton
-Cretaceous Granitoid
-Jurassic-Triassic feldspar porphyry plutons
-Triassic quartz feldspar porphyry plutons, meta-carbonates, volcanogenic conglomerate, shale, fossiliferous limestone, carbonate, lithic/crystal tuff
-Mesozoic-Paleozoic Felsite, schist, sandstone/mudstone/conglomerate, carbonate rocks, shale

Previously completed and ongoing research projects in the region provide a platform from which to launch the proposed FORGE investigation at Fallon. For example, detailed studies of the stratigraphic and structural framework of the region, including in-depth analyses of most of the known geothermal fields in the area, such as Salt Wells, Desert Peak, Brady's, Soda Lake, and Lee-Allen (e.g., Hinz et al., 2008, 2010, 2011, 2014; Faulds et al., 2006; 2010, 2011, 2012; McLachlan et al., 2011; Blake and Davatzes, 2012), have been completed. In addition, a detailed gravity survey and derivative depth-to-basement maps of the entire Carson Sink were recently completed (Faulds et al., 2014). The DOE-funded Nevada play fairways project involves detailed analysis of the geothermal potential of the Carson Sink and surrounding region (Faulds et al., 2015), including interpretation of several hundred miles of existing seismic reflection profiles and integration of all available geological and geophysical data for the region into a regional 3D model of the Carson Sink. While much data is available for the FORGE site, these regional data are critical for further evaluating the stratigraphic and structural framework and determining depths to suitable rock for EGS research and development in the Fallon area.

A primary task for phase 1 of FORGE is to develop a detailed geologic model of the proposed site. We have recently reviewed ~14,500 meters of core, cuttings, and thin sections of core and cuttings to refine existing summary studies on the stratigraphic and structural framework. We are currently analyzing about 250 km of reflection seismic lines and are working to generate a digital 3D geologic model of Fallon FORGE with EarthVision software. This paper provides of summary of the stratigraphic and structural framework accomplished to date.

2. FORGE SITE DESCRIPTION

The Fallon FORGE site is located ~12 km southeast of the City of Fallon on two parcels that include land owned by the NASF and Ormat Nevada, Inc. Ormat has both privately held land and geothermal leases. The project area is bounded by the Fallon agricultural district on the north and west, Lahontan and Bunejug Mountains to the east, and the Carson Lake wetlands at the base of the White Throne Mountains to the south (Figs. 2 and 3). Most of the surrounding lands in the Ormat lease area and NASF are open to monitoring and instrumentation activities. However, the area of the airstrip on the NASF northwest of the proposed FORGE site and the northeastern part of the Ormat lease block are both "no surface occupancy" zones, where activities resulting in ground disturbance are limited and/or not allowed. Nonetheless, this leaves ~4.5 km^2 for development of infrastructure on the FORGE site and another ~40 km^2 for monitoring and instrumentation on the surrounding lands. The proposed area is fully accessible, with an excellent network of paved and dirt roads (Fig. 3), which facilitates significant research and development activities. U.S. Highway 50 lies ~1 to 5 km to the east and northeast of the primary FORGE site and cuts through the northeastern part of the Ormat lease area.

Since the 1970s, more than 45 wells have been drilled for geothermal exploration within the NASF and Ormat lease area. These include 4 temperature gradient wells and 7 additional wells on the FORGE site and 27 temperature gradient wells and 10 additional wells on the NASF and Ormat monitoring areas. Four exploration wells within the FORGE site (82-36, 61-36, 88-24, and 86-25) are available for use in the project. Several additional wells are available for monitoring outside the central FORGE site within the NASF and Ormat lease area. In addition, there is an existing, ten-station micro-seismic earthquake (MEQ) array that has been collecting data since 2001; the MEQ array can be expanded to encompass the entire Fallon project. The abundant well data and detailed geophysical surveys (e.g., ~1200 gravity stations and associated models, 186 MT stations and associated models, 15 years of MEQ data, and ~250 km of seismic reflection profiles) provide subsurface control for the site.

