Frontier Observatory for Research in Geothermal Energy

Milford Site, Utah

Phase 2B Final Topical Report

DOE Project DE-EE0007080

Delivered by: EGI at the University of

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OUTLINE

I. Overview of Phase 2A & 2B Activities

II. Results

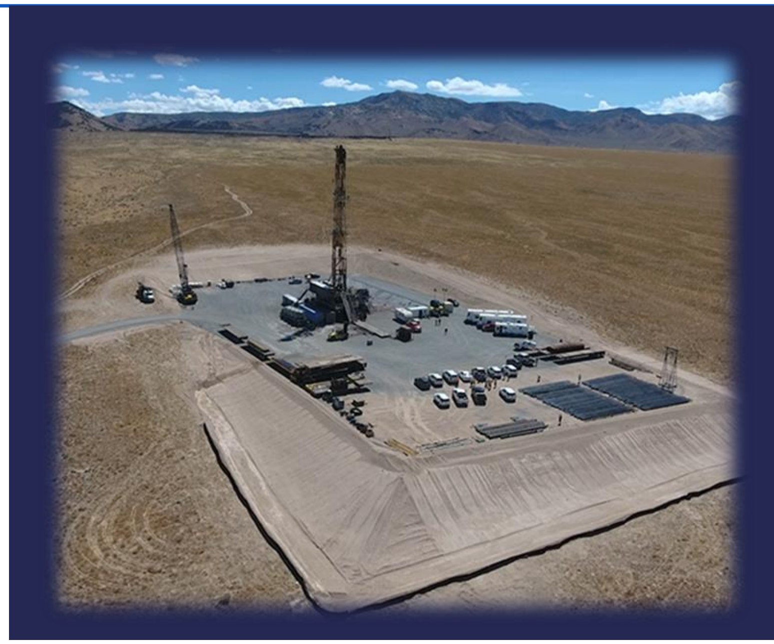
1. Conceptual Geologic Model
2. NEPA
3. Seismic Monitoring

III. Lessons Learned

IV. Conclusions

V. Appendices

A1. Conceptual Geologic Model
A2. Site Characterization Data Inventory
A3. Characterization Data Uploaded to GDR
A4. Updated Permitting Inventory
A5. EA and FONSI
A6. Stakeholders Engagement Status Update
A7. Final Seismicity Mitigation Plan
A8. Techno-Econ Infrastructure Assessment



Frontier Observatory for Research in Geothermal Energy – Milford Site, Utah

Section I. OVERVIEW of 2A/2B Activities

UTAH FORGE
U.S. Department of Energy

March 15, 2018

I OVERVIEW OF 2A/2B ACTIVITIES

SUMMARY

The Utah FORGE field laboratory will demonstrate that Enhanced Geothermal Systems (EGS) technology can tap the hundreds of Giga-Watts of heat energy stored in thermally-elevated, low-permeability crystalline rocks. The project will attract the most creative minds in the EGS field to interactively develop and optimize EGS methodology. Through public education and outreach, Utah FORGE will support the widespread adoption of EGS as an energy source. Our research group will be strongly proactive in seeking the proper mix of geoscientists and engineers to achieve the most rapid progress.

Logistics favor the Utah FORGE site. The site is located 217 miles (350 km) south of Salt Lake City and a similar distance north of Las Vegas, NV (Figures I.1 and I.2). It lies 10 miles (16 km) north of Milford, a small community of 1400 people. Milford has motel accommodations, a supermarket, hardware store, and a hospital. Beaver, a larger population center, lies 35 miles (56 km) east from Milford adjacent to Interstate I-15, a major thoroughfare. The Union Pacific Railroad passes through Milford, allowing the shipping of heavy equipment by rail and then by truck to the FORGE site. The Milford Municipal Airport, located a few kilometers north of Milford, has a 1524 m long sealed runway that can accommodate piston or turboprop, single- or twin-engine planes. The runway can also serve freight-handling planes such as the C-130.

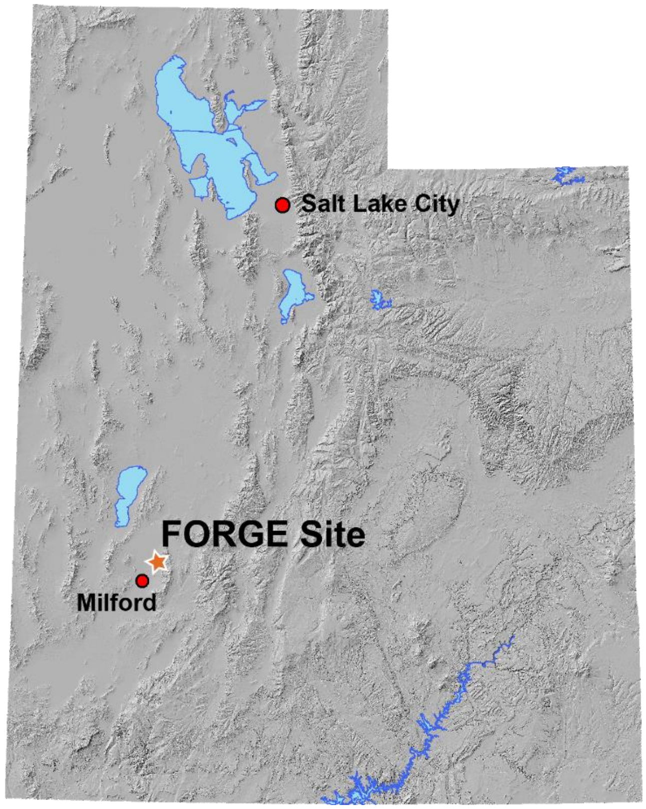


Figure I.1. *Location of the FORGE site.*

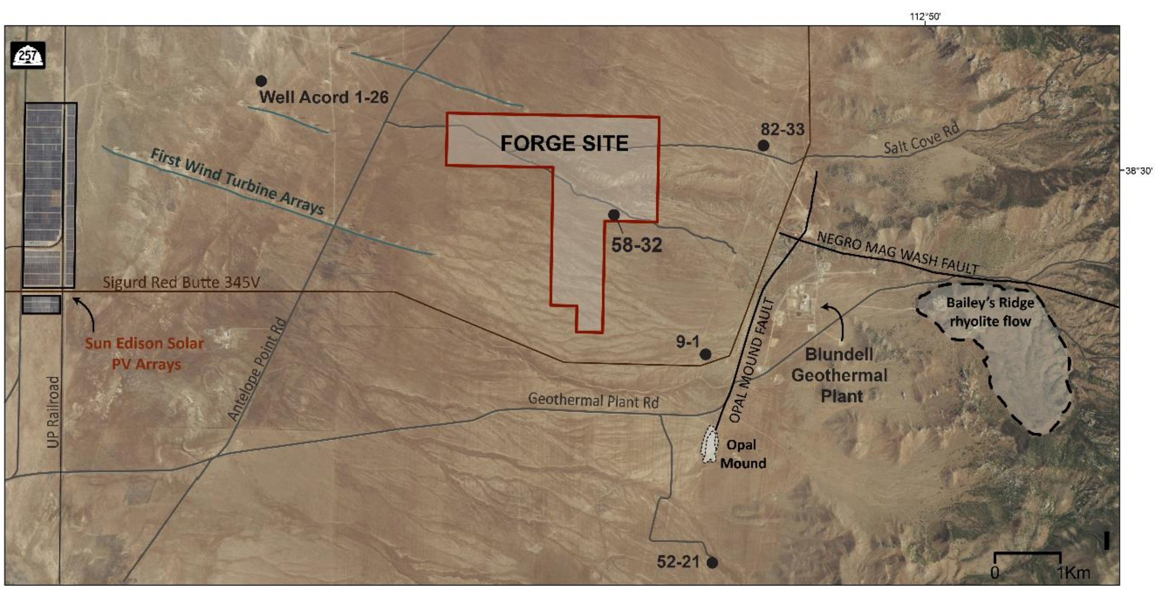


Figure I.2. *Infrastructure and renewable energy projects surrounding the FORGE. Milford is located 10 miles southwest of well 58-32.*

Milford has motel accommodations, a supermarket, hardware store, and a hospital. Beaver, a larger population center, is located 35 miles (56 km) from Milford adjacent to Interstate I-15, a major interstate. The Union Pacific Railroad passes through Milford, offering the possibility of shipping heavy equipment by rail and then by truck to the FORGE site. The Milford Municipal Airport, located a few kilometers north of Milford, has a 1524 m long sealed runway that can accommodate piston or turboprop, single- or twin-engine planes. The runway can also accommodate freight handling planes such as the C-130.

The FORGE site is unpopulated and covers an area of about 5 km^2. It is situated within Utah's Renewable Energy Corridor adjacent to a 306 MWe wind farm, a 240 MWe solar field and PacifiCorp Energy's 38 MWe Blundell geothermal plant at Roosevelt Hot Springs. Cyrq Energy's 10.5 MWe geothermal field at Thermo and a biogas facility are located approximately the same distance south of Milford. The location of the FORGE site within the Corridor will provide an important showcase for geothermal energy and its role in powering the nation.There are no cultural or environmental restrictions that would limit drilling and research activities and the Utah team has aquired sufficient non potable water for all testing needs. Furthermore the risk of induced seismicity is low. The community, the State, and the regulatory agencies have enthusiastically supported the project.

The thrust of Phase 2A and 2B has been to demonstrate the site meets all of the support, environmental and subsurface needs of the FORGE project. A video illustrating the three dimensional conceptual model of the FORGE site can be found at *https://youtu.be/KHSCq4fdhEA.* Figure I.3 is a screen shot from the video.

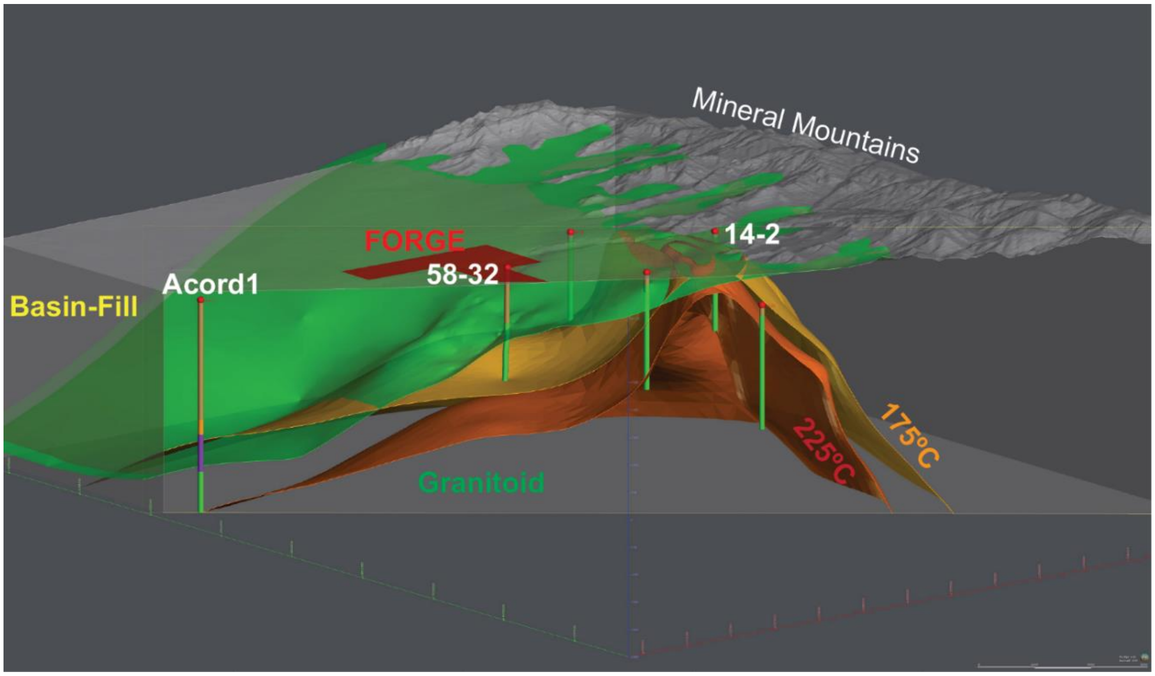


Figure I.3. *Screen shot of video showing the earth model output for this presentation was generated using Leapfrog Software. Copyright © Aranz Geo Limited.*

OVERVIEW OF PHASE 2A

The foundation for Phase 2A was created in Phase 1 of the FORGE project. In Phase 2A, we established baseline information necessary to ensure that FORGE activities would present no incompatible site conditions, and that all necessary environmental factors and NEPA requirements could be met in an appropriate timeframe.

The DOE has determined that the ideal FORGE site must have the following characteristics:

1) Rock type: crystalline (granitic) rocks
2) Volume: greater than 1 km^3
3) Temperature: 175^o to 225^{o}C
4) Depth: 1.5 to 4 km
5) Low permeability
6) Known stress orientations and magnitudes
7) Low risk of induced seismicity and seismic hazards
8) No connection to existing hydrothermal system
9) No/low environmental risks
10) Adequate infrastructure to support research activities, stimulation and circulation testing

Phase 2A activities are shown in Table I.1. An Environmental Information Volume (EIV) describing the environmental actions that will take place to satisfy NEPA requirements was completed, and existing and future infrastructure needs were identified to ensure project requirements will be met. High resolution seismometers ($M_{comp}0$) were incorporated into the existing surface telemetered seismic array to lower the detection threshold and improve hypocenter locations. Expanded outreach activities ensure that the social license to develop and operate FORGE is of the highest professional standard and effectiveness. Twenty-three outreach activities were conducted in Phase 2A.

Table I.1. *Phase 2A activities and deliverables. Task numbers refer to the tasks in the SOPO prepared for Phases 2A.*

Phase 2A Tasks	**Task**	**Major Activity**
Update PMP	2A.1	Updated PMP
Prepare EIV	2A.2.1	EIV prepared
Update cost proposal	2A.2.2	Prepared updated cost proposal
Cultural Resource Clearance	2A.2.3	Cultural survey completed
Obtain necessary permits	2A.2.4	Required permits obtained
Install telemetered seismic array	2A.3.1	5 high resolution seismometers installed; microseismicity data collected and telemetered to UUSS; available at http://quake.utah.edu/forge-map
Install nodal seismic array	2A.3.2	30 days of nodal microseismicity data collected
Lidar acquisition	2A.4	Acquired 200 sq miles of LiDAR data
Detailed Techno-economic Infrastructure Assessment	2A.5	Techno-economic Assessment prepared
Outreach and Communications	2A.6	Outreach/Communications program expanded; 23 activities conducted
Update Site Characterization and Monitoring Data to GDR	2A.7	Data uploaded to GDR
Go/No Go Decision Point Presentation/Report	2A.8	Presentation/Report submitted to DOE

OVERVIEW OF PHASE 2B

The primary objectives of Phase 2B were to confirm the geological suitability of the FORGE site through direct measurements and to achieve full NEPA compliance. Both of these objectives have been well met at Utah FORGE. The key Phase 2B activities are summarized in Table 2.

Table I.2. *Phase 2B activities and deliverables. Task numbers refer to the tasks in the SOPO prepared for Phases 2B.*

Phase 2B Tasks	**Task**	**Major Activity**
Update PMP	2B.1	PMP updated
Complete NEPA/Permitting Requirements	2B.2	Draft EA issued 1/31/18. No comments from the public, any agency or Tribe were received. FONSI expected prior to 3/29/2018.
Gravity survey	2B.3	Data from 417 new stations collected and analyzed
LiDAR survey and geologic mapping	2B.4	Surface fault rupture map prepared; fracture mapping in Mineral Range conducted
Perform road work and construct drill pad	2B.5	Access road upgraded and drill pad prepared
Drill deep test well	2B.6	Well 58-32 drilled to 7536 ft under budget and ahead of schedule; two cores collected; complete suite of geophysical logs run and Diagnostic Fracture Injection Test (DFIT) conducted; measured natural and induced fractures, rock type, temperature, stress magnitude and direction, permeability, porosity
3D seismic reflection survey	2B.7	3D survey centered on well 52-38 completed and analyzed-no faults detected that offset alluvium/granite contact.
Petrologic, geophysical and geochemical characterization of reservoir rocks	2B.8	Petrologic, geophysical and geochemical properties of rocks from 58-32 measured
Conduct CO_2 and He isotope soil gas surveys	2B.9	No CO_2 or He anomalies detected over FORGE site indicating no hydrothermal flow beneath site
Sample groundwater and analyze fluid chemistry	2B.10	Groundwater collected and analyzed; pump test completed
Perform Transient Electromagnetic (TEM) survey	2B.11	TEM survey conducted

Carry out seismic monitoring	2B.12	Seismic data collected and telemetered to UUSS; available at http://quake.utah.edu/forge-map
Undertake geomechanical modeling and stress analysis	2B.13	Numerical simulations conducted and an earth model developed
Update the geologic model	2B.14	Geologic model updated and refined
Develop Induced Seismicity Mitigation Plan	2B.15	Induced Seismicity Mitigation Plan completed
Upload data to GDR	2B.16	All 2B data uploaded to GDR
Define and undertake Outreach and Communications activities	2B.17	Outreach/Communications program expanded; 53 activities conducted (including field trips, videos, STEM modules, electronic media, conference papers)
Topical Report	2B.18	Presentation to DOE conducted.

The most significant characterization activity in Phase 2B was the drilling of well 52-38 which resoundingly met the DOE criteria for defining a FORGE EGS research site. This well enabled direct measurement of rock type, fracture distributions and orientations, in-situ stress conditions, permeability, porosity, fluid content, and temperature (see Table 1, Task 2B.6). Well 58-32, drilled between July and September, 2017, reached a depth of 7536 ft and recorded a bottom hole temperature of 386°F (197°C) after penetrating more than 4500 ft of granite. A full suite of geophysical logs was run in the open hole section of the well from the base of the 9 5/8-inch casing at 2172 ft to total depth prior to setting 7-inch casing at 7375 ft. Core was collected at 6800-6810.25 ft and 7440-7452.15 ft for geomechanical and permeability testing.

Permeability and stress magnitudes were determined from a Diagnostic Fracture Injection Test (DFIT) after running the 7-inch casing. Stress orientations were determined from analysis of the Formation Microscanner Image (FMI) log, run before and again after the DFIT; stress gradients were determined from the DFIT. More than 2000 natural and induced fractures were imaged within the granitic rocks encountered in 58-32. The following stress orientations and gradients were determined:

1. minimum horizontal stress (σ_3) orientation = ESE-WSW; stress gradient = 0.62 psi/ft;
2. maximum horizontal stress (σ_2) orientation = NNE-SSW; stress gradient = 0.77 psi/ft;
3. vertical stress (σ_1), stress gradient = 1.13 psi/ft)

The maximum horizontal stress direction based on FMI logging (~N25°E) coincides with the orientations predicted from geologic mapping and televiewer surveys in geothermal production wells to the east. Permeabilities determined from the DFIT and core testing are low, ranging from 6 to 80 microdarcies. These permeabilities are appropriate for EGS development.

Since the 1970s, more than 100 wells have been drilled in support of the exploration and development of Roosevelt Hot Springs. Of these, 80 were <1500 ft and 20 were >1500 ft wells, including Acord-1, a 12,650 ft deep well 1.8 mile west of 58-32. Temperatures in 58-32 were accurately predicted from existing temperature and heat flow analyses, providing evidence of the efficacy of the thermal model. The volume of the reservoir beneath the FORGE footprint, based on the extent of the crystalline rocks at temperatures between 175° and 225°C, is close to 4.6 km^3. The volume of hot crystalline rock suitable for EGS development expands to nearly 100 km^3 if we include granite shallower than 4 km and at temperatures greater than 175°C between the Opal Mound fault on the east, Acord-1 well on the west, 82-33 on the north and 52-21 on the south.

The 3D seismic reflection survey and supplementary new and legacy 2D lines covered more than 7 sq miles centered on well 52-38. The top of the granite is imaged as a clearly defined reflector that can be traced across the entire survey area without observable disruption. Gravity data support the seismic analyses that Milford Valley is a deep, asymmetrical basin with the top of the granite basement dipping at a shallow angle to the west on the east side of the Valley.

The microseismic network first established more than 3 decades ago and augmented in 2016 with high resolution seismometers ($M_{comp}0$) has not detected any seismic events beneath the FORGE site, although events have been detected beneath the Roosevelt Hot Springs borefield and to the east. Analysis of the seismic data, including a probabilistic seismic hazard analysis, has been incorporated into the Induced Seismic Mitigation Plan. Analysis of the data indicate the risk of induced seismicity and of seismic hazards is low.

New geologic mapping of surface ruptures within the alluvium and fractures in the Mineral Range has been conducted. Maps of the alluvium incorporate LiDAR data obtained during Phase 2A. No faults were identified within the FORGE footprint, consistent with the undisturbed nature of the alluvial deposits imaged in the FMI logs of 58-32, lack of CO_2 flux over the site, and 3D seismic data. Fracture orientations within the Mineral Mountains confirm continuity across the FORGE site.

Numerical reservoir modelling was initiated to inform Phase 3 drilling and stimulation activities. The models support the results of the DFIT and other associated injection tests, which demonstrated that natural fractures can be stimulated under relatively low injection pressures. The simulations will be tested in Phase 2C by stimulating fractures predicted to slip and dilate that would interconnect the injection and production wells. While the numerical simulations confirm that hydraulic shearing can occur, analysis of post injection Formation Microscanner Image (FMI) logs strongly demonstrates new and/or enhancement of tensile fracturing along the wellbore. This is an ideal scenario – a combination of tensile and reactivation of critically stressed shear fractures aligned in nominally the same direction as the maximum principal stress. The reactivation of favorably aligned naturally fractures, possibly conjugate to the hydraulic fracture (~N25°E) accomplishes two important tasks 1) it insures that breakdown pressure is not unreasonably high and 2) it insures a narrow azimuthal spread for individual fracture networks

Measurements of water levels in existing wells, coupled with a TEM survey define the piezometric surface throughout the site. Sufficient water rights have been obtained for the FORGE project. Three hundred acre feet of water has been leased from the State and an additional 200 acre feet of water can be purchased from Smithfield under an MOU between Smithfield and the University of Utah. Water can also be purchased directly from the City of Milford, as was done for the drilling of 58-32. Smithfield and State water is not potable and cannot be used for human consumption or agriculture. Pump tests of several existing wells indicate two to three water wells can provide the quantity of water required for drilling, stimulation and circulation testing.

In Phase 2B, Outreach and Communication activities were further expanded. In addition to funding from the FORGE project, a grant from the Governor's Office of Energy Development supported Outreach activities for K-12 and the general public. Funds were utilized to produce three additional videos, STEM (Science, Technology, Engineering and Math) modules and hands-on activities, PowerPoint presentations, and Frequently Asked Questions in English and Spanish.

Additional information on the FORGE site can be found on our website and Facebook page, press releases, videos, school visits, meetings for the general public, presentations at scientific conferences, field trips, science fairs, and newspaper and industry interviews and articles. A total of fifty-three Outreach activities were conducted in Phase 2B.

KEY DELIVERABLES

The key deliverables resulting from Phase 2A and 2B activities are summarized in Table I.3 along with the parameters they impact. These deliverables are supported by detailed specialist reports in the Appendix A2.

Table I. 4 illustrates how Phase 2A & 2B results have been integrated with legacy data to refine the "Conceptual Geologic Model" of the FORGE site. Quantitative analysis of the data demonstrates uncertainties in the key parameters are small.

Table I.3. *Key deliverables and their bearing on the FORGE site's suitability and merits.*

Key Deliverables	Impact
Direct measurements of temperature, rock type, fracture characteristics, permeability, porosity, stress directions, and stress magnitudes within the hot crystalline rocks penetrated in well 58-32	Confirms all applicable geologic requirements have been met (see Table 4)
Results of the DFIT	Confirms stress characteristics, permeability (see Table 4)
Geomechanical testing of core samples and analysis of geophysical logs	Defines rock characteristics (e.g. strength, permeability) necessary for numerical modelling (see Table 4)
Petrology of cuttings and core samples and physical measurements of the samples from well 58-32 and legacy wells	Confirms lithology, alteration, rock characteristics (see Table 4)
Gravity and 2D/3D seismic reflection surveys	Confirms extent of reservoir (see Table 4)
Fault rupture and fracture mapping	Informs seismic risk and stress orientations (see Table 4)
CO_2 and He analyses	Confirms lack of hydrothermal system beneath FORGE (see Table 4)
Seismic monitoring	Demonstrates low natural seismicity at the FORGE site (see Table 4)
Induced Seismicity Mitigation Plan	Informs seismic risk from induced and tectonic seismic events (see Table 4)
Draft EA	Confirms no environmental risks
Outreach Communications activities	Engages stakeholders including local community, regulatory agencies, State and DOE
Techno-economic assessment	Confirms all infrastructure needs can be met

Table 4. *Direct evidence of FORGE reservoir characteristics.*

Direct Measurement	Crystalline Lithology	Reservoir Extent (>1Km^3)	Stress Conditions	Permea-bility	Porosity	Connection to Hydrothermal System	Tempera-ture	Seismicity	Structure	Water Availability
58-32 Temp and Geophysical Logs	✓	✓	✓				✓		✓	
DFIT			✓	✓						
2D/3D reflection survey	✓	✓							✓	
Gravity		✓							✓	
Geol Mapping			✓						✓	
Legacy well data (T, P, lithology)	✓					✓	✓		✓	✓
Seismic Monitoring								✓	✓	
TEM										✓
Thin section/SEM	✓			✓	✓					
X-Ray Diffraction	✓									
Core Testing				✓	✓					
58-32 core and cuttings samples	✓	✓		✓						

In summary, the key attributes of the FORGE site that bear on its suitability and merits are as follows.

1. The site meets all requirements established by the DOE for temperature, depth, rock type, stress, permeability and porosity.
2. The reservoir is composed of homogeneous crystalline rock lacking lithologic and structural discontinuities. The simplicity of the reservoir will promote stable drilling conditions, an important consideration when drilling long, highly deviated wells and allow comparison of different drilling techniques and in situ mechanical testing and stimulation technologies. This simplicity will promote the creation of a continuous EGS reservoir volume.
3. The crystalline granitic rocks of the Utah FORGE reservoir are characteristic of basement rocks across much of the USA. Thus, all the information that is learned from this project has broad and relevant application that can be readily transferred to other EGS sites.
4. The DFIT provides *prima facie* evidence the FORGE site is ideal for EGS development
5. Unlike complex metamorphic basement sequences with wide-ranging mechanical properties, a simple crystalline reservoir lithology will reveal key developmental lessons and promote the transfer of technologies to other sites, including the much larger (> 100 km^3) region of hot rock surrounding the FORGE site.
6. There are no major population centers nearby. The risk of induced seismicity and of seismic hazards is low.
7. There are no environmental constraints that will preclude drilling operations or scientific activities-there are no endangered flora or fauna, the groundwater is not potable and underutilized. Sufficient water rights for FORGE activities has been secured
8. The site can be accessed year-round via existing roads.
9. The local infrastructure is well-developed (roads, railroad, airport, communications) and nearby communities can adequately support the project needs (construction companies, motels, fuel, potable water).
10. All critical operations will be conducted on Utah State land.
11. There are no high security or sensitive operations being conducted nearby
12. There is strong support from the landowners, state, county and federal regulatory agencies and the local communities.

