INL/LTD-16-38127 R1
DE-EE0007159

The Snake River Geothermal Consortium is a research partnership focused on advancing geothermal energy, hosted by Idaho National Laboratory.

Phase 1 Topical Report

May 2016

SRG Consortium
Snake River Geothermal

FORGE
U.S. Department of Energy

INL/LTD-16-38127 R1

Phase 1 Topical Report

Principal Investigator
Dr. Robert K. Podgorney
(208) 526-1524
robert.podgorney@inl.gov

May 2016

Snake River Geothermal Consortium
Hosted by Idaho National Laboratory
Idaho Falls, Idaho

www.snakerivergeothermal.org

Submitted to the
U.S. Department of Energy
National Energy Technology Laboratory
Stephen J. Henry
stephen.henry@netl.doe.gov
Agreement DE-EE0007159

CONTENTS

FIGURES

TABLES

ACRONYMS

3D	three dimensional
CAES	Center for Advanced Energy Studies
DOE	U.S. Department of Energy
EA	environmental assessment
EGS	enhanced geothermal systems
EMS	Environmental Management System
ES&H	environmental, safety, and health
ESRP	Eastern Snake River Plain
FORGE	Frontier Observatory for Research in Geothermal Energy
GDR	Geothermal Data Repository
GRRA	Geothermal Resource Research Area
GTO	Geothermal Technologies Office
IDWR	Idaho Department of Water Resources
INL	Idaho National Laboratory
NEPA	National Environmental Policy Act
PMP	project management plan
R&D	research and development
SRGC	Snake River Geothermal Consortium
STAT	Science and Technical Analysis Team
STEM	science, technology, engineering, and math
TOT	Technical Opportunity Team
USGS	United States Geological Survey

Phase 1 Topical Report

1. OVERVIEW OF PHASE 1 ACTIVITIES

In 2015, the Snake River Geothermal Consortium (SRGC) was one of 5 groups selected by the Geothermal Technologies Office (GTO) of the U.S. Department of Energy (DOE) to conduct a Phase 1 study for establishing the Frontier Observatory for Research in Geothermal Energy (FORGE). SRGC's goal is to establish and manage a dedicated site where the scientific and engineering community will develop, test, and improve technologies and techniques for enhanced geothermal systems (EGS) in a favorable research environment. This topical report and the Phase 1 Presentation are the final deliverables for Phase 1 activities.

During Phase 1, we focused on areas such as the geologic conceptual model that had the greatest impact on FORGE site selection while still achieving deliverables needed to meet the requirements of the GTO. We also refined and expanded our objectives for Phases 2 and 3:

1. Bring together the geothermal research community and test site to facilitate the science and engineering required for comprehensive EGS technology development
2. Drive innovation through a FORGE team roadmapping effort that includes an open annual EGS technical meeting that is modeled after the highly regarded and effective Gordon Conference Series
3. Leverage innovative, nontraditional stimulation techniques to create a stable fracture network for geothermal energy transfer
4. Use advanced modeling and simulation tools to optimize reservoir energy output
5. Build and operate the FORGE site on Idaho's Snake River Plain for geothermal research, development, deployment, testing, and validation
6. Educate and inform the public about the promise of geothermal energy in general and EGS specifically

Idaho National Laboratory (INL), which is one of the largest laboratories (2,300 km^2 [890 mi^2]) owned by the U.S. Department of Energy (DOE), will host FORGE. Approximately 110 km^2 (42.6 mi^2) known as the Geothermal Resource Research Area (GRRA) has been dedicated for FORGE. This physical and administrative setting at INL provides SRGC with numerous advantages over other candidate sites. First, it allows us to immediately focus attention on the geologic conceptual model without sacrificing the robustness of other key planning activities. This is because INL is accustomed to hosting multidisciplinary scientific user facilities that are similar in complexity and magnitude to FORGE, so many policies, procedures, and site requirements that apply to FORGE are already in place. For example, INL has an established environmental, safety, and health (ES&H) program; extensive infrastructure (roads, electric power, water rights, work control processes, quality assurance systems, emergency services, etc.); a geologic core library and sample control procedures; an in-house National Environmental Policy Act (NEPA) compliance staff; and strong community engagement and support.

In addition to the advantages of the INL Site, the SRGC offers a leadership team composed of experts from national laboratories, industry, academia, and federal/state institutions. SRGC brings personnel with combined decades worth of organizational operations and technical experience to FORGE in an atmosphere of open collaboration and idea sharing, singly focused on advancing EGS through FORGE. The national laboratory members of the SRGC strongly represent GTO's core capabilities, ranging from exploration through deployment. University and industry partners complete the team by bringing technical expertise in the few remaining capability areas.

The Phase 1 findings, which are summarized below, guided our vision for FORGE Phases 2 and 3.

1.1 Project Management Plan

The first Phase 1 FORGE deliverable was a revised project management plan (PMP), which laid out our vision and Phase 1 execution plans for FORGE. We executed Phase 1 according to requirements presented in the Phase 1 PMP, achieved all of the deliverables in a timely fashion, and stayed within budget.

1.2 Communications and Outreach Plan

The FORGE *Communications and Outreach Plan* (Ulrich and Podgorney, 2016) (see Appendix G) describes our approach to communicate with and provide outreach to FORGE stakeholders and defines our internal communication protocols. Previous EGS developments have clearly shown that EGS projects are more successful when engaging key internal and external stakeholders on an individual basis, when possible.

The plan defines target external and internal audiences (stakeholders), including the general public, academia, government leadership, industry, media members, SRGC members, DOE staff and program leadership, and INL leadership. The SRGC has also actively engaged with local Native American tribes and special interest environmental non-governmental organizations and will continue to do so throughout the project.

The plan defines how we use communications tools (e.g., traditional news releases, social media posts, marketing materials (like infographics), fact sheets, web content, booklets, videos, and presentations and tours) to educate, inform, and expand the support base for EGS by increasing stakeholder literacy in the areas of geothermal science and technology. Using these carefully selected and tested tools, we will broaden the general public's understanding of FORGE, EGS, and use of EGS as a baseload energy source and will maintain community support for the FORGE site. Building on well-established public and educational outreach programs at SRGC member facilities, the plan also describes how we leverage existing staff and activities to share FORGE and EGS information with stakeholders.

Our internal communications tools and protocols allow the team to communicate "virtually under one roof." using an interactive content management website and virtual meetings; these are augmented with in-person visits, as needed. We will also ensure that the INL community, as the physical host of FORGE, is actively engaged and supportive of the development of the FORGE site. Finally, we are equipped to tactically handle crisis communications using planned messages and talking points (which can be adapted to situations, as needed), protocols, and draft content for websites and media releases to help the SRGC respond quickly and effectively to inquiries during a crisis, either real or perceived.

An action plan and implementation schedule provide clear action items that identify the frequency of activities and the steps needed to prepare and maintain materials for future use to continue engaging stakeholders. Metrics and reporting guidelines explain how we will continue to track communication and outreach success throughout the project.

The FORGE *Communications and Outreach Plan* (Ulrich and Podgorney, 2016) also provides the results of an assessment of communications and outreach performance through February 2016 as a baseline for techniques that have worked and should continue to be used as the FORGE project progresses. The assessment quantifies successful SRGC engagement with the local community, special interest groups, disadvantaged groups, and the general public as a whole, as well as our steady growth of the SRGC traditional and social media presence.

As of May 11, 2016, the SRGC had participated in 18 outreach events throughout the world, met with 57 regional and national stakeholder groups, and shared information about FORGE and EGS with 1,607 people on 89 tours through the Center for Advanced Energy Studies (CAES) in Idaho Falls, Idaho, where the SRGC is based. **Of the 93 articles published about FORGE from**

January 1, 2015, to May 11, 2016, more than 34% of all FORGE coverage was INL/SRGC site-specific coverage, and 88% of those SRGC media mentions were a direct result of SRGC media outreach efforts.

See Appendix H for more information on our stakeholder engagement efforts and status.

1.3 Data Dissemination and Intellectual Property Plan

The FORGE *Data Dissemination and Intellectual Property Plan* (Weers and Podgorney, 2016) (see Appendix F) details the methods and approaches that will be used to provide data generated by FORGE in a transparent and easy-to-access manner. **The SRGC has developed a preliminary website (www.snakerivergeothermal.org) that provides information to increase public understanding of EGS and FORGE and to act as a team communications portal.** The website engages stakeholders, describes the fundamentals of EGS technology, provides transparency in FORGE operations, provides information on the Eastern Snake River Plain's (ESRP's) deep geothermal system, and informs local communities of FORGE activities. In Phase 2, additional website capabilities will be added facilitate access to FORGE data and advance the adoption of EGS technologies. In addition to the methods and approaches that will be used to provide access to FORGE data, the plan describes the existing platforms, tools, and expertise that will be leveraged to construct a data management platform that is fully compatible with the Geothermal Data Repository (GDR) and the National Geothermal Data System in a cost-effective and timely manner.

The SRGC data repository will be housed in the National Renewable Energy Laboratory's new secure Amazon cloud environment. This state-of-the-art environment has already undergone a rigorous approval and testing process, has been fully vetted by DOE cyber security, and , uniquely, has been granted authority to operate with moderate, sensitive data in "the cloud." It also allows for processing large data sets quickly and efficiently. This secure platform and repository will be fully compatible with the existing GDR architecture and the National Geothermal Data System while providing secure access from anywhere in the world for FORGE partners to collaborate on sensitive data before public release. (See Appendix B for an update regarding characterization data we have uploaded to the GDR.)

Finally, the plan details the SRGC's intellectual property management strategy, which is based on previous successfully implemented plans for collaborative projects involving multiple national laboratories, universities, and industry partners (for example, the NREL led National Advanced Biofuels Consortium).

