PROCEEDINGS, 41st Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 22-24, 2016
SGP-TR-209

A Snake River Plain Field Laboratory for Enhanced Geothermal Systems: An Overview of the Snake River Geothermal Consortium's Proposed FORGE Site

Robert K. Podgorney*, Neil Snyder, Leland (Roy) Mink, and Travis McLing

Idaho National Laboratory, PO Box 1625, Idaho Falls, ID 83415

robert.podgorney@inl.goov

Keywords: FORGE, EGS, Snake River Plain

ABSTRACT

Geothermal energy generation occurs almost exclusively in hydrothermal systems, whereas approximately 90% of the potential geothermal power resource in the United States has been estimated to reside in EGS settings. Enabling EGS development could provide 10 to 100+ GWe or more, and make geothermal energy a significant component of the nation's renewable energy portfolio. To enable development and deployment of EGS technologies, the U.S. Department of Energy Geothermal Technologies Office (GTO) has solicited teams to bring multidisciplinary, world-class researchers together with industry to find innovative solutions and creative, transformational paths via a new Frontier Observatory for Research in Geothermal Energy (FORGE) Laboratory.

To meet the challenges and drive the solutions for EGS, the Snake River Geothermal Consortium (SRGC), a research partnership focused on advancing geothermal energy, was established. The SRGC is comprised of national laboratories, academic institutions, federal/state agencies, and private industry partners. National laboratory partners include Idaho National Laboratory (INL), the National Renewable Energy Laboratory and Lawrence Livermore National Laboratory, which support the full spectrum RD&D on energy technologies. In addition to the national laboratories, six academic institutions are SRGC partners, including the Center for Advanced Energy Studies (University of Idaho, Idaho State University, Boise State University, University of Wyoming), University of Utah, and University of Oklahoma; they add diversity of research innovation and network to the broader STEM educational functions and outreach that will be instrumental in helping secure the long-term goals for EGS. Also, six private partners participate as SRGC members and bring key perspectives to the research team and provide a context for commercializing the research outcomes; they include Mink GeoHydro, Baker Hughes, Geothermal Resource Group, Chena Power, Campbell Scientific, and US Geothermal. The team also has participants from federal and state agencies, including the USGS, Idaho Department of Water Resources, and the Idaho Geologic Survey.

The INL, one of DOE's largest laboratories (2,300 sq. km (890 sq. mi)), intends to host the FORGE Laboratory within its site on the Eastern Snake River Plain, providing the central physical location for the research. It has dedicated 100 sq. km (39 sq. mi) of land as a Geothermal Resource Research Area (GRRA), and has an established permitting framework for projects such as FORGE. The INL is located on the track of the Yellowstone Hotspot, and deep well data indicate that the GRRA occupies an area of high subsurface temperature, with regional stress conditions and rock mechanical properties favorable for reservoir stimulation. The GRRA also has abundant groundwater resources and water rights for geothermal research, development, and deployment.

1. INTRODUCTION

The geothermal energy sector has enormous potential as a contributor to the nation's renewable energy mix. Currently, geothermal energy provides only a small fraction of the nation's renewable electricity generation (**Error! Reference source not found.**), which makes up less than 9 percent of the nation's overall electricity consumption (*Annual Energy Review, 2011* 2012). At present, however, geothermal energy generation occurs almost exclusively in hydrothermal systems, whereas approximately 90% of the potential geothermal power resource in the United States has been estimated to reside in EGS settings Phillips, Ziagos, Thorsteinsson, and Hass (2013). Enabling EGS development could provide 10 to 100+ GWe, and make geothermal energy a significant component of the nation's renewable energy portfolio. Because EGS requires advancements in technology and in knowledge of deep subsurface systems, a significant investment in RD&D is required to jump-start the industry.