Frontier Observatory for Research in Geothermal Energy – Milford Site, Utah

Section II. RESULTS - Discussion of the Conceptual Geologic Model

UTAH FORGE
U.S. Department of Energy

March 15, 2018

II.1 CONCEPTUAL GEOLOGIC MODEL

The Utah FORGE site is located on gently sloping alluvial cover, about midway between the crest of the Mineral Mountains to the east and the center of the north Milford valley to the west. The site lies inside the southeast margin of the Great Basin in a broad zone that is characterized by elevated heat flow, which has been the subject of several DOE funded projects related to hot sedimentary aquifers, play fairway analysis, and critical elements in produced fluids (e.g., Allis et al., 2012; Simmons et al., 2015, 2017, 2018; Wannamaker et al., 2015, 2016; 2017). The regional stratigraphy consists of folded and imbricated Paleozoic-Mesozoic carbonates and clastics. These have been overprinted by eruption of Tertiary-Recent mafic-felsic magmatic centers, including in the Mineral Mountains, and widespread Basin and Range style extension (e.g. Nielson et al., 1986; Coleman et al., 2001). The local lithology is divided into two broadly defined units, comprising crystalline basement rocks and the overlying basin fill sedimentary deposits. In the geologic map and cross section, these units are further subdivided in order to show some of the fine-scale variability in rock type (Fig. II.1.1). The regional context and basin structure are depicted in profile based on legacy seismic reflection and new gravity surveying and interpretation (Fig. II.1.2).

The basement rocks are dominated by Miocene age granitic rocks, which make up the core of the Mineral Mountains (e.g. Capuano and Cole, 1982; Nielson et al., 1986; Coleman and Walker, 1992; Coleman et al., 1997; Simmons et al., 2016). For simplicity, these granitic rocks are collectively referred to as granitoid. The plutonic lithologies, along with the localized eruption of rhyolite that form Bailey ridge and Little Bearskin mountain, span a semi-continuous record of magmatism from 25 to 0.5 Ma, (Lipman et al., 1978; Coleman and Walker, 1992; Moore and Nielson, 1994; Coleman et al., 1997). The granitoid is composed of quartz, plagioclase, K-feldspar, biotite, clinopyroxene, hornblende, and magnetite-ilmenite (Nielson et al., 1986; Coleman and Walker, 1992; this study), and it was intruded into tightly folded Precambrian (early Proterozoic) gneiss (~1720 Ma) made of biotite, hornblende, K-feldspar, plagioclase, quartz, and sillimanite, (Nielson et al., 1986; Aleinikoff et al., 1987).

The basin fill consists of a layered sequence of poorly consolidated sedimentary deposits that is more than 3000 m thick in the deepest part of the basin. The most complete record of basin filling is preserved in the units penetrated by the Acord 1 well, and the cuttings have been subject to new petrographic and X-ray diffraction analyses. Below about 1200 m depth down to the contact with the basement, the strata consist of volcaniclastic sandstones and gravels, lacustrine sediments, tuffaceous deposits, and localized flows of andesitic lavas. At shallower depths, calcareous lacustrine deposits made of siltstone and sandstone dominate. From west to east, the surface of these deposits forms a gently curving catenary profile across the north Milford valley that backfills steep-sided valleys of the western Mineral Mountains. The surface in the vicinity of the FORGE site overlies alluvial fan deposits whereas the very fine-grained lacustrine sediments to the west were deposited in the Pleistocene Lake Bonneville. Older alluvial deposits (0.5-1 Ma?) form the surface across the Roosevelt Hot Springs-Blundell production field, extending eastward beneath Bailey ridge; the oldest deposits date back several million years, and they are restricted to a few isolated exposures.

Structurally, the Utah FORGE site is comparatively simple, and the post-Miocene stratigraphy is largely undeformed (Fig. II.1.1). Four faults and fault systems have been identified, based on field observations, seismic reflection, and correlation of drill logs, and they are attributed to Basin and Range extension, which have dominated the region since the Eocene (e.g. Dickinson, 2006). The Opal Mound and Negro Mag faults are relatively short length structures that intersect at an orthogonal angle to form the boundaries of the Roosevelt Hot Springs reservoir. The Mineral Mountains West fault system comprises a series of parallel north-south trending, normal fault segments with small offsets. The traces of these three faults are exposed at the surface. The fourth fault is unnamed, but it is the most significant fault in the vicinity of the FORGE site. This fault marks the contact between overlying basin fill and the underlying crystalline basement rock, forming an inclined ramp that dips ~20-35° west; it is labeled "unconformity-detachment" in cross section (Fig. II.1.1). This structure likely accommodated a large amount displacement in the relatively distant past (mid-Miocene), but it is now inactive having rotated to a low-angle during uplift and exhumation of the Mineral Mountains more than six million years ago (Coleman et al., 2001). No other faults are known, consistent with the absence of scarps and faceted spurs along the Mineral Mountains range front.

Fracture patterns in basement granitoid mapped in the central Mineral Mountains have lengths that range from 20 to 200 m, and fracture spacings that range from 5-15 m (Fig. II.1.3). Fracture azimuths range widely, with about half the population being randomly oriented. The remaining fracture azimuths fall into two predominant populations of 80 to 120° and 0 to 30°. The E-W trending distribution dips steeply to the north, whereas the NNE-SSW population dips steeply and gently west to form a conjugate set. The geometry of the conjugate NNE-SSW fracture set is interpreted to have formed with the maximum compressive stress being vertical, followed by ~40° of eastward tilt in the footwall of the normal fault that forms the contact between granitoid and basin fill (Fig. II.1.1). Because fracture intersection relationships indicate that the conjugate set formed after the E-W steep fractures, all three main fracture sets appear to have formed before or early during Basin and Range faulting, and therefore in the middle Miocene shortly after the batholith was emplaced (Coleman et al., 2001). Observations of fracture patterns in the Quaternary lavas bear little resemblance to fracture patterns in nearby exposures of granitoid rocks. Steep fractures predominate in all of the rhyolite bodies, but otherwise there are few similarities from one body to another.

Natural seismicity below the broader Milford valley over the period 1965-2012 has been quiet, where regional events are associated with large-scale tectonic movements. There has been no seismicity beneath in the vicinity of the FORGE site and no evidence of injection-induced seismicity in the nearby Roosevelt Hot Springs reservoir. Most natural seismicity is clustered near Milford (0.46 to 3.87 M), which is the site of the 4.1M earthquake in 1908, and diffuse low magnitude activity occurs beneath the Mineral Mountains. Legacy well data, the focal mechanism of recent seismic events, and geologic data indicate a normal faulting regime prevails with a maximum horizontal compressive stress oriented approximately N25°E (Glenn and Hulen, 1979; Yusas and Bruhn, 1979; Smith et al., 1989).

THERMAL STRUCTURE & HEAT FLOW

The three-dimensional understanding of heat flow and temperature gradients is based on analysis of temperature profiles from approximately 100 wells drilled from 200 to 4000 m depth (Allis et al. 2016, 2018; Gwynn et al., 2016). A geometrically simple thermal structure has been defined (Fig. II.1.1 cross section), reflecting high conductive heat flow in the basement rocks (50-70°C/km) around and through the FORGE reservoir, which is surrounded by more than 100 km^3 granitoid rock at >175°C. The Opal Mound fault forms the eastern boundary to this large conductive thermal regime, separating it from Roosevelt Hot Springs to the east where convective hydrothermal heat flow prevails and covers a smaller area of ~10 km^2.

GEOHYDROLOGICAL MODEL

Regionally beneath the Utah FORGE site, shallow unconsolidated basin fill forms the primary aquifer, ranging in thickness from 100 to >500 feet (Mower and Cordova, 1974; Kirby, 2012). New groundwater well test data confirm transmissivities that range from 240 to 1600 ft^2/day, which is ample groundwater supply for future EGS activities at the FORGE site.

Groundwater resources for the FORGE site are confined to basin fill sediments that overlie the granitoid basement rocks (Fig. II.1.4). Beneath the FORGE deep drill site, the groundwater elevation is approximately 5100 feet and the depth to water is between 200 and 500 feet, consistent with new transient electromagnetic (TEM) data (Fig. II.1.4). The depth to groundwater is approximately 150 feet at nearby sites for potential supply wells.

The compositions of the groundwaters vary systematically according to location and geologic setting, comprising four separate domains (Fig. II.1.4). The Mineral Mountains cold springs discharge fresh groundwaters representative of modern meteoric waters. Roosevelt Hot Springs consist of boiled neutral pH chloride waters that formed from deep circulation of paleo-meteoric water followed by high temperature water-rock interaction with fractured granitoid, and then boiling before discharging at the surface (Simmons et al., 2018). Beneath the vicinity of the FORGE site, warm neutral pH chloride groundwaters represent the dispersion and northwesterly outflow from Roosevelt Hot Springs that have been partially diluted. In the north Milford valley, groundwaters reflect distal outflow from Roosevelt Hot Springs that have been modified by varying amounts of dilution and mineral dissolution that have elevated aqueous concentrations of bicarbonate. Within the vicinity of the FORGE site, the groundwaters contain a significant proportion of Roosevelt Hot Springs waters, which makes them non-potable, chemically benign, non-potable, and highly suitable for EGS heat transfer experiments (Simmons et al., 2016).

SOIL GAS SURVEYS

As a check on the possible existence of cryptic hydrothermal flow within and around the FORGE site, CO_2 soil gas surveys were performed in June, 2017, and January, 2018. A helium isotope soil gas survey was performed in November, 2017 (Fig. II.1.5). The results confirm the absence of detectable hydrothermal upflow beneath the FORGE site. Instead and as expected, anomalously high CO_2 fluxes and mantle helium were detected east of the Opal Mound fault in the area of known hydrothermal activity associated with Roosevelt Hot Springs.

BASEMENT CONTACT FROM 2D & 3D SEISMIC REFLECTION SURVEY

New 2D and 3D seismic reflection surveys covering more than 7 mi^2 centered on the Utah FORGE site and the location of well 58-32 were conducted. The profiles show a continuous band of strong, close-spaced reflectors that represent the basement contact. The contact surface is thus also continuous, and it strikes north-south and dips between 15° and 35° west (Fig. II.1.6 and II.1.7). A second set of semi-continuous horizontal reflectors at shallower depth represent stratification within the basin fill sedimentary units. There is no evidence of sub-vertical faults in any of the profiles beneath the FORGE site.

FORGE RESERVOIR-WELL 58-32

Well 58-32, spudded on July 31, 2017, was drilled vertically to 7536 ft (2298 m) depth in 57 days (Fig. II.1.8). The well penetrated layered alluvium deposits down to 3176 ft (968 m), where it crossed the contact with underlying crystalline basement rocks, which make up the rest of the stratigraphy to the bottom of the hole. The upper interval of layered alluvium (0-3176 ft; 0-968 m) consists of poorly sorted and poorly lithified sediment made of quartz and feldspar eroded from the plutonic rocks in the Mineral Mountains.

The lower interval (3176-7536 ft; 968-2298 m) consists of granitoids (i.e. siliceous plutonic igneous rocks), petrographically identical to those exposed in the Mineral Mountains. Based on thin section and X-ray diffraction analyses of cuttings and cores, plagioclase, K-feldspar, and quartz are the dominant minerals, with minor amounts of biotite, hornblende, clinopyroxene, apatite, titanite, zircon, and magnetite-ilmenite (Fig. II.I.8). They are intergrown and coarsely crystalline forming a strong low porosity reservoir rock, ranging from granite to monzodiorite to quartz monzodiorite in composition, plus minor diorite (Fig. II.I.9). Illite and chlorite are the main clay minerals, but they constitute <5% of the rock. Trace amounts of other secondary minerals include carbonate and anhydrite, and fractures in the cored intervals are locally lined with chlorite or epidote. These hydrothermal minerals are products of paleo-hydrothermal activity, and there is no evidence of modern hydrothermal fluid flow.

TEMPERATURE PROFILE 58-32

The wireline temperature survey run 37 days after the completion of the testing of well 58-32, proves an anomalously high conductive temperature gradient in the basement and reservoir rocks of 70°C/km (Allis et al., 2018); the maximum temperature of 197°C was measured at the bottom of the hole at 7536 ft (2298 m depth).

LOG ANALYSIS 58-32

The azimuths and dips of approximately 2000 natural fractures were detected below 3176 ft (968 m) depth in the basement interval of the 58-32 FMI well log. These fractures have predominant orientations in the north-south, east-west, and northeast-southwest directions, consistent with observations in the central Mineral Mountains (Fig. II.1.10). Subvertical tensile fractures induced by drilling and by the diagnostic fracture injection test (DFIT) both indicate the maximum horizontal stress is oriented N25°E (Fig. II.1.10).

GEOMECHANICAL PROPERTIES AND STRESS ANALYSIS 58-32

Mechanical properties measured on cores were used to calibrate well logs (e.g. density, dipole sonic, imager) in order to quantify continuous profiles of stress magnitude. The DFIT in the uncased section of the well indicate these principal stress gradients:

- maximum horizontal stress (N25°E azimuth) ~0.77 psi/ft
- minimum horizontal stress ~0.62 psi/ft
- vertical stress is 1.13 psi/ft.

As expected, the measured compressive strengths on core plugs are very high (up to 80,000 psi), whereas the measured porosities (<0.1 to 1%) and permeabilities (0.1 to 80 micro-darcy) are very low. The DFIT injection test program proves that it will be possible to stimulate multiple, independent sets of fracture networks at surface pressures that are well within achievable operational range (Fig II.1.11).

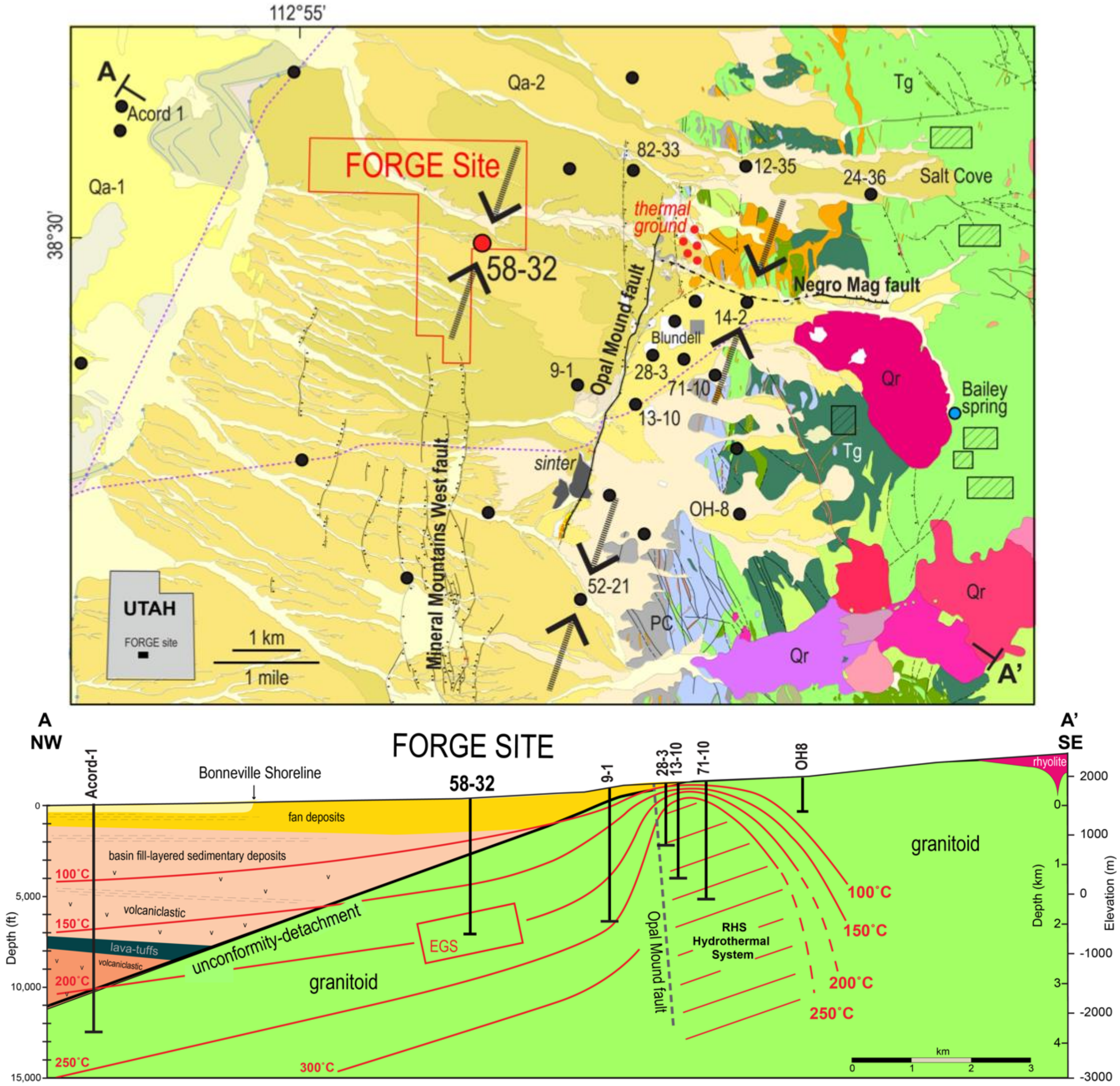
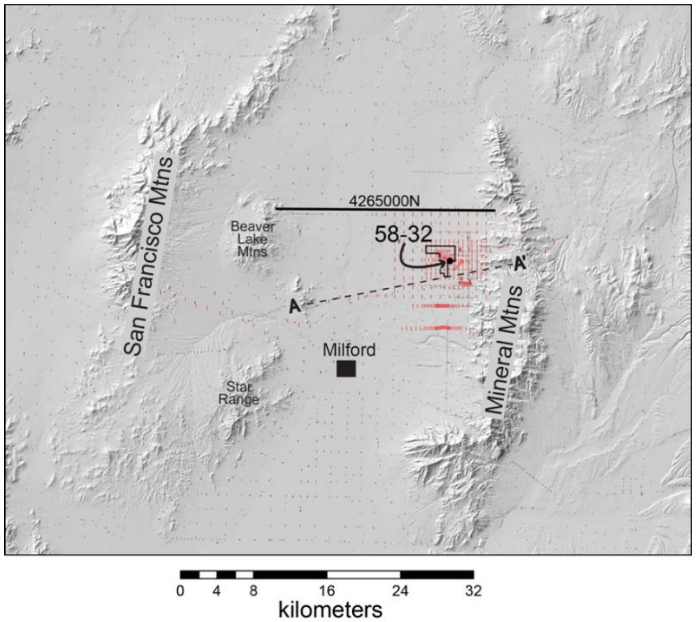
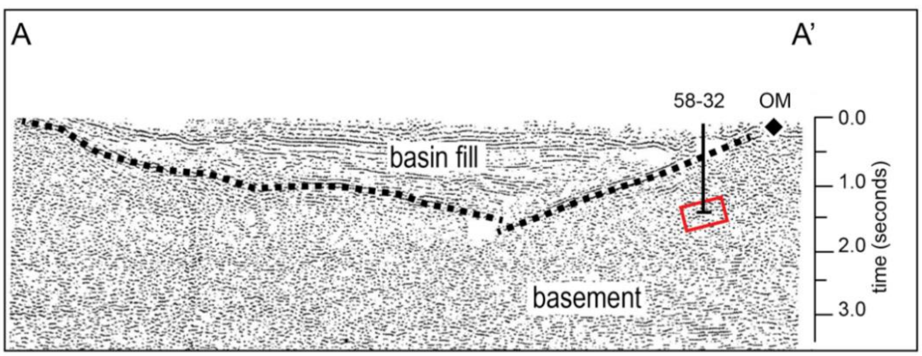


Figure II.1.1. *Geologic map (upper) and cross section (lower) for the Utah FORGE site (Nielson et al., 1986; Sibbet and Nielson, 2017; Allis et al., 2018; this study-A2.Task2.4 Forge_Geology_Plate1 SKirby.pdf A2). Black arrows indicate maximum horizontal stress orientations measured in wells 58-32, 14-2 and 52-21. Black outlined hatched rectangles represent fracture pattern study sites in the Central Mineral Mountains (Task2B Fractures in the Mineral Mountains JBartley.pdf). The rhyolite flow (red) west of Bailey spring makes up Bailey ridge. Abbreviations: Qa-1=Lake Bonneville silts and sands; Qa-2=alluvial fan deposits; Qr=Quaternary rhyolite lava and pyroclastic deposits; Tg=Tertiary granitoid; PC=Precambrian gneiss; black filled circles=wells. In cross section, the red box represents approximate position of the FORGE EGS reservoir; RHS=Roosevelt Hot Springs.*

A



B



C

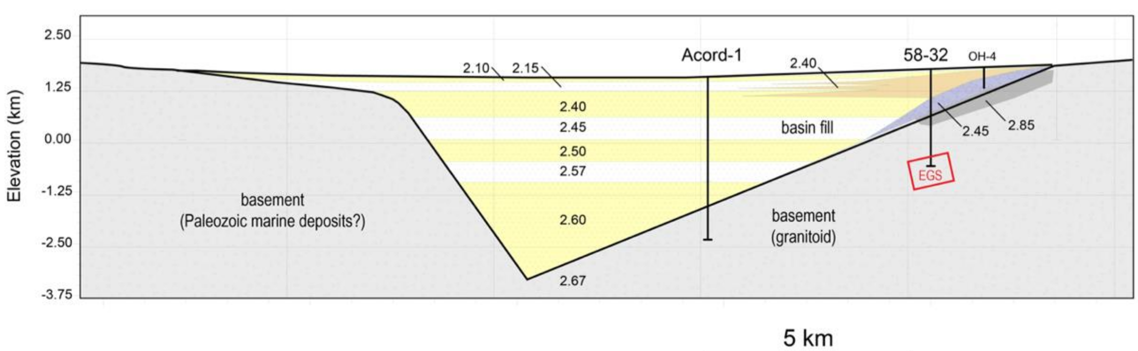


Figure II.1.2. *Geologic structure of the north Milford valley: A) Shaded relief map showing lines of seismic reflection and gravity profiles; B) Legacy seismic reflection profile (Smith et al., 1989); C) Bouger gravity anomaly profile (A2.Task2B.3 Gravity: CHardwick.pdf).*

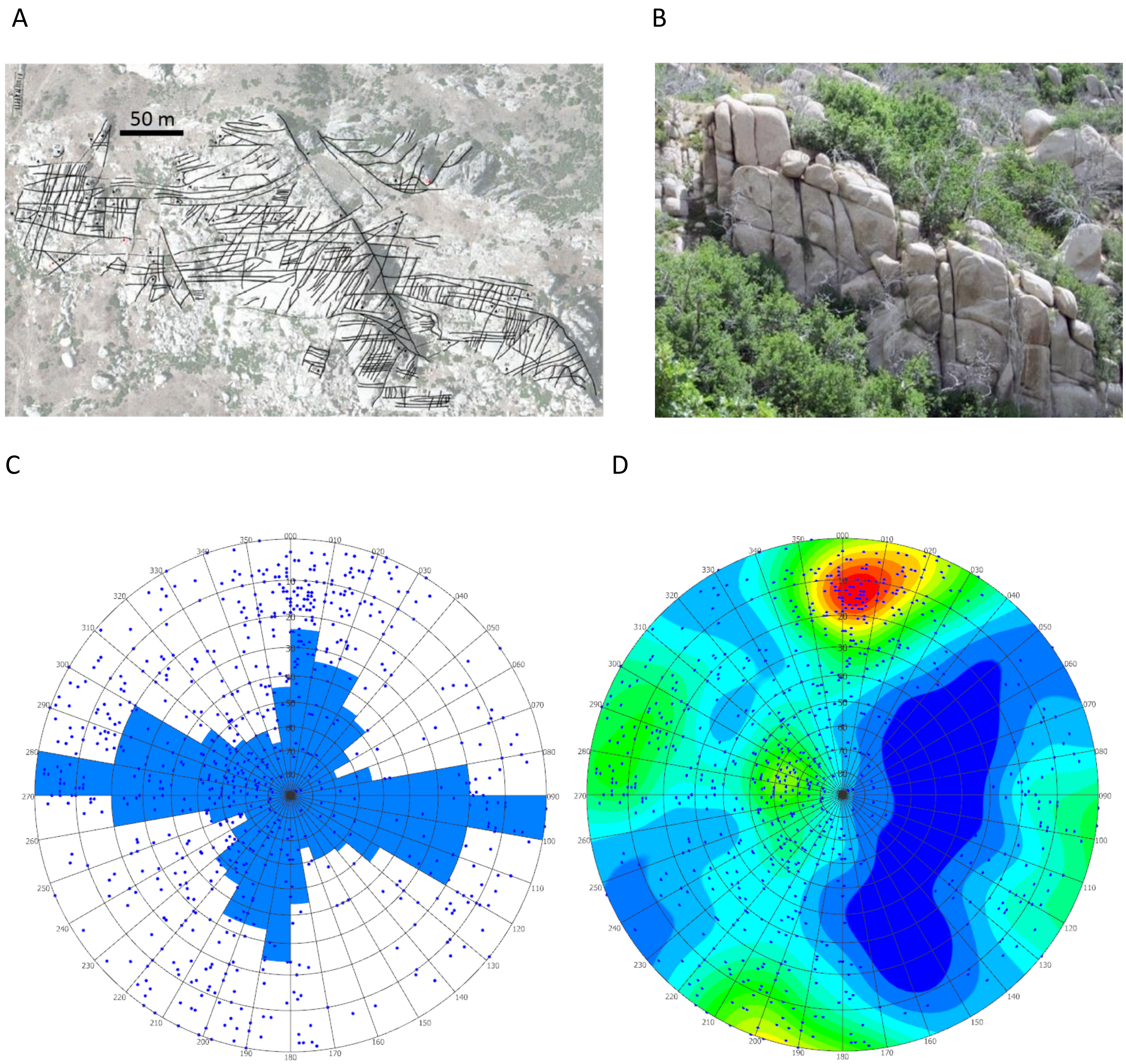


Figure II.1.3. *Fracture patterns in the central Mineral Mountains: A) Aerial view of fracture patterns in granitoid (scale bar=50 m); B) South facing view of conjugate fracture set rotated ~40°E during mid-Miocene uplift and exhumation; C) Rose diagram of fracture azimuths and stereo net showing poles to fractures projected to the upper hemisphere; D) Contoured stereo net of poles to fractures (upper hemisphere). In C and D, fracture azimuths fall into three predominant populations of 80 to 120°, dipping steeply to the north, and 0 to 30°, dipping steeply and gently west (the latter pair form the conjugate set in B).*