3. STRATIGRAPHIC FRAMEWORK

The Carson Sink in the vicinity of the Fallon site is covered by Quaternary deposits, including alluvial fan, eolian, and lacustrine sediments (Morrison, 1964; Bell and House, 2010). No bedrock units crop out in the proposed site. Within the primary FORGE footprint and designated surrounding FORGE monitor area, four wells (Figs. 2, 4, and 5; wells 61-36, FOH-3D, 82-36, and 84-31) penetrate the entire Neogene section and terminate in Mesozoic basement. Late Miocene to Quaternary basin-fill sediments are 0.5 to 1.0 km thick and overlie Miocene volcanic and lesser sedimentary rocks. The volcanic section is 0.7 to 1.1 km thick and dominated by middle Miocene mafic lavas. As evidenced by numerous drill holes, seismic reflection profiles, and gravity data, the total thickness of the Neogene section ranges from ~1.3 to 2.8 km in the overall project area. The Neogene section rests nonconformably on heterogeneous Mesozoic basement, which consists of medium- to high-grade Triassic-Jurassic metavolcanic and metasedimentary rocks intruded by granitic plutons of probable Jurassic or Cretaceous age. The Mesozoic units exposed in the wells include plutonic rocks (quartz monzonite), metasedimentary rocks (metaquartzite, marble, slate), and metavolcanic rocks (felsic tuffs, felsic volcaniclastic sediments, and basaltic andesite lavas). The metavolcanic and metasedimentary rocks are locally hornfels-grade metamorphosed, probably as a result of intrusion by one more plutons. These Mesozoic units are typical of much of western Nevada and formed in the back-arc region of the Sierran arc (e.g., Oldow, 1984; Lutz and Hulen, 2002; Fig. 2).

4. STRUCTURAL FRAMEWORK

The FORGE footprint occupies a broad, gently west-tilted block between a synclinal accommodation zone to the west and an anticlinal accommodation zone to the east (Hinz et al., 2014). This intervening block cut by several moderately to steeply dipping north- to north-northeast-striking normal faults that dip both east and west, and exhibit minor stratigraphic throw, as evidenced by seismic reflection profiles and gravity data (Fig. 6; Gray et al., 2013). Extensional anticlines and synclines result from the overlap of oppositely dipping systems of normal faults that dip toward one another (Faulds and Varga, 1998).