To enable development and deployment of EGS technologies, the U.S. Department of Energy Geothermal Technologies Office (GTO) has solicited teams to bring multidisciplinary, world-class researchers together with industry to find innovative solutions and creative, transformational paths via a new Frontier Observatory for Research in Geothermal Energy (FORGE) Laboratory. Our purpose in responding to the solicitation is to establish a well-organized, cross-disciplinary, sustained effort to identify the problems facing EGS and find short-, intermediate-, and long-term solutions. Our team is eager to meet the challenge GTO has put forth.

To meet the challenges to, and drive the solutions for, EGS, we established the Snake River Geothermal Consortium (SRGC), a synergistic group led by the Idaho National Laboratory (INL) and comprised of national laboratories, academic institutions, federal/state agencies, and private industry partners.

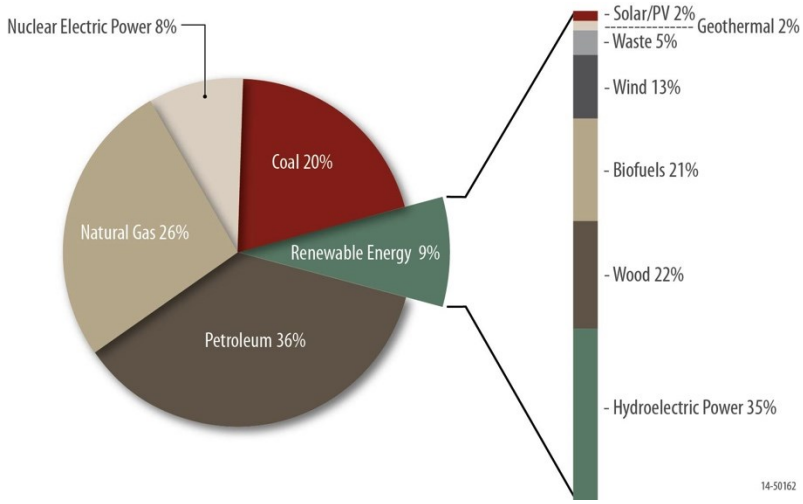


Figure 1: Energy generation sources in the United States.

2. SNAKE RIVER PLAIN

2.1 Geologic Setting Overview

The ESRP is an arcuate structural depression 50 to 100 km wide, encompassing approximately 12,700 km^2 of southeastern Idaho formed as a result of caldera forming eruptions associated with the Yellowstone Hotspot (Figure 2) and post caldera basalt flow. The ESRP rises from approximately 1,000 m on its western border to more than 1,500 m on the east, and is bounded on the north and south by mountains rising more than 2,500 m above the plain. Mountain ranges to the north of the plain are composed of deformed Paleozoic and Mesozoic carbonates and silici-clastic sedimentary rocks. These sedimentary rocks in turn have been uplifted relative to the basins by normal faults striking in a northwesterly direction (Kuntz, 1992). This type of structural development is typical of the Basin and Range Province through which the ESRP cuts a northeast-trending swath (Pierce and Morgan, 1992).

The ESRP consists of thick volcanic ash-flow tuffs, which are overlain by >1 km of Quaternary basaltic flows (Figure 3). The surface morphology of the plain is dominated by a sequence of basalt flows that are covered in some areas by a thin layer of fluvial sediments and loess. Individual basalt flows are relatively small in volume and were extruded primarily from northwest-trending fracture systems and from numerous shield volcanoes ((Kuntz, Covington, & Schorr, 1992; Pierce & Morgan, 1992). At depth, the basalts are inter-layered with sediments including carbonate and silici-clastic fluvial sands and gravels, carbonate-rich eolian silt, lacustrine deposits, and minor reworked silicic tuffs. The thick sequences of interlayered basalt flows in the upper 1 km of the ESRP host an exceptionally productive cold-water aquifer (Whitehead, 1992; Wood & Low, 1986).