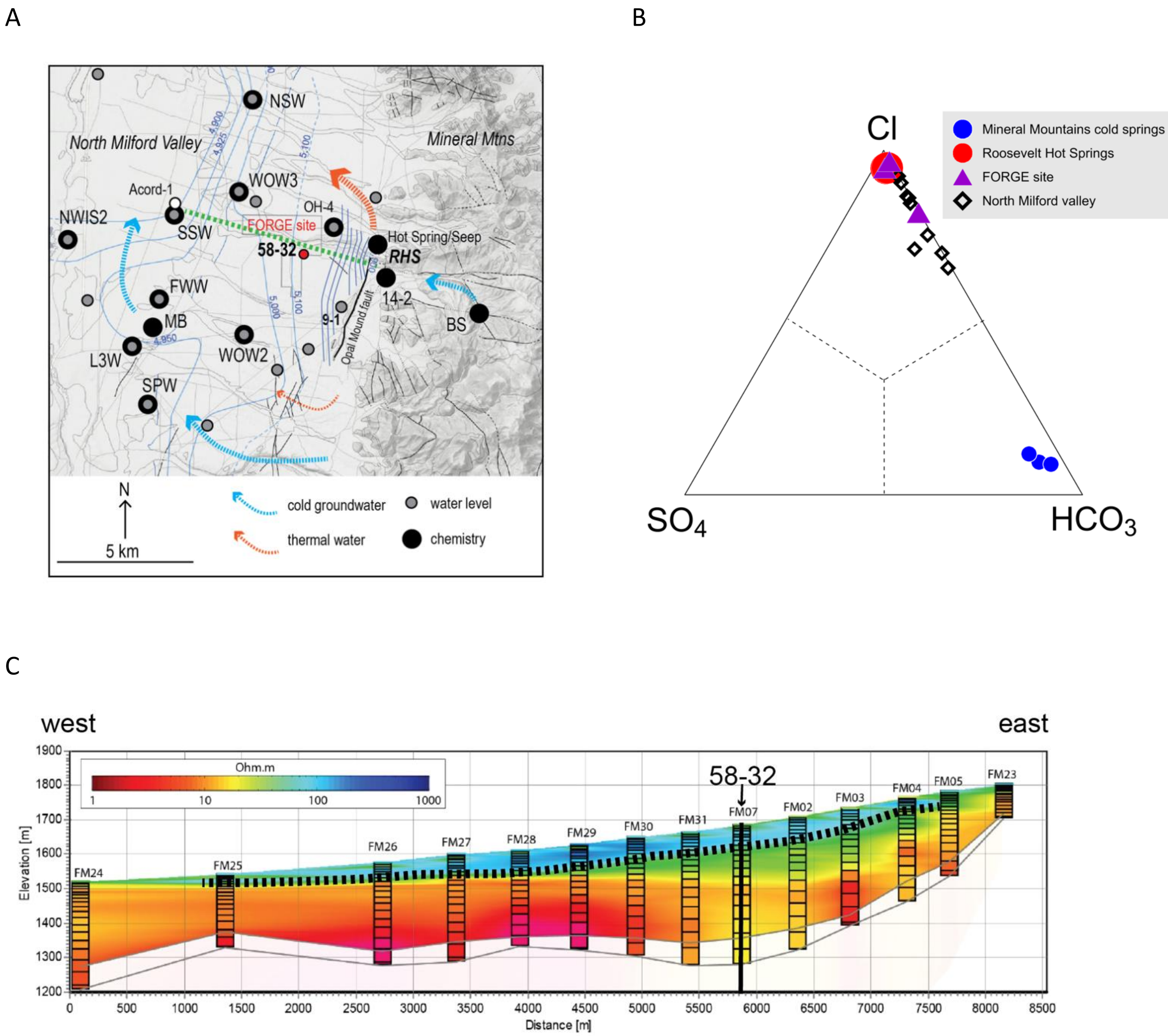


Figure II.1.4. *Geohydrology and groundwater composition and flow: A) Physiographic map showing shallow wells, piezometric level (blue contours), and groundwater flow paths (red and blue arrows) (RHS=Roosevelt Hot Springs); B) Cl-HCO_3-SO_4 plot showing geospatial variation in water compositions; C) Transient electromagnetic (TEM) pseudo-section, showing the shallow east-west resistivity structure (green dashed line in A) and the location of the water-table (dashed black line) over the FORGE site.*

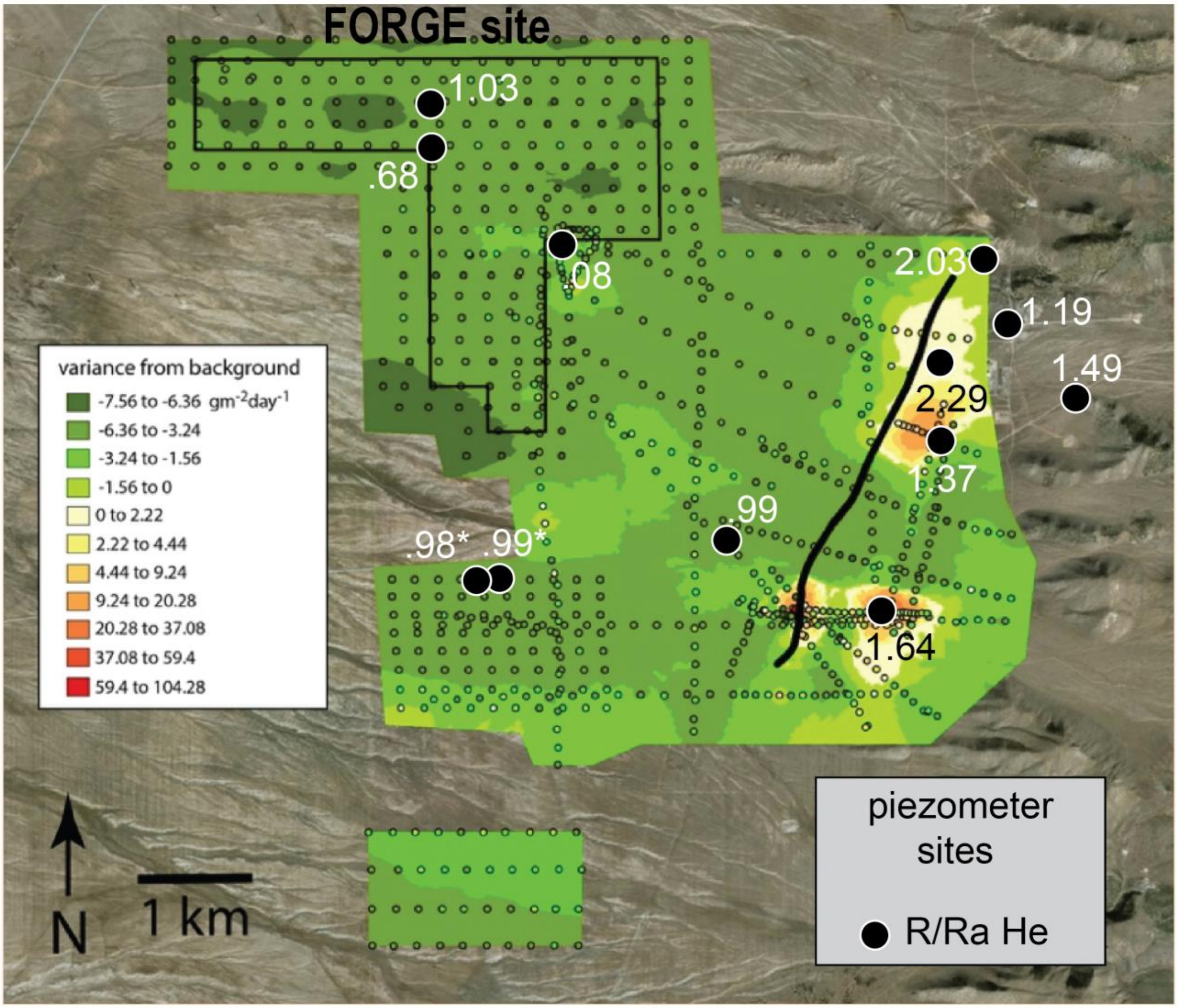
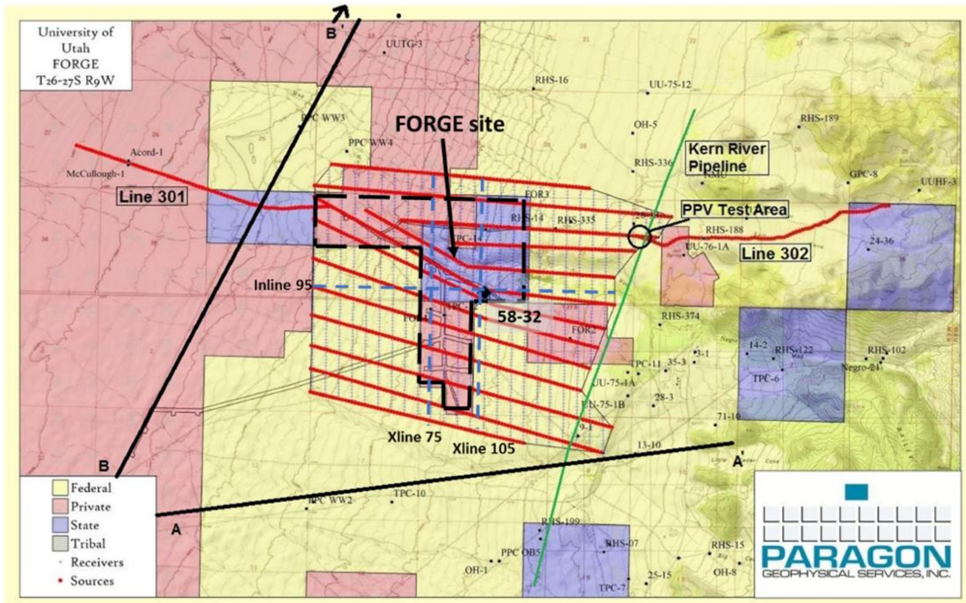


Figure II.1.5. *Soil gas carbon dioxide flux and helium isotopes, indicating the absence of hydrothermal activity beneath the FORGE site. The small open circles represent sample sites for carbon dioxide flux measurements obtained June, 8-26, 2017 and January 5-15, 2018. The statistical background flux for June 2017 is 7.56 gm^{-2}day^{-1} and for January, the background flux is 5.46 gm^{-2}day^{-1}. All green colors are at or below calculated background flux values, attributed to vegetation. Yellow to orange colors represent values above background associated with hydrothermal activity east of the Opal Mound fault (black line). Black filled circles are sample sites for diffusion samplers used to obtain helium isotope R/Ra data; values >1 are mainly located east of the Opal Mound fault, and they indicate a component of mantle helium associated with Roosevelt Hot Springs.*

A



B

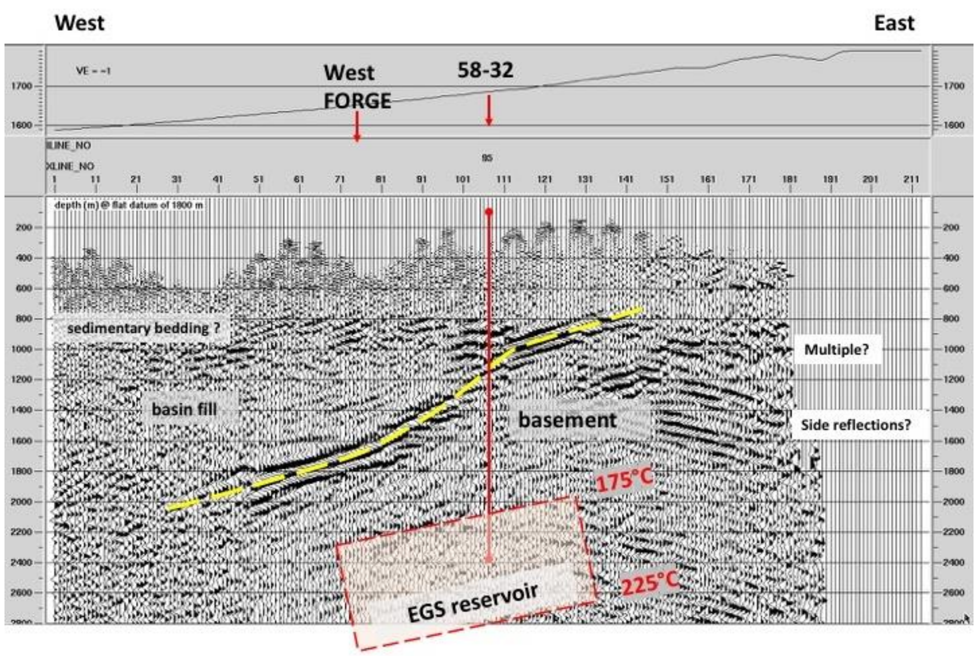


Figure II.1.6. *2D and 3D seismic reflection surveys and profile over the FORGE site; A) Seismic survey locations acquired November, 2017; B) East-west profile on Inline 95, which runs through well 58-32. Basement contact is highlighted with dashed yellow line.*

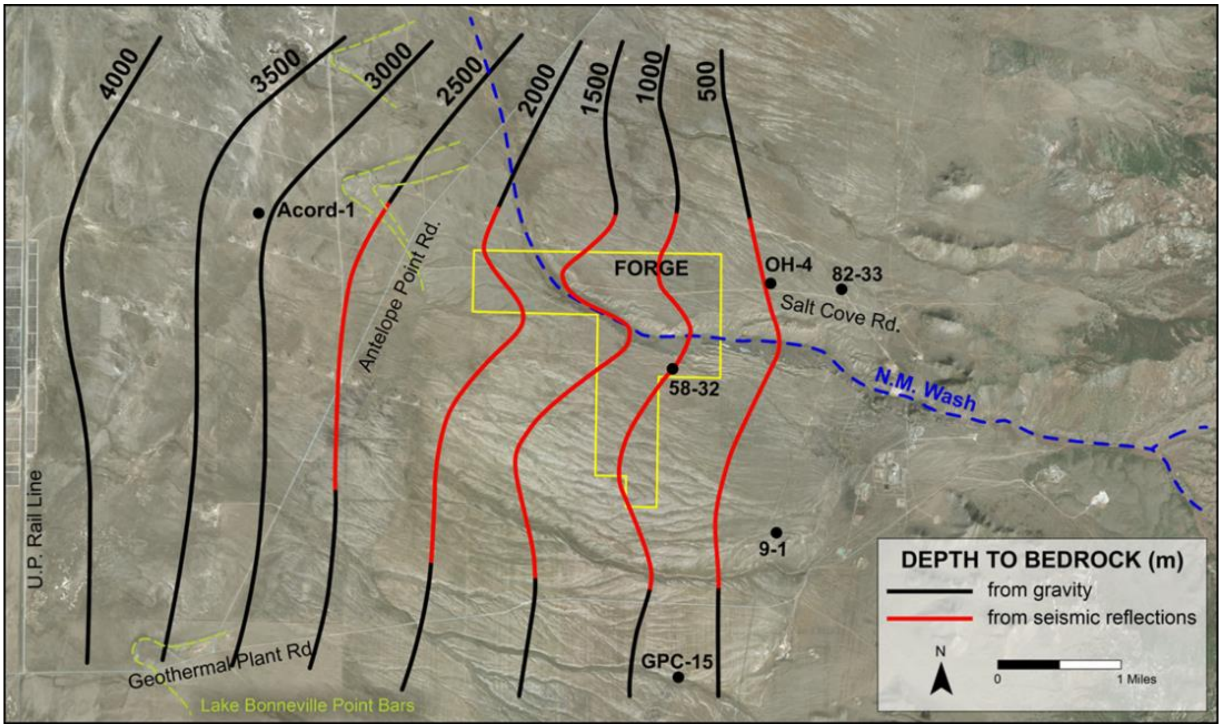


Figure II.1.7. *Structure contour map of the basement contact beneath the FORGE site from seismic reflection surveys and gravity modeling. Contours represent depth below a horizontal datum of 1800 m asl. N.M. wash=Negro Mag wash.*

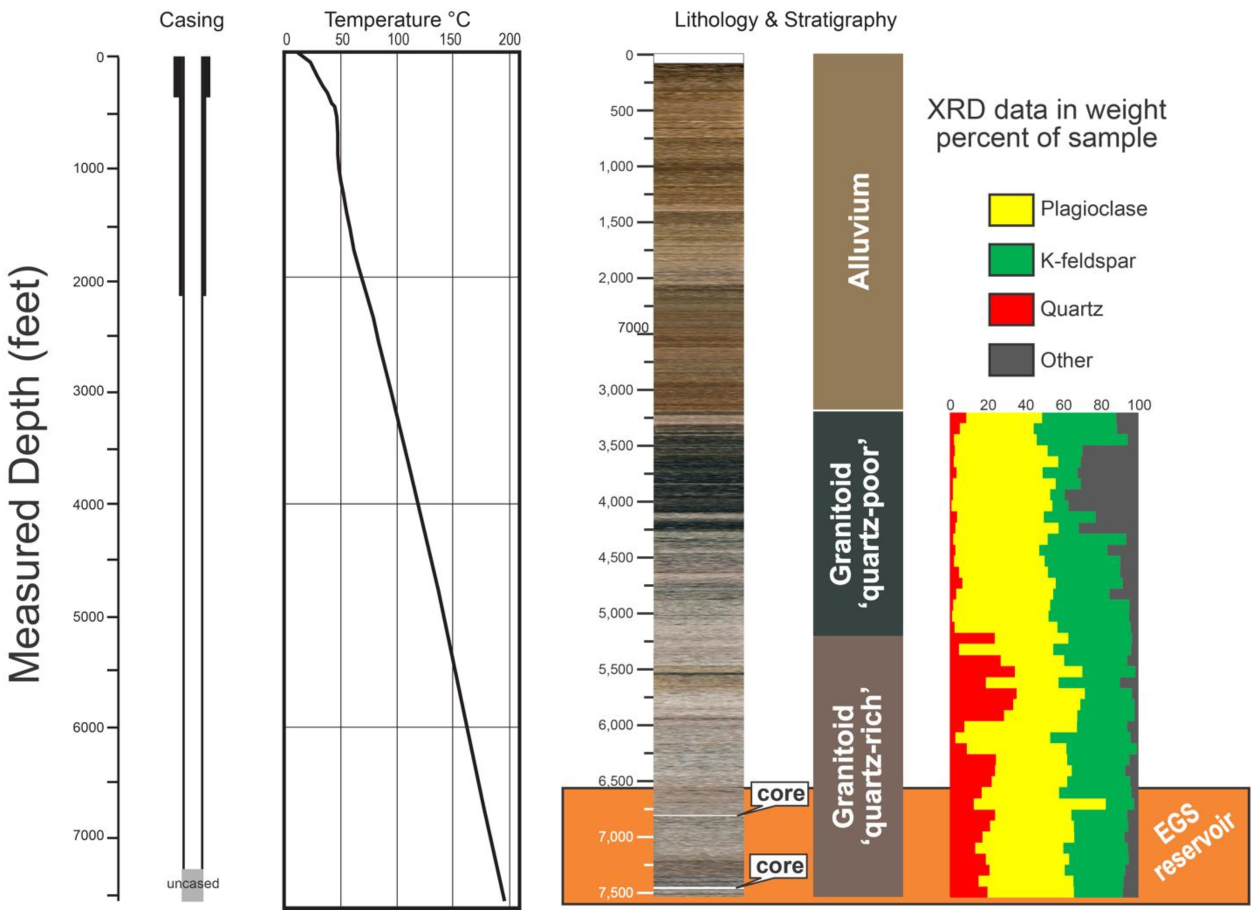


Figure II.1.8. *Well 58-32 casing profile, temperature gradient, stratigraphic and lithologic columns, and quantitative mineralogy, based on X-ray diffraction and thin section analyses.*

A

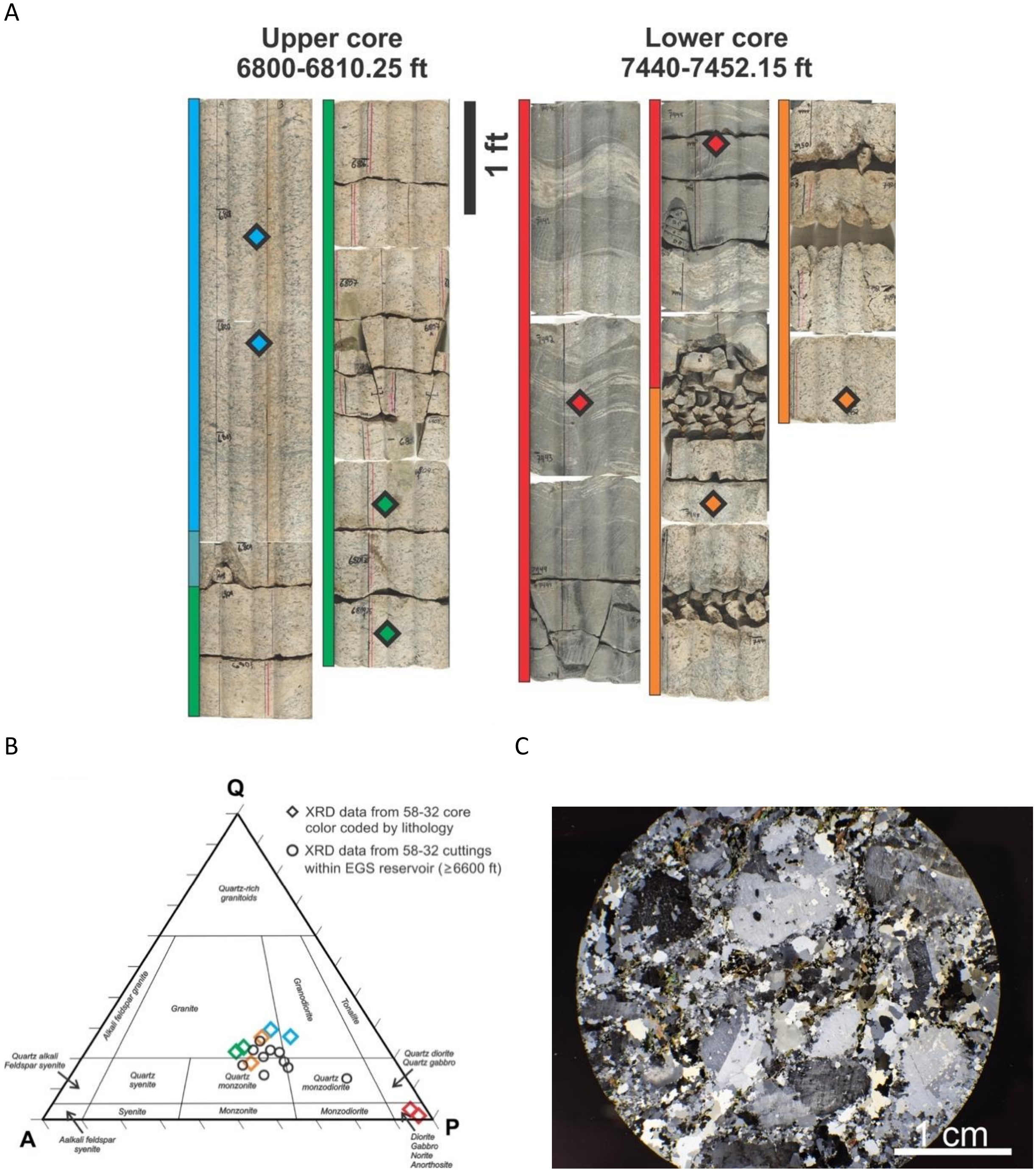


Figure II.1.9: *Upper and lower core intervals from 58-32. A) Cored intervals of crystalline plutonic rock where the light colored interval is granite and the dark colored interval is diorite. Below 5400 ft depth, the dominant plutonic rock type is granite, with rare diorite. B) IUGS classification scheme for plutonic rocks based on the proportion of quartz, alkali feldspar and plagioclase. C) Thin section (cross polars) of granite 7451.85 ft depth, showing interlocking texture and nil porosity.*

A B

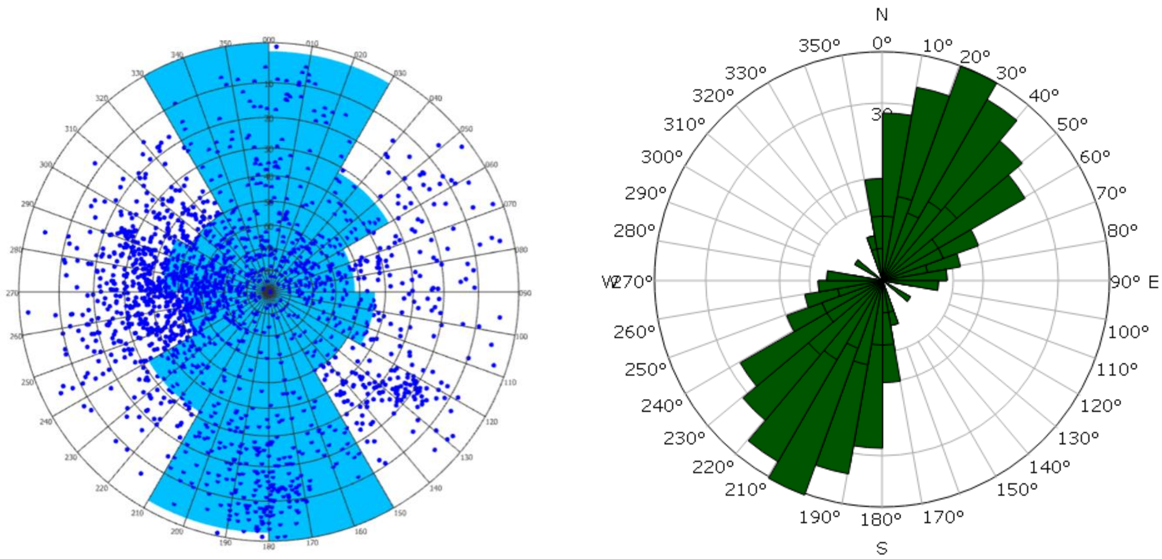
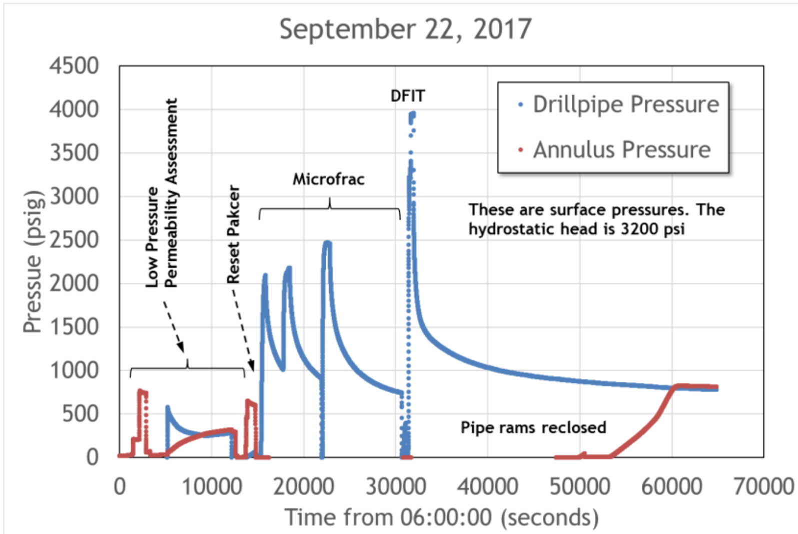


Figure II.1.10. *Well 58-32 fracture data: A) Rose diagram of fracture azimuths and stereo net of poles to ~2000 natural fractures (upper hemisphere projection); (B) Rose plot of azimuths of 356 drilling induced subvertical tensile fractures.*

A



B

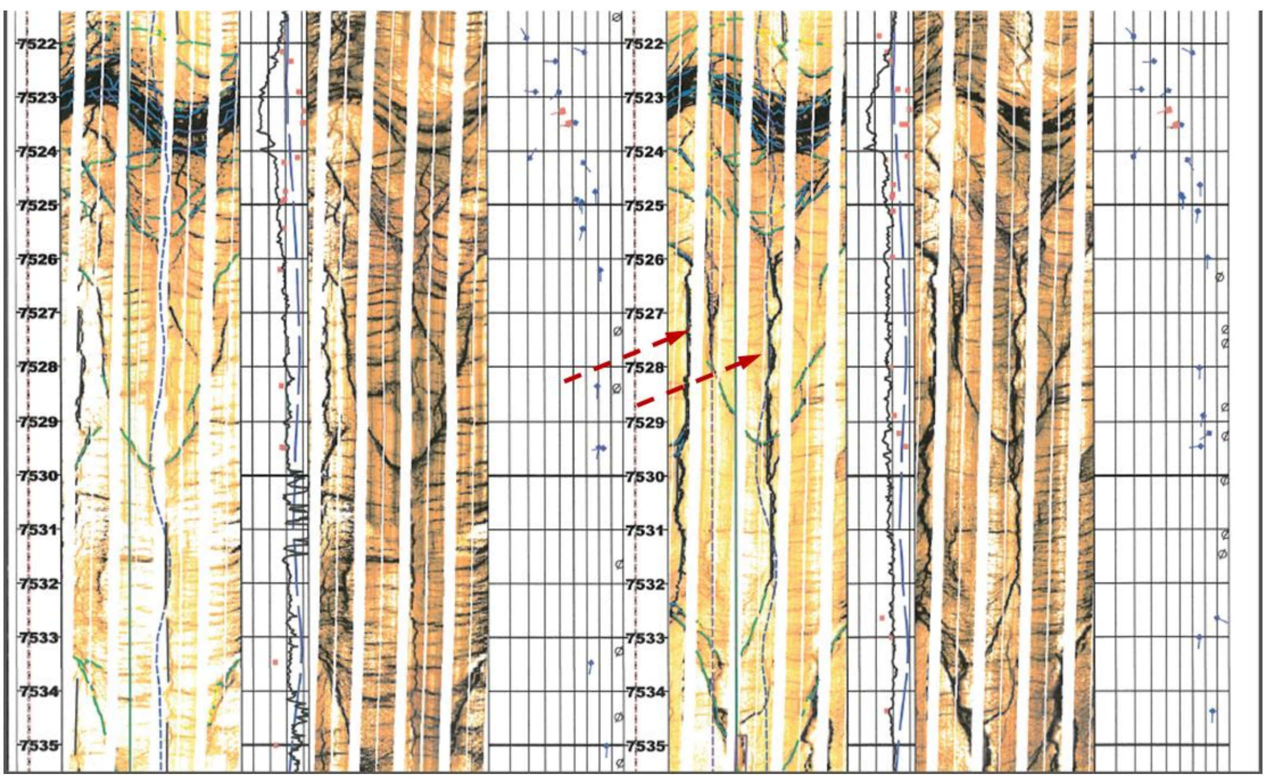


Figure II.1.11. *58-32 injection testing results. A) Time series of surface pressure measured at the wellhead; B) Comparison of FMI logs before (left two FMI images) and after (right two FMI images) injection, showing enhancement and growth of vertical fractures and the maximum horizontal stress in the north northeast direction. Symbols: tadpole=natural fracture showing orientation (dip azimuth and dip angle); circle with diagonal line=induced fracture and the angle represents strike azimuth.*

UNCERTAINTY ANALYSIS

Uncertainty is an important element of the Utah FORGE project since it quantifies confidence in the system model. Establishing uncertainty in this context is data intensive. Spatial error in geospatial datasets can be problematic since these data are often used to create statistical surfaces through various interpolation algorithms. Probability kriging and the calculation of the standard error of prediction using simple kriging have been used in this project for uncertainty analysis. Other data, such as seismic, have industry standards for error or known instrumentation error. Additionally, for some data, such as geology maps, certainty is virtually impossible to calculate due to the many factors involved. Multiple lines of direct measurement inform our confidence and increase certainty. The following describe the probability kriging results.