1.4 Geologic Conceptual Model

The FORGE *Geologic Conceptual Model* (St. Clair et al., 2016) (see Appendix A) documents a geologic model of the proposed FORGE site on the ESRP. The goals of our conceptual modeling effort were to (1) develop a set of conceptual model scenarios of the subsurface beneath the GRRA that honor the existing data, (2) demonstrate that the subsurface beneath the GRRA meets the criteria for FORGE, (3) develop a preliminary geomechanical model to assist in well and reservoir development planning, (4) develop a characterization plan to reduce uncertainty in the geologic model and reduce the risks for establishing FORGE, and (5) show that our proposed site is representative of the EGS potential throughout the ESRP and large parts of the United States, demonstrating that technical advances at FORGE may be applicable to a much larger EGS resource.

The SRGC's FORGE site, located within the track of the Yellowstone Hotspot, provides an excellent geological test bed of favorable subsurface temperature and regional stress conditions. Over the past 17 Ma as the North American plate has moved southwest over the stationary hotspot, mantle-derived magmas have been injected into the upper crust, melting the silicic upper crust and producing numerous rhyolitic eruptions that formed calderas similar to those observed in and around Yellowstone National Park. Today, these calderas in the ESRP are buried under 1 to 2 km (0.6 to 1.5 mi) of interbedded basalt flows and sediments, including intra- or extra-caldera rhyolite flows or extra-caldera ignimbrite deposits, and are our target reservoir rocks for EGS at the GRRA.

Deep boreholes throughout the ESRP verify the widespread occurrence of low-permeability hydrothermally altered rhyolites and high heat flows (>110 mW/m^2) beneath the basalt layer. Permeability measurements have been completed on samples from representative lithologies in deep boreholes near the GRRA. Intra-caldera facies sampled from depths of 1.485 and 3.15 km (4,872 and 10,335 ft) have permeabilities of 7×10^{-20} to 1.8×10^{-17} m^2 (0.068 to 18.2 μD), respectively, and an extra-caldera sample from 1.34-km (4,396-ft) depth has a permeability of 2×10^{-18} m^2 (2 μD). **These potential EGS reservoir rocks are encountered in every deep well that penetrates through the overlying basalts and sediments on the ESRP**.

As a risk-mitigation measure, we developed two geologic structural models that differ in how the geometry of the subsurface is interpreted, and we overlaid conductive temperature gradients measured in deep boreholes nearest the GRRA that range between 44.4 and 76.6°C/km (2.4 and 4.2°F/100 ft). These gradients predict that the 175°C (347°F) isotherm will be encountered at depths between 2.4 and 3.8 km (7,874 and 12,460 ft). **Based on all available data and under every conceptual scenario tested, our site meets the temperature, depth, and permeability criteria defined by DOE.**

We also developed a preliminary one-dimensional geomechanical model to assess suitability of the site for horizontal or highly deviated well stability and reservoir stimulation, and we present a workflow for extending this model into three dimensions. **Based on the available data and our analysis, the GRRA presents an optimal geologic location for FORGE.**

1.5 Sample and Core Curation Plan

The physical samples—including lithologic cores, cuttings, and water samples—generated during FORGE will provide a wealth of scientific knowledge about the ESRP's deep geothermal system and will contribute to areas of science and engineering through researcher studies. **Our FORGE *Sample and Core Curation Plan* (Snyder et al., 2016) (see Appendix I) provides long-term storage of FORGE rock and water samples, as well as researcher access to the core in perpetuity, at no long-term cost to the DOE Office of Energy Efficiency & Renewable Energy.** The United States Geological Survey (USGS) Lithologic Core Storage Library and Water Archive Library, which are a 10-minute drive from the FORGE site, will be used to store the samples and provides a central location for researchers to analyze the samples. The Water Archive Laboratory has been in place since 1966, and the Lithologic Core Storage Library has been continuously supporting geological studies on the INL Site since 1990.

The FORGE *Sample and Core Curation Plan* specifies organizational responsibilities, the FORGE Phase 2 and 3 procedures for physical sample generation, the facilities that will be used to handle and store physical samples that are generated, and an overview of the processes that will be used to manage these physical samples from their point of origin through long-term storage. These processes address drilling, collecting the cores, processing them, storing them, and providing final core disposition. Finally, this plan defines the process for easy access to data, records, and stored physical samples by internal and external researchers for scientific and engineering studies.

1.6 Research and Development Implementation Plan

The FORGE *Research and Development Implementation Plan* (Podgorney et al., 2016) (see Appendix L) provides the approach for effectively managing and coordinating all aspects of testing and evaluating EGS at FORGE. The project will support not only advanced research and development (R&D) of EGS technologies and techniques developed by SRGC partners but will also welcome a new, thriving, multidisciplinary, multiorganizational user community from across the nation and world to test geothermal solutions in real time.

The overarching vision of the SRGC is ***to enable geothermal energy of the future by accelerating EGS commercialization.*** This aligns perfectly with the FORGE mission defined by the GTO. Our leading-edge R&D infrastructure positions the SRGC to realize the FORGE mission, with INL physically hosting the FORGE site and SRGC's 19 partners from academia, national laboratories, state and federal agencies, and industry contributing their expertise. Our 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 is coupled with an equally innovative collaboration and management platform, as well as focused, intentional communications and outreach

Specifically, the SRGC FORGE team, joined by the oil and gas industry, geothermal specialists, small businesses, and the research community, will focus on:

- Understanding the key mechanisms controlling EGS success
- Adapting oil and gas technologies to initiate and sustain fracture networks in basement rock formations
- Designing and testing a reproducible model for developing large-scale, economically sustainable, subsurface heat exchange systems
- Reducing risk to industry by reducing the cost of EGS commercialization

Preliminary R&D activities by SRGC members and FORGE partners will include (1) coordinated characterization efforts; (2) geologic and reservoir modeling; (3) state-of-the-art drilling techniques; (4) innovative well completion and reservoir stimulation activities; (5) well connectivity and flow-testing efforts; (6) detailed geological, geophysical, and geochemical data collection, mining, and cataloging for FORGE users; and (7) protecting overlying groundwater aquifers. FORGE user R&D activities will play a critical role in the development and performance of FORGE, where open solicitations will allow users to test, synthesize, predict, and verify reservoir properties and performance for their own projects but with the results being shared with the broader scientific and engineering community.

Importantly, the FORGE *Research and Development Implementation Plan* presents an organizational structure and decision-making strategy that vets the potential results of proposed projects against the risks to key FORGE infrastructure. The plan also clearly defines the roles of the researchers, the SRGC, the Science and Technical Analysis Team (STAT), and GTO in the decision-making process.

1.7 Preliminary Induced Seismicity Mitigation Plan

The FORGE *Preliminary Induced Seismicity Mitigation Plan* (Templeton et al., 2016) (see Appendix J) describes the protocol that will be used to identify and mitigate any negative consequences of induced seismicity resulting from FORGE development and operations. Our plan follows the DOE's *Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems* (Majer et al., 2012) and the *Best Practices for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems* (Majer et al., 2014). **Our preliminary screening, as based on the guidelines presented in documents mentioned above, suggests that induced seismicity at the FORGE site presents a low overall risk** given the favorable regulatory environment (DOE and the Bureau of Land Management), limited radius of influence, and low impact.

Our mature communications and outreach program addresses seismic risks and monitoring, a key element of EGS development. **The SRGC FORGE site is well-equipped for seismic monitoring with an existing 33-station (surface and borehole) telemetered network that already achieves the requirements in the protocol mentioned above.** In addition, an extensive high-quality catalog that dates from 1972 permits an accurate characterization of seismogenic geologic structures near the FORGE site. A Global Positioning System network also spans the area. Additional seismic stations will be installed during Phase 2 of the FORGE project for high-resolution monitoring and characterization of the site.

During stimulation, near real-time monitoring will be conducted with predefined thresholds to mark exceptional events that warrant further attention. Monitoring will also include vibration monitoring in accordance with local regulations.

Extensive seismic-hazard and risk analyses have been performed for facilities at the INL Site. The analyses for these facilities will be used as the foundation for a seismic hazard analysis specific to the FORGE project. **The existing probabilistic seismic hazard analyses indicate that the seismic hazard is almost entirely from Basin and Range events outside the boundaries of the ESRP**, upon which the INL Site is situated. Faults within the ESRP are mostly related to minor volcanic rifts and contribute little to the seismic hazard. The specific EGS probabilistic seismic hazard analysis includes the hazard from induced events, as well as natural events. The risk depends on the seismic hazard and the potential impact, including physical damage to facilities or smaller events that affect quality of life and the public's perception of the project. INL has significant facilities within 20 km (12.4 mi) of the FORGE site; all of them have been designed to withstand substantial ground motions from natural seismicity. Risk mitigation will be based on two primary elements: (1) a "traffic light" system that defines responses based on levels of ground motion and (2) education and outreach efforts. Properly managed EGS reservoir stimulation is extremely unlikely to produce induced seismicity greater than Magnitude 2.5; therefore, our primary goal regarding induced seismicity is to address potential publicly perceived nuisance-level effects.

1.8 Environmental, Safety, and Health Plan

The FORGE *Environmental, Safety, and Health Plan* (Smith et al., 2016) (see Appendix K) describes the measures used to mitigate or eliminate hazards associated with FORGE. Because INL is hosting FORGE, the SRGC will leverage INL's established ES&H program, which is capable of mitigating hazards to human health and the environment posed by Phases 2 and 3 of the project.