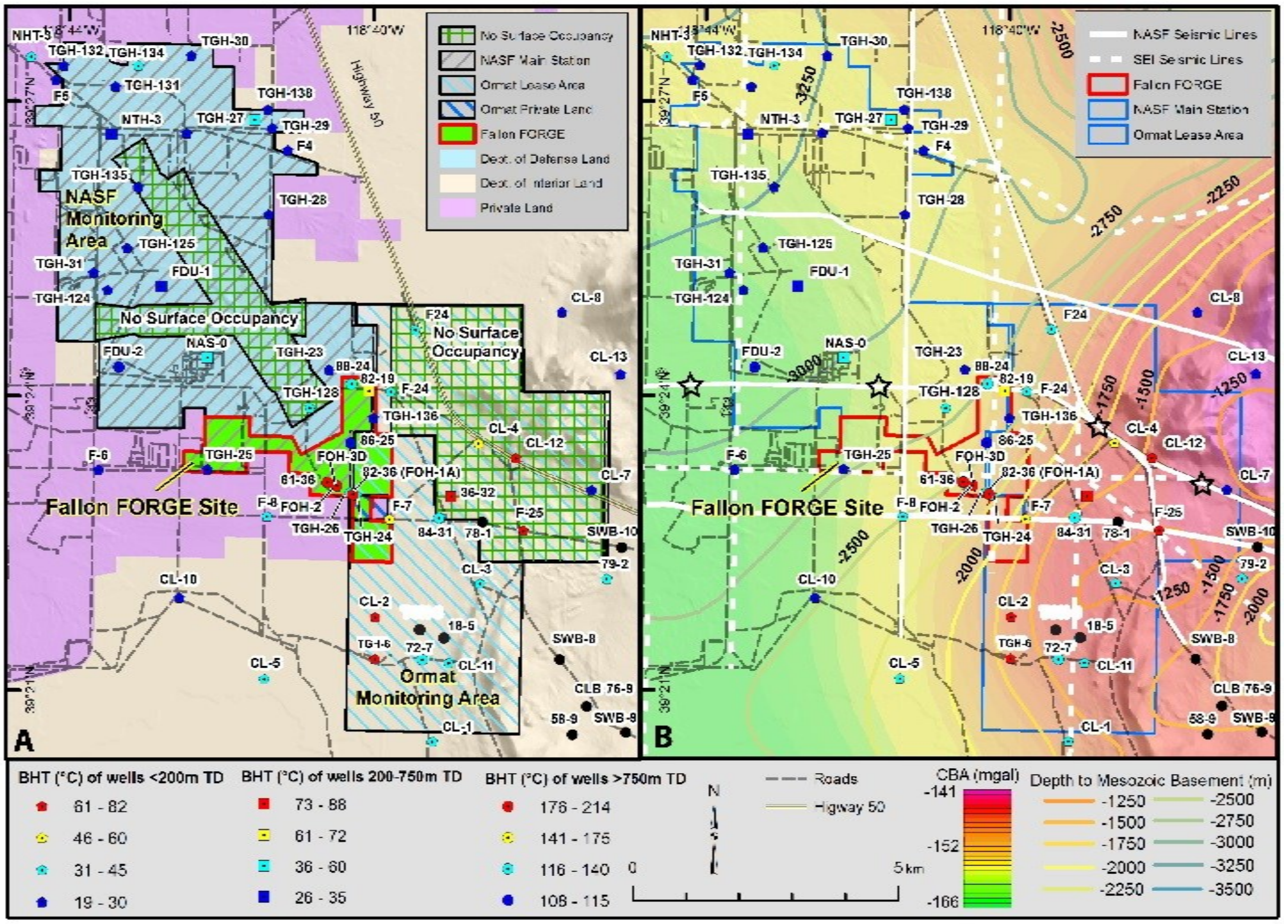


Figure 3: Fallon FORGE site with adjacent NASF and Ormat lease area. (A) Fallon FORGE site (in green and outlined in red), land ownership, and geothermal wells. Note that no surface occupancy is permitted in the vicinity of the runways at NASF or in the northeastern part of the Ormat lease area. Other parts of the NASF and Ormat lease block are accessible for instrumentation and monitoring, and full research and development is allowed on the Fallon FORGE site. (B) Fallon FORGE site (outlined in red) showing geothermal wells, CBA gravity (shaded colors), depth to basement (colored contours), and available seismic reflection profiles (white lines).

Quaternary faults have not been observed within the proposed FORGE site, and only a few small, < M2.0 historic earthquakes have occurred at the site. The nearest Quaternary scarp lies ~5 km southeast of the southeastern corner of the primary FORGE site and cuts late Pleistocene lacustrine sediments (Hinz et al., 2011). The USGS Quaternary fault and fold database (USGS, 2006) shows a Quaternary fault 2.5 km east of the FORGE site, but recent analysis indicates that this scarp is probably a late Pleistocene lake shoreline rather than a fault (Bell and Hinz, unpublished data). The Rainbow Mountains fault ~10-15 km east of the site ruptured in a M6.9 earthquake in 1954, accommodating oblique normal-dextral motion (Caskey et al., 2004). The Rainbow Mountains fault terminates southward in the vicinity of the Salt Wells geothermal field, 15 km to the southeast of the FORGE site. Increased permeability associated with the horse-tailing southern end of this fault corresponds with the production well field at Salt Wells (Hinz et al., 2014). It is notable that most geothermal systems in the Great Basin region are proximal to recent faults (Bell and Ramelli, 2007; Faulds et al., 2015). The absence of Quaternary faulting at the Fallon FORGE site may explain the lack of sufficient permeability in the area.

Borehole data and kinematic analysis of fault surfaces indicate an approximately west- to west-northwest-trending least principal stress in the area. Borehole breakouts and tensile fractures in wells within the FORGE site (Fig. 3) indicate a least principal stress trending N83^{o}W in FOH-3D (Blake and Davatzes, 2012), N85°W in 88-24, N64°W in 86-25, and N69°W in 61-36 (Blake et al., 2015). Similarly, inversion of fault slip data and the orientation of silica veins from the nearby Bunejug Mountains yield a least principal stress trending N80^{o}W (Hinz et al., 2014). Directly northwest of the Carson Sink in the Hot Springs Mountains (Fig. 2), a similar west-northwest-trending least principal stress orientation is suggested by both borehole breakout data (Robertson-Tait et al., 2004; Davatzes and Hickman, 2009) and inversion of fault-slip data (Faulds et al., 2010a, b). Determination of the magnitudes and directions of the principal stresses is crucial for 1) determining the slip and dilation tendency of faults and fractures in the area, 2) defining the parameters (injection pressures, duration of injection, etc.) for EGS stimulation experiments, and 3) predictive modeling of such experiments, including induced seismicity. In this regard, analyses of borehole televiewer and formation microscanner logs in Fallon FORGE wells (Blake et al., 2015; Blake and Davatzes, 2012) revealed abundant natural fractures and foliation planes that are well oriented for normal faulting in the current stress field, and thus amenable to shear stimulation during future EGS operations. The availability of these data is another reason that Fallon fits the target range for the FORGE initiative.