FAULT MAPPING

Quaternary fault mapping was done using field observation, aerial photo interpretation (digital orthophotography), and LiDAR digital elevation model interpretation. The LiDAR data was acquired and processed by Quantum Spatial, Inc. using a Leica ALS 80 LiDAR sensor with an average point density of 9.7 pts/m2. The resulting DEM had a spatial resolution of 0.5 m with an accuracy of ~5 cm RSME. Additionally, the geochronology of select faults was determined using Infrared Stimulated Luminescence which has an uncertainty of 5%-10% of the age of the sample (Roberts, et al., 2015).

TEMPERATURE ISOTHERMS

Isotherm maps were created by the Utah Geological Survey at several depth intervals in the FORGE study area. Spatial error for these data is shown in standard error of prediction maps, created using simple kriging (Figs. II.1.12– II.1.16). The error for these data is generally low for most of the FORGE site, although it usually increases somewhat in the northwestern part of the site.

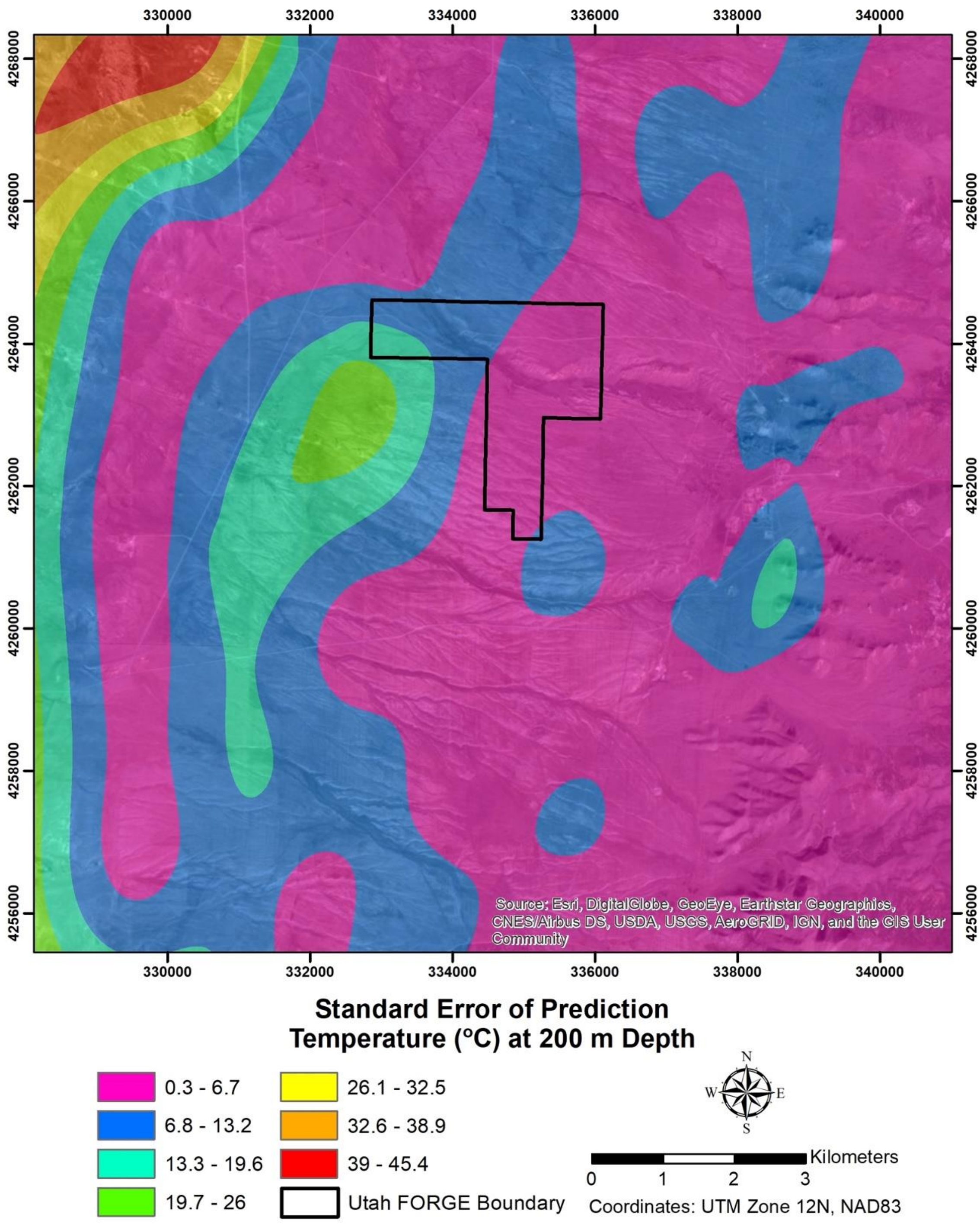


Figure II.1.12. *Standard error of prediction for 200 m depth isotherms, where spatial error is represented in °C. The error in the FORGE site is from low to very low, although it increases somewhat to the extreme northwest where data are sparse.*

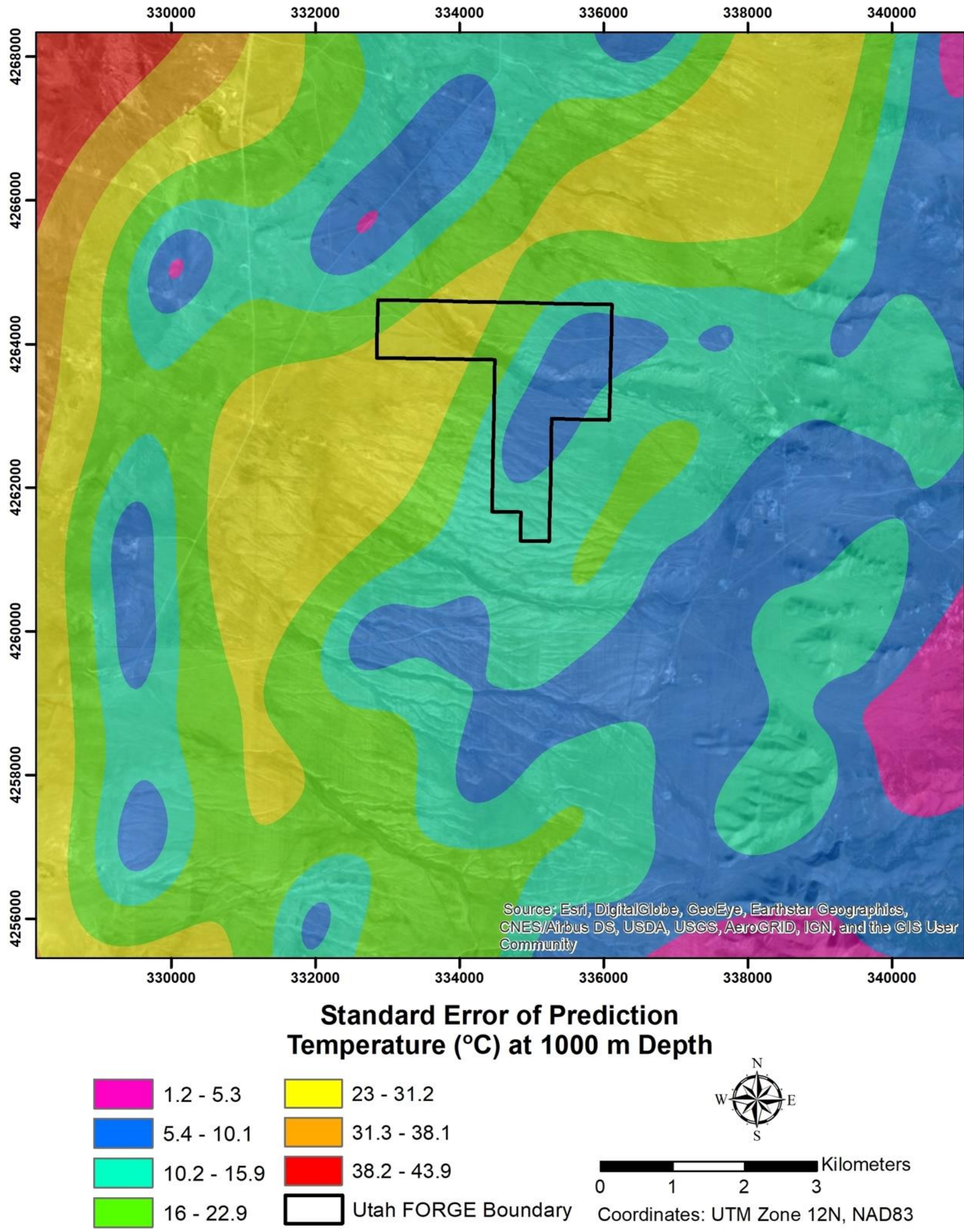


Figure II.1.13. *Standard error of prediction for 1000 m depth isotherms, where spatial error is represented in °C. The error in the FORGE site is generally low or medium-low, although it increases in the northwest.*

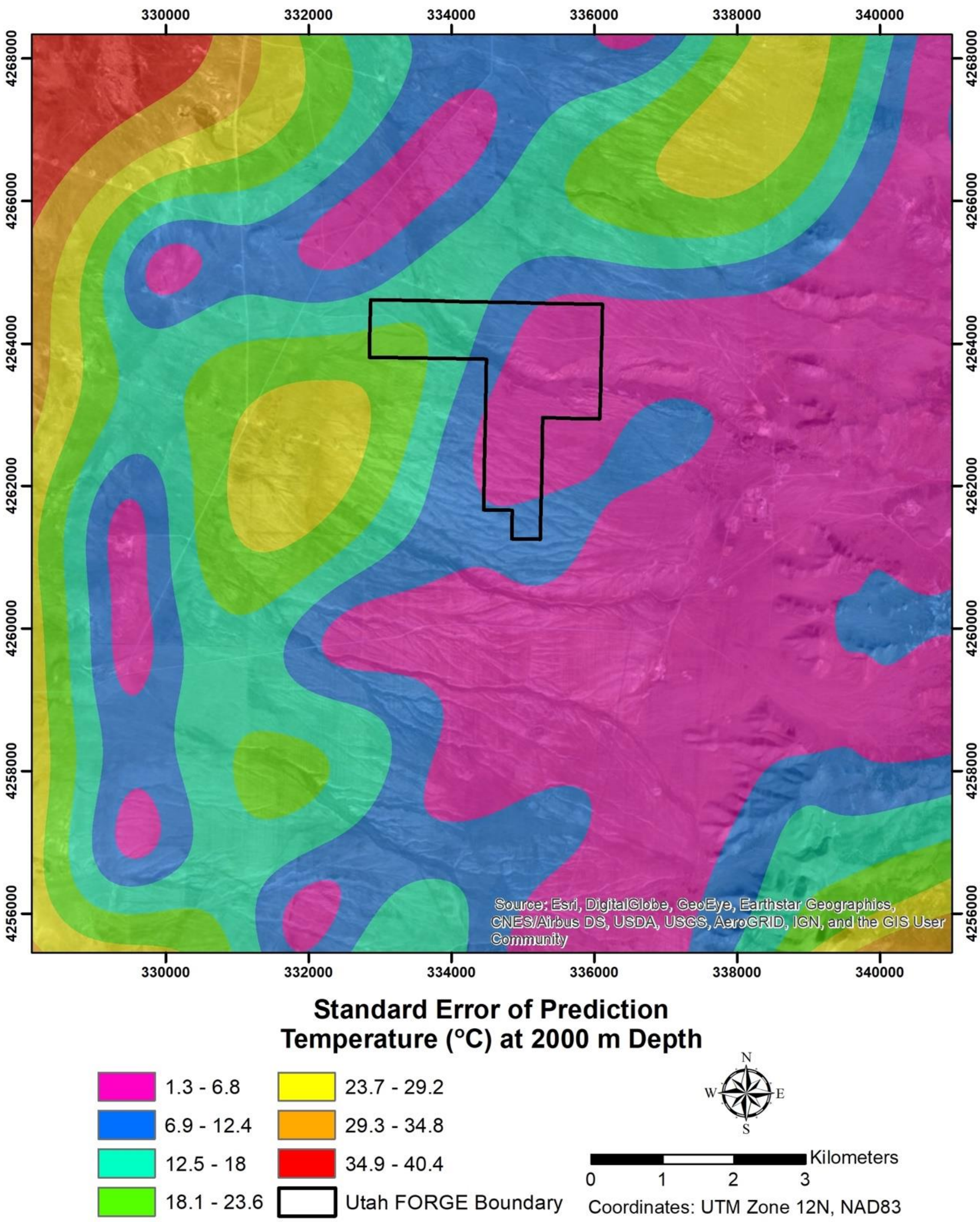


Figure II.1.14. *Standard error of prediction for 2000 m depth isotherms, where spatial error is represented in °C. The error in the FORGE site is from low to very low in general, although it is a bit higher in the northwest.*

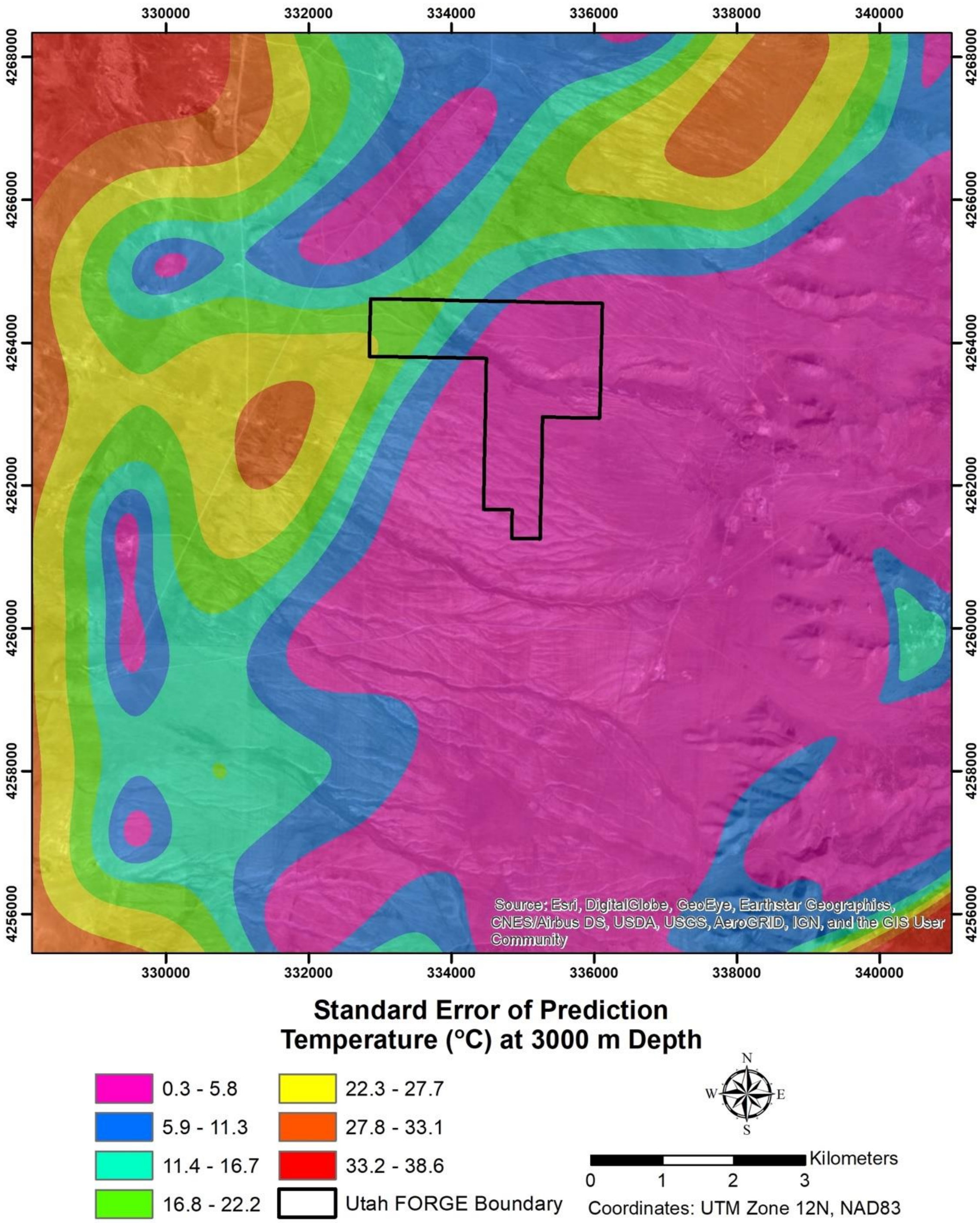


Figure II.1.15. *Standard error of prediction for 3000 m depth isotherms, where spatial error is represented in °C. The error in the FORGE site is generally very low, although it increases in the northwest*

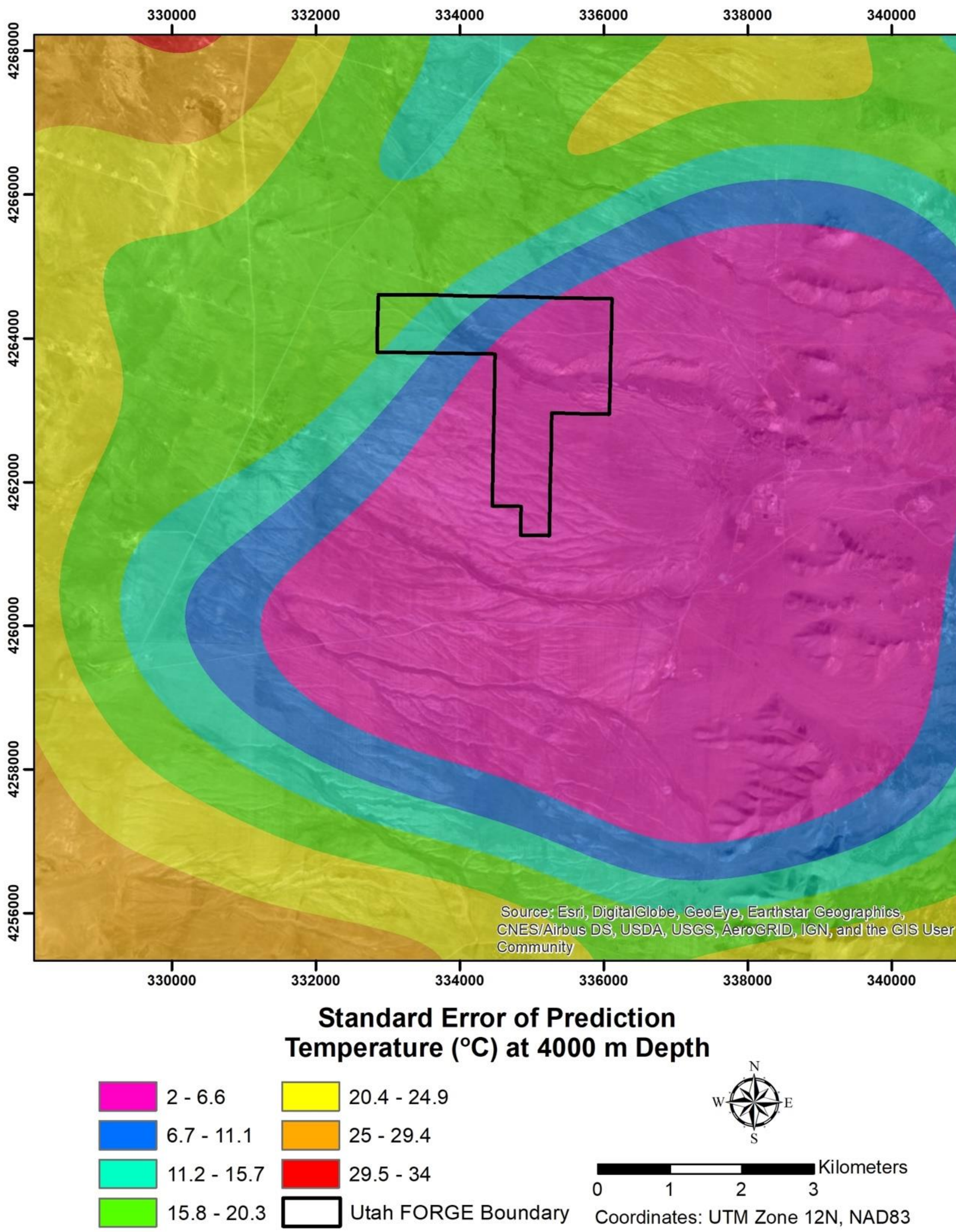


Figure II.1.16. *Standard error of prediction for 4000 m depth isotherms, where spatial error is represented in °C. The error in the FORGE site is generally very low, although it increases in the northwest. As expected, for greater depths the uncertainty contours become smoother.*

GRAVITY

A gravity survey over the broader Utah FORGE region was performed by the Utah Geological Survey to aid in the understating of the geologic structure. Stations were occupied using a Scintrex CG-5 Autograv, which has a measurement precision of 0.001 mGal and accuracy better than 0.005 mGal. The CG-5 gravimeter measures relative gravity using a base station loop which requires post-processing to obtain observed gravity values. Our post-processing of the FORGE gravity data resulted in 0.001 mGal of RMS error. The survey also used high-precision GPS equipment that consistently achieved better than 0.10 m in elevation control. Terrain corrections were computed by hand to 0.001 mGal for each station. Spatial error can be seen in Figure II.1.17, where the greatest error occurs in the Mineral Mountains on the east-southeast side of the map. In the general FORGE area, error is relatively low.

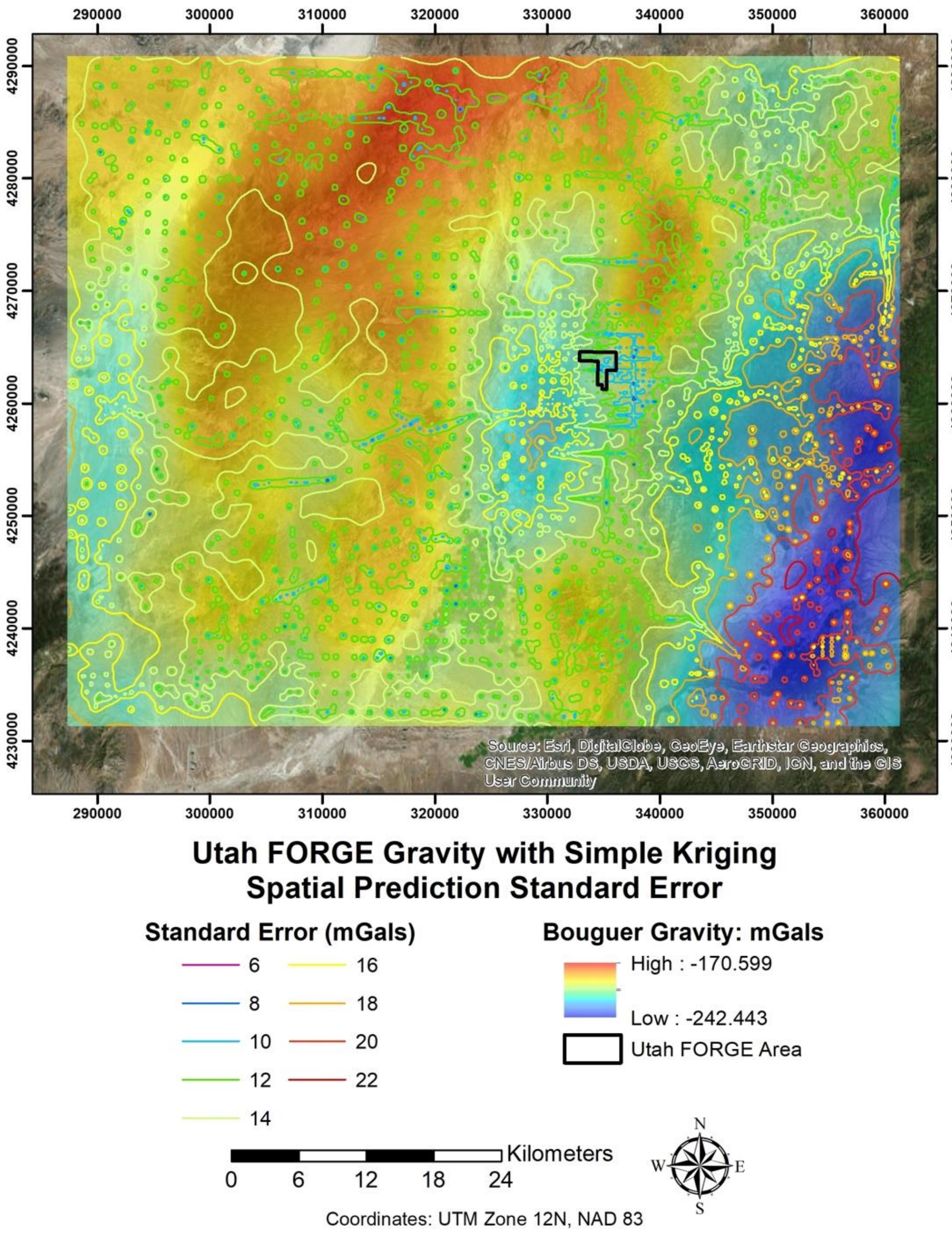


Figure II.1.17. *Simple kriging was used to convert gravity station Bouguer corrected values to a statistical surface. The standard error of prediction, which relates to spatial error, is seen in the contours in mGals. The FORGE area shows relatively low error.*

SEISMIC REFLECTION

Seismic reflection results were used to map the top of crystalline rock (granitoid) beneath the Utah FORGE project area (Fig. II.1.18). The main source of uncertainty in reflection seismic profiling rests with the determination of velocity directly from the seismic data and subsequent depth to the reflecting interfaces. Velocity determination depends on adequate source-receiver offset (the distance between the seismic source and the receiver farthest away from it) relative to the depth of the target that is to be imaged. The maximum source-receiver offset in the 3D patch, greater than 3000m, is suitable for determining the velocity field with a high degree of confidence. In addition, we have measured velocity and depth in well 58-32, which assisted in calibrating the velocity analysis. To test the accuracy, we used Inline 93, which intersects the well. We converted that line from time to depth using only the well velocities, and then converted it to depth using seismic-derived velocities. The difference in depth to the granite interface was less 20 meters, which at 1000m total depth to the granite interface is less than 2%. In addition, the velocity field away from the wellsite was consistent, and structural contours on the top of the basement derived from the seismic data integrate seamlessly with gravity modeling (Fig. II.1.2).