INL's Environmental Management System (EMS) integrates environmental protection, environmental compliance, pollution prevention, and continual improvement into work planning and execution throughout the work areas as a part of the Integrated Safety Management System. INL bases its EMS on elements identified in the EMS standard developed by the International Organization for Standardization (i.e., ISO 14001) and integrates those elements into the core functions of integrated safety management. In 2014, INL recertified for the internationally recognized ISO-14001 EMS standard. In addition to being integrated with EMS, the Integrated Safety Management System is integrated with other critical management processes at INL, including Integrated Safeguards and Security Management, the Worker Safety and Health Program, and the Voluntary Protection Program. **Work control processes for nearly all anticipated FORGE activities have been in place and used at INL for many years** to conduct field-based research, have been vetted by relevant subject matter experts, and have undergone at least one 5-year review to revise the procedures based on lessons learned over many years of research activities.

Importantly, SRGC will leverage INL's organization and management structure, which optimizes efficiency and mitigates risk as research is being conducted. An independent operations organization manages the ES&H aspects of research (provides subject matter experts, permitting planning, safety reviews, etc.), allowing researchers to focus on developing and performing *research*. Equally important is that the ES&H support is funded internally by INL, not by specific projects, thus keeping the ES&H process independent and unbiased. Under this arrangement, we estimate that the annual cost to FORGE for ES&H support service will amount to approximately 10% of one full-time equivalent employee (i.e., 200 labor hours per fiscal year).

1.9 Environmental Information Synopsis

The SRGC has held numerous meetings with regulatory and permitting agencies and has an in-house NEPA group that works closely with the site owner, the DOE Idaho Operations Office. As discussed in the FORGE *Environmental Information Synopsis* (Irving and Podgorney, 2016) (see Appendix C), DOE requires an **environmental assessment (EA) for FORGE that will likely take 8 to 10 months spread between Phases 2A and 2B to complete.** The EA will identify permitting requirements related to geothermal well-drilling and stimulation activities and will identify other permitting or survey actions, as discussed in subsequent sections.

We have established a graded approach to permitting FORGE activities. Our approach will use action-specific environmental checklists for evaluating research and characterization activities that need to occur prior to completing the full NEPA analysis. This will allow characterization to proceed in parallel with the permitting process. **Importantly, INL has negotiated a permitting procedure with the Idaho Department of Water Resources (IDWR) that allows INL to drill and install monitoring wells as needed and without prior notice, permitting wells annually rather than individually**.

Appendix E contains our updated permitting inventory.

2. RESULTS

Our proposed FORGE site has many distinguishing characteristics and important advantages among the FORGE candidate sites:

- The study site location on the ESRP is representative of a large area (i.e., 23,000 km^2 [8,880 mi^2])
- The site is owned by DOE and brings with it the necessary infrastructure (including transportation, electric power, water, and security) to carry out large-scale studies
- Public, industry, and political support is strong, enthusiastic, and vocal
- The impact on the environment and other resources is low

The results of our planning study indicate favorable EGS conditions across the ESRP, thus providing an opportunity for GTO to succeed in FORGE while opening vast new areas for geothermal development. The ESRP has long been recognized as one of the most promising geothermal resource areas in the United States due to the area's high heat flow, supportive rock type, and regional stress regime. Yet little to no development of this resource exists, largely due to the lack of hydrothermal systems. While deep well data on the plain are limited and widely distributed, all of the data from these wells point to favorable conditions.

In contrast to other FORGE candidate sites that are either located adjacent to existing hydrothermal systems or in geologic regimes with unique geology, our FORGE site offers a combination of subsurface depth, temperature, and stress conditions that are representative of a much larger geographic region. Our site also has optimal surface ownership and infrastructure. These conditions will help to ensure long-term access and public support.

The following sections highlight a few key results from the Phase 1 activities related to the technical amenability of the site to FORGE activities.

2.1 Geologic Modeling Results

Our geologic model depicts a system of nested calderas within the 10-Ma Picabo volcanic field on the ESRP and represents the synthesis of more than 40 years of geologic and geophysical research on the ESRP. Because of the ESRP's geologic setting and the importance of the Yellowstone Hotspot, a large number of studies have been directed at understanding the composition, evolution, and structure of the ESRP on a regional and crustal scale. For example, it is well documented that the drift of the North American Plate over the Yellowstone Hotspot played a major role in establishing the current geological conditions on the ESRP, including its thermal regime, and that a number of large calderas similar to those observed at the currently active Yellowstone volcanic center are buried beneath 1 to 2 km (0.6 to 1.2 mi) of post-caldera, mantle-derived basalt flows. Additionally, the ESRP aquifer, which resides in the upper few hundred meters of the ESRP basaltic units, has been studied extensively because of its significance as a regional water source and because of previous and ongoing DOE activities on the INL Site. Despite the great scientific interest in the ESRP, prior to SRGC's FORGE Phase 1 effort, no attempts had been made to create a three-dimensional (3D) model of the structure of calderas within the Picabo volcanic field or any other of the ESRP volcanic fields.

Our Phase 1 modeling efforts have increased the understanding of subsurface conditions beneath the GRRA and enhanced our confidence that our chosen location will provide the required favorable EGS environment for the scientific and engineering community to develop, test, and improve new technologies and techniques. These efforts have also helped us to identify focus areas for Phase 2 characterization activities. Here, we briefly describe our conceptual geologic model, what we learned during Phase 1, and how we plan to decrease the model uncertainties during Phase 2. Our geologic model consists of three primary components: (1) the geologic structure at depth, (2) the thermal structure of the target reservoir, and (3) in situ conditions (rock strength, permeability, and stress). Figure 1 shows some of the geological attributes of the selected site obtained from the 3D geologic model.

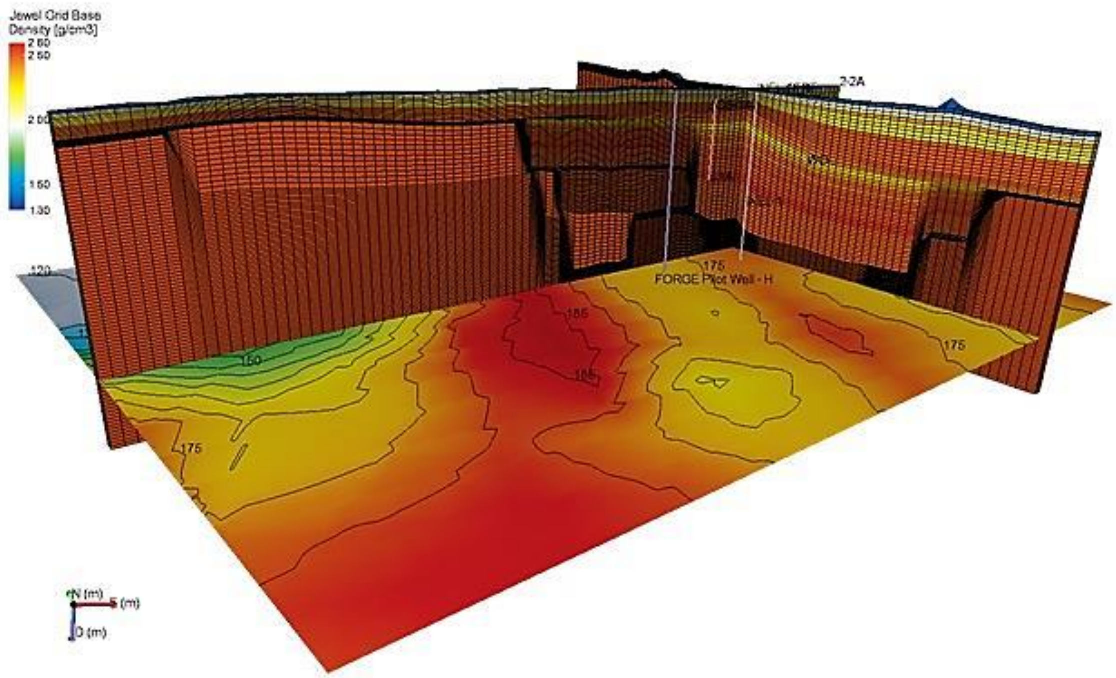

Figure 1. Density distribution (walls) mapped into the 3D structural model. The contoured horizon is the temperature distribution (°C) at 3.5 km (11,500 ft) below the surface, as predicted by Blackwell et al. (2011).

2.1.1 Geologic Structure

Direct observation of calderas and associated structures within the Picabo volcanic field is not possible because they are buried beneath 1 to 2 km (0.6 to 1.2 mi) of basalt and rhyolites originating from the younger Heise volcanic field to the northeast. The widespread existence of intra- and extra-caldera rhyolites is known from deep boreholes that penetrate the ESRP basalts. Seismic refraction and deep Schlumberger soundings indicate that these rocks are laterally continuous over many tens of kilometers. Intra-caldera units from the youngest of the Picabo calderas persist to at least 3.15-km (10,335-ft) depth at the INEL-1 borehole (McCurry et al., 2016). A seismic refraction survey over this area suggests that the northern boundary of this caldera is marked by a steeply dipping structure near the northwestern boundary of the GRRA (Pankratz and Ackerman, 1982). The deep resistivity soundings revealed a 20 to 40 Ohm-m layer that is interpreted to be volcanic tuffs persisting to a depth of ~3.7 km (~12,100 ft) beneath the GRRA and greater than 6 km (~19,700 ft) near the city of Blackfoot, Idaho (Zohdy and Stanley, 1973). Beneath this unit, the data indicate a more resistive layer (>500 Ohm-m), which was originally interpreted to represent the Paleozoic rocks that compose the mountain ranges north of the GRRA. However, geophysical logs obtained from the deep borehole, INEL-1, recorded a mean resistivity of ~1,000 Ohm-m within a 500-m (1,640-ft)-thick unit of rhyodacites underlying a >1,000-m (3,281-ft)-thick, less-resistive rhyolitic tuff. These data suggest that the resistive basement consists of rhyodacites similar to those observed at the bottom of the INEL-1 borehole and not Paleozoic sediments, as had been previously suggested. These data indicate that rocks of rhyolitic composition are present from the base of the basalt layers to at least 3.7 km (12,100 ft) beneath the GRRA—and probably to much greater depths.