Unlike the flood basalts of the Columbia River Plateau to the west, individual basalt flows in the ESRP are of a relatively small volume. These flows were extruded primarily from northwest trending fracture systems or from the numerous small shields that dot the plain. Welded rhyolite tuff and tuffaceous sediments dominate at depths greater than ~1 km ((Hughes, Smith, Hackett, & Anderson, 1999; Pierce & Morgan, 1992). Due to the recent volcanic activity and associated tectonic setting the ESRP is recognized as having a high potential for geothermal resources. In 2006 the ESRP was highlighted by MIT (Tester et al., 2006) for it potential for high-grade enhanced geothermal system (EGS) with up to 75% of the 27,900-km^2 area having temperatures >200°C at a depth of 4 km.

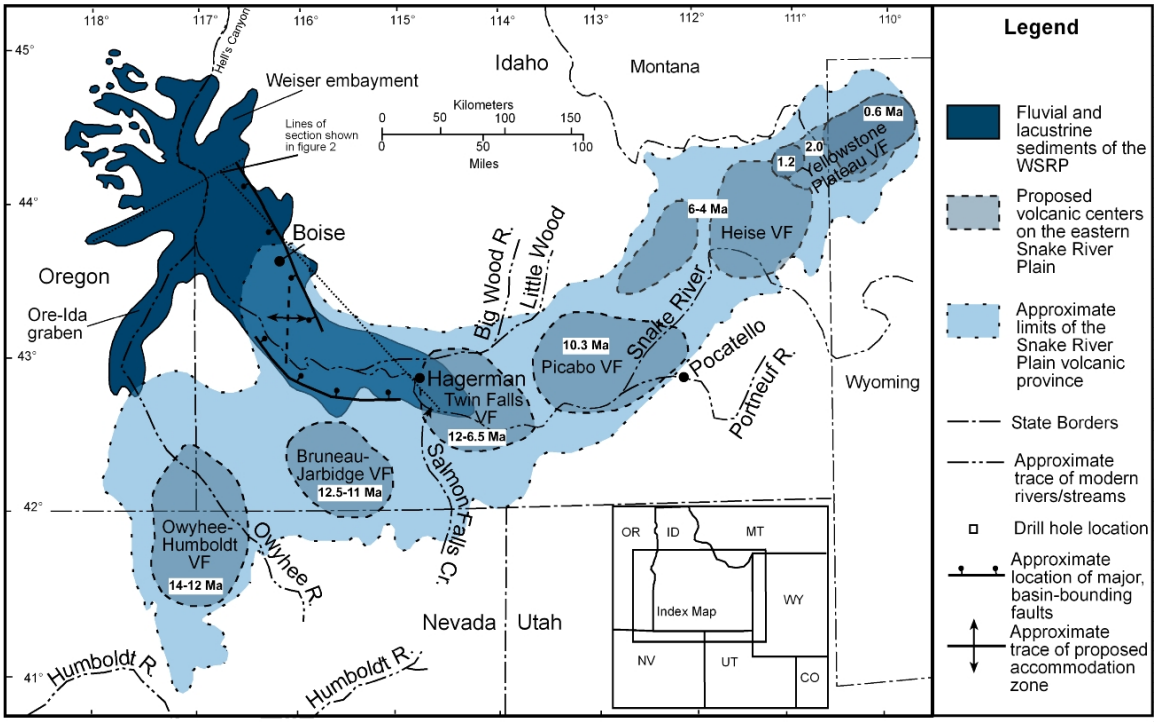


Figure 2. Caldera boundaries associated with eruption of the Yellowstone Hot Spot over the past 10 Ma (figure from Idaho Statue University's Digital Geology of Idaho, http://geology.isu.edu/Digital_Geology_Idaho/Module11/mod11.htm.)