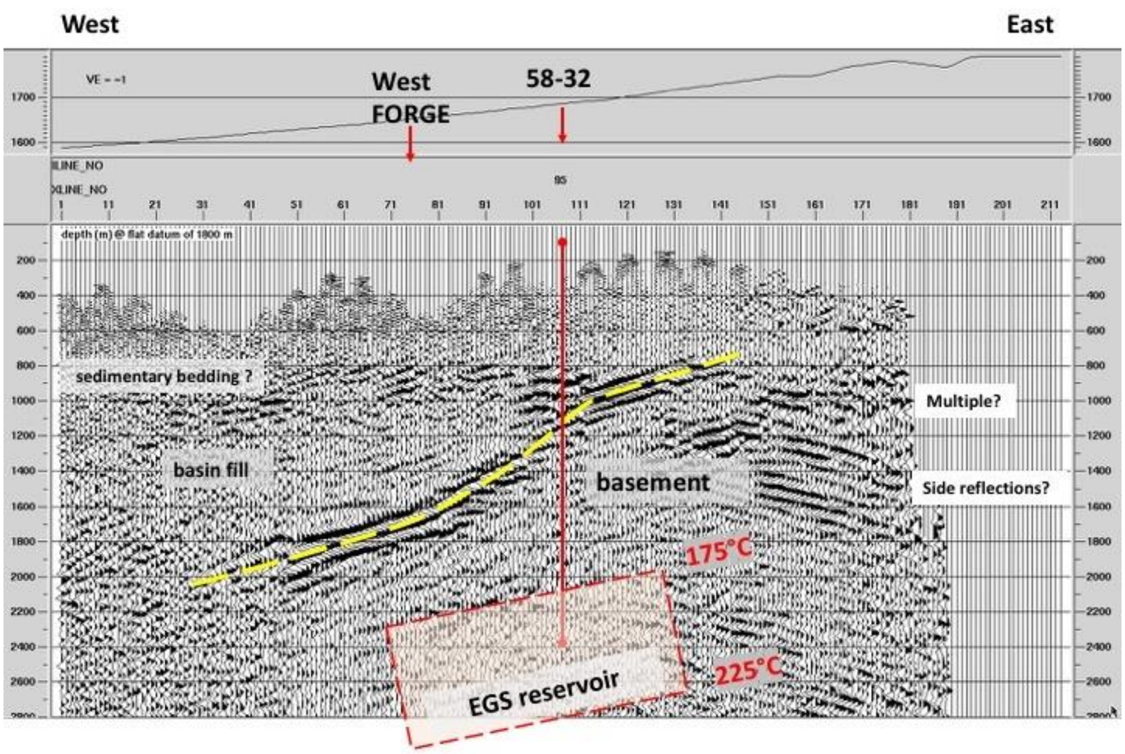


Figure II.1.18. Seismic reflection profile on Xline 95, showing the basement contact dips west between 25 and 35° west.

TRANSIENT ELECTROMAGNETIC (TEM) SURVEY

A TEM survey was completed by Utah Geological Survey to aid in structural interpretation and to identify the ground water surface. The data quality is good for nearly all stations and depth of investigation values average 300 m. On this scale, uncertainty in depth of detected features is on the order of 5–10 m and model nRMS values are typically less than 1.

SOIL GAS GEOCHEMISTRY

Helium isotope (R/RA) and CO_2 flux surveys can help identify blind hydrothermal systems. For the Utah FORGE site, it is important to eliminate this possibility. Figure II.1.19 shows a probability map of soil helium R/Ra values in relation to the atmospheric R/Ra value (1.0). Probabilistically, the R/Ra values in the Utah FORGE site are at or very near that of atmospheric R/Ra, and there is a clear demarcation between the Blundell Power Plant geothermal well field on the eastern side of the map and the FORGE site.

Figure II.1.20 shows the simple kriging standard error of prediction for CO_2 variability, which is from very low to low in the FORGE site. This data was analyzed with a PP Systems EMG-4 or EMG-5 portable carbon dioxide analyzer which has an error of ±2.7%. The favorable CO_2 variability coupled with R/Ra probability indicates that the FORGE site lacks evidence of subsurface hydrothermal fluid flow.

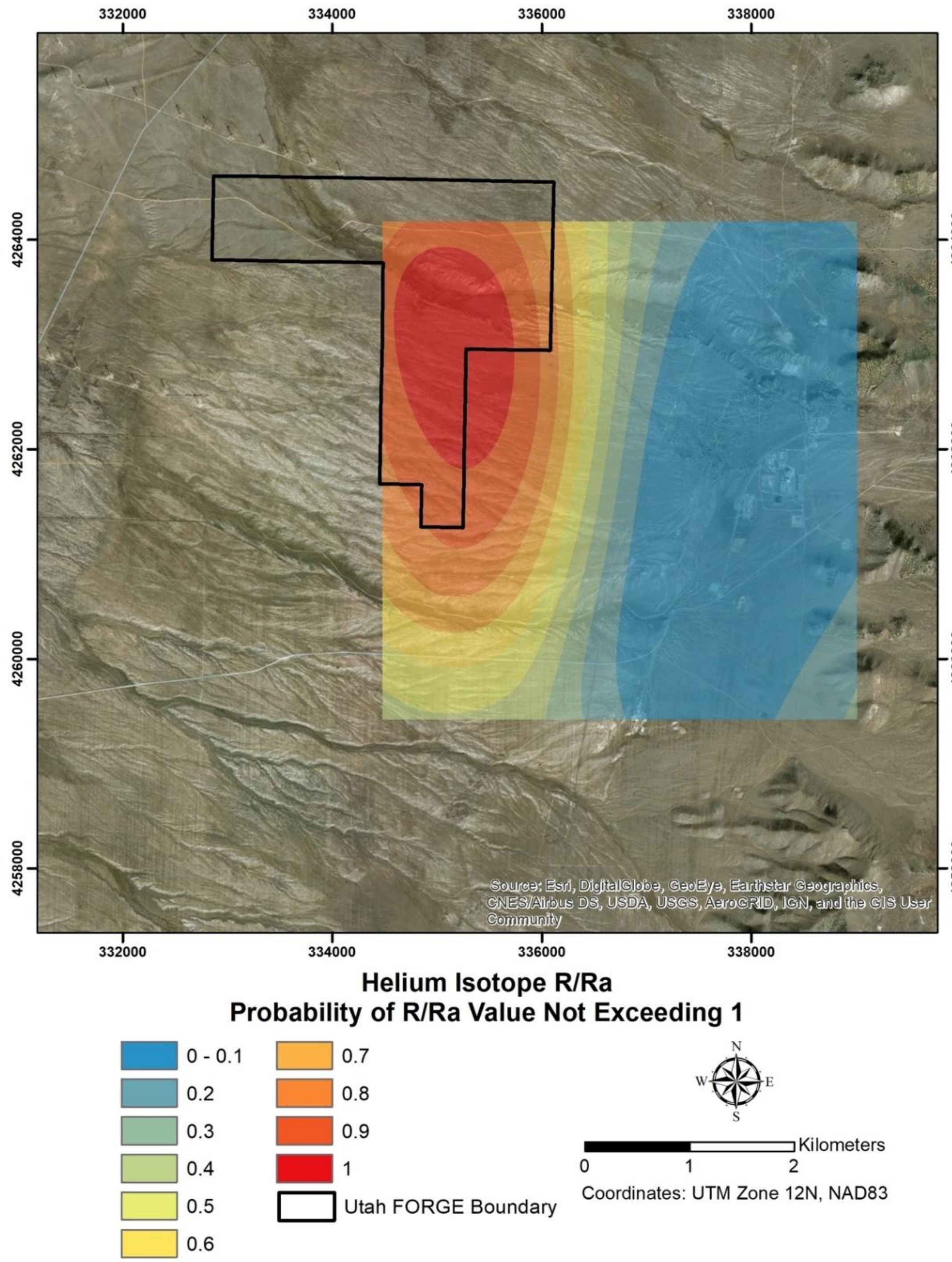


Figure II.1.19. *The probability of helium R/Ra resembling background values. The FORGE site, where data was available, generally has probability in the range of 0.08-1.0 indicating a high certainty of no hydrothermal activity, while the area near Roosevelt Hot Springs, to the east, shows low probability indicating an active system.*

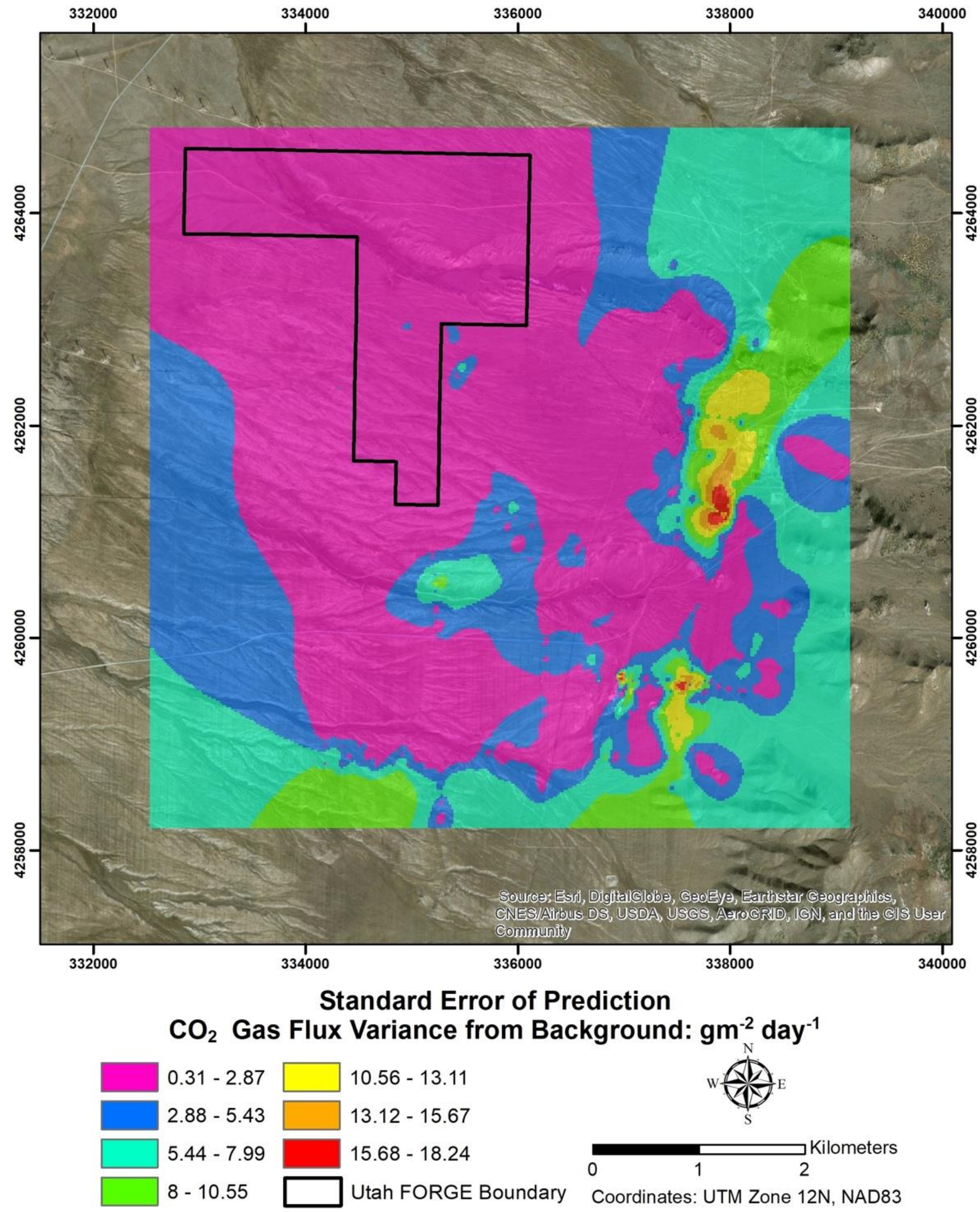


Figure II.1.20. *This map shows the standard error of prediction for soil CO_2 flux variance from background, calculated using simple kriging. The FORGE site shows very low error potential, thus giving high certainty of the CO_2 flux variability in this area, which compared well with background flux suggesting no hydrothermal activity.*

GROUNDWATER

The quality and availability of groundwater is an important element of FORGE. The quality is affected by total dissolved solids (TDS), which are predicted to be high within the FORGE site. Figure II.1.21 shows the standard error of prediction, in TDS mg/L, from simple kriging. The error is relatively high in the FORGE area, but wells to the east all have high TDS levels. Figure II.1.22. shows potential spatial error for the top of the water table.

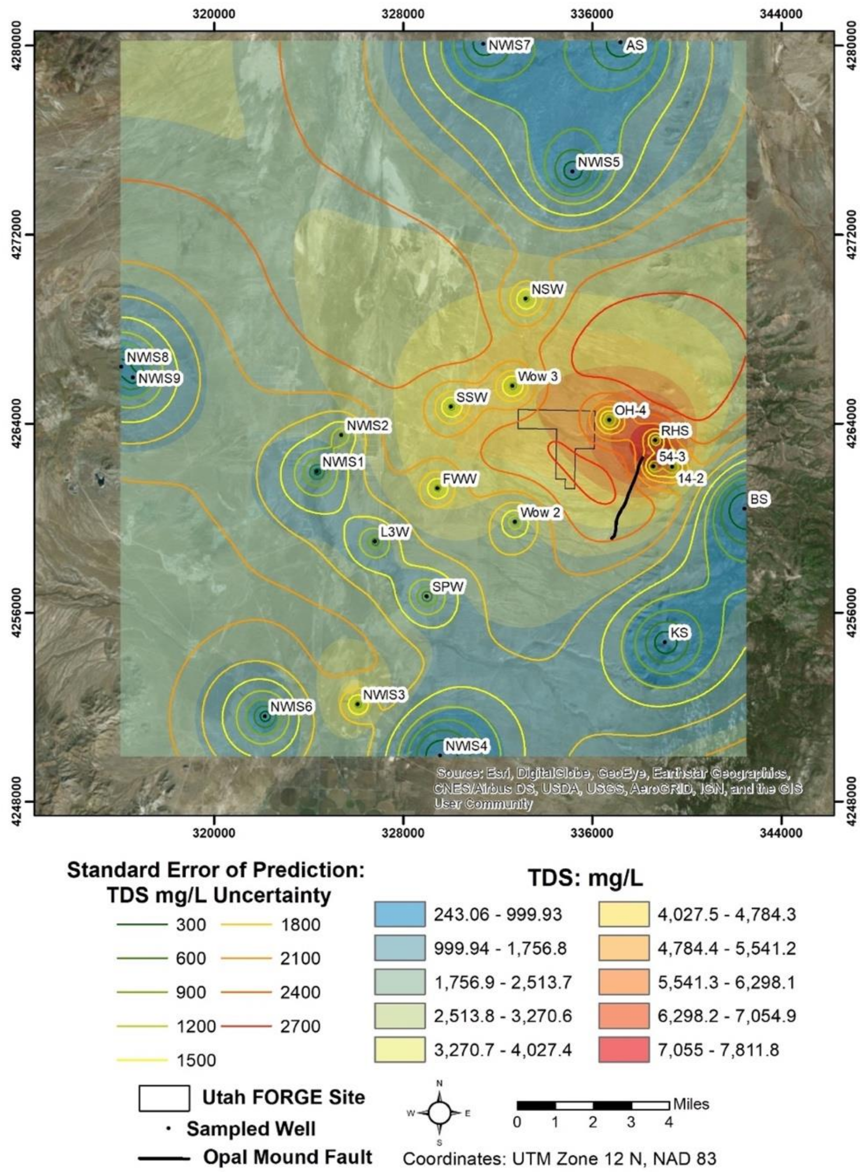


Figure II.1.21. *This map shows simple kriging standard error of prediction contours superimposed on a TDS statistical surface. The error is relatively high in at the FORGE site.*

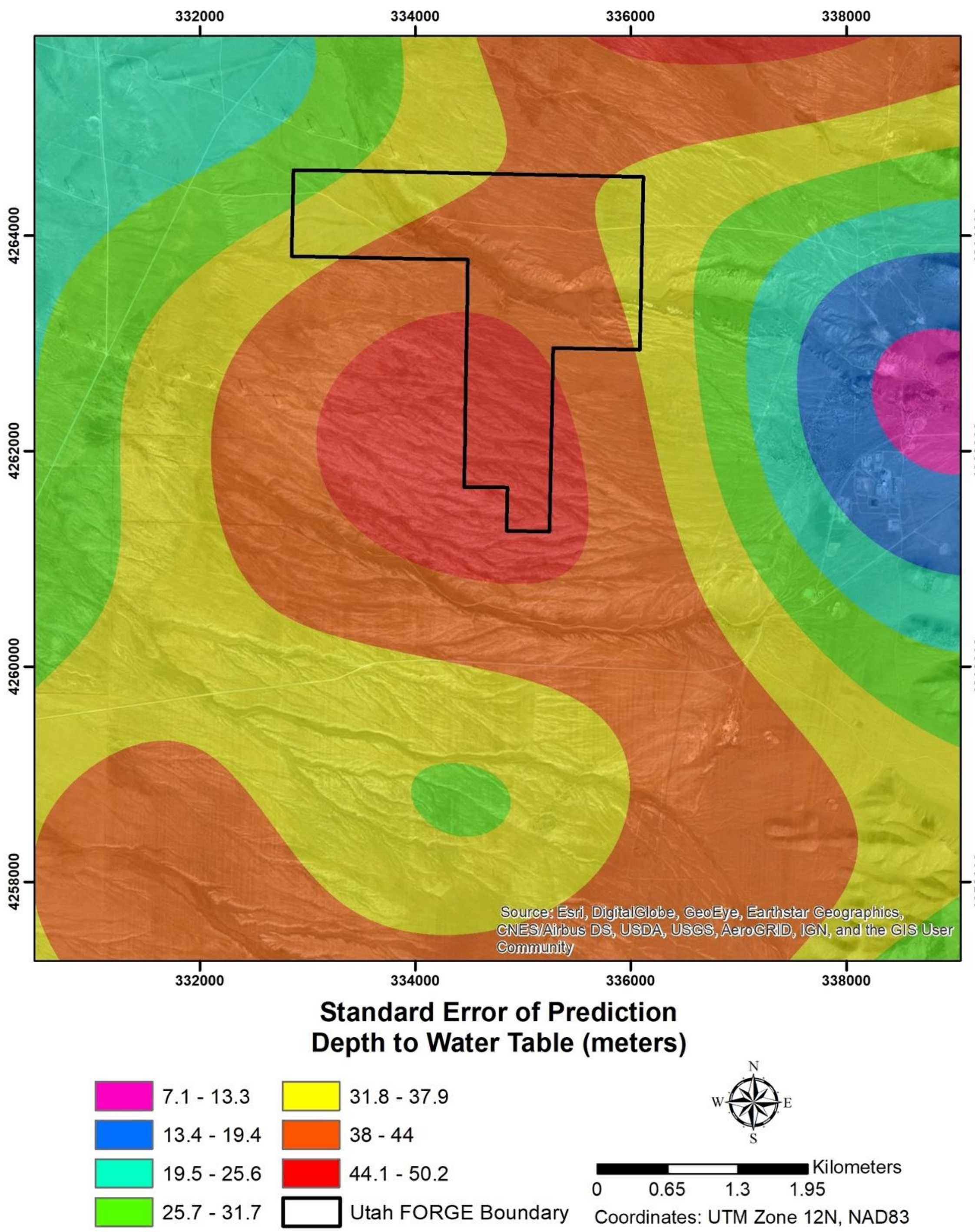


Figure II.1.22. *This map shows potential spatial error for the top of the water table in depth m. This was created using simple kriging standard error of prediction. The error in the FORGE area is relatively high, however, the range of depth to ground water is relatively shallow in nearby wells, ranging from 15 m to 166 m.*

DISCRETE FRACTURE NETWORK MODEL

Discrete Fracture Network (DFN) modeling develops a probabilistic representation of *in situ* fractures. Construction of the model required processing of nearby field mapping, in-well logging, core, and well test information. Uncertainties in the DFN model were characterized by generating multiple stochastic realizations of the background fractures. A normal distribution probability density function was used to determine a range of probabilities for fracture dip azimuths and lengths. An example for dip azimuths is shown in Table II.1.1.

Table II.1.1. *An example of probability ranges for fracture dip angles.*

Probability (%)	Dip Azimuth Range
100	352-76^{o} (172-256^{o})
50	22-38^{o} (202-218^{o})
25	4-57^{o} (184-237^{o})

PERMEABILITY TESTING

The certainty of permeability testing was insured by the use of best practices, which included the following steps: (1) labeling of the samples using a permanent marker; (2) photographing the samples; (3) samples were cut to 3+ inches in length and both ends machine ground to ISRM tolerances and the sample ends were flat and parallel; (4) the clipped ends of the samples were saved and sent for SEM, XRD, and high magnification thin sections; (5) using calipers to carefully determined dimensions -- four measurements were averaged for the length (90° apart) and four measurements for diameter; (6) weights were recorded as an average of four measurements in an as-received condition; (7) porosity was measured using an UltraPore 300 porosimeter after which the sample weight was recorded; (8) all flow lines were prefilled with DI water as required; (9) the sample was installed in the core holder and placed in the permeability apparatus; (10) 500 psi was applied on the back pressure regulator and 2500 psi confining pressure; (11) the temperature was 25°C; (12) started flowing water and waited for steady state and the flow rate was determined according to the pressure provided across the sample and, If the flow rate was inadequate, confining pressure could be increased to allow a greater flow rate -- the maximum upstream pressure could not exceed the confining pressure or the flow would bypass the sample (between the membrane and the sample); (13) recorded the pressure differential until it stabilized, calculated the permeability, and ensured that three pore volumes (minimum) had been flowed; (14) increased the temperature to 140°C and repeated steps 12 and 13 at this temperature; (15) reduced the temperature to 25°C, increased confining pressure to 7500 psi, and repeated step 12 and 13; (16) increased the temperature to

140°C, repeated steps 12 and 13 to determine the effective permeability to water at that confining pressure and 140°C; (17) after all testing, the sample was removed and weighed.

X-RAY DIFFRACTION

X-ray diffraction (XRD) has been an important tool for this project to identify and quantify the mineralogy of outcrop rock samples as well and core and drill cuttings. According to Hillier (2000) the accuracy of this type of analysis is ~±3 wt.% at the 95% confidence level and it was found by Lu et al. (2016) to have a mean error of ~3%. The instrument used in this project for XRD is the Bruker D8 Advance.

INDUCED SEISMIC HAZARD MITIGATION

Induced seismic hazards in geothermal production areas must be considered. Figure II.1.23 depicts probabilistic seismic hazards at the FORGE site based upon historical occurrences.

Additionally, the 2014 U.S. Geological Survey National Seismic Hazard Maps (Peterson et al., 2008) shows the Utah FORGE study area to be in a region of low to moderate seismic hazard. There is a 10% probability that the peak ground acceleration (PGA) will exceed 20% g in the next 50 years. Deaggregation shows that the largest contribution to the PGA 10% in 50 years hazard comes from M < 6.5 earthquakes within 50 km of the site. There is a 10% probability that the peak ground acceleration (PGA) will exceed 35% g in the next 50 years.

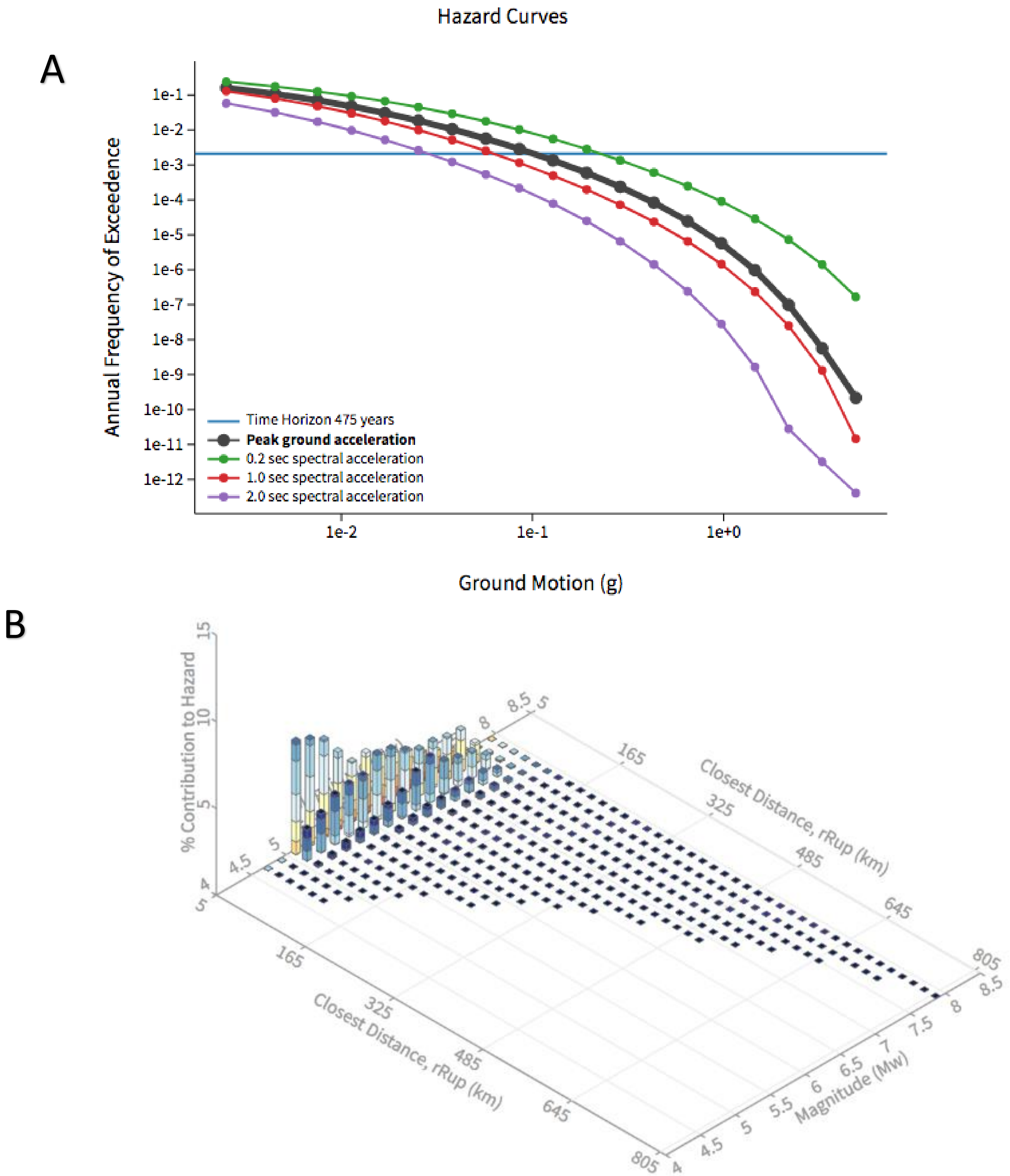


Figure II.1.23*. Probabilistic seismic hazard at the FORGE site from the 2014 National Seismic Hazard map and tools found at (https://earthquake.usgs.gov/hazards/interactive/; last accessed 1/29/2017). (a) Hazard curves for the FORGE site. (b) Deaggregation for the 10% in 50 yrs PGA hazard (475 yr return period). Results show that the largest contribution to this hazard is from M 5.2 earthquakes at <20 km distance.*

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Frontier Observatory for Research in Geothermal Energy – Milford Site, Utah

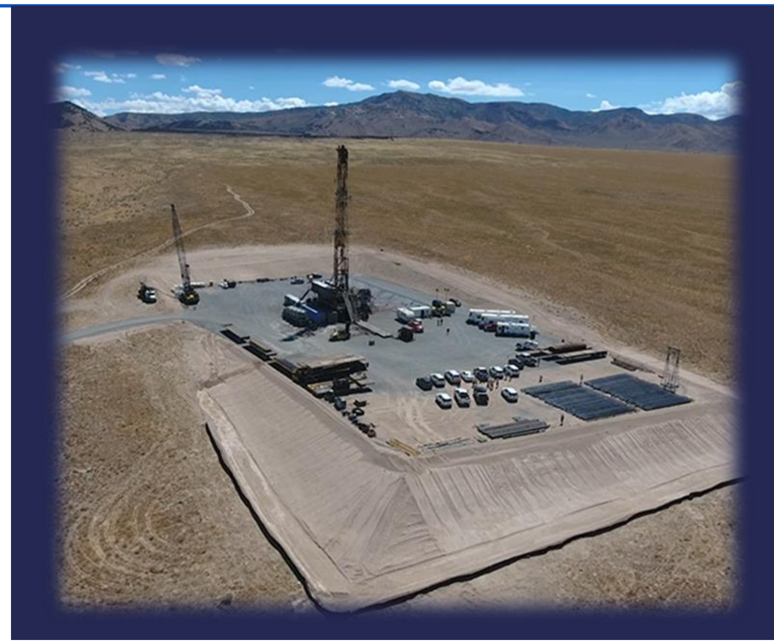
Section II. RESULTS - Discussion of Current Status of the NEPA Process

UTAH FORGE
U.S. Department of Energy

March 15, 2018

II.2 NEPA STATUS

In Phase 2B, a Draft Environmental Assessment entitled “Frontier Observatory for Research into Geothermal Energy (FORGE), Milford, Utah (DOE/EA-2070D)” was prepared under a cooperative agreement between EGI, SWCA (EGI’s environmental consultant), and NETL (refer to Appendix A5). A draft EA was issued on 1/31/18. The public comment period was closed on 3/2/18, with no comments from the public, any agency or Tribe. A final version of the EA is being prepared prior to NETL issuing a FONSI. The FONSI is expected prior to 3/29/18. Although limited periods of restricted access to public lands may be required to accommodate hawk nesting periods, activities during this period can be conducted on ground unsuitable for nesting hawks, as they were during the drilling of well 58-32.