The geologic data indicate that our target lithologies are present beneath the GRRA. However, the proximity of our site to the northern margin of the ESRP, where Neogene volcanic rocks transition to the Paleozoic sedimentary rocks that make up the mountain ranges to the north, yields some degree of uncertainty about how the thickness of the rhyolite varies with distance from the ESRP margin. To assess this uncertainty and the potential risks to FORGE at this site, we constructed models with two end-member structural scenarios.

In the first scenario (Model 1 in the FORGE *Geologic Conceptual Model* report [St. Clair et al., 2016]), we used published estimates of caldera boundaries (Anders et al., 2014; McCurry et al., 2016) and assumed a conservative 1 km (3,300 ft) of subsidence for each caldera. Because the inferred caldera boundaries extend to the margin of the ESRP, this model shows intra-caldera rhyolites at depths greater than 4 km (13,100 ft) within ~4 km (~13,100 ft) of the ESRP margin. This model is supported by a seismic refraction survey that imaged a near-vertical structure separating ESRP volcanic rock from the Paleozoic rocks north of the GRRA. The seismically imaged structure lies approximately 1.8 km (5,900 ft) from the ESRP margin and extends to a depth of ~1.75 km (~5,700 ft) beneath the northernmost corner of the GRRA (Pankratz and Ackermann, 1982).

Our second, more conservative model (Model 2 in the FORGE *Geologic Conceptual Model* report [St. Clair et al., 2016]) is based on the crustal flexure model of McQuarrie and Rodgers (1998), which seeks to explain the attitude of Mesozoic fold hinges found in the mountain ranges north of the ESRP. The fold axes plunge toward the ESRP and systematically increase southward to ~25 to 30 degrees before plunging beneath the volcanic section. For this scenario, we model the boundary separating ESRP volcanics from the Paleozoic sedimentary rocks as a planar feature dipping ~30 degrees to the south before leveling out at a depth of 4 km (13,123 ft), ~6.9 km (~4.3 mi) from the ESRP margin. This model indicates that in order to avoid penetrating the Paleozoic section within 4 km of the surface, we must choose a site at least 6.9 km from the ESRP margin. The site we have chosen is approximately 9 km (5.5 mi) from the margin.

Key structural uncertainties include the location of caldera boundaries and the geometry of the boundary separating the ESRP volcanics from the Paleozoic section thought to exist at depth. During Phase 2, we plan to address these uncertainties through a combination of surface geophysical investigations (seismic, gravity, and magnetotelluric) and borehole geophysics in both the existing INEL-1 borehole and a new borehole that we plan to drill to ~1,200 m (~4,000 ft) at the FORGE site.

2.1.2 Thermal Structure

Similar to the end-member structural models discussed above, our understanding of the temperature conditions at reservoir depths is limited by the number of deep boreholes in the area and their proximity to the GRRA. Using observations from five deep boreholes that are within ~30 km (~19 mi) of the proposed site and whose conductive temperature gradients have been reliably measured, we bracketed the range of temperatures likely to exist at our FORGE site. Among the representative wells, the observed temperature gradients range from 44.4 to 76.6°C/km (2.4 and 4.2°F/100 ft), predicting that the 175°C

(347°F) isotherm will be encountered at depths between 2.4 and 3.8 km (7,874 and 12,460 ft). Notably, the nearest observed temperature gradient to the site is 49°C/km (2.7°F/100 ft), which is hotter than our most conservative estimate; thus, our coldest end-member scenario is unlikely to be realized.

Though our predicted temperature range is wide, it was necessary to capture the degree of uncertainty associated with the available data; it shows that our site meets the temperature conditions required by DOE, regardless of the chosen thermal regime. As discussed above, during Phase 2, we will drill an exploration hole to approximately 1,200 m (~4,000 ft). The temperature gradient measured in this hole will reduce the range of uncertainty considerably because the temperature gradient measured in the upper portions of deep wells have been shown to predict temperatures at depth reasonably well.

2.1.3 Fracturing and In Situ Stress Conditions

To predict the in situ reservoir conditions, we relied heavily on observations from the 3.15-km (10,335-ft)-deep INEL-1 borehole. Our team measured permeability and rock strength from core samples taken at 1.485- and 3.15-km (4,872- and 10,335-ft) depths. We combined the new rock strength measurements with observations from INEL-1 to estimate in situ stress conditions and used acoustic televiewer logs from a 1990 survey to characterize the existing fracture populations.

Below the basalt layers, the rocks in INEL-1 are hydrothermally altered rhyodacites that have in situ permeabilities of 8.5×10^{-20} m^2. Thus, **the available data indicate that our site is well within the permeability range defined by DOE**. During Phase 2C, we plan to collect core samples from greater depths at our proposed site and perform similar laboratory measurements. One open-hole pumping test conducted over a large interval (1.3- to 3.15-km [4,265- to 10,335-ft] depths) in INEL-1 (Mann, 1986) predicted a permeability of 7.2×10^{-16} m^2, but based on observations of thermal profiles, the well is likely encountering a permeable fracture zone at depths less than 2 km (6,562 ft) (see Figure 11 in the FORGE *Geologic Conceptual Model* report [St. Clair et al., 2016]), resulting in an anomalously high permeability.

In INEL-1, the vertical stress S_v at 3,500 m (11,483 ft) is estimated to be 82 MPa based on integrated density logs recorded in the borehole. The water table measured in INEL-1 is at 91 m (298 ft), indicating pore pressure is sub-hydrostatic at a value of 34 MPa at this depth. Wireline data and drilling experience from the INEL-1 borehole provide an estimate for the least horizontal principal stress, S_{Hmin}, of 58 MPa +/- 2 MPa at this depth. The lack of leak-off or mini-frac tests in any of the site boreholes limits our ability to accurately measure the least principal stress gradient; however, from the available data, the maximum horizontal stress magnitude can be constrained as transitional between normal faulting and strike-slip faulting, $S_v \geq S_{Hmax} > S_{Hmin}$, with S_{Hmax} of 89 MPa +/- 11 MPa at 3,500 m (11,483 ft).

Existing acoustic televiewer images in INEL-1 collected in 1990 provide insights to fracture sets available for stimulation within our proposed reservoir. In the rhyolitic welded tuffs, there are two main fracture populations:

- Striking northeast-southwest and dipping steeply to the northwest
- Oriented roughly north-south and dipping steeply to the west

In the deeper rhyodacites, there are three dominant fracture populations:

- Northeast-southwest set, steeply dipping both northwest and southeast
- East-northeast set, dipping to the south
- South-southeast set, dipping to the north

The variability of fracture trends revealed by the image data analysis indicates there is a well-developed network of existing fractures that can provide a base reservoir volume for stimulation. Our Phase 2 characterization plan calls for improved fracture characterization using state-of-the-art fracture imaging technology in both the existing INEL-1 borehole and the proposed new boreholes. Data from these efforts will greatly improve our knowledge of the existing fracture networks and in situ stress conditions.

2.1.4 Geologic Uncertainty and Risks

Geologic uncertainty and potential risks for establishing FORGE at the GRRA are largely related to uncertainties in the thermal and geologic structure models. Given the end-member thermal and structural models, we analyzed four scenarios, to choose a site that provided a large volume of reservoir rock at the required temperature of 175°C (347°F). **At our chosen site, using either of the structural models and even with the most conservative temperature gradient, we predict that rhyolitic rocks at temperatures greater than 175°C (347°F) will be encountered within the required 1.5- to 4-km (4,900- to 13,100-ft) depth interval.**

As a result of a greatly improved geologic model, the primary target site for FORGE was moved a few kilometers south of the original location. A significant side benefit of this change is that the new site is adjacent to a major U.S. highway with a parallel power line; the proximity to this highway will reduce infrastructure development costs and provide easier access to existing INL services.

2.2 NEPA and Permitting Results

The SRGC will use INL's established EMS and strong relationships with permitting and regulatory agencies to establish FORGE and manage environmental activities. INL's EMS integrates environmental protection, environmental compliance, pollution prevention, and continual improvement into work planning and execution. **INL routinely conducts environmental evaluations under NEPA. Based on projects of similar scope and potential impact, the estimated cost and timeframe required for preparing an EA is approximately $300,000 over 8 to 10 months**. Public response through our extensive and ongoing outreach and engagement activities has been overwhelmingly positive, and we expect no significant opposition or delays in permitting.

We will follow well-established NEPA processes to scope, prepare, and approve an EA. The EA will describe and analyze the potential environmental impacts associated with an EGS field laboratory on the INL Site. INL possesses all disciplines needed to conduct a full environmental evaluation for siting, constructing, operating, and maintaining the FORGE field laboratory.

The SRGC has also prepared a permitting strategy for FORGE activities, and we estimate that all necessary permits required for FORGE can be obtained within 3 months of submitting the application. The SRGC includes representatives from the permitting agencies, which have provided guidance and direction for our planning process from the onset, ensuring a clear and achievable path to obtaining all permits. Table 1 provides details regarding the required permits and estimated time to obtain them.

Table 1. Overview of FORGE permitting strategy.