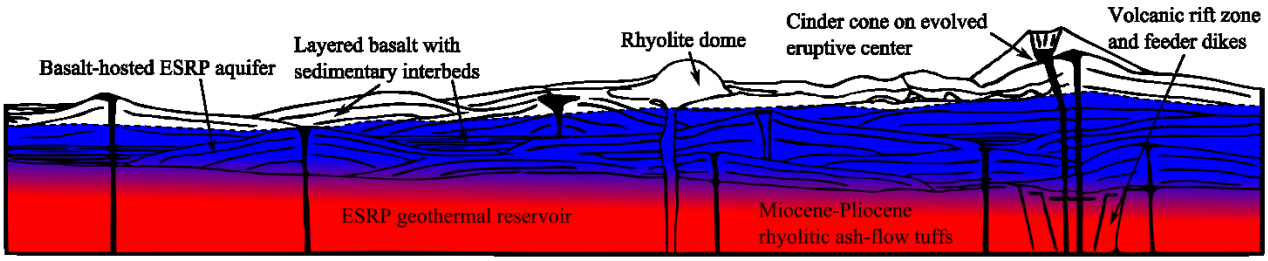


Figure 3. Stylized ESRP cross-section (modified from Hughes et al. (1999); (Neupane et al., 2014)). This figure shows the relative position of the deep silicic rhyolitic ash-flow tuffs and the younger basalts that overly them. This figure also shows presence of the cold fast flowing ESRP aquifer (blue).

2.2 Favorability Analysis

Prior to choosing a potential location for FORGE operations, a "favorability analysis" study was conducted, where initially a number of screening parameters were qualitatively compared at a large scale. Parameters such as expected temperature at depth were assigned values ranging from zero to one, with one representing the highest temperatures. Figure 4 shows the results of this analysis on a 10-mile by 10-mile grid. Hotter colors one Figure 4 were deemed to have a higher favorability for EGS operations. Figure 5 shows the results of further refining the favorability analysis by using a smaller grid (1-mile by 1-mile) and including cultural and infrastructure features such as land ownership, power lines, and perceived paths to permitting.

After careful consideration of a number of potential sites, we selected the INL desert complex on the eastern SRP for FORGE. INL's established infrastructure, applied research culture, and its proven expertise with government regulations and environmental compliance, as well as broad-based regional public support were important considerations; but its physical attributes were the primary deciding factor. Tester et al. (2006) identified the SRP as a high priority target for EGS, based on the high heat flow and vast regional extent. The mechanical properties of the deep volcanic reservoir rocks underlying the SRP opens opportunities of widespread transferability of oil and gas reservoir creation technologies not available elsewhere.