Frontier Observatory for Research in Geothermal Energy – Milford Site, Utah

Section II. RESULTS – Overview of Seismic Monitoring Activities

UTAH FORGE
U.S. Department of Energy

March 15, 2018

TASK 2B.12: SEISMIC MONITORING PHASE2B FINAL REPORT

This report summarizes work related to seismic monitoring from Phase 1 through Phase 2B to give as complete as possible picture of the seismicity located in the region surrounding the FORGE site (Figure II.3.1). There is also discussion at the end regarding different projects aimed at using seismic data collected for the project in imaging analyses.

To evaluate the historical seismicity, we review four relevant earthquake catalogs: (1) a uniform moment magnitude catalog (1850–September, 2012; Arabasz et al., 2015); (2) the microseismic catalog (August, 1979–August, 1981) collected by Zandt et al. (1982); (3) the UUSS earthquake catalog, 1981–2016; and (4) the catalog collected as part of the FORGE project (November, 2016–February, 2018). For all four catalogs, seismicity near the FORGE site is low-magnitude and low-frequency. Using the Arabasz et al. (2015) catalog, we observe that the largest event in the study area (M_W 4.05) occurred in 1908 and was located near the town of Milford (Figure II.3.1). The closest significant earthquake (M > 6) occurred in 1901 in the Tushar Mountains north of Beaver ~50 km to the northeast of the Utah FORGE site.

Before production at Roosevelt Hot Springs, Zandt et al. (1982) installed a local seismic array to detail the background seismicity. During the approximate 2 year deployment, they concluded that there are few earthquakes M > 2. They did capture one energetic seismic swarm (1044 earthquakes M ≤ 1.5) during June through August 1981. This swarm occurred east of the present borefield at the Blundell Power Plant, primarily in the Mineral Mountains (Figure II.3.1). The seismicity trend was mostly east-west. They concluded that the swarm was primarily naturally occurring and was consistent with either (or both) seismicity occurring along the projection of the east-west trending Negro Mag fault or along northwest trending faults mapped by Nielson et al. (1978). A few of the earthquakes located on the west end of the swarm may have occurred along the Opal Mound Fault, but this interpretation remains speculative.

In support of the Utah FORGE project, events in the UUSS catalog (1981–2016) were relocated using updated velocity models, with depths set relative to sea level (Figure II.3.1). The relocation of the events caused slight changes in location, but overall provided tighter spatial clustering. No earthquakes in this time period locate within the proposed FORGE footprint (Figure II.3.1). Earthquakes occurring outside the Utah FORGE footprint during this time period range in magnitude from M -0.09 to 3.91. The average horizontal and vertical 90% confidence errors for these earthquakes are 0.879 km and 4.863 km, respectively. Spatially, there are three distinct clusters: (1) north northwest of Milford, (2) northeast of Milford, and (3) scattered seismicity in the Mineral Mountains (Figure II.3.1).

Waveform analysis and event timing indicates that events in the northwest cluster (labeled Quarry, Figure II.3.1) are quarry blasts, not tectonic earthquakes. Evidence for this conclusion includes their epicentral proximity to quarries (conspicuous on Google maps), small magnitudes

(M 0.49 to 2.05), shallow depths, restricted timing (all events occur during daylight hours), and highly correlated waveforms implying a similar location and source mechanism. The second cluster is located northeast of Milford near the Milford airport and not far from the M_W 4.05 1908 Milford earthquake (Figure II.3.1). The magnitudes in this cluster range from M 0.46 to 3.91, and the events occur throughout the day (random timing). This cluster is interpreted as tectonic in origin.

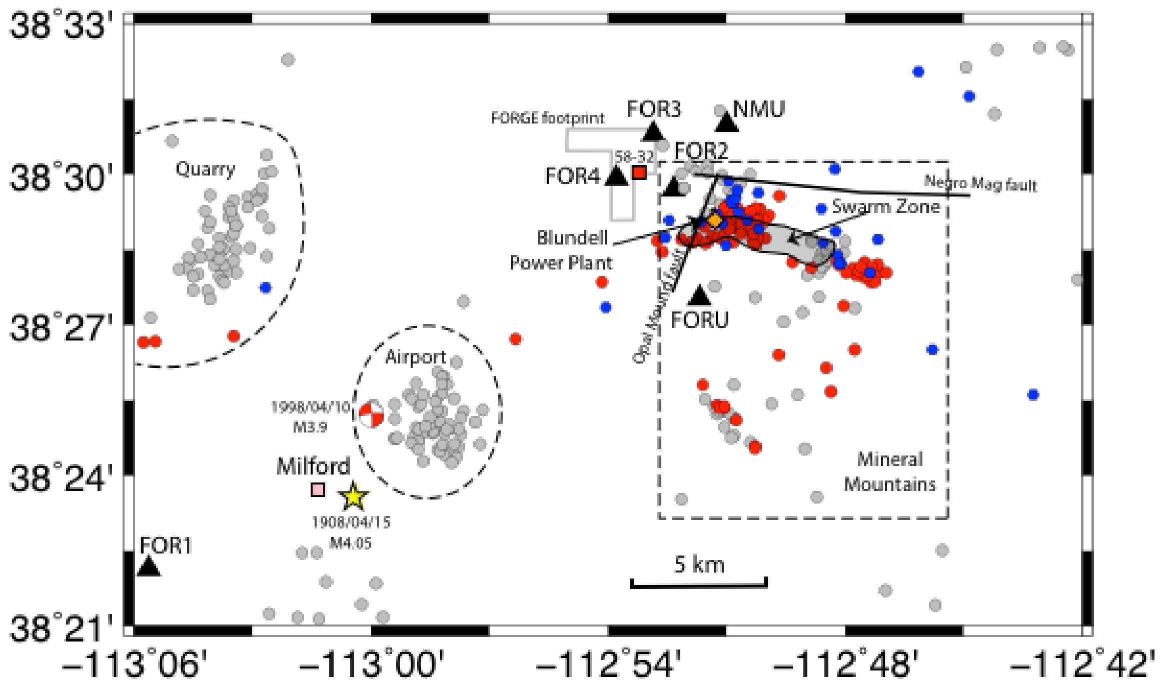


Figure II.3.1*. Utah FORGE earthquake catalog. Grey circles, earthquakes from the UUSS catalog 1981–2016 relocated with an updated velocity model. Red circles, earthquakes located after installation of the broadband network. Blue hexagons, earthquakes detected with Nodal array. Dashed polygons denote the three source zones discussed in the text. Black triangles, locations of seismic sensors. Grey shaded polygon labeled Swarm Zone, boundaries for earthquake swarm identified in Zandt et al., (1982).*

Of the remaining seismicity located in the Mineral Mountains, most locates east of the Opal Mound Fault. Spatially there is some clustering of events around the Opal Mound Fault, clustering on the eastern edge of the Zandt swarm region, and clustering to the south of station FORU (Figure II.3.1).

Few events were located from April 2011 through August 2016 in the study area (Figure II.3.2). To explore this quiescence period in the UUSS catalog, a subspace detection analysis (Chambers et al., 2015) was performed to look for previously undetected earthquakes (Potter, 2017). Using events from the UUSS catalog to construct the subspaces, continuous data from nearby regional stations for the time period 2011 through 2016 was scanned. This analysis showed that there were seismic events, 61 were detected in the Mineral Mountains region M -0.55 to 1.52 and nine events in the airport region M -1.49 to 0.91. These events are below the M_{comp} determined for the regional network.

Waveform clustering analysis (Potter, 2017) indicates that there are several distinct clusters of seismic events in the Mineral Mountain area. Based on the different clusters and the proximity to the Blundell Power Plant, we investigated possible correlations with the pumping history and found that there is no observable connection to the events cataloged in the area to the injection/withdrawal history of the power plant (Figure II.3.3). The plant was completed in 1984 and although the pumping history is not available further back than 1992, there is only one event cataloged from completion of the plant to 1992. The plant opened a binary power plant in 2007 (allowing more heat to be pulled from the recovered fluids) and no change is visible in the seismic activity.

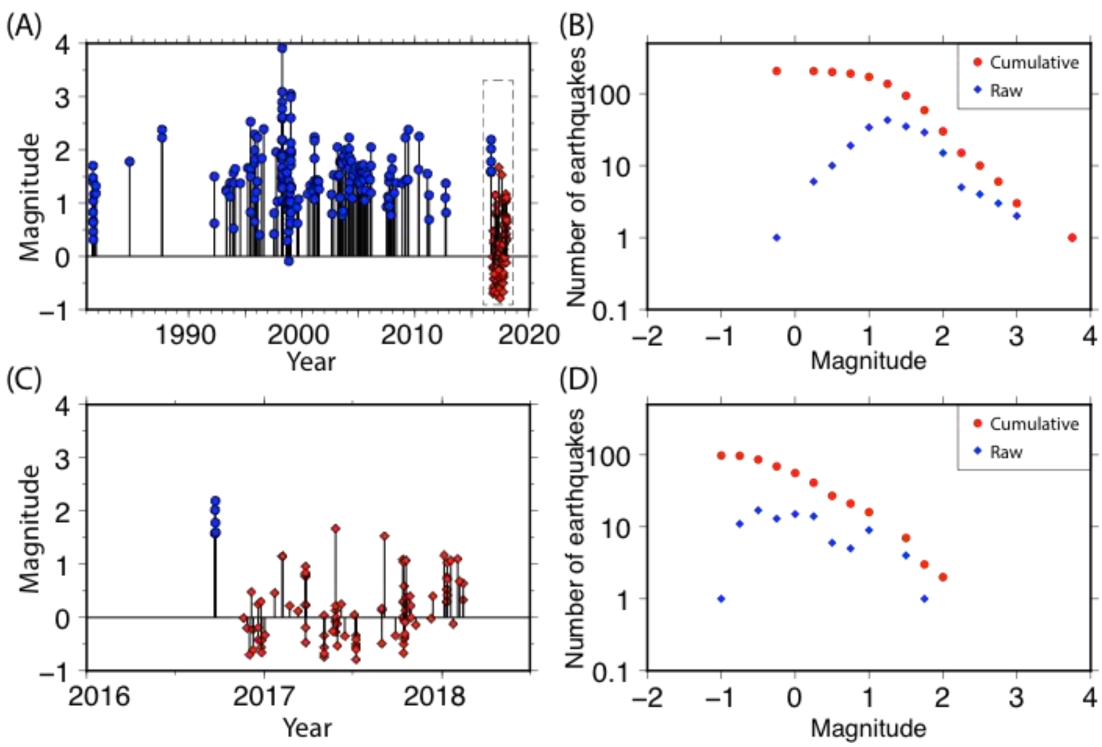


Figure II.3.2. *Magnitude time plot for events shown in Figure II.3.1. (A) Full time period of the catalog, red indicates events located after installation of local broadband network. (B) Magnitude distribution of numbers of events for time period shown in (A). (C) Magnitude time distribution for events from 2016. (D) magnitude distribution of numbers of events for time period shown in (C).*

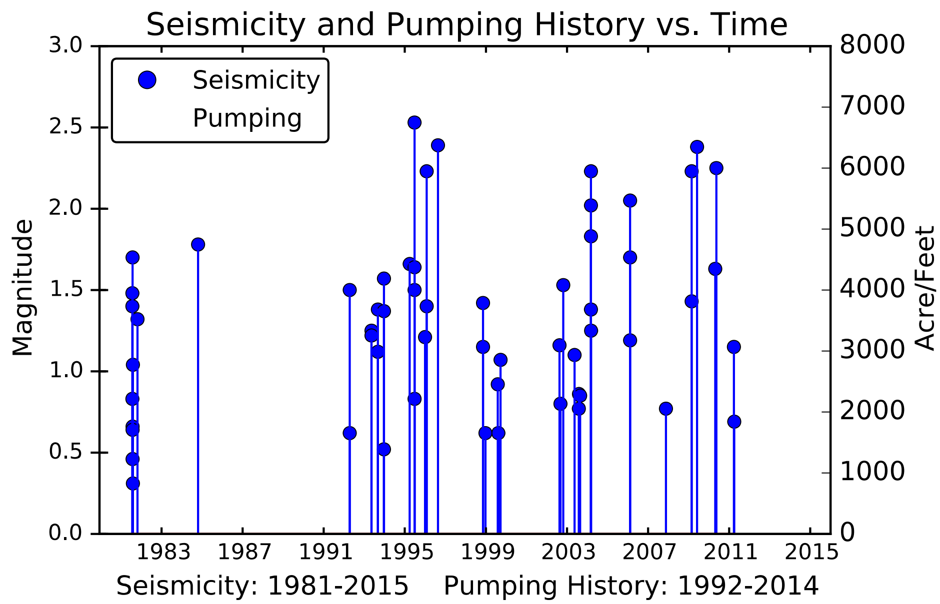


Figure II.3.3. *Magnitude time plot of events in the Mineral Mountains, with Blundell power plant pumping history taken from http://www.waterrights.utah.gov/cgi-bin/wuseview.exe?Modinfo=Indview&SYSTEM_ID=2732. The seismicity occurring in 1981 is part of the swarm described by Zandt et al. (1982). The plant was completed in 1984, but the available pumping history only extends back to 1992. Years 2003, 2004 and 2006 show low pumping history, which is believed to be due to a reporting error.*

The broadband seismic array installed for the FORGE project combined with nearby UUSS regional seismic stations greatly improves the seismic detection level for the study area. Figure II.3.2A shows that most detections after the installation of the broadband array are well-below the regional network M_{comp} of 1.5 to 1.7. We estimate a current M_{comp} of around 0.0 for the FORGE area (Figure II.3.2D). Because there are stations closer to the source zones, 90% confidence location errors decreased relative to the regional array to 0.68 and 2.98 km horizontal and vertical, respectively. Spatially, most of the seismic events locate east of the Opal Mound Fault primarily in or near to the Zandt swarm region (Figure II.3.4). There is also a small cluster in the southern Mineral Mountain source zone. Importantly no events are located in the FORGE footprint.

Data from the two Nodal experiments were also processed. Using this dataset 42 events are added to the catalog (Trow et al., *in review*). Formal magnitudes for these events were not calculated, but we estimate the magnitudes to be ≤ -0.5 based on tuning of the detection algorithms. These events locate in previously identified source areas.

Based on the multiple-levels of seismic monitoring, we conclude that (1) no naturally occurring seismic events locate within the Utah FORGE footprint; (2) seismicity occurs at low rates and with low magnitudes, typically M < 1.5; (3) most seismic events in this area occur under the

Mineral Mountains to the east of the Opal Mound Fault with a less pronounced source zone near the Milford airport.

Regarding seismic imaging, we measured the average velocity in the upper 30 meters (Vs30) for three sites: the FORGE footprint (400 m/s), near the Blundell Power Plant (408 m/s), and in the town of Milford (333 m/s). We have had limited success with ambient noise tomography. The ambient noise source did not have coherent, isotropic energy in the period bands appropriate for the station spacing of the Nodal array for the first Nodal deployment. We are starting to have more success from the time period that the drill rig was operating (second deployment), but we do not have a model at this time. We also had limited success in calculating receiver functions. Here we were pushing current methodology to look at shallow depths. The signal to noise ratios in the receiver functions are low. To sort out signal from noisy data, we are trying to use models based on the recently determined 3D seismic survey.

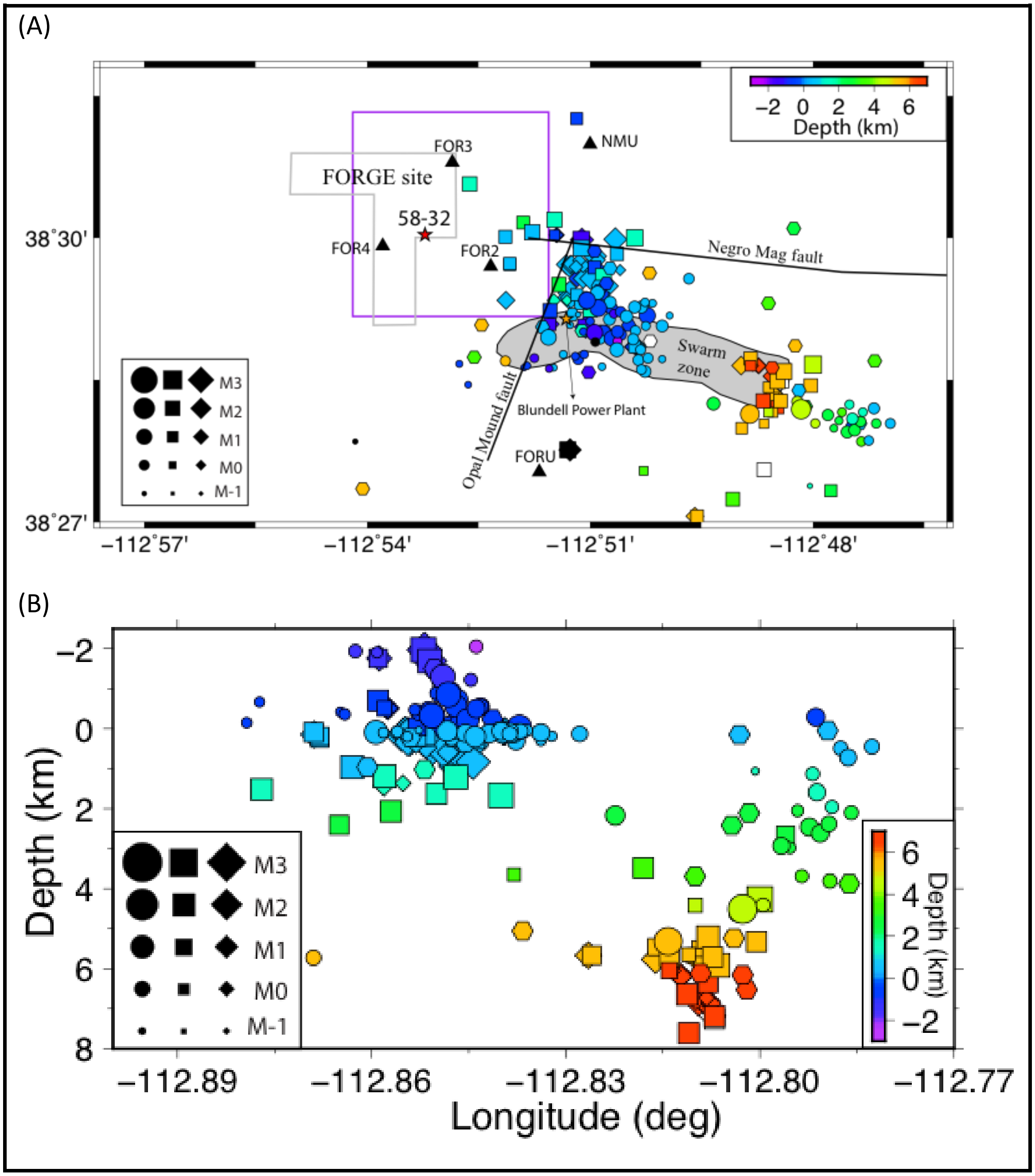
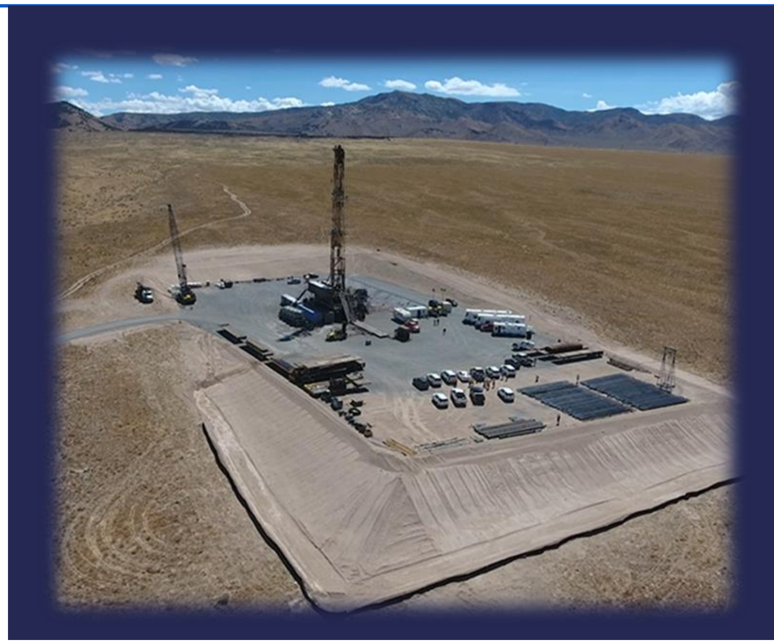


Figure II.3.4. *(A) Map of seismic network (black triangles) nearby the FORGE testing well 58-32 and earthquakes in the aforementioned four catalogs: UUSS catalog from August 1981 through October 2016 (squares), UUSS catalog from November 2016 through February 2018 after the deployment of stations FORU and FOR2-4 (circles), detected earthquake (diamonds) catalog created by Potter (2017) using the software Detex (Chambers et al., 2015), and the catalog of earthquakes detected on the Nodal arrays (hexagons). All symbols are colored coded by earthquake depth. The purple rectangle indicates the boundaries for the dense Nodal array. (B) Cross-section of events located in Figure II.3.4(A).*



Frontier Observatory for Research in Geothermal Energy – Milford Site, Utah

Section III. Lessons Learned

UTAH FORGE
U.S. Department of Energy

March 15, 2018

LESSONS LEARNED

The activities conducted during Phase 2A and B have solidified our understanding of the Utah FORGE site. These data demonstrate that the site is ideally suited for the development of an EGS reservoir and that it meets or exceeds all DOE requirements. In this section, we summarize the new understandings and lessons learned from Phase 2 activities. We describe how these activities have solidified our understanding of the geological and environmental setting of the site. Since the FORGE project was initiated, Smithfield has constructed four new hog farms southwest of the FORGE site. The impact of the new infrastructure to support the farms will have a positive impact on the FORGE project. These improvements have been incorporated into our analysis of infrastructure needs. Comments and feedback from stakeholders have resulted in an expansion of our outreach and communication program. Finally, we summarize lessons learned from the drilling of well 58-32. These lessons have the potential to significantly reduce drilling costs.

SITE AND GEOLOGY

Drilling, geological, geophysical, geochemical and geomechanical studies at the FORGE site have confirmed and enhanced our understanding of the geological setting and have significantly reduced potential uncertainties associated with temperatures, rock type, permeability, stress magnitudes and directions, and permeability of the crystalline (granitic) reservoir rock is low (e.g. <80 microdarcies).

Petrologic studies of core and cuttings recovered from well 58-32, when integrated with the results of gravity and newly-acquired high resolution 3-D seismic surveys have greatly improved appreciation of the regional geology, the stress field and the extent of the reservoir. The data unequivocally demonstrate that the granitic reservoir rock volume surrounding well 58-32 is enormous. The potential EGS reservoir volume between temperatures of 175^o and 225^{o}C within the FORGE footprint is nearly 5 km^3, with an additional 90 km^3 in the immediate vicinity of the footprint.

Comparison of the measured induced fracture orientations in well 58-32 with field observations (orientation of Opal Mound fault, borehole breakouts) demonstrates that the stress direction is consistent throughout the FORGE site, with (σ_{HMAX} striking approximately N25^{o}E). Stress magnitudes, based on a Diagnostic Fracture Injection Test (DFIT) are very appropriate for EGS development (σ_{HMIN} = 0.58 - 0.63 psi/ft; σ_{HMAX} = 0.68 - 0.82 psi/ft and σ_V = 1.13 psi/ft). The consistency in the stress orientations, natural fracture orientations, and lithologies (see below) in the Mineral Mountains and well 52-38 will greatly simplify prediction and analysis of the FORGE reservoir.

New insight into the structural framework of the FORGE site has important implications in terms of potential induced seismicity and seismic hazards. 3D and 2D seismic reflection data confirm the surface ruptures mapped in the alluvium are shallow features without observable offset of the alluvium-granite contact and pose little risk of induced seismicity.

The lessons learned that bear directly on the suitability, merits and transferability are summarized in the following paragraphs.

TEMPERATURE OF THE FORGE RESERVOIR

One of the primary objectives of well 58-32 was the direct determination of temperature at the FORGE site. **Accurate predication of reservoir temperatures in 58-32 provides an important metric for demonstrating the efficacy of the thermal modelling developed as part of the Conceptual Geologic Model.** Prior to drilling well 58-32, a temperature of 175^{o}C (minimum required temperature at top of reservoir) was predicted at a depth of 6500 ft. This temperature was encountered within several 10s of feet of the predicted depth, clearly demonstrating the thermal models accuracy.

LITHOLOGY AND EXTENT OF TARGET ZONE

Regional mapping in Phase 2, as well as extensive legacy data supplement newly acquired cuttings, logging and coring data from well 58-32. Petrographic and lithologic variations have been identified but are relatively subtle within the granitic rocks. This is an essential attribute for the ultimate FORGE site. A reservoir composed of homogeneous crystalline rock lacking lithologic and structural discontinuities will promote stable drilling conditions, an important consideration when drilling long, highly deviated wells and allow comparison of different drilling techniques and in situ mechanical testing and stimulation technologies. This simplicity will promote the creation of a continuous EGS reservoir volume.