Permit	Agency	Regulatory Requirement	Estimated Time to Obtain Permit	Comments
Biological				
None	—	—	—	While there are no permits, project activities will require consultation with the U.S. Fish and Wildlife Service and the Idaho Department of Fish and Game.
Cultural				
None	—	—	—	While there are no permits, project activities will require consultation with the Idaho State Historic Preservation Office and the Advisory Council on Historic Preservation. Consultation takes about 30 days but restarts with requests for additional information.
Water				
Injection Well Permit	IDWR	IDAPA 37.03.03	3 Months	IDWR estimated the time at 3 months. However, the permit goes out for public review and could be delayed if there are significant public comments.
Monitoring Well Drilling Permits	IDWR	IDAPA 37.03.09	Immediate	IDWR has agreed (Stenzel, 2009) to allow INL to submit an annual monitoring well drilling application. If a well is drilled that was not on the application, it is allowed to be included in the following year's application. However, every attempt should be made to include the well in the permit before drilling.
Production Well Drilling Permit	IDWR	IDAPA 37.03.09	2 Months	For production wells, the normal permitting process is followed.
Geothermal Well	IDWR	IDAPA 37.03.04	3 Months	—
NPDES General Permit for Discharges from Construction Activities (CGP)	EPA	40 CFR 122 and General Permit	2 Months	The new location overlaps with part of INL's stormwater corridor. Projects in the corridor must follow the NPDES stormwater requirements for construction activities if the project disturbs 4,047 m^2 (1 acre) or more. The CGP will require a stormwater pollution prevention plan and will require final stabilization (e.g., revegetation and asphalt) of the disturbed area.
Air				
None	—	—	—	Fugitive emissions from combustion engines associated with well drilling (e.g., boilers for heat) will require an Air Permitting Applicability Determination but will likely be within INL permitted limits, not requiring a permit/permit modification.
Waste				
None	—	—	—	—
CFR = Code of Federal Regulations CGP = construction general permit		EPA = U.S. Environmental Protection Agency IDAPA = Idaho Administrative Procedures Act		IDWR = Idaho Department of Water Resources NPDES = National Pollutant Discharge Elimination System

2.3 Operational Plans Results

2.3.1 Physical Characteristics of the SRGC Site

In addition to the highly favorable subsurface geologic conditions discussed above, the site selected for FORGE operations also benefits from several favorable surface characteristics shown on Figure 2. Although it is isolated from inhabited areas (nearest inhabitants are 24 km [15 mi] away), **the site is adjacent to a U.S. highway with year-round, all-weather access. Power line access is also located in close proximity** to the site, less than 150 m (492 ft) away. **An additional favorable characteristic is the flat topography** of the site, allowing for minimal excavation to establish the operations pad.

The prolific ESRP aquifer is located beneath the site, and **INL possesses more than sufficient water rights for extraction and use of the water.** Depth to groundwater is expected to be approximately 150 to 180 m (492 to 590 ft) below land surface.

Figure 2. Photograph of the SRGC FORGE site looking eastward (toward Idaho Falls, Idaho). Note the proximity of power lines and highway to the site and the flat topography.

2.3.2 Physical Infrastructure of SRGC's FORGE Site

One key attribute of our site is INL's invaluable commitment of land. INL has dedicated approximately 110 km^2 (42.6 mi^2) of land as the GRRA to physically host FORGE and associated geothermal research. INL also has abundant groundwater resources and water rights that can be utilized for geothermal R&D. Because we are proposing that FORGE be located on DOE land managed by INL, long-term access for GTO is secured, and leveraging for other DOE research programs is possible.

In addition to offering land with favorable geothermal conditions, INL will contribute other valuable resources to the project. As a DOE laboratory and host of several scientific user facilities, INL has all of the necessary ES&H processes and infrastructure in place to support FORGE. INL will also provide access to all elements of existing infrastructure necessary for siting FORGE. INL has a history of nearly 70 years of enabling innovation through large-scale demonstration projects. **Working through INL allows the SRGC to take advantage of established permitting, regulatory, and ES&H frameworks to quickly and cost-effectively establish FORGE.** Table 2 summarizes some of the key infrastructure assets for the SRGC FORGE site.

Table 2. Infrastructure and support summary.

Infrastructure Type	Status
Road access	Road access will be from U.S. Highway 20/26, approximately 11 km (7 mi) from the INL Central Facilities Area and 84 km (52 mi) from Idaho Falls. Approximately 0.4 km (0.25 mi) of gravel road will require improvement. We have an agreement from the Idaho Department of Transportation to supply the materials/road base and some engineering and labor support for this road improvement.
Well/operations pad	An approximately 2-hectare (5-acre) well/operations pad will have to be constructed. We have an agreement from the Idaho Department of Transportation to supply the materials/road base and some engineering and labor support to construct and access to the operations pad.
Electrical power	Commercial electrical transmission lines are available within approximately 150 m (492 ft) of the FORGE site. A small substation will be required to step down the voltage from transmission to distribution levels. Rocky Mountain Power is engaged and on our advisory panel. INL power-distribution lines are also available near the FORGE site and are already at distribution voltages. These lines are approximately 5.6 km (3.5 mi) away and have enough capacity to support FORGE operations. Final selection of the power source will be made as part of the detailed infrastructure assessment in Phase 2 of the FORGE project.
Water supply	A water-supply well is needed onsite for drilling the deep geothermal test well and for long-term FORGE operations. This well is anticipated to be approximately 180 m (590 ft) deep and drilled using an air-rotary drilling method. A USGS drilling crew will drill this well. The well will be used for the USGS monitoring network once FORGE activities are completed. INL has a large water right and has allocated 4.5 cfs for FORGE activities. Additional water is available if needed.
Medical facilities/ emergency response	The FORGE site is located at INL along U.S. Highway 20/26, approximately 11 km (7 mi) from the INL Central Facilities Area, where fire-station and medical facilities, including ambulance services, operate 24 hours a day, 7 days a week. The ambulance responds to emergencies on the INL Site and on the highway. INL also has a good-neighbor agreement with the Butte County Emergency Services.
Road maintenance and material handling	INL facilities and services are located 11 km (7 mi) from the FORGE site and will be available to support FORGE needs. Year-round access on this portion of the highway is maintained by the Idaho Department of Transportation.
Site security	The INL Site is protected by a dedicated security force that patrols the interior and outer boundaries of the INL Site on a routine basis, 24 hours a day, 7 days a week. In addition to INL security, the proposed FORGE location is under the protection of the Butte County Sherriff's Department and the Idaho State Police.

2.3.3 Supporting Facilities

Another significant contribution to the SRGC FORGE team comes from CAES. Located in Idaho Falls, Idaho, CAES is the SRGC base of operations and is less than an hour's drive from the proposed FORGE site. **CAES is a unique public-private partnership between INL and regional research universities. This partnership focuses on collaboration that inspires innovation**, **fuels energy transitions, and spurs economic growth for the future.** As part of the CAES program, the State of Idaho constructed the 5,119-m^2 (55,000-ft^2) CAES research facility. The CAES facility is adjacent to INL facilities in Idaho Falls, but has no DOE security access restrictions. **Office space at CAES will be available to FORGE, providing a vehicle for FORGE collaboration and hosting visiting scientists and engineers**.

2.3.4 Operational Plans and Long-Term Strategy

Phase 1 planning developed organizational structures for the SRGC FORGE team. The structure reporting to the SRGC leadership and management team will consist of only three line organizations (the Outreach Team, the Operations Team, and the Technical Opportunity Team [TOT]), providing a lean and efficient configuration. **The SRGC director and deputy director will each have dual roles, with the director leading the Outreach Team and the deputy director leading the Operations Team, creating operational efficiency and cost savings**. The SRGC chief scientist will chair the STAT, and Dr. Chad Augustine from the National Renewable Energy Laboratory will fill the role of STAT coordinator. The STAT coordinator will be responsible for ensuring that the STAT and the major SRGC organizations have solid and continuous two-way communications and that the mandates of the STAT are executed by SRGC.

The TOT will be established as the third major line organizational element and will be led by Travis McLing of INL. This team will include the five technical area leads; minor changes to the focus areas have been made as a result of an enhanced understanding of technical priorities. The TOT's role is to ensure technical coordination of planned FORGE experiments and to ensure seamless integration with field operations.

The Operations Team will bring field operations, business functions, and data management under one umbrella organization to ensure coordination and seamless execution of all operational activities, and the Outreach Team will bring together the strengths of SRGC organizations to ensure a robust outreach program. A decision-making framework has also been established to balance technical and operational needs in the execution of the FORGE mission.

SRGC has also developed a post-FORGE research, development, and management vision. The vision for post-FORGE use of the site centers on two main areas:

1. Partnering among SRGC members INL, U.S. Geothermal, and POWER Engineers will—once FORGE activities are complete—leverage the FORGE site for operation of a power plant. The commercially operated plant will supply electricity to meet INL's DOE-mandated onsite renewable energy generation goals. A portion of the power sales will be used to fund continued EGS research.
2. Subsurface R&D will continue through the use of the FORGE laboratory and the SRGC as the nucleus of a Regional Clean Energy Innovation Center, initially using funding from the power sales described above followed by growing the industrial user base. Leveraging the DOE infrastructure investment, coupled with continued funding from the power sales, will allow for long-term operation of the site without EERE financial obligation.

While these plans are preliminary, U.S. Geothermal, POWER Engineers, and INL have already agreed on a framework for the power generation aspects. The R&D scope for follow-on activities will be further developed as FORGE progresses and the future success and lessons learned become clear.

2.4 Induced Seismicity Mitigation Infrastructure and Activities Results

Potential impacts from induced seismicity range from physical damage caused by shaking to economic disruption caused by closures of buildings and facilities. Our efforts aim to minimize smaller-magnitude nuisance shaking due to EGS activities and to take steps to preclude larger induced seismic events that can cause damage. The site selected for FORGE operations lies in an area of very low population density, with no significant structures within 8 km (5 mi). As shown on Figure 3, there are no permanent residents within a 16 km (10 mi) radius.