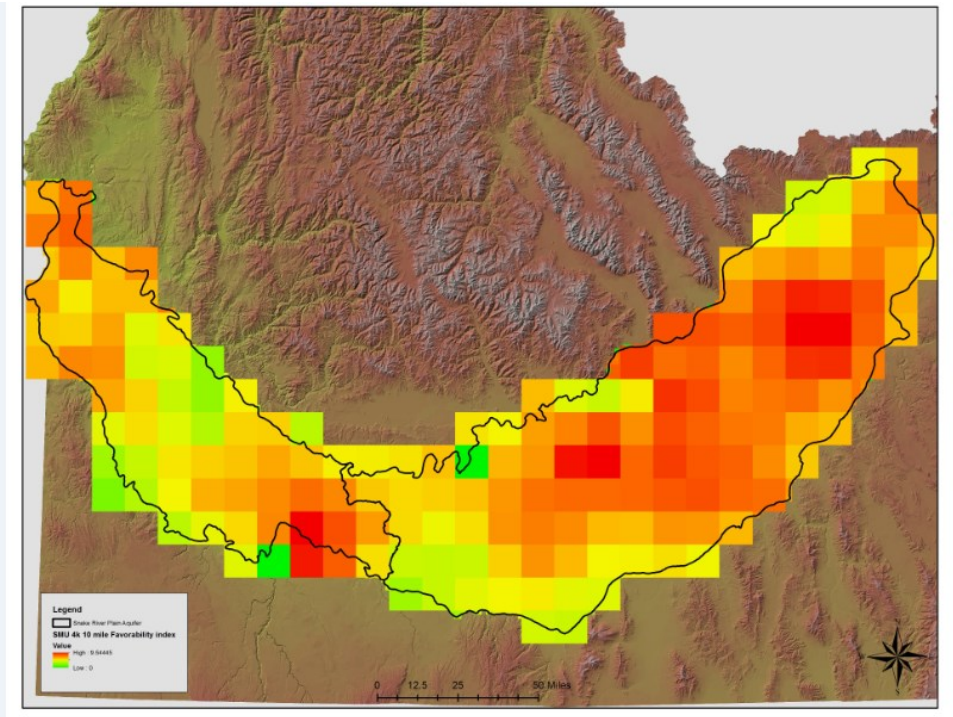


Figure 4: Screening level favorability index for the Snake River Plain on a 10x10mile grid.

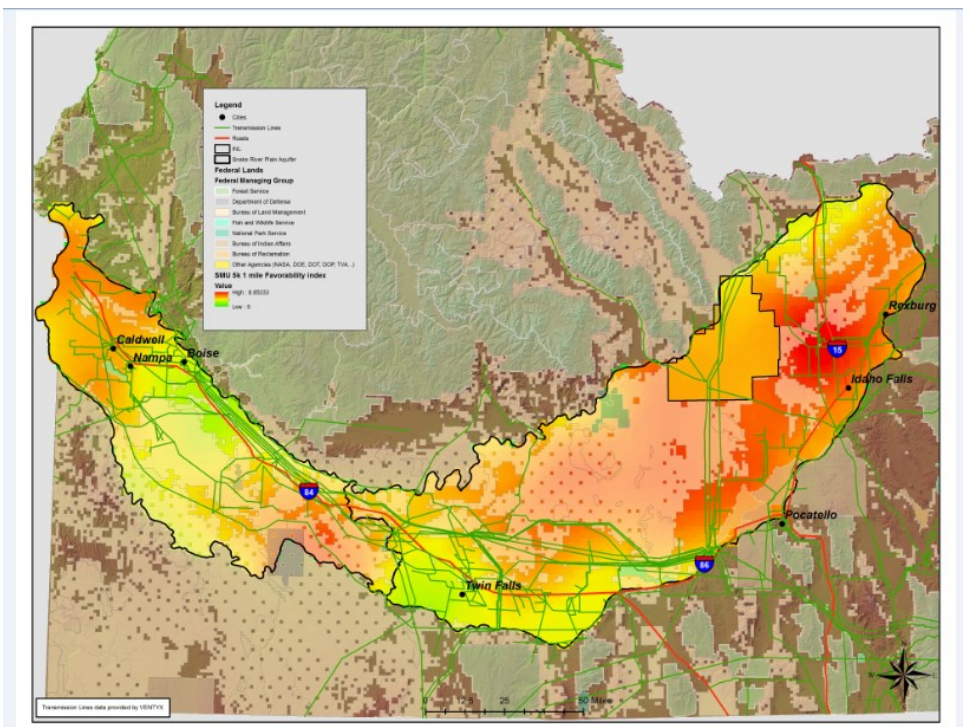


Figure 5: The favorability index on a 1x1mile grid with power lines, roads, land ownership Location and general features of the Snake River Plain.

The INL complex is located on the eastern SRP in southeastern Idaho and includes portions of five Idaho counties: Butte, Bingham, Bonneville, Clark, and Jefferson. Several INL facilities, each taking up less than 5 sq. km (2 sq. mi), are located across the ~2,300 sq. km (890 sq. mi) of the INL Complex that is otherwise undeveloped, semi-arid volcanic terrain. Tens of square km of undeveloped land separates most of the developed sites.

2.3 Snake River Plain Play Fairway Analysis

Shervais et al. (2015; 2016) recently completed at Phase 1 geothermal play fairway analysis of the Snake River Plain, and identified a number of potential hydrothermal plays. Of particular interest is the C-1 prospect near Arco, Idaho (Figure 6). This prospect is directly southwest, and includes a significant port of an area on the INL designated as a Geothermal Resource Research Area (GRRA).