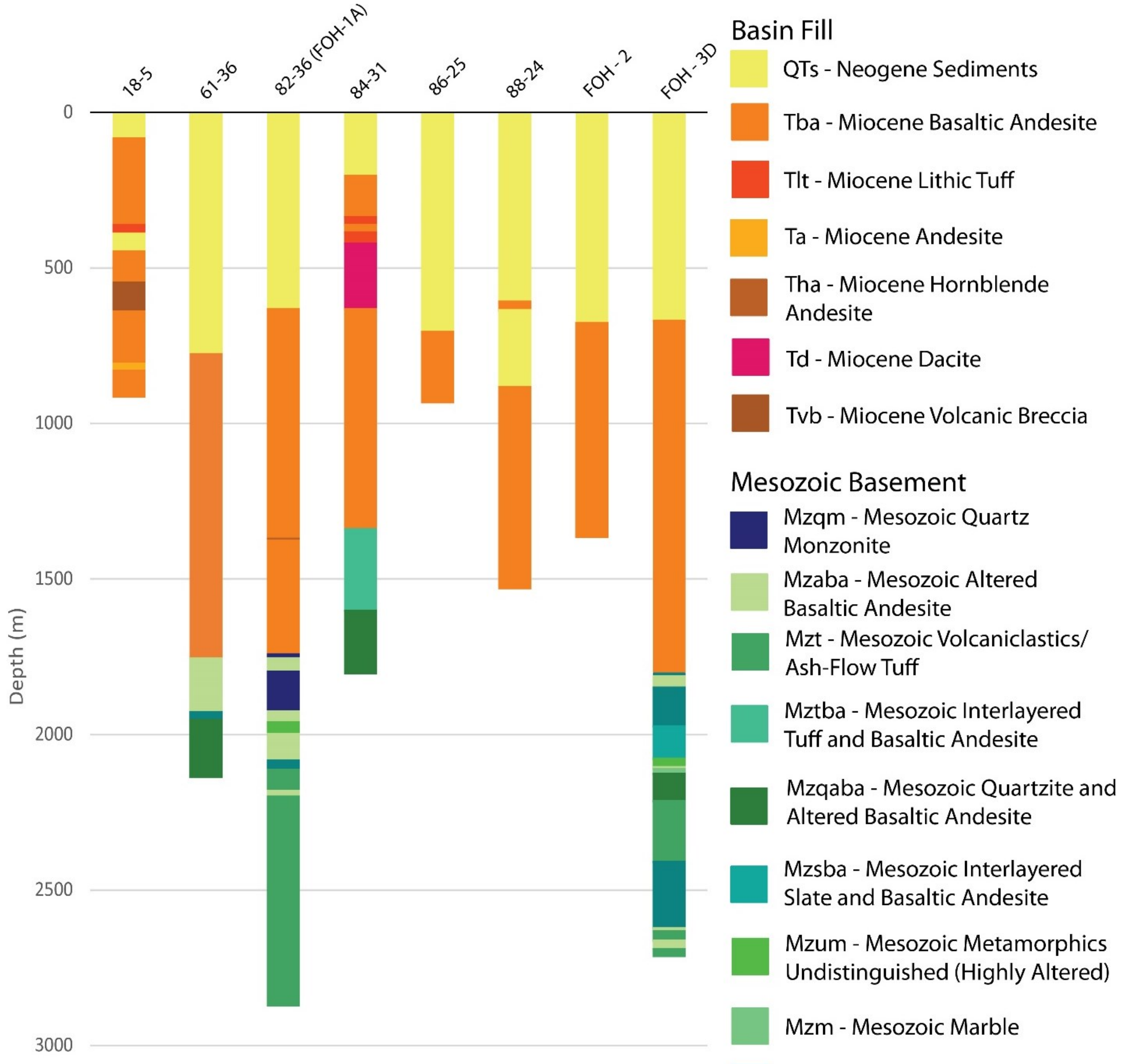


Figure 4 - Above: Lithologies of the 8 deepest wells on Fallon FORGE and the surrounding monitor area (Fig. 3). All available cuttings, core, petrographic thin sections of cuttings and core, and down-hole logs for these wells were reviewed in Phase 1 of this project.