Lithologic complexity will adversely complicate future research programs. **For this stage of EGS development, lithologic simplicity and lateral extent – as demonstrated – are essential, favorable attributes of this site.**

PERMEABILITY AND FRACTURE DENSITY THROUGHOUT TARGET REGIME

Permeability was measured in situ using After Closure Analyses following injection testing. This was supplemented by laboratory permeability measurements on two cores recovered from well 58-32. The permeability was in the low microdarcy range, conducive to an effective EGS laboratory environment. Temperature profiling, permeability and fracture mapping indicate an ideal blend of natural fracturing. The natural fracturing is not extensive enough to create a high permeability or convective flow environment. There are adequate natural fractures present to enable hydraulic fracture creation – extensional, reactivation, and/or dilatant shearing – without extreme difficulties in fracture initiation. **This is an ideal conductive environment with**

enough natural fractures to support extensional and hydraulic shearing mechanisms to interconnect wellbores, with minor fluid loss.

STRESS ORIENTATION AND MAGNITUDE THROUGHOUT TARGET ZONE

The complete stress tensor was determined by physical measurements in the barefoot section of well 58-32. These have been used to calibrate logging-based predictions from a Dipole Sonic Imager (Dipole Sonic Imager) survey. Directionality has been constrained from Formation Microscanner Imager (FMI) surveys before and after the stress measurement program. The vertical stress has been reliably inferred from the density logging. The minimum horizontal stress was identified from microhydraulic fracturing and DFITs. The maximum horizontal stress is naturally determined with less reliability but has been constrained – using inflection evaluations during after closure analysis, using conventional breakdown pressure calculations and using stress polygon analyses. **The measured stress tensor (magnitudes and directions of the total principal stresses) are consistent with a priori geologic inferences, mapping in adjacent outcrops and inferences from legacy wellbores. They confirm the planned trajectories of the Phase 3 wellbores.**

GEOLOGIC MODEL:

The extensive field and laboratory measurements have enabled construction of a high quality geologic model that integrates all data and will be appropriate for well planning, drilling and completion in Phase 3. **This high resolution, dynamic reservoir model is an essential element for planning future research to be carried out at the facility.**

GENERAL SITE SUITABILITY

The Utah FORGE site is located on State land within Utah's Renewable Energy Corridor that includes producing geothermal plants, a large windfarm and solar operations. Nearby are biogas and compressed air storage facilities. The FORGE site can be accessed by the public year round. **The site is adjacent to major highways, improved secondary roads, towns with support facilities, motels and restaurants, a railroad and an airport. No high security operations are conducted near the site.** Interaction with local contractors, ease of site access, and strong geologic and engineering attributes reinforce the overall merits and suitability of the FORGE site.

ENVIRONMENTAL CONSTRAINTS/RISKS

Assessment of the environmental and cultural impacts of the FORGE project were initiated in Phase 1. The team worked closely with the BLM, Utah State Historic Preservation Office (SHIPO), State Institutional Trust Land Administration (SITLA), Beaver County, Smithfield and other landowners to ensure minimal cultural and environmental impact to the area as a result of our activities. **These interactions guided our schedules and plans for infrastructure development.** In Phase 2A, an Environmental Information Volume was prepared. No cultural issues were identified, and none of the proposed sites required relocation. No endangered flora or fauna were identified. The environmental study concluded that limited periods of restricted access to public lands may be required to accommodate hawk nesting periods, but activities could be conducted on ground unsuitable for nesting hawks, as they were during the drilling of well 58-32.

TECHNO-ECONOMIC ISSUES/COSTS

New developments by Smithfield are having a positive benefit on the FORGE project. In late 2017, Smithfield began expansion of their hog farming operations north of Milford. Currently there are four hog farms under construction southwest of the FORGE site. The farms will be operational in the Spring of 2018. **This expansion will require improvements to the existing road system and a new transmission line with a capacity to support future hog farm operations. Beaver Country has requested a grant for $365,000 from the Office of Economic Development (GOED) to help pay for the cost of the new transmission line.** The application has been favorably received by GOED and is expected to be approved. This transmission line would directly benefit Smithfield, the Utah FORGE project and future developments in the valley.

STAKEHOLDER INVOLVEMENT ACTIVITIES

The Utah FORGE team has developed a vigorous outreach program to educate and inform stakeholders, including the DOE, the general public, the scientific community and government and regulatory agencies on project performance and activities. Fifty-three separate activities were conducted during Phase 2B, nearly twice the number of activities in Phase 2A (refer to Appendix 6). Stakeholders have informed us the activities of greatest interest to them are: have:

1. Obtaining current information on FORGE activities
2. Field trips to see activities occurring at the FORGE site, firsthand.
3. High quality, informative videos of Utah FORGE site activities and EGS development
4. Additional educational material for the general public, particularly for students in grades K-12.

We have addressed these requests in several ways. Information on the Utah FORGE website (www.forgeutah.com) has been kept current and is updated frequently. Links are provided for real time access to seismic data, an interactive map showing site characteristics, news about the project and recent publications. A Facebook page allows the public to interact with the team.

Field trips were conducted frequently during Phase 2, especially during the drilling of well 58-32. These trips included visits to the FORGE well site, tours of the drilling rig, geothermal features in the area (hot spring deposits, fumaroles, and altered ground) and the Blundell Power Plant. We conducted trips for the DOE geothermal managers, regulators and the public, University of Utah students and for overseas collaborators. **For many, the field trips provided a unique and first-time opportunity to visit a drill rig, and visualize the impact that EGS technology will ultimately have on energy production. Regulators commented on the care taken to avoid environmental impacts at the FORGE site.** Others noted the small footprint of geothermal activities compared to the large areal extent of the windfarm and solar fields located adjacent to the FORGE site.

Three videos are being released during Phase 2. A previous video released in March 2016 (*https://youtu.be/4-6UgHq_Xe4*) is also available on the DOE website. This video was widely praised by the DOE communications specialists and the new videos display the same standard of excellence. Video 1 of the Phase 2 video series was released at the annual GRC meeting in early October 2017. In this video, Ms. Lauren Boyd, DOE Manager of the FORGE program, described the objectives of the FORGE program and DOE requirements for an EGS reservoir. The video can be accessed at *https://youtu.be/MhrUXF7ffaq*. Video 2 will be released in late March 2018. The video provides additional details on the creation of EGS reservoirs and operations at the FORGE site. Video 3 will be released in early April. It will highlight the important results of the FORGE project.

Additional activities during Phase 2 include: press releases, videos, school visits, meetings for the general public, presentations at scientific conferences, field trips, STEM (Science, Technology, Engineering and Math) activities (educational modules and hands on activities, PowerPoint presentations, Frequently Asked Questions in English and Spanish. The video and STEM activities were supported by a $20,000 grant from the State of Utah Governor’s Office of Energy Development. We have engaged Milford High School students through lectures and by placing a ground motion sensor at the school to monitor seismic activity.

Close ties have been developed with other organizations interested in EGS worldwide. Chinese organizations, have been particularly receptive to collaboration. We are working with the Chinese Geological Survey, Sinopec Research Institute of Petroleum Engineering, Jilin University, Southwest Petroleum University, and China University of Petroleum, Beijing.

DRILLING

Drilling costs associated with well 58-32 represent approximately one-half of the total Phase 2B expenses or close to $5M. In Phase 3, the cost of drilling highly deviated injection and production wells will significantly increase. Our current estimates, based on past experience, suggest each production and injection well will each cost $11-13M to drill and an equal amount to stimulate at least one of the wells. Clearly, applying the best technology and techniques to FORGE drilling will be critical to success.

The team assembled in Phase 2B for designing, constructing, completing and testing well 58-32 was the most experienced available in the business of drilling geothermal wells. The combined experience of the team leaders was more than two centuries. It is perhaps unsurprising that this team was able to deliver well 58-32 ahead of schedule and under budget. Nevertheless, this group recognized from the outset that they would learn new lessons and apply old lessons. They have endeavored to document those lessons, new and old, as Recommended Actions from Lessons Learned, presented herein as Appendix A2.Task2B.6 58-32 Lessons_Learned.pdf. All aspects of the well 58-32 design, contracting, and drilling program were reviewed to identify those components of the program that could produce savings in time and cost.

Four factors distinguish Utah FORGE well drilling from common geothermal practice and therefore point the way to improvements:

1. Unusual formation types

Manufacturers and suppliers of tools and services are accustomed to hard, abrasive rocks, but these are commonly volcanic or metamorphic in origin. Granitic (i.e., igneous) rocks are usually considered basement rocks and little drilled. We found, for example, that the most successful drilling methods in the granitic rocks encountered were not the same as in equally-hard volcanic rocks. Among the consequences of this observation is the need to stock a greater variety of bits and associated tools on site than would typically be the case. Operations such as coring also need to include specialists with relevant experience.

2. Premium on solids control

A few tool failures, such as washed-out drilling jars, point to the cuttings from the granites as being particularly abrasive. In Phase 3 more complex directional drilling equipment will be introduced, making such failures more costly. Superior solids control equipment will not only reduce drilling fluid costs, but will also be important to protect the advanced drilling tools. Such equipment is available, but is not economical for typical geothermal wells. For FORGE, it will be essential.

3. Special emphasis on quality control

Drilling the research wells needed for the Utah FORGE mission will involve multiple suppliers of tools and equipment that are produced in small quantities by custom manufacturing. The dimensional compatibility and correct performance of all these tools is vital to efficient drilling operations, whether cementing, coring, stimulating or drilling highly deviated holes. Verifying dimensional conformance well in advance of use is particularly cost-effective due to the shipping cost and time for replacements. Improvements in wear performance of some tools are needed to keep the hole at full diameter ("in gauge"). Utah FORGE's drilling consultants will work with the manufacturers to improve tungsten carbide insert material, density, and placement for future wells. Similarly, integral blade type stabilizers will replace welded ones on downhole motors.

4. Advanced equipment needed to optimize drilling parameters

Phase 3 drilling will involve more complex equipment for drilling highly-deviated holes in the granite reservoir rock. Making the best use of this equipment will be essential for cost-effective performance and new technologies will make this possible. For example, more precise and instantaneous drill string torque measurement is needed. Real time acquisition and processing of this data can enable engineers to use a technique known as Mechanical Specific Energy for drilling diagnosis and improvement. This technique has proven its value in oil and gas drilling and in geothermal drilling operations in other parts of the world.

Frontier Observatory for Research in Geothermal Energy – Milford Site, Utah

Section IV. CONCLUSION

UTAH FORGE
U.S. Department of Energy

March 15, 2018

IV. CONCLUSION

VISION

FORGE's mission is to enable impactful research, drilling and technology testing. The venue and the management structure allow scientists to identify and advance a replicable, commercial pathway to EGS implementation on a geographically diverse scale. In addition to the facilities, infrastructure, and collaborative environment, the FORGE effort embraces a sophisticated and comprehensive network of instrumentation, data collection, and data dissemination to capture and share data and activities occurring. The innovative research, coupled with an equally-innovative collaboration and management platform, is a "first-of-its-kind endeavor."

VISION FOR FORGE R&D IMPLEMENTATION

The overarching vision of the Utah FORGE team is to enable geothermal energy of the future by accelerating the commercialization of EGS. As presented in the following sections, we plan to achieve this vision by focusing on:

- Identifying the key mechanisms controlling EGS success and implementing research programs to understand those mechanism
- Enabling the development and adaptation of technologies to initiate and sustain independent, conductive fracture networks in basement rock formations
- Designing and testing a reproducible model for developing large-scale, economically sustainable subsurface heat exchange systems

A comprehensive R&D Vision and Implementation Plan has been developed that addresses the R&D needs throughout all phases of the project. The plan details the approach to effectively manage all logistical, administrative, analytical and technical support for the planning, solicitation, review, and selection of technologies that will be tested and evaluated at the FORGE site. The R&D Vision and Implementation Plan outlines recurring cycles for planning, review, and selection of FORGE-related technologies for testing and evaluation.

THE UTAH FORGE VISION SUPPORTS GTO GOALS AND OBJECTIVES

The FORGE mission, as defined by the GTO, is to enable cutting-edge research and drilling and technology testing. This will allow scientists to identify a replicable, commercial pathway to EGS implementation and acceptance. In addition to the FORGE site itself, the FORGE effort will include robust instrumentation, data-collection, and data-dissemination components to capture and share data and activities occurring at FORGE in real time. The innovative research, coupled with an equally innovative collaboration and management platform and focused, intentional communications and outreach, is truly unparalleled.

All research and development activities at FORGE will focus on strengthening our understanding of the key mechanisms controlling EGS success – specifically, how to initiate develop, control, and sustain multiple conductive and independent fracture networks in basement rock formations. This critical knowledge will be used to design and test methodologies for developing large-scale, economically viable and sustainable heat exchange systems. This, in turn, will facilitate rigorous and reproducible approaches that will reduce industry development risk and facilitate EGS commercialization. R&D activities include improved and innovative drilling methods, as well as reservoir stimulation and management techniques. Procedures for insuring, enhancing and sustaining well connectivity are essential. Monitoring and testing procedures include flow-testing and continuous monitoring of geophysical and geochemical signals.

Dynamic reservoir modeling is an integral role in FORGE. It insures operational integrity and oversight by synthesizing, predicting, and verifying reservoir properties and performance. An updated, publically disseminated reservoir model promotes active and passive research. Passive research is undertaken by scientists, engineers, economists, business analysts and policy makers who use these findings. Active research arises from funding research at the facility. High quality, updated site information reduces the cost of subsequent research and accelerates implementation and value. Funded R&D activities will have open participation, via competitive solicitations to the entire scientific and engineering community.

As advancements are made over the course of FORGE's operation, R&D priorities are likely to shift and change. As a result, FORGE will be a dynamic, flexible effort that can adjust to and accommodate the newest and most compelling challenges in the energy frontier. The vision for Utah FORGE clearly supports achieving the GTO's Goals and Objectives for FORGE. The attributes of the site, the experience and competence of the team, support from the state of Utah, and the structure of the organization (as well as our demonstrated performance to date on Phases 1, 2A, and 2B) are all purposefully aligned with GTO's Goals and Objectives. Details are provided in the sections that follow, but a few noteworthy examples include:

- The drilling activities for well 58-32 incorporated evaluations of different drill bits and mud motors during the successful Phase 2B drilling activities. These activities have been widely publicized, as have the lessons learned that will be enfranchised into future drilling. In candor, even using best available technology has indicated room for improvement in drilling activities. An example is more effective use of recorded drilling data and particularly in improved acquisition and use of torque and drag information.

- The drilling has been supplemented by comprehensive noninvasive and in-well measurements. These include thermal monitoring, gravity surveys, three-dimensional seismic surveys, outcrop mapping, LIDAR and seismic monitoring. In well activities have included coring and laboratory core analysis, quadcombo and image logging, stress and permeability measurements as well as pilot scale stimulations.
- We have developed a robust, three-dimensional earth model that incorporates existing/historical data and newly collected geologic information. This visualization platform further enfranchises other raw and interpreted data. It is the starting point for thermal reservoir assessment using available and evolving numerical tools and workflows to create multi-scale, multi-physics (THMC) numerical models of the site.
- Most importantly, we have developed the workflows to effectively distribute site data so that other parties can easily create numerical models of the site AND return their results for quantitative comparison with our reference models - allowing for greater understanding and study of the processes involved.
- Using the acquired information, discrete fracture network modelling and thermal reservoir management simulations have established a groundwork for developing detailed well and stimulation designs and implementation in Phases 2C and 3.
- The Utah FORGE team is particularly proud of its outreach activities to the immediate stakeholders and to future stakeholders who will benefit from expansion of geothermal energy opportunities. A collaborative effort from the FORGE scientific and management staff, educators at the University of Utah and The Utah Governor's Office of Energy Development has produced widely acclaimed videos, developed lesson plans and FAQs for EGS and geothermal in general and done numerous interactive, hands on demonstrations promoting EGS.

SUMMARY OF THE MAJOR PLANNED ACHIEVEMENTS

The Utah FORGE Team will provide an outstanding test site that meets or exceeds all acceptance criteria. With the site comes experienced management, and operational and thought leadership to enable research advancing large-scale commercialization of EGS. A major achievement will be demonstrating EGS viability at FORGE and "radiating" the technology (and the excitement) outward to the region, nation, and internationally. The term FORGE already has a strong DOE association. Local, domestic and international recognition and participation will broaden that association and lead to technology dissemination. Many significant supporting achievements will be required in order to achieve this goal. In the sections that follow, planned supporting activities or necessary actions are presented and discussed, along with how our site and team are situated to successfully accomplish these goals.

IV.1 INTRODUCTION

The “Research and Development Vision and Implementation Plan” implements the “Project Vision.” The vision is to:

Construct and manage an internationally recognized in-situ research facility centered on two (initially) directionally drilled wells in Central Utah. This well-characterized and controlled field laboratory will enable developing, testing, optimizing and validating technologies that will expedite EGS implementation in commercial settings elsewhere.

The Project Vision and the aligned Research and Development Implementation Plan explicitly align with GTO’s goals and objectives. In particular, the field laboratory development and the supplementary research solicitations are designed to:

- Develop field testing data that demonstrate best practices (and required research) for targeting, initiating, reopening, reactivating and extending natural and latent fracture networks and hydraulically comminuting virgin basement rock. *The potential for successfully doing this has been demonstrated in well 58-32 during small and medium scale injection testing.*
- Assess sustainability of hydraulic conductivity and thermal deliverability. If either of these are jeopardized, assess technologies for remediation or restoration. *Extensive geomechanical and thermomechanical modelling has been undertaken and published* (see for example, Asai et al., 2018). Additional evaluations are planned in Phase 2C.
- From these field data, collaterally develop fundamental scientific comprehension. *This will be an ongoing and dynamic process where the geologic model and engineering experiences are continually updated to afford the most complete set of information for future research programs at the FORGE Utah location.*
- During well construction, identify technology gaps related to drilling and completion, and implement solutions where applicable. After commissioning of the experimental laboratory, encourage testing of stimulation technologies, monitoring methodologies, fluid handling methods at the surface, potentially assess alternative working fluids, enable verification/validation of numerical simulation methods, test logging and monitoring methods, and so on. ***Phase 2B has provided proof of concept assurance of the suitability of the Milford, Utah location to be developed as a FORGE laboratory.***
- Function in harmony with stakeholders, disseminate information, and provide opportunities for outreach and information to local, national and international students and scientists.

Procedures are described in the R&D Vision and Implementation Plan for effectively incorporating R&D activities in a safe and scientifically satisfying manner. Logistical, administrative, and techno-analytical support is described for site operation and for soliciting, reviewing and selecting research programs after commissioning of the laboratory. Procedures are outlined for evaluation of the FORGE project to ensure that the objectives of the GTO are met and that the research is fairly, logically and transparently solicited, administered, evaluated, implemented and reported. This is incumbent on the Project Management Team (PMT) and the Scientific Technical Advisory Team (STAT). The concepts, charters and compositions for both of these teams are outlined, with particular emphasis on avoidance of conflict of interest (COI).

IV.2 VISION FOR PHASES 2C AND 3: FEASIBILITY SPACE FOR ENHANCED GEOTHERMAL SYSTEMS

One of the main goals of FORGE Utah is to create a well-characterized and controlled environment where the most creative minds in the field can develop and optimize EGS technologies. The laboratory will function as a platform for technical interaction and public education to support the widespread adoption of EGS as an energy source. The vision of the FORGE Utah site starts with the assessment of the feasibility space for Enhanced Geothermal Systems, as shown in Figure IV.1.

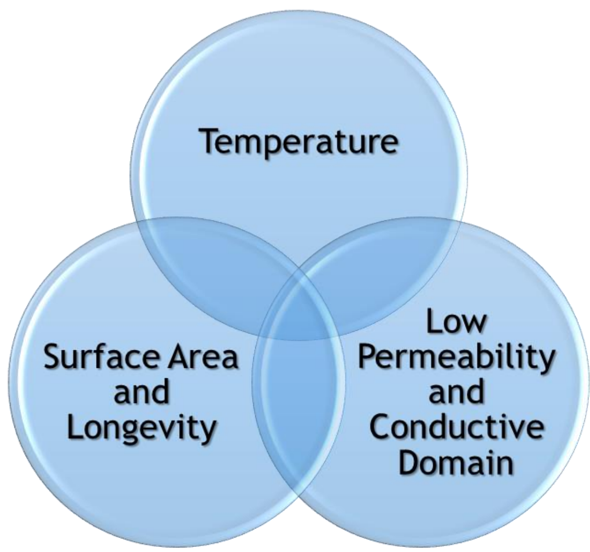


***Figure IV.1**. The attributes and challenges of EGS encapsulate the FORGE Utah vision for future research opportunities (concept after Dershowitz, 2018).*

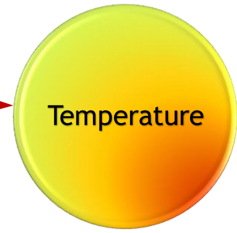
Figure IV.1 might be expressed in different ways by different individuals. However, it incorporates the essential elements of a successful EGS operation as the intersection of the three defining commercial criteria – temperature, hydraulic communication between an array of injectors and producers without significant sinks or short circuits (faults and discontinuities), and the ability to create adequate fracture surface area in contact with the thermal reservoir (and ultimately control and manipulate over time). The degree of uncertainty in any or all of the elements in Figure IV.1 impacts the viability of an EGS program.

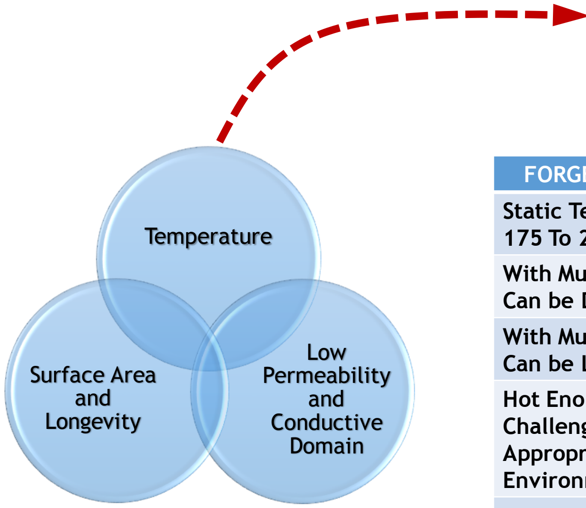
FORGE Laboratory construction and research opportunities all correlate with the three themes shown in Figure IV.1. Each is considered on its own in Figures IV.2 through 4.

IV.2.1 TEMPERATURE (FIGURE IV.2):

Temperature turns out to be one of the more straightforward elements for EGS creation. Techniques employed for predicting the temperature in well 58-32 were very successful, reflecting the long history of thermal prospecting for conventional geothermal energy applications and modeling of thermal conductivity measurements. The temperature range for the Utah FORGE EGS reservoir will be in the range of 175^{o} to 225°C. Temperatures near 200^{o}C are optimal; they are generally considered appropriate for commercial EGS systems but will still challenge drilling operations (e.g., motors and other BHA components as well as bit selection). A temperature of 200^{o}C was encountered at the base of well 58-32, but higher temperatures can be found by drilling deeper while easily staying within a mandated depth of 4 km.

Other geothermal and petroleum experience supports the ability to drill two subparallel wells – one above the other. The length of each lateral in the prescribed temperature domain will be a kilometer. Detailed trajectory designs with evaluations of torque and drag and circulation will be undertaken to optimize the drilling, stimulation and testing operations, and maintain exposure to the requisite temperatures.





FORGE Site Attributes	Research Opportunites
Static Temperatures of 175 To 200˚C	Research Opportunities During Drilling
With Mud Cooling, Wells Can be Drilled	Bit Selection and Motor Performance, MSE
With Mud Cooling, Wells Can be Logged	Logging and Characterization
Hot Enough to be Challenging yet Afford an Appropriate Research Environment	Thermal Reservoir Management and Performance
…	…

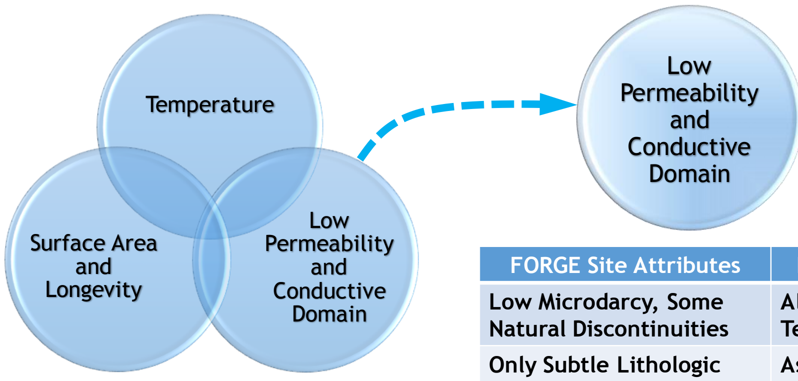
Figure IV.2. *Temperatures will be in the range of 175 to 200+°C. This temperature range provides a research environment for testing tools, logging techniques, in situ monitoring methods that is at the limits of current methods – and hence provides an opportunity for incremental research developments – incremental successes at this level will lead to greater technological advances during commercialization and future implementation.*

At 200°C, the temperature is high enough to promote development of new practices and implementation of sophisticated and relevant research programs. There will be significant opportunities for improving drilling technologies. Ideally hydraulic stimulation will only be done in the active, injection well. If connections are not adequate different programs of hydraulic injection may be required in the passive (production) well or in both wells concurrently.

Research proposals relating to analysis of the drilling operations, implementing new logging and monitoring methods (e.g. permanent fiber optics emplacement for DAS and DTS, measurements while drilling) in a carefully monitored injection/microseismic fracture propagation environment will be solicited. Other proposals will focus on reservoir management tests and simulations to assess efficiency and longevity.

IV.2.2 LOW PERMEABILITY AND CONDUCTIVE DOMAIN (FIGURE IV.3):

Fluid and heat transport are the next major component of the EGS feasibility. Challenges are shown in the Venn diagram (Figure IV.1). The geologic environment at the Utah FORGE location is now well established. The temperature regime west of the Opal Mound fault is conductive. This is the ideal situation for creating a true endmember EGS reservoir. Creation and growth of this reservoir will require hydraulic fracturing or other stimulation technologies to connect the injection (active) and production (passive) wells. This EGS reservoir will differ significantly from hybrid systems in which existing fault systems are thermally or chemically stimulated to produce a commercial geothermal system.



FORGE Site Attributes	Research Opportunites
Low Microdarcy, Some Natural Discontinuities	Alternative Initiation Techniques
Only Subtle Lithologic Variations	Assessment of Possibility for Hydraulic Shearing
Demonstrated Conductive Thermal Regime	Thermoelastic Fracture Control
Possibility for Extension, Reactivation, and Dilatancy	Chemomechanical Fracture Creation and Modification
…	…

Figure IV.3. *Permeability is low and the thermal regime is conductive. This is appropriate for an endmember EGS system – i.e., not a hybrid system where the stimulation connects a pre-existing fracture to an existing hydrothermal system. Low permeability enables research related to creating conductivity.*

Previous successful EGS stimulation experiments (e.g., Desert Peak, Geysers, Landau, Soultz-sous-Fôrets, and Raft River) have all relied on interactions with pre-existing structures. Tests at locations without such structures (e.g., Newberry, Fenton Hill) have been discouraging because of the inadequate surface area for heat exchange. The Utah FORGE site is suitable for studying the fundamental geologic conditions necessary for successful heat extraction, and for developing engineering protocols that will increase the number of potential sites for EGS energy development.