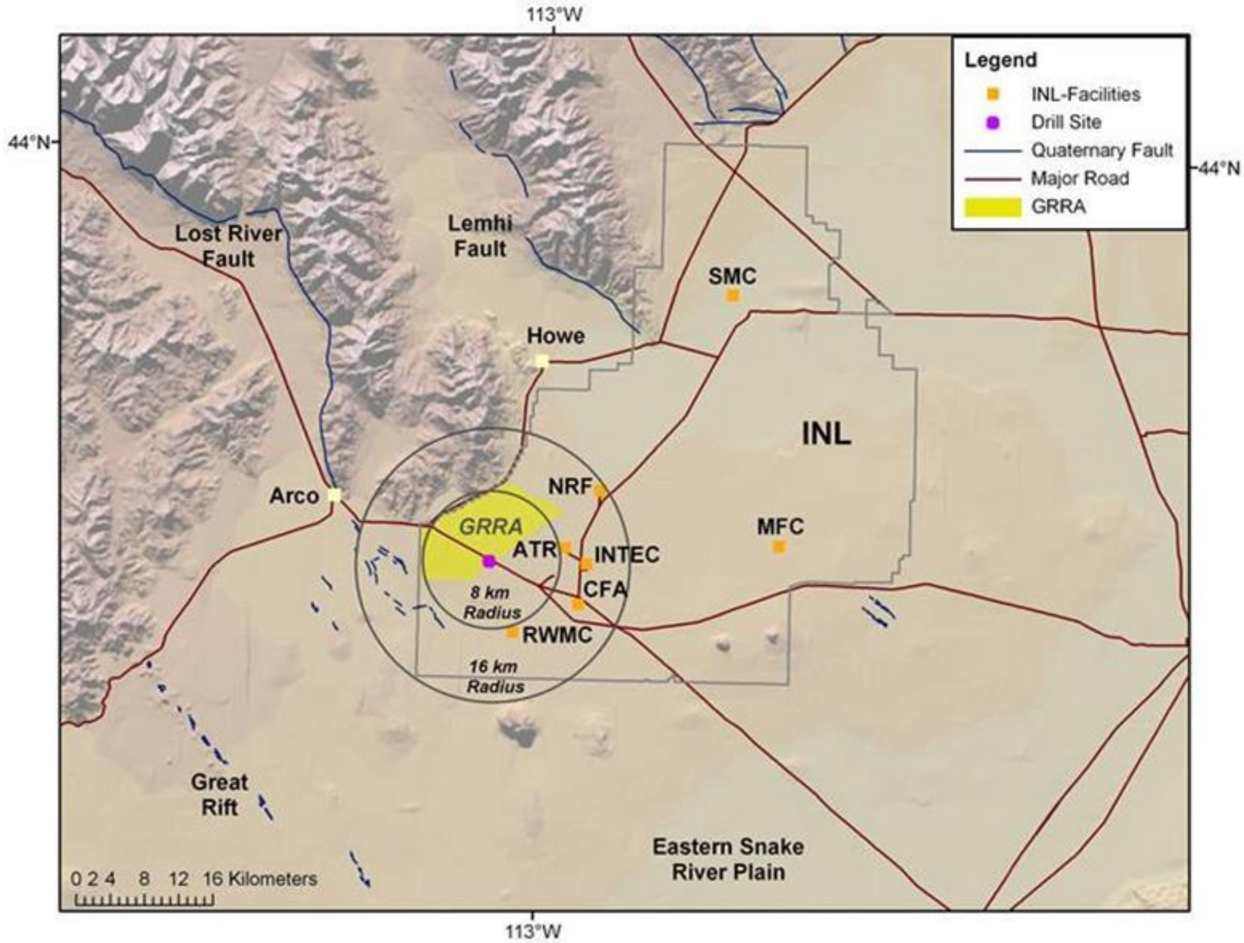

Figure 3. Map of FORGE location and nearby stakeholders. (ATR = Advanced Test Reactor, CFA = Central Facilities Area, INTEC = Idaho Nuclear Technology and Engineering Center, MFC = Materials and Fuels Complex, NRF = Naval Reactors Facility, RWMC = Radiological Waste Management Complex, SMC = Specific Manufacturing Capability). Also shown are nearby towns of Arco and Howe.

Based on our analyses, which considers the favorable regulatory environment, limited radius of influence, low potential impacts, and interactions with the local communities, we gauge the induced seismicity risk level to be low. To finalize FORGE planning, we have identified specific Phase 2 analyses (e.g., refined radius of influence and estimates of potential damage) that will verify our risk analyses are robust.

2.5 Communications and Outreach Activities Results

Communications and outreach activities began in 2012 and will continue throughout all phases of FORGE. The goal is to use well-tested tactics to educate, inform, and expand the support base for EGS, paving the way for the success of FORGE and EGS adoption and deployment locally, nationally, and internationally.

We will continue to pursue three key activities. The first is community engagement to gain acceptance, which will be accomplished through public tours, educational outreach, outreach events, and engaging with special interest groups. The CAES facility in Idaho Falls, Idaho, hosts regular tours for the public, elected officials, researchers, students, and educators. A portion of each tour is dedicated to discussing the FORGE project, EGS, and hydrothermal energy and how they can benefit the local community and the world. Educational outreach is directed at three broad audiences: (1) K-12 science, technology, engineering, and math (STEM) students and educators, (2) undergraduate and graduate students and postdoctoral fellows, and (3) the general public. SRGC partners with a wide range of educational institutions to participate in a variety of programs—for example, High School STEM Career Day and the University of Wyoming's Science Posse. Past and planned outreach events include workshops, conferences, seminars, and other meetings for both technical and nontechnical audiences. We have also targeted special interest groups, providing education to address questions and concerns about FORGE.

The second key activity is communications and outreach. Tools for this activity include our website, social media, an e-newsletter, and multimedia such as videos, photos, and infographics. The external website contains frequently asked questions, an About Us section (with SRGC member information), contact information, a button to subscribe to event and information updates via email, a What's Happening section to share program activities, and a director's blog. In the future, the website will include notifications of upcoming funding opportunity announcements, select SRGC FORGE data sets, and a variety of principal researcher and student resources. We also use four social media platforms: Facebook, Twitter, YouTube, and the blog on our website. The website and social media have been used to share multimedia, which have received enthusiastic interest; examples include a YouTube video about FORGE and a photo of an SRGC member giving a presentation on geothermal energy. We plan to launch an e-newsletter during Phase 2 that will provide regular updates to audiences, offer education on geothermal issues, promote local successes, and develop awareness of the FORGE site.

The third key activity is media reach. As part of our plan, we will issue news releases, launch targeted pitches, and post a reporter's guide on our website (www.snakerivergeothermal.org). We will invite specific media outlets to visit the FORGE site and encourage them to share the story and purpose of FORGE. Publications such as *Power Magazine*, *Electric Perspectives Magazine* (Edison Electric Institute), *The Leading Edge* (Society of Exploration Geophysicists), and the *Geothermal Energy Journal* will be targeted as we seek to publish bylined articles.

3. LESSONS LEARNED

Many lessons were learned during our Phase 1 activities, several of which are documented below. Many lessons centered on the developments and evolution of our geologic models, mitigation of potential environmental risks or concerns prior to their onset, use of focused and effective communications and outreach, and obtaining a better understanding of the techno-economic factors associated with establishing the site.

3.1 Understanding of the Site and its Geology

3.1.1 Geologic Modeling Lessons Learned

During Phase 1, we constructed the first ever 3D models of caldera systems beneath the ESRP. These first-generation models are constrained by historic and contemporary data sets spanning a wide range of quality, resolution, and spatial extent. While integrating these observations into a conceptual geologic model provided many challenges, it also resulted in an improved understanding of geologic conditions underlying the GRRA. Most importantly, constructing these models helped us to identify the primary uncertainties regarding the subsurface. This process also allowed us to develop characterization plans to address these uncertainties and mitigate potential risks.

We chose to build our geologic and geomechanical models using software packages that are common in the oil and gas industry. We constructed our structural models using Schlumberger's Petrel™ exploration and production platform, and we extended the models using Baker Hughes' JewelSuite™ subsurface modeling software to analyze well logs and develop the geomechanical model. The primary challenge in constructing these models was the lack of direct subsurface observations for facies correlation due to the sparse number of wells. The low number of deep wells also presented challenges in analyzing the model's uncertainties. However, the modeling process, and drawing upon the expertise of multiple scientists and engineers who have worked on the ESRP, also allowed for several key successes. These included (1) developing a set of justifiable end-member structural and thermal models that allowed us to bracket the range of expected reservoir volumes and temperatures and (2) creating an improved estimate of the in situ stress conditions for our site.

3.1.1.1 Model Construction and Uncertainty Analysis

Challenges: Oil and gas reservoirs are commonly found in sedimentary environments where the geology can be described by spatially continuous layers that are possibly offset by faults. Seismic methods work well in these environments and allow facies observed in wells to be correlated over long distances. Typical geologic model development workflows involve loading seismic volumes and well information into the program so that primary lithologic units can be interpolated into surfaces and faults can be identified and tracked throughout the study area. Physical reservoir properties can then be interpolated onto a grid using geostatistical methods or rock physics relationships, and simulations can be run to assess uncertainties in the model.

The GRRA is located on the ESRP, a volcanic basin filled with a large volume of rhyolite originating from a number of calderas whose exact spatial locations are unknown. Overlying these rhyolites is ~1 to 2 km (~0.6 to 1.2 mi) of basalt flows with interbedded sediments. A number of widely spaced, deep boreholes that penetrate the basalt layers provide information on the spatial extent of rhyolite units to a depth of ~1,400 m (~4,593 ft) below land surface. Two low-resolution geophysical surveys traverse the study area and provide constraints on the geometry of the boundary separating the volcanic basin from the Paleozoic rocks to the north, and a few studies have mapped out the distribution of calderas within the study area. Modifying the oil and gas workflow to this volcanic setting, with significantly less well control, proved difficult but provided unique opportunities.