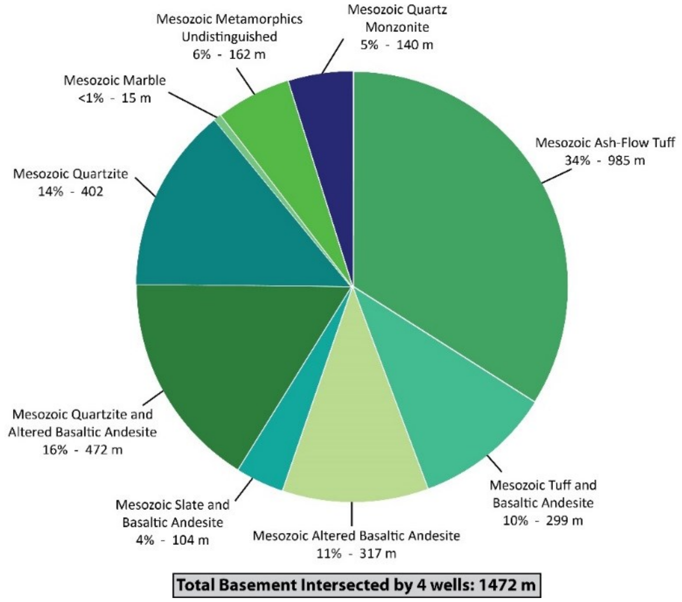


Figure 5 - Left: Percent abundance of Mesozoic lithologic units in for wells shown in Figure 4 relative to the total well path length.

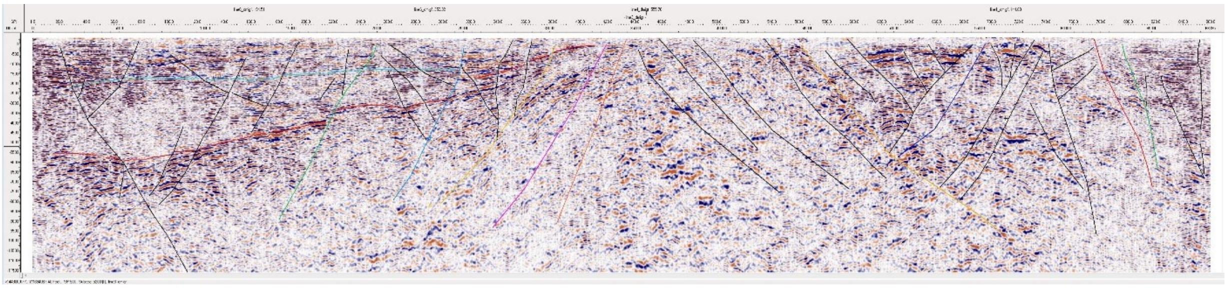


Figure 6: Approximately east-west-trending, interpreted seismic reflection line NAS-94-003 (from Gray et al., 2013), which extends through both the NASF and Ormat lease area. The profile crosses the northeastern-most part of the FORGE site, but most of the FORGE site lies directly south of the western half of this profile (see Fig. 3 for location, noted by black stars). Profile view is to the north, with west on the left and east to the right. The west-tilted half graben is evident in the profile as are several steeply east- and west-dipping normal faults.

5. PREVIOUS GEOTHERMAL EXPLORATION

Geothermal exploration in the southeast portion of the Carson Sink has been ongoing since 1973, when Phillips Petroleum initiated a drilling program that included 28 shallow gradient holes. In total, about 60 temperature gradient holes were drilled in the area during the 1970s and 1980s between Phillips Petroleum, Anadarko, Hunt Oil, the Navy GPO, and the USGS (Bruce, 1979; Trexler et al., 1981; Katzenstein and Bjornstad, 1987; Benoit, 1990; Combs et al., 1995; Ross et al., 1996; Desormier, 1997). This early work identified a prominent shallow thermal anomaly ~5 km long, elongate north-northeast, transecting the southeast part of Ormat's leases, and became known as the Carson Lake geothermal prospect (Fig. 3; Benoit, 1990). The temperature gradient well with the greatest thermal gradient is TGH-6 which was drilled to 50 m deep, recorded a bottom-hole temperature of 77^{o} C, and remains open and flowing today. Silica and cation geothermometry from fluids collected in TGH-6 indicate 146° C geothermometry (Faulds et al., 2015). In 1981, Unocal sited vertical slim hole, 72-7, a distance of one km east of TGH-6, drilled it to 881 m total depth, and recorded a maximum down-hole temperature of 131° C. At the time petroleum companies were primarily only interested in resources >100 MWe, so after the 1980s, the petroleum companies moved on from the region when it was clear that high enthalpy hydrothermal resources (e.g., The Geysers or Cerro Prieto) were not present. A couple of additional exploration wells have been drilled by Ormat within the shallow thermal anomaly, but the Carson Lake hydrothermal resource has yet to be developed.