This is the opportunity: The reservoir is thermally conductive, permeability is low, the stress contrast is favorable and the fracture network is modest and apparently discrete. Opportunities exist for creating a conductive fracture system connecting two or more wells. This heat exchange network will be comprised of independent engineering fracture corridors. Research opportunities relate to the possibilities for creating these conductive systems, which includes initiation, growth/propagation, and preservation of conductivity.

Some of the critical questions include:

- Critical stress analysis based on the FMI data and in-situ stress measurements from well 58-32 by Golder and Associates and EGI scientists and engineers, suggest that certain zones would be favorable to hydraulic shearing. In fact, simple tests of this are conceived for Phase 2C of this program.
- Can a dilatant, conductive network be created?
- Can a dilatant, conductive network be enhanced by thermoelasticity – long term injection can lead to aperture enhancement, as was demonstrated by this same team at Raft River, Idaho?
- Depending on the temperature of the injected fluids (and their pressure) will asperity override degrade with time because of creep and possibly even interpenetration or pressure solutioning? If adequate slip occurs, the result may be a dilatant, self-propped fracture. From a geomechanical perspective, can this self-propping last over the productive life of a thermal reservoir?
- Is high temperature acidizing a viable technology. Using mud acid – at the best of times – is complicated and can result in unforeseen precipitation and damage. Can acid systems be designed that can be effectively used with high and/or low pressure hydraulic injection?
- From a modelling, forecasting and exploration point of view, how are sweet spots identified where connections between wellbores can be facilitated.
- What pre-existing fracturing and stress states of the reservoir rocks are necessary for EGS development? A corollary is, *if fractures are sparse, how can conditioning procedures (e.g. aggressive perforation, propellant, cyclic thermal or cryogenic injection) overcome these limitations?*
- What will happen if a selected zone cannot be broken down and a fracture initiated? Incorporation of existing zones of weakness (veins, fractures) into the isolated zone in the wellbore, with an added requirement of closely spaced stimulations, will likely be required unless the natural fracture frequency is high. This was not an issue in the openhole section at the bottom of well 58-32 but could occur in the production and injection wells. Implementation of breakdown procedures (e.g. perforating in openhole, multiple perforation runs, propellant, aggressive abrasive slotting, and/or cryogenic fluids) may be required in addition to hydraulic stimulation.

While we do not have all the answers to these questions, and certainly there are many more questions to ask, we have shown that these questions can be answered by establishing FORGE at the Milford Utah Site. We will engage the STAT, GTO, our project team, and the community at large to high-grade and expand on these questions and solicit experimentation to resolve them.

IV.2.3 SURFACE AREA AND PRODUCTIVE LONGEVITY (FIGURE IV.4):

No matter how hard one tries, all considerations eventually mandate designing experiments to test and increase productive longevity. This entails evaluations of stimulation technologies for creating nominally independent surface areas, with multiple connections between multiple wells. There is a significant level of experience that can be learned from the petroleum industry about placement and growth of multiple fractures. Perforation clusters in horizontal wells in the oil and gas domain are now as close as twenty feet. Nevertheless, the oil and gas experience is poorly quantified – either because of confidentiality issues or because the only validation of success is production. Carefully conceived experiments and numerical modeling are required to assess optimal fracture spacing.

FORGE Site Attributes	Research Opportunites
Moderate but Not Extreme Stress Contrast	High Temperature Tools for Isolation
Nominally Homogeneous Reservoir	High Temperature Tools or Techniques for Reservoir Management
Favorable Conditions for Intersecting Production Well at Multiple Locations	Opportunities for Modern Mapping of Fracture Growth
Relatively Few Significant Structural Features	Long Term Heat Exchange Experiments
Well Characterized	Alternative Stimulation Technologies
High Resolution Geologic Environment	Testing of Coupled Numerical Simulations
Low Seismic Risk	…

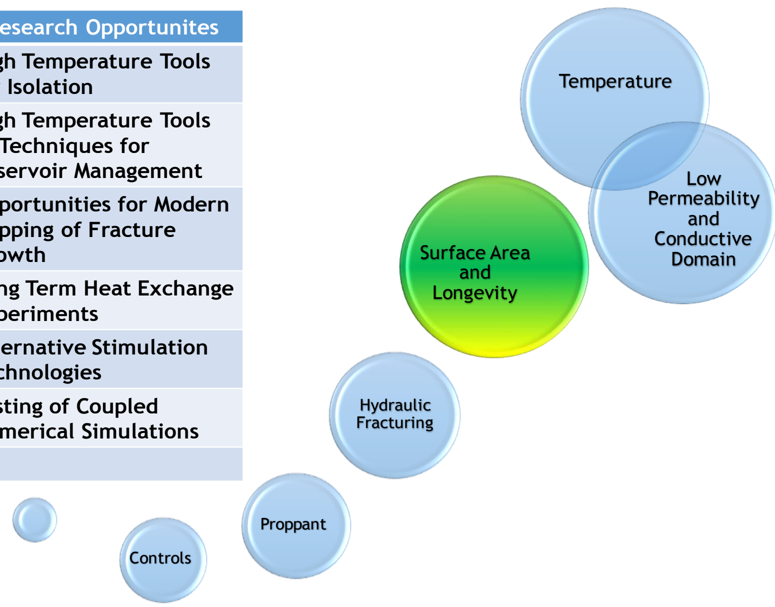


Figure IV.4. *This is the greatest research challenge – establishing adequate surface area and being able to proactively impose sophisticated reservoir management methods to insure commercial viability and longevity.*

Geothermal experience will be relevant as well. For example, “Can the success at Raft River be duplicated on a smaller scale (e.g. within individual stages of a multistage completion) for a composite stimulation incorporating thermal enhancement, hydraulic shearing, and high-pressure injection?” Injectivity in Raft River RRG-9 ST1 increased from 20 gpm to nearly 1,500 gpm with a combination of patient, low-temperature injection at low pressure along with intermittent, aggressive hydraulic stimulations. The question is “Will a multi-rate treatment or cyclic injection program most effectively connect the two wells?” The opportunities for field experimentation and numerical “validation” are extensive.

IV. CONCLUSION

We can also ask if there are other considerations for preserving or expanding the surface area with limited effort. Are some of the chemomechanical considerations that could be exploited? For example, can stress corrosion cracking –in existing, latent fractures – be used to develop a long-acting, inexpensive method for maintaining and renewing thermally-virgin surface area over the life of the reservoir?

However, the real challenge, from a perspective of longevity might be to develop the ability for multiple, independent flow networks to be opened and closed. The opportunities for control systems or tactical diverters are exceptional. Numerical simulations and previous projects, worldwide, demonstrate that to extract useful heat over prolonged periods we need a better understanding of how to stimulate, maintain and quantify fracture networks in crystalline basement rocks.

IV.3 INVOLVEMENT AND COLLABORATION IN RESEARCH AND DEVELOPMENT

In order to achieve rapid progress, the Utah FORGE R&D Vision and Implementation Plan will encourage involvement and collaboration of geoscientists and engineers. The Utah FORGE Project Management Team (PMT) will support the research with staff professionals as needed to maintain progress. Aspects of the plan pertaining to Phase 2C will be implemented as early as possible so as to involve the community of geothermal researchers in the laboratory development. Collaborative relationships are essential for FORGE success and the following measures have or will be taken.

- ***DOE Collab:*** Utah FORGE would solicit input and advice from the DOE Collab program. A line item budget entry would be allocated to involve Collab scientists and engineers in Phase 2C and 3 projects. In addition, the PMT would request participation from one to two senior Collab scientists (likely from LBNL or SNL) on the STAT. We would envision a joint workshop, likely during Phase 2C, to present to the Collab Investigators for critique and recommendations.
- ***Idaho National Laboratory:*** Dr. Robert Podgorney, with INL, is assuming a lead management role in the FORGE Utah project. Dr. Podgorney is also the lead on the Collab Task related to FORGE Integration.
- ***Pacific Northwest National Laboratory:*** Recognizing the opportunities for additional research in Phase 2C, Dr. Alain Bonneville and Dr. Carlos Fernandez are designing fracturing experiments to be undertaken during Phase 2C. The opportunities for real learning in Phase 2C are strongly acknowledged. Phase 2C provides the opportunity for refining hydraulic fracturing technologies required in Phase 3.
- ***National Renewable Energy Laboratory****:* Mr. Jon Weers will lead development of a web portal to showcase data generated by the FORGE project. The portal will be integrated with the GTO/NREL-developed, NGDS-compatible data management system (Collab DMS) and the DOE Geothermal Data Repository (GDR). The new portal

will provide users with custom visualizations and streamlined access to publicly available Utah FORGE data.

- ***International Collaboration:*** One of the important aspects of the Utah FORGE site is free access to scientists from around the world. In fact, the pace of geothermal development is rapid in other countries, particularly China, Western Europe and Africa.
  - The Utah FORGE team collaborates with Chinese EGS scientists and Engineers from multiple universities and energy companies. Dr. Xiaochun Jin (Ph.D., University of Oklahoma) will provide liaison so that we are up to date with the rapidly evolving geothermal research community in China. Specifically, EGI has close collaborative activities with Prof. G. Li's geothermal research group at China University of Petroleum, Beijing; and with Prof. Q. Liu's geothermal drilling research group at Southwest Petroleum University in Chengdu.
  - Utah FORGE team members are working with Chinese companies interested in geothermal development in Tibet and southern China, on the border with Myanmar.
  - Utah FORGE team members collaborate strongly with researchers from the Geothermal Energy and Geofluids Group at ETH-Zurich. In fact, they have recently selected the INL developed MOOSE computing platform for modeling and simulation code development. INL staff will be teaching a short course at ETH the week of March 19th, 2018. Dr. Robert Podgorney will provide liaison with this research team.
  - Utah FORGE members interact with Canadian geothermal researchers (low grade hydrothermal and ground source) but who are exploring for EGS opportunities. The strongest relationship is with Prof. M. Dusseault at the University of Waterloo.

IV.4 PROJECT MANAGEMENT TEAM

The Project Management Team (PMT) will administer the FORGE R&D Vision and Implementation Plan. The managing and administrative staff will be housed at the University of Utah, led by the Utah FORGE Managing PI, Dr. Joseph Moore. The PMT will consist of Dr. Robert Podgorny, Dr. John McLennan, Dr. Rick Allis, Dr. Philip Wannamaker and Dr. Stuart Simmons. Dr. Moore will assume primary responsibility for day-to-day communications and financial management of Utah FORGE. The PMT will ensure that the logistical administrative, analytical and technical support required for on-site R&D, maintenance and monitoring operations will be available. The PMT will review cooperative agreements, intellectual property issues and conflicts of interest that may arise, develop educational programs and facilitate data sharing, access. All data generated by the project will be made available to the public through the National Geothermal Data System. EGI and the University of Utah have extensive experience in operating large, federal research centers and conducting collaborative research with US federal laboratories, other universities, government organizations, and the oil and gas and geothermal communities.

Utah FORGE activities have evolved through the project timeline, and as presented above our management team is evolving to address the changes in program needs and requirements. In Phase 1 and Phases 2A and 2B, requirements were for insuring that the environmental, and geologic criteria were paramount. The effort, still with significant input from these areas moves to developing infrastructure, refining methods for administering third party research and in developing the field laboratory. The Utah FORGE team further recognizes that the project requirements will evolve with time. The composition of the STAT and FORGE team will change as necessary to reflect those changing requirements (Table IV.1).

Table IV.1. Project Evolution and Required Specializations

Evolution of Technical Specialties in Utah FORGE Teams

Phase	Activity		Environmental Specialist	Structural Geologist	Geochemist	Rock Mechanics	Geophysics	Reservoir Engineering	Drilling and Completion Engineering
2A	NEPA Approval Well 58-32 Geomodel	***Non-Invasive Studies*** Reflection Seismic Passive Seismic (MEQ) Magnetotelluric LIDAR Hyperspectral Imaging Precision Land Surveying Gravity Soil Gas ***Subsurface Studies*** Temperature Surveys Geophysical Logs Fluid Sampling DFIT, Other Injection Core Testing	✓						
2B			✓	✓	✓	✓	✓	✓	✓
2C	Infrastructure and Characterization			✓	✓	✓	✓	✓	✓
3 (early)	Well Construction	Drilling and Stimulation				✓	✓	✓	✓
3 (later)	Monitoring		✓		✓		✓	✓	
	Reservoir Modeling	Rock and Fluid Mechanics			✓	✓	✓	✓	
	Analysis	Geoscience and Economics	✓	✓	✓	✓	✓	✓	✓

IV.5 OVERVIEW OF PHASE 2C AND 3 ACTIVITIES

Activities during Phases 2A and 2B demonstrated that the laboratory site met DOE's technical requirements for temperature, rock type and depth. Appropriate temperatures and an extensive, relatively homogenous crystalline, basement granitic thermal reservoir were confirmed. The thermal reservoir is away from large-scale tectonic structures. Seismic monitoring has not detected any events beneath the site. Direct measurements have been made of the in-situ stresses. Mechanical properties and permeability were also directly measured. Based on the analysis of legacy and newly acquired data, a ~10 km^2 site area is designated for the deep drilling venue. No environmental issues that would constrain FORGE activity were identified.

Phase 2C and 3 activities will emphasize readying the FORGE Laboratory for operation as well as conducting and soliciting experimentation for the advancement of EGS technologies. The result will be a program with the following goals:

1. Drill and steer highly deviated wells into granitic rocks with a temperature of ~175 to 225°C in the 2.5 km true vertical depth range at the Milford, Utah FORGE location. Figure IV.5 is a schematic for preparing the laboratory facility for formalized research programs.
2. Solicit, develop and test innovative technologies for reservoir stimulation, monitoring and testing, as highlighted in Figures IV.2 through 4.
3. Create a network of highly conductive fluid pathways connecting the wells (without short-circuiting), demonstrate long-term reservoir sustainability and monitor performance and thermal extraction efficiency.
4. Characterize the reservoir volume (productive, sustained surface area), fracture morphology, directions, surface area and interconnectivity; formulate and validate reservoir and site models.
5. Provide a facility where high-temperature logging and fracture imaging tools and equipment can be tested, and expert teams can visit and test novel stimulation and heat exchange techniques.
6. Provide a site that showcases EGS technologies to the public, stakeholders, and the energy industry; demonstrating that they are viable and have the potential to contribute significantly to power generation and direct use applications.
7. Provide educational and research opportunities at all levels - from grade school to graduate programs, as well as the general public, national and international specialists and laypersons.

In Phase 2C, working in concert with the DOE, the STAT will be established and convened to assess the "state of the art" (e.g., exploration and testing, drilling and completion, stimulation, production, reservoir management, and sustainability), to define R&D directions and to prepare the first solicitation for R&D investigations The solicitation will be released at the beginning of

Phase 3. The STAT will contribute to the development of the stimulation program and its metrics.

Phase 3 will involve full implementation of FORGE, including drilling, stimulation, flow and pressure transient analysis, and monitoring to achieve incremental as well as substantial additions to the important findings from earlier field demonstrations, domestically and internationally. R&D projects will be solicited, reviewed, selected and incorporated in the Phase 3 activities, as appropriate. These research projects will solicit new and novel tools and methods for the drilling, stimulation and maintenance of EGS reservoirs. These efforts are anticipated to include development of tools capable of withstanding elevated temperatures for long periods of time. Tools are needed to increase the Rate of Penetration (ROP), improve geosteering and perform Logging While Drilling (LWD) in these extreme environments. New technologies that can substantially improve EGS development include smart tracers and other fracture mapping/quantification methods, geophysical and well testing techniques for reservoir monitoring, and new reservoir models and simulation methodologies. Ruggedized downhole valves that can be operated remotely, hydraulically or mechanically may be key developments for long-term management of enhanced geothermal systems. In any configuration of highly inclined wells, control of the flow through the fractures connecting the injection well and the production well(s) will be important in order to avoid “short circuits.” Inflatable packers, controllable valves, downhole pumps, or potentially pressure-sensitive sliding sleeves - combined with quasi-continuous temperature and flow monitoring – will likely be required to optimize and manage power generation.

During Phase 3, two wells will be drilled and interconnecting hydraulic fracturing will be emplaced. The facility will allow development, testing, refinement and comparison of different EGS stimulation, monitoring, prediction, mapping, heat extraction, and prediction technologies. To meet DOE requirements for EGS development we propose to drill two or more wells vertically to a depth of approximately 2500 m and complete them with legs drilled to the southeast at approximately 60° or more from the vertical. We anticipate drilling the deviated legs of these wells not more than 200 m apart. As discussed below, we propose a staged stimulation program beginning at the toe of the first well drilled, rather than attempting to stimulate the entire reservoir section at one time. This will allow implementation and assessment of additional or alternative stimulation and completion methods uphole from these initial fractures.

Consultation with various service providers indicates that horizontal drilling would be possible but setting isolation tools may be less problematic at a slightly smaller inclination.

The azimuth will be selected to be orthogonal to the measured maximum horizontal stress direction. The maximum horizontal stress acts at ~N25E. The wells will be one above another and will pass to the north of well 58-32 (vertical well drilled during 2017). Completing the wells north of well 58-32 will result in improved resolution of microseismic measurements to be performed by Schlumberger.

By starting at the toe (remote end) of the lateral legs, it will be possible to test different hydraulic fracturing and propping technologies, stage by stage, while working toward the near end (heel). High-risk experiments will be conducted at the far end of the lateral leg. This will allow any damaged zone resulting from a failed experiment to be isolated. We will conduct a detailed evaluation of all proposed research programs – in terms of risk management and avoiding unintended consequences.

IV.5.1 POTENTIAL FORGE EXPERIMENTS

Although the engineering of wells and reservoirs under conditions that are representative for the commercial deployment of EGS will be an important focus for FORGE, this engineering must also enable a much broader range of R&D. The well and reservoir configurations discussed above will enable many experimental investigations to be conducted with a minimum of interference between them. Our approach to FORGE will facilitate and encourage cooperation between the research teams that conduct experiments at the site and support integration of experimental activities with numerical modeling of reservoir performance. The well and reservoir configurations introduced above will allow for additional research opportunities. A wide variety of experiments will be solicited and potentially conducted at the FORGE site, with a final test plan developed in conjunction with the STAT and GTO. Potential experiments at the FORGE site include:

Reservoir Stimulation Technologies – As discussed above, we will design our wells so that multiple stimulation experiments can be conducted, including quantitative evaluation of stimulation methodologies. We also have the infrastructure to conduct both short-duration and long-term stimulation experiments.

Use of Proppants – The wells will be drilled and designed using standard oilfield approaches, allowing for selective emplacement of proppant into limited intervals of the wells.

Restimulation and Cyclic Stimulation – Leveraging the proposed well design, and having access to a large, low-total-dissolved-solids water, onsite electrical power, it will be possible to conduct longer-term injection tests including cyclic-restimulation experiments.

Survivability of Downhole Equipment and Measurement/Monitoring Methods – It is possible to drill a pilot well for installation of monitoring or service equipment for long periods of time and then retrieved for inspection of metallurgy, seals, threads, and sensors.

Corrosion and Corrosion Inhibition Testing – It will be possible to include bypass sections in the production piping system so that corrosion testing can be conducted at different pressures and temperatures. The ability to perform long-term corrosion tests will be an asset for FORGE.

Chemical Treatments to Improve Fracture Conductivity – Chemical stimulation methods and reservoir treatments have been shown to increase reservoir performance and can be evaluated at the FORGE site.

Scale Inhibitor Testing (scale inhibition in propped fractures and in the well) – Similar to the chemical treatments and the corrosion testing side-stream capability mentioned above, experiments evaluating scale inhibition in both wells and fractures can be conducted.

Heat Transfer Fluids – While the current vision for long-term FORGE operations takes advantage of abundant water resources, it will be reasonable to test other working fluids (e.g., CO_2) and additives (e.g., nanoparticles).

Induced Seismicity Monitoring and Detection – The well field and downhole signal generators can be used to advance signal processing methods.

Coupling Reservoir Operations with Numerical Models of Reservoir Performance – In the later years of Phase 3, operation control experiments can be conducted by linking reservoir models, data/monitoring systems, and flow control at the site to conduct optimization experiments.

CAVE – We will utilize the Idaho National laboratory's CAES Advanced Visualization Laboratory to evaluate and optimize proposed field-scale experiments.

The evaluation of proposed onsite experiments will be much more complex than evaluation of experiments at a typical user facility, where proposal evaluation is based primarily on the balance between cost (e.g. instrument time, processor hours, beam time) and the probable value of the results that will be obtained. At FORGE, there is a much higher likelihood that one experiment will negatively impact others being conducted at the same time or in the future. There is also a much higher risk that an experiment will cause damage that is very expensive to repair. Oversight by the PMT and the experience of the STAT will alleviate this risk.

IV.6 R&D IMPLEMENTATION PLAN

The R&D Implementation Plan has been designed to promote the development of new technologies and to provide the flexibility required to address the evolving needs of the project. Fifty percent of the funds provided by DOE will be used for R&D subcontracts; the remainder will be allocated to drilling, stimulation and related activities, operations and management, as well as routine periodic or continuous monitoring activities. R&D activities will be generated, funded and managed through a recurring series of Funding Opportunity Announcements (FOAs). The mechanisms and protocols that will be used to address R&D needs throughout all phases of the Utah FORGE project are described in the following R&D Implementation Plan. Proposals submitted outside the scope of the FOAs will be considered based on the level of funding available, the needs of the project, their impact on ongoing activities, and the STAT's assessment of their contributions to advancing EGS application and viability. R&D projects will not be limited to topics addressed by the FOAs

The scope of the R&D Implementation Plan includes:

1. Management of the R&D program

2. Selection of technical experts to serve on the STAT and defining STAT obligations to the R&D program
3. Identification of technologies and research that address FORGE and future EGS needs,
4. Preparation of FOAs
5. Selection of proposed research projects
6. Management of these technology development/validation and research projects
7. Management of conflicts of interest

The STAT will consist of DOE representatives, their appointed technical experts, as well as experts from the geothermal, petroleum, and rock mechanics communities; the latter appointed by the PMT. The PMT will oversee all day-to-day operations and management, including administrative and financial activities of Utah FORGE.

IV.6.1 MANAGEMENT OF THE R&D PROGRAM

IV.6.1.1 The Obligations of the PMT

Specific responsibilities of the PMT include:

1. Oversight of day-to-day site operations and maintenance
2. Conducting technical, financial and administrative activities, including oversight of scheduling and engagement of subcontractors for field services; ensuring the safe and cost-effective execution of Utah FORGE and development of EGS technologies. The PMT will be supported by the Finance Manager
3. Developing and implementing formal procedures for Utah FORGE and for reviewing and awarding funding for R&D technology development and/or validation or conceptual demonstration
4. Ensuring that all state and federal permits have been acquired and are compliant with NEPA and Protocols for Induced Seismicity Associated with Enhanced Geothermal Systems. The PMT will be supported by the Technical Lead on Seismic Monitoring
5. Maintaining effective communication with the DOE and interested stakeholders on project activities and technical results. The Managing PI will serve as the primary point of contact with the DOE and assume overall responsibility for communication and outreach activities. He will be supported by the Outreach Coordinator
6. Making FORGE data available through a dedicated node on the National Geothermal Data System (NGDS). The PMT will be supported by the Data Manager.
7. Preparation of an annual operating plan (AOP) in Phase 3 for approval by the DOE.

IV.6.1.2 Science Technology and Advisory Team

The STAT will provide technical guidance on research directions, identify specific research topics and ensure continued significance of the FORGE mission throughout Phases 2C and 3. The STAT will:

1. Assess and summarize the current state-of-the-art and identify technology gaps
2. Establish technical baseline information and performance metrics
3. Determine topics for initial and subsequent rounds of solicitations during Phase 3, and
4. Provide a draft of the solicitations for release at the beginning of Phase 3
5. Review proposals and R&D progress

Phase 2C activities will focus on infrastructure development, formation of the STAT and it's charter and governance structure. It will include provisions for modifying the STAT membership to meet the project's evolving needs.

In order to bridge the gap between the engineering and scientific aspects of the project, members of the STAT will include world class experts in site characterization, drilling and well stimulation, reservoir management and engineering, rock mechanics, and induced seismicity. The STAT members will be drawn from the geothermal and oil and gas industries, national laboratories, research organizations, energy technology companies and academic institutions. The STAT will consist of approximately 10 standing members, up to seven of whom will be selected by the PMT and at least three by the DOE. We will provide the names of all STAT candidates to the DOE for comment prior to forming the committee. Several world-class experts have indicated their interest in serving on the STAT.

The DOE will choose one member of the STAT to serve as Chairperson. This individual will serve as the primary contact between the STAT and the Managing PI. The Chairperson will ensure that the goals and objectives of the DOE program are being considered and incorporated into the R&D projects.

The STAT will meet at least twice a year. The STAT, including its governance and charter, will be established within two months of the Phase 2C award. The first meeting of the STAT will be convened in Salt Lake City within month 3. At this meeting, the STAT will hold discussions on:

1. The current state-of-the-technology
2. Baseline information and performance metrics for Utah FORGE
3. The topics for the first round of solicitations. Writing responsibilities for the first round of solicitations will be assigned

IV.6.1.3 Planned Solicitation Topics

Solicitations will be issued in the following three EGS life cycle categories:

- Reservoir characterization (coupled imaging, drilling for interrogation and monitoring, high temperature tools and sensors)
- Reservoir creation (formation access, fracture characterization, zonal isolation stimulation technologies)
- Reservoir sustainability (long-term testing, monitoring, and operational feedback)

Solicitations will be released by Month 5. The STAT will meet again at approximately Month 7 to review the proposals submitted under the Phase 2C solicitations (assuming Phase 2C is 8 months long). We anticipate completing contract negotiations at the start of Phase 3. The solicitation process will be repeated annually in Phase 3 following a similar schedule. The STAT will meet during the first quarter to determine topics for the year's solicitations. This meeting will be combined with a Peer Review of activities related to R&D projects, Operations and Maintenance, and projects being conducted by Utah FORGE personnel. The solicitations will be reviewed at the second STAT meeting, which will be convened at approximately Month 10, with contract negotiations completed within the following 60 days

IV.7 SUMMARY

The Utah FORGE team recognizes that the project requirements will evolve with time. The composition of the STAT and FORGE team will change as necessary to reflect those changing requirements. In Phase 2C, a critical focus of the work will be to install necessary infrastructure and surface and downhole monitoring equipment in support of Phase 3 drilling and research activities and conduct well tests and numerical simulations that will inform Phase 3 drilling and stimulation activities. Early in Phase 3 the emphasis will be on drilling and stimulation. The later phases of Phase 3 will focus on long-term monitoring, reservoir modeling and analysis of early predictions.

FORGE's mission is to enable impactful research, drilling and technology testing. The venue and the management structure allow scientists to identify and advance a replicable, commercial pathway to EGS implementation on a geographically diverse scale. In addition to the facilities, infrastructure, and collaborative environment, the FORGE effort embraces a sophisticated and comprehensive network of instrumentation, data collection, and data dissemination to capture and share data and activities occurring. The innovative research, coupled with an equally-innovative collaboration and management platform, is a "first-of-its-kind endeavor."

SITE DISPOSITION

Activities conducted during Phase 2A and 2B affecting the land surface included road grading and the construction of the well 58-32 drill pad. The road crosses School and Institutional Trust Land Administration (SITLA) and BLM land; the pad lies entirely on SITLA property. We have been informed the road can remain but the well must be plugged and abandoned and the pad regraded if the Utah FORGE team is not awarded the project. SITLA will not accept any liability for the well.

REFERENCES

Asai, P., Panja, P., McLennan, J., Moore, J. (2018). Performance Evaluation of Enhanced Geothermal System (EGS): Surrogate Models, Sensitivity Study and Ranking Key Parameters. *Renewable Energy*. Vol. 122 (2018) 184e195. 02/06/2018.