Successes: Given the sparse distribution of subsurface data, traditional workflows were not possible. Instead, we constructed a 3D geologic model using several two-dimensional cross sections that honored surface, borehole, and geophysical observations. We then imported the two-dimensional cross sections into the modeling software to construct surfaces separating caldera facies of different ages. After defining the surfaces, we constructed a grid to populate the model with physical properties observed in the 3.15-km (10,335-ft)-deep INEL-1 borehole. Because this is the only borehole that approaches reservoir depths and contains a full suite of geophysical logs, extrapolating these properties to the entire grid cannot adequately describe spatial variability within our site. However, this model provides a good starting point that will evolve throughout the characterization phase.

The most relevant features of our model for assessing site suitability for FORGE are geologic structure, permeability, and temperature. Permeability measurements near our site at depths and temperatures that are less than those targeted for FORGE are all well within the required values ($<10^{-16}$ m^2), and there is little reason to suspect that regions of high permeability exist at greater depths or temperatures beneath our site. The quality, resolution, and spatial extent of structural data proved highly variable, and in most cases, uncertainty estimates were not provided in the literature sources. **The small number of deep boreholes did not allow for a geostatistical analysis of temperature distributions, because there are not enough data pairs to construct meaningful variograms. We chose instead to define extreme end-member scenarios that bracket the range of possible structural and thermal scenarios. We then used these scenarios to explore the implications of these uncertainties for EGS development at our site. The two structural models and two end-member thermal gradients provided us with four model scenarios that span the range of possible reservoir volumes meeting DOE's criteria for FORGE. In all four cases, our site provides a potential EGS reservoir.**

3.1.1.2 In Situ Stress Estimates and Fracture Analysis

Challenges: The ESPR cuts an arcuate swath ~250 km (~155 mi) long and 75 km (46.6 mi) wide through the northern Basin and Range Province. Focal mechanism analysis from earthquakes that have occurred to the north and the south of the ESRP reveals that the northern Basin and Range is characterized by normal faulting and that the direction of maximum horizontal compression is oriented roughly north-northwest. However, because of the lack of seismicity within and beneath the ESRP, the state of stress in this region has historically been difficult to define. It was hoped that during the drilling of INEL-1 in 1979 that borehole breakouts and drilling-induced fractures would allow the orientations and magnitudes of the principal stresses to be determined, but neither of these phenomena were observed at that time. The borehole acoustic televiewer tools used to collect the original data sets lacked the necessary resolution.

Success: During Phase 1, our team measured the strength of rocks obtained from the INEL-1 core. Combining these measurements with the lack of borehole breakouts and drilling-induced fractures allowed us to constrain the magnitudes of S_{hmin} and S_{hmax}; vertically integrating the density logs from INEL-1 provides S_v. Our results indicate that at INEL-1, the ESRP is transitional between a normal faulting and strike-slip environment ($S_v \geq S_{Hmax} > S_{Hmin}$) and the magnitudes of the principal stress components are S_v = 82 MPa, S_{Hmax} = 89 +/- 11 MPa, and S_{Hmin} = 58 +/-2 at a depth of 3.5 km (11,483 ft).

Reanalyzing the borehole televiewer logs using modern oil and gas industry workflow contributed significantly to our understanding of the in situ fracturing in INEL-1 and the orientation of the measured fracture sets with the current stress regime. **Multiple fracture sets at different orientations to one another and to the expected regional stress field have been identified, allowing for flexibility and unique opportunities for reservoir stimulation.**

3.2 Environmental Constraints and/or Risks

Our efforts and lessons learned regarding environmental constraints and risks were largely formed on other previous large-scale R&D activities at INL and by reviewing the lessons learned from other projects. We have put those lessons learned into practice for FORGE and can report that, to date, environmental and permitting risks are minimal. While it is possible that as-yet unidentified antidevelopment or antiestablishment groups will oppose FORGE during the NEPA process, we have built a strong base of local and regional support that should ensure success. The following are some of the successful activities we have engaged in so far.

Highly Successful Activity: Early engagement and site selection in regard to sage grouse

The SRGC began engaging regularly with agencies regarding sage grouse in 2014, leveraging INL's efforts to develop a sage grouse conservation area and mapping of leks. In January 2016, the SRGC made a presentation to the U.S. Fish and Wildlife Service, the Idaho Department of Fish and Game, and the INL Environmental Protection Group regarding FORGE activities as part of this group's efforts to reduce impacts to the sage grouse population (specifically, impacts on leks). The presentation went into great detail regarding potential environmental impacts from FORGE activities, including noise, infrastructure, and land disturbance. Because no sage grouse leks are located near the FORGE site, the result of this engagement was a finding of no impact.

Lesson Learned: All other things being equal, choose a site as far away as possible from areas frequented by sage grouse.

Highly Successful Activity: Early engagement with regulatory agencies

The SRGC has practiced a proactive approach to permitting of FORGE research activities by engaging all relevant regulatory agencies, as well as the INL Environmental Compliance Office, as early as 2013. The results of these efforts have largely been positive, with an identified path forward for the permitting of FORGE.

Lesson Learned: By engaging the permitting agencies early in the process, the SRGC has avoided the adversarial relationship that often results from conflict caused by research objectives and regulator review timelines.

Highly Successful Activity: Early engagement with Native American groups

The SRGC has engaged the local tribal council for many years regarding the development of geothermal resources, including FORGE. The Shoshone-Bannock Tribes have been very supportive of the concept of geothermal development on the INL Site and in the region, including the Fort Hall Reservation. This early engagement has resulted in SRGC researchers conducting an evaluation of geothermal resources on tribal lands.

Lesson Learned: Engagement with tribal leaders needs to be initiated with a questioning attitude, asking them about how they would like to see the project proceed and how they would like to be involved. Patience is a must, as is a humble attitude.

Highly Successful Activity: Public perception of the national laboratory system

Although INL is the lead nuclear research laboratory for the United States, it is also a multipurpose energy research laboratory. The concept of EGS research and FORGE has been exceptionally well received by the eastern Idaho community and the INL staff. The increased visibility that FORGE has brought to INL has helped to better define the regional relevance of the national laboratory.

Lesson Learned: Give the broad community group a sense of ownership in the FORGE project. In this case, the community includes the SRGC and, more importantly, those responsible for the INL research facilities and the community at large.

3.3 Public Engagement

The SRGC has pursued public engagement through a variety of activities. Overall, responses have been favorable, with most ranging from fascination and enthusiasm to mild interest and approval. While many of these efforts have yielded positive results, we have gleaned valuable lessons from all of our efforts, as noted below. These lessons will help us engage the public even more effectively during Phases 2 and 3.

Highly Successful Activity: Initiating public outreach very early, starting in 2012

Lessons Learned: Based on reviews from previous EGS projects, the SRGC determined that to successfully develop and operate FORGE, a significant level of public outreach would be necessary, not only for establishment of the site but also to continue operations should a seismic event occur. Interactions with the community that build trust and personal relationships, and that are based on transparency and openness, have been shown to be a significant deciding factor in the success of projects. Several examples highlight this point, including the following:

- Geothermal projects in Basel and St. Gallen, Switzerland, encountered earthquakes of Magnitude 3.4 and 3.5, respectively. The Basel project was stopped, but the St. Gallen project continued.

Conversations with Swiss geothermal industry colleagues familiar with both projects indicated that positive relationships built by project advocates with the local community contributed to the continuation of work at San Gallen.

- A more recent example is the failure of a deep borehole test site that was being developed by Battelle Memorial Institute and Sandia National Laboratory. Originally planned for South Dakota, failure to property engage the local community led to a moratorium of deep drilling in the county where the test was planned. The DOE Office of Nuclear Energy site selection officials informally remarked that the borehole team "…should have followed the Podgorney model."

Highly Successful Activity: TEDxIdahoFalls Geothermal/EGS Presentation by Dr. Robert Podgorney, "We're Sitting on the Sun"

Lessons Learned: Generally speaking, the public loves short, concise information that makes the science behind EGS easy to understand. Most people likely will not invest the time to read a several-page-long article on geothermal energy, but many respond well to short presentations. The TEDx presentation was less than 13 minutes long. As of May 15, 2016 (after only 2 weeks online), the video has been viewed more than 640 times.

Highly Successful Activity: Video explaining EGS and FORGE

Lessons Learned: The public responds well to short videos that make the science behind EGS easy to understand. A video can get the same amount of information across in a short amount of time as several pages of text. The video is 3 minutes and 33 seconds long. It was hosted on INL's YouTube channel and widely shared on social media and continues to be viewed. As of May 15, 2016, the video has been viewed more than 449 times worldwide.

Medium to Highly Successful Activity: Social media posts

Lessons Learned: Our best-performing social media posts had multimedia content (photos or videos) and linked to content that explained the basics of geothermal energy and how EGS works. Traditional media on its own is not as successful at reaching a large audience but is quite effective when shared using social media channels.

Medium to Highly Successful Activity: Public meetings

Lessons Learned: Feedback from attendees at public meetings and events indicates that the general public's knowledge about geothermal energy is quite limited, including its potential to provide large amounts of baseload power. In general, once members of the public learn of this potential, they are enthusiastic and supportive of geothermal energy production. The key is getting the public to want to attend the meetings.

Not as Successful: Traditional media (print articles and publications)

Lessons Learned: Articles that appear in traditional media are not always written in an easily digestible, on-the-go format and have a shorter shelf life (becomes outdated or old news) than newer types of media. However, using traditional media as part of an overall communications strategy and leveraging these pieces through more modern media channels can be effective at getting the content to the public.