During this same time, multiple deep exploration wells were drilled on NASF property 3 to 4 km north and northwest of the primary shallow thermal anomaly. Three of the NASF wells terminated in Mesozoic basement rocks, reached maximum temperatures of 175 to 205° C at depths of 2000 to 2650 m (Fig. 7). Geothermal exploration by the Navy GPO was put on hold in 2013 as a result of low permeabilities in otherwise hot rocks. Nearby, exploration was also initiated at the Salt Wells geothermal area during the 1970s, 8 to 15 km to the southeast, and now houses a 13.4 MWe capacity power plant that has been operated by ENEL since 2009 (Fig. 2). The structural setting of the producing hydrothermal system at Salt Wells area differs significantly from that at Fallon. Salt Wells occupies a prominent fault termination in a synclinal accommodation zone with numerous Quaternary and historic fault scarps. FORGE occupies a gently tilted block between two regional accommodation zones with locally minor magnitude internal faulting and no known Quaternary faults. It appears that the faults in the FORGE site lacks significant discontinuities that would be favorable for generating a hydrothermal system, such as step-overs or terminations (e.g., Faulds et al., 2011). The lack of major terminations or steps in gravity anomalies supports this premise.

6. 3D GEOLOGICAL MODEL

A primary task for phase 1 of FORGE is to develop a detailed 3D geologic and thermal model of the proposed site. Developing the 3D geologic model involves integrating well data, seismic reflection data, and gravity data in a stepwise process as described by Hinz et al. (2013). Geologic cross-sections are constructed by projecting well data onto the 2D seismic reflection profiles. The 2D geologic cross-sections are then digitized in 3D space, integrated with intervening well data, and used as a skeletal framework for developing a 3D model. To date, we have reviewed all of the ~14,500 meters of core, cuttings, and thin sections of core and cuttings. We are currently in the process of analyzing about 250 km of reflection seismic lines and are working to generate a digital 3D geologic model of Fallon FORGE with EarthVision software (Figs. 8A, 8B). The thermal model is a 3D grid based off all available down-hole temperature data from the Fallon FORGE site and immediately adjacent areas (Fig. 8C).

7. CONCLUSIONS

Review of more than 250 km of seismic reflection profiles and gravity models indicate that the FORGE footprint occupies a broad, gently west-tilted block between a synclinal accommodation zone to the west and an anticlinal accommodation zone to the east. Accommodation zones are known as a favorable structural setting for hydrothermal systems (Faulds and Hinz, 2015). The Carson Lake geothermal resource may be related to the anticlinal accommodation zone 3-4 km southeast of Fallon FORGE. The positioning of the FORGE footprint well between the two accommodation zones is an ideal structural setting for low permeability.

Review of ~14,500 meters of core, cuttings, thin sections of core and cuttings, and well logs have established that a sizeable area (~5 km^2) has adequate temperatures in crystalline basement for geothermal development but lacks sufficient permeability in the proposed FORGE site (Fig. 3). Three wells show temperatures in the range (~175-215° C) required for the FORGE site (Fig. 7; FOH-3D, 82-36, and 61-36). Flow testing demonstrates limited permeability of ~10^{-16}/m^2 in the deep wells, including FOH-3D and 82-36. These results suggest that a conventional hydrothermal system does not underlie the FORGE site, but hot (~175-215 °C) dry rock abounds at FORGE target depths of 1.5 to 4.0 km. The size of the high-temperature, low permeability volume that would be suitable for FORGE probably exceeds ~3 km^3 at Fallon.