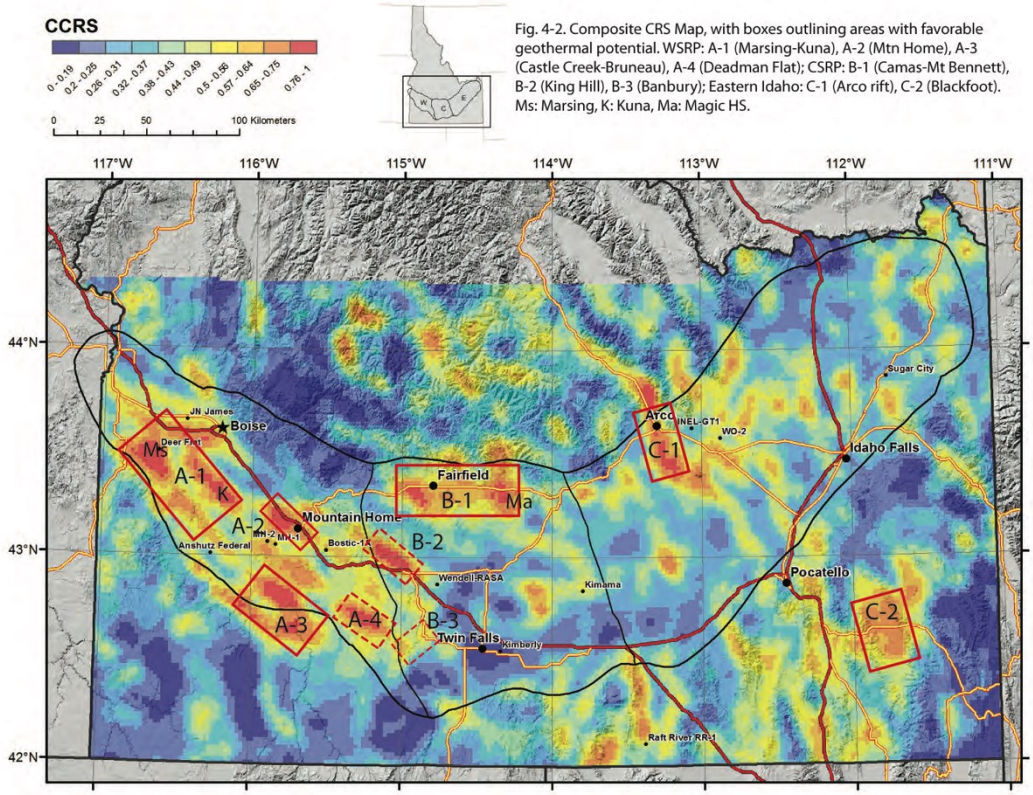


Figure 6: The Composite Common Risk Segment (CCRS) map for southern Idaho produced by the Snake River Plain Play Fairway team (Shervais et al., 2015).

3.0 THE INL GEOTHERMAL RESOURCE RESEARCH AREA

The location for the FORGE Laboratory will be within the GRRA, a dedicated area of approximately 100 sq. km (39 sq. mi) within the INL (see Figure 7), a contiguous parcel of secure DOE land. Located just inside INL's western boundary, the GRRA has significant transmission, roads, seismic monitoring, and year-round access while remaining far removed from population centers (Figure 8). The GRRA area is entirely in Butte County, Idaho and has strong community support. The combination of strong site control, minimal potential stakeholder disturbance, and strong local stakeholder support make this a prime location from a project execution standpoint.

While the entire GRRA will be available for FORGE activities, the active area of operations is expected to be considerably smaller. The area envisioned for active FORGE operations has been chosen to minimize required surface disturbance while maximizing subsurface access. An approximately 2-acre well pad will be constructed in a previously disturbed area that has an existing road and power line. All major FORGE activities on the INL are planned to take place on lands that were impacted by a range fire in 1994, which removed most of the native vegetation. Note that on 8 a "Reference Point" is defined; this will be the basis for distances to other areas of interest in the region discussed herein.