Not as Successful: SRGC blog posts

Lessons Learned: To date, the blog posts on our website (www.snakerivergeothermal.org) are not getting many views. This is due to the feature being relatively new and not well known. The posts are a useful way to keep the public and other stakeholders engaged, and the strategy moving forward is to promote the posts more aggressively through social media and other outreach channels.

3.4 Techno-Economic Issues Associated with FORGE Infrastructure Requirements

Techno-economic estimates for FORGE must consider short- and long-term estimates of costs to establish and operate the site. The location we have chosen for FORGE benefits from being on an existing DOE national laboratory site with a multitude of existing infrastructure and support services. The location can be considered a “greenfield” site, however, because no development has taken place. The site will require construction of an operations pad and local site infrastructure such as electric power.

Design and construction of the operations pad will be completed using a combination of SRGC’s topside focus area lead and INL’s construction management organization. A preliminary cost estimate is shown in Table 3. It is important to note that these costs are considered “pre-conceptual” and will be refined considerably during Phase 2A activities.

Table 3. Operations pad construction and related infrastructure cost summary.

Infrastructure Type	Estimated Cost Range ($K)	Status
Well/operations pad	280–350	An approximately 2-hectare (5-acre) well/operations pad will have to be constructed. We have an agreement from the Idaho Department of Transportation to supply the materials/road base and some engineering and labor support to construct and access the operations pad. The cost share of these materials and services is not deducted from the cost estimate.
Electrical power	100–200	Commercial electrical transmission lines are available within approximately 150 m (492 ft) of the FORGE site. INL power-distribution lines are also available near the FORGE site and are already at distribution voltages. These lines are approximately 5.6 km (3.5 mi) away and have enough capacity to support FORGE operations. Final selection of the power source will be made as part of the detailed infrastructure assessment in Phase 2.
Water supply well	200–250	A water-supply well is needed onsite for drilling of the deep geothermal test well and for long-term FORGE operations. USGS will drill this well.
Water storage	47–115	Water storage is needed for operational flexibility. We will use a “Frac Lake” during periods of active stimulation and several “Frac Tanks” year-round as operational buffers.
Office/work trailers	20–50	Temporary office and working space is for SRGC staff and FORGE users. This includes portable restroom facilities.
Lighting	20–40	Light poles are needed to illuminate the site for 24-hour operations.
Fencing	20-40	A fence around the entire operations pad will be needed to control access and to keep livestock out.
Secure storage	10–30	Separate storage space for up to eight individual FORGE users or groups is needed to protect their property (both physical and intellectual).
Total	697–1,075	—

4. CONCLUSION

The Phase 1 results demonstrate that **our site, our team, and our region are ideal for hosting the FORGE laboratory and stand ready to begin.** The favorable subsurface characteristics and locating FORGE at an existing DOE site maximize cutting-edge EGS R&D while minimizing risks. The following advantages are provided by this site:

- The depth and temperature characteristics at the proposed FORGE in the ESRP meet DOE's selection criteria and are representative of 346,000 km^2 (133,591 mi^2) throughout the United States, thereby facilitating widespread adoption of the technologies developed at FORGE.
- Locating FORGE at INL allows SRGC to take advantage of existing infrastructure, policies, and procedures (e.g., availability of nearby emergency services, proximity to a major all-weather U.S. highway, existing ES&H plans, access to electric power and water supply, historical and ongoing environmental monitoring, and site security).
- Our partnership with nearby CAES campus provides additional office, meeting, and laboratory facilities for FORGE researchers.
- The relative remoteness of the site from permanent population centers provides a buffer against the potential for negative impacts from seismic activity, traffic, noise, or other sources.
- Local and regional stakeholders are very supportive and actively engaged in the project. Most consider the INL Site to be a showcase of some of the greatest technological advancements our nation has to offer; energy creation from the earth is a logical progression resulting from the past achievements at INL.

As the FORGE operator, SRGC brings the ability to create representative models at multiple levels and provides access to necessary supercomputing capabilities. We have expertise in modeling reservoir behavior, fracture mechanics, seismicity, groundwater fate and transport, system dynamics, economics, 3D visualization, and more. We will use these models to synthesize, predict, and verify reservoir properties and performance in near real time and to provide modeling support to FORGE users. The feedback loop among modeling, experimental design, and results is critically important to any project but specifically to a project with the complexity of FORGE. We also bring expertise in managing competitive solicitations, data collection and management, cyber security, training the next generation of scientists and engineers, and communicating scientific concepts to the public.

Ultimately, the success of FORGE depends on developing a replicable methodology for creating large-scale, economically sustainable subsurface heat recovery systems to tap a nearly inexhaustible source of clean, renewable, baseload energy. To facilitate EGS commercialization, we must reduce industry development risks by engaging with scientists and engineers from a diverse set of specialties. No one organization or institution hosts all the pieces necessary to make this goal a reality; therefore, the SRGC has built a collaborative team from a wide range of disciplines in industry, national laboratories, state and federal agencies, non-governmental organizations, and academic institutions. This results in a dynamic management team that adapts to shifting priorities and will encourage innovative drilling and reservoir stimulation techniques in ways that allow honest appraisals of fracture connectivity and accurate flow testing of production zones created in the reservoir.

We believe our team at this site offers DOE the greatest chance for a successful FORGE project.

REFERENCES

40 CFR 122, EPA Administered Permit Programs: The National Pollutant Discharge Elimination System.

Anders, M.H., Rodgers, D.W., Hemming, S.R., Saltzman, J., DiVenere, V.J., Hagstrum, J.T., Embree, G.F., and Walter, R.C., 2014, A fixed sublithospheric source for the late Neogene track of the Yellowstone hotspot: Implications of the Heise and Picabo volcanic fields: Journal of Geophysical Research: Solid Earth, v. 119, no. 4, p. 2871–2906, doi: 10.1002/2013JB010483.

Blackwell, D., Richards, M., Frone, Z., Batir, J., Ruzo, A., Dingwall, R., and Williams, M., 2011, Temperature at depth maps for the conterminous US and geothermal resource estimates: Geothermal Resources Council Transactions, v. 35, p. 1545–1550, GRC Record 1029452.

Irving, J., and Podgorney, R.K., 2016, Environmental Information Synopsis, Snake River Geothermal Consortium, INL/LTD-16-38126.

ISO 14001, 2015, Environmental management systems – Requirements with guidance for use, International Organization for Standardization, 35 p.

Majer, E., Nelson, J., Robertson-Tait, A., Savy, J., and Wong, I., 2012, Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems, DOE/EE-0662, U.S. Department of Energy: https://www1.eere.energy.gov/geothermal/pdfs/geothermal_seismicity_protocol_012012.pdf (accessed March 2016).

Majer E., Nelson, J., Robertson-Tait, A., Savy, J., and Wong, I., 2014, Best Practices for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems (EGS), LBNL Paper LBNL-6532E: http://escholarship.org/uc/item/3446g9cf (accessed March 2016).

Mann, L.J., 1986, Hydraulic properties of rock units and chemical quality of water for INEL-1: a 10,365-foot deep test hole drilled at the Idaho National Engineering Laboratory, Idaho: U.S. Geological Survey Water Resources Investigations Report 86-4020.

McCurry, M., McLing, T., Smith, R.P., Hackett, W.R., Goldsby, R., Lochridge, W., Podgornery, R., Wood, T., Pearson, E., Welhan, J., and Plummer, M., 2016, Geologic setting of the Idaho National Laboratory Geothermal Resource Research Area: *in* Proceedings, 41st Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, SGP-TR-209.

McQuarrie, N., and Rodgers, D.W., 1998, Subsidence of a volcanic basin by flexure and lower crustal flow: The eastern Snake River Plain, Idaho: Tectonics, v. 17, no. 2, p. 203, doi: 10.1029/97TC03762.

Pankratz, L.W., and Ackermann, H.D., 1982, Structure along the northwest edge of the Snake River Plain interpreted from seismic refraction: Journal of Geophysical Research, v. 87, no. B4, p. 2676, doi: 10.1029/JB087iB04p02676.

Podgorney, R.K., Snyder, N., Mink, R., McLing, T., Johnson, H., Smith, P., Rickard, W., Barton, C., Wood, T., and Hassing, K., 2016, Research and Development Implementation Plan: Snake River Geothermal Consortium, INL/LTD-16-38123.

Smith, P., Visser, C., and Rickard, W., 2016, Environmental, Safety, and Health Plan: Snake River Geothermal Consortium, INL/LTD-16-38125.

Snyder, N., Bartholomay, R., Hodges, M., and McLing, T., 2016, Sample and Core Curation Plan: Snake River Geothermal Consortium, INL/LTD-16-38122.

St. Clair, J., et al., 2016, Conceptual Geologic Model: Snake River Geothermal Consortium, INL/LTD-16-38121.

Stenzel, J.A., Idaho National Laboratory, to Dunn, D., Idaho Department of Water Resources, December 22, 2009, Record of Meeting Concerning Well Permitting, Maintenance, and Decommissioning at the Idaho National Laboratory: CCN 219522.

Templeton, D., Mellors, R., Payne, S., Irving, J.S., Ulrich, J., and Podgorney, R.K., 2016, Preliminary Induced Seismicity Mitigation Plan: Snake River Geothermal Consortium, INL/LTD-16-38124.

Ulrich, J., and Podgorney, R.K., 2016, Communications and Outreach Plan: Snake River Geothermal Consortium, INL/LTD-16-38119.

Weers, J., and Podgorney, R.K., 2016, Data Dissemination and Intellectual Property Plan: Snake River Geothermal Consortium, INL/LTD-16-38120.

Zohdy, A.A.R., and Stanley, W.D., 1973, Preliminary interpretation of electrical sounding curves obtained across the Snake River Plain from Blackfoot to Arco, Idaho: U. S. Geological Survey Open-File Report, v. 73-370.