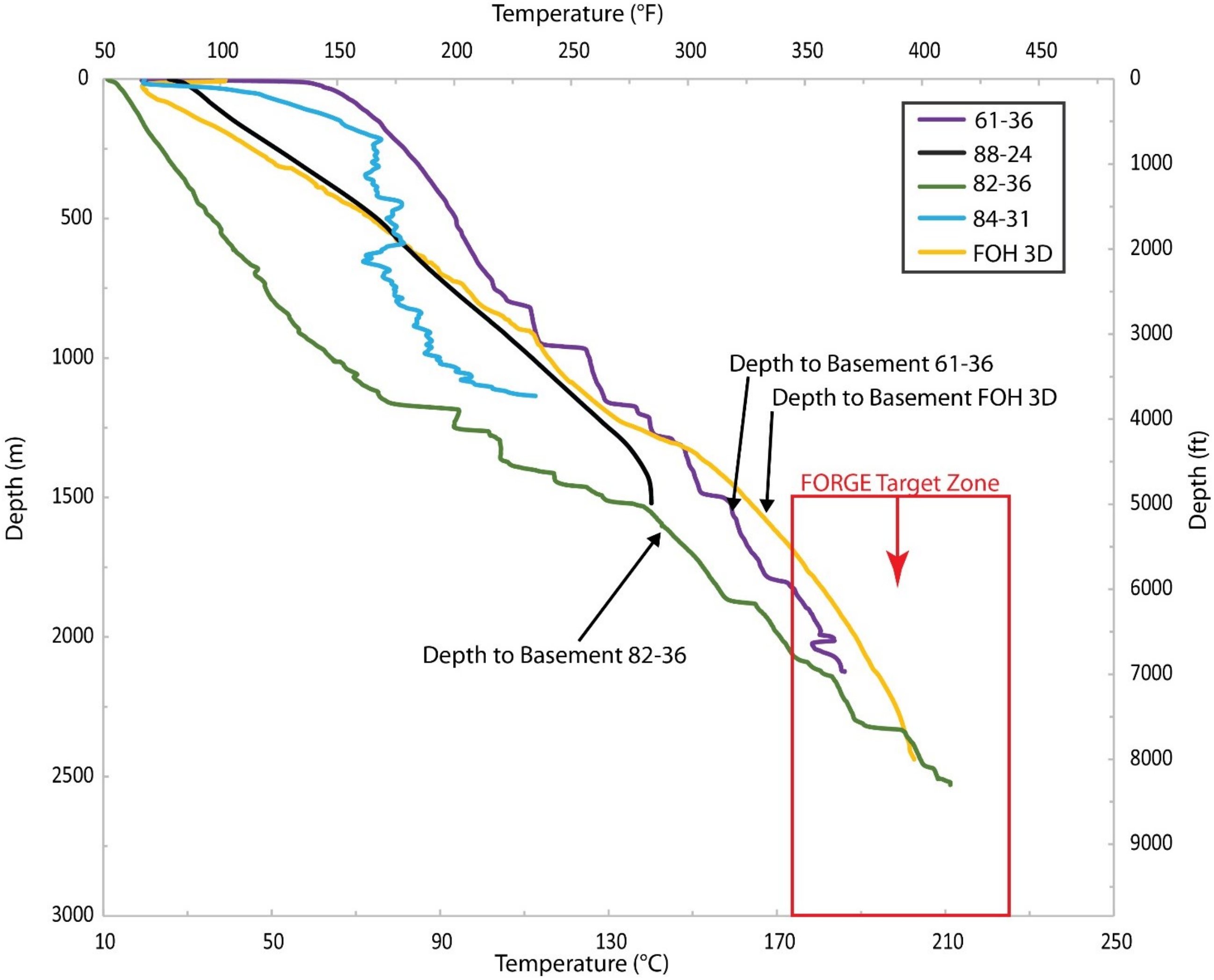


Figure 7: Equilibrated well temperature profiles for Fallon FORGE (Fig. 3). Depth is true vertical depth, adjusted for well path deviation from vertical. Depth to basement noted for the three wells that intersect the FORGE Target Zone. The target zone for FORGE is designated as 1.5 to 4 km depth and 175 to 225° C per DOE-GTO FOA guidelines.

There are at least three possible competent target formations for stimulation in the FORGE project area: 1) Triassic to Jurassic felsic metavolcanic rocks, 2) Jurassic metaquartzite (probable Boyer Ranch Formation; Speed and Jones, 1969) and 3) Jurassic to Cretaceous granitic intrusions. These units were formed in the Sierran back-arc region during the Mesozoic and are widespread across western Nevada (Fig. 2). Metavolcanic rocks act as reservoir host rocks for the nearby Desert Peak geothermal field (Fig. 2), with geomechanical properties, fracture orientations, and stress conditions that contributed to a successful EGS stimulation at that site (Davatzes and Hickman, 2009; Lutz et al., 2010; Hickman and Davatzes, 2010; Chabora et al., 2012). Granitic rocks have been successfully stimulated at Soultz in the Rhine graben in France (e.g., Genter et al., 2010). Silicified slate may also be competent enough to sustain significant EGS stimulation.

Quaternary faults have not been found in the FORGE area. The absence of Quaternary faults is fitting for low permeability as the distribution of Quaternary faults correlate favorably with conventional hydrothermal resources (Faulds et al., 2015). The permeability studies for the Fallon FORGE wells indicate that the existing faults and fractures are presently not enabling hydrothermal fluid flow. It is however, also noteworthy that the Carson Sink area has some of the higher regional strain rates in the Great Basin region (Fig. 1A). High strain rates and rocks that are critically (or near critically) stressed for frictional failure in the current stress field not only favor conventional geothermal energy production (Hickman et al., 1998; Barton et al, 1998) but also facilitate EGS research and development. The reason for this is that permeability enhancement due to reactivation of shear fractures during hydraulic stimulation is more readily accomplished under such conditions (e.g., Hickman and Davatzes, 2010; Chabora et al., 2012; Dempsey et al., 2013). The detailed 3D geological model and existing stress analyses from wells at the Fallon FORGE area (Blake and Davatzes, 2012; Blake et al., 2015) will facilitate the accurate design for achieving permeability enhancement in future EGS studies should Fallon be selected as the final FORGE site.

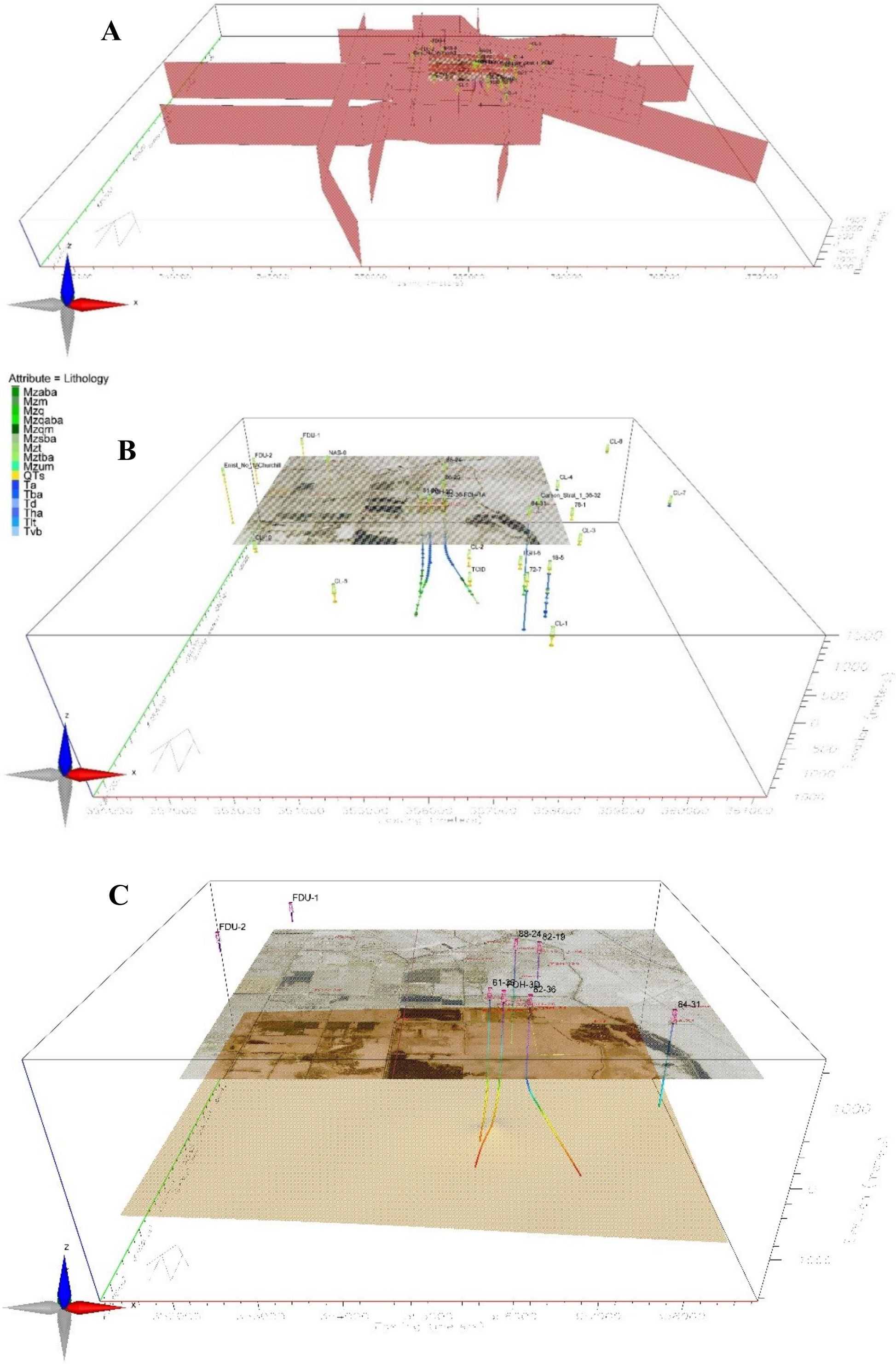


Figure 8: 3D modeling in progress for Fallon FORGE. (A) 3D view of well paths with lithology data. (B) 3D view of almost 300 km of seismic reflection profiles available from the Navy GPO and SEI, and being used for developing the 3D geological model. (C) The 175° C isotherm from the Fallon FORGE thermal model. Figures from DGI EarthVision software.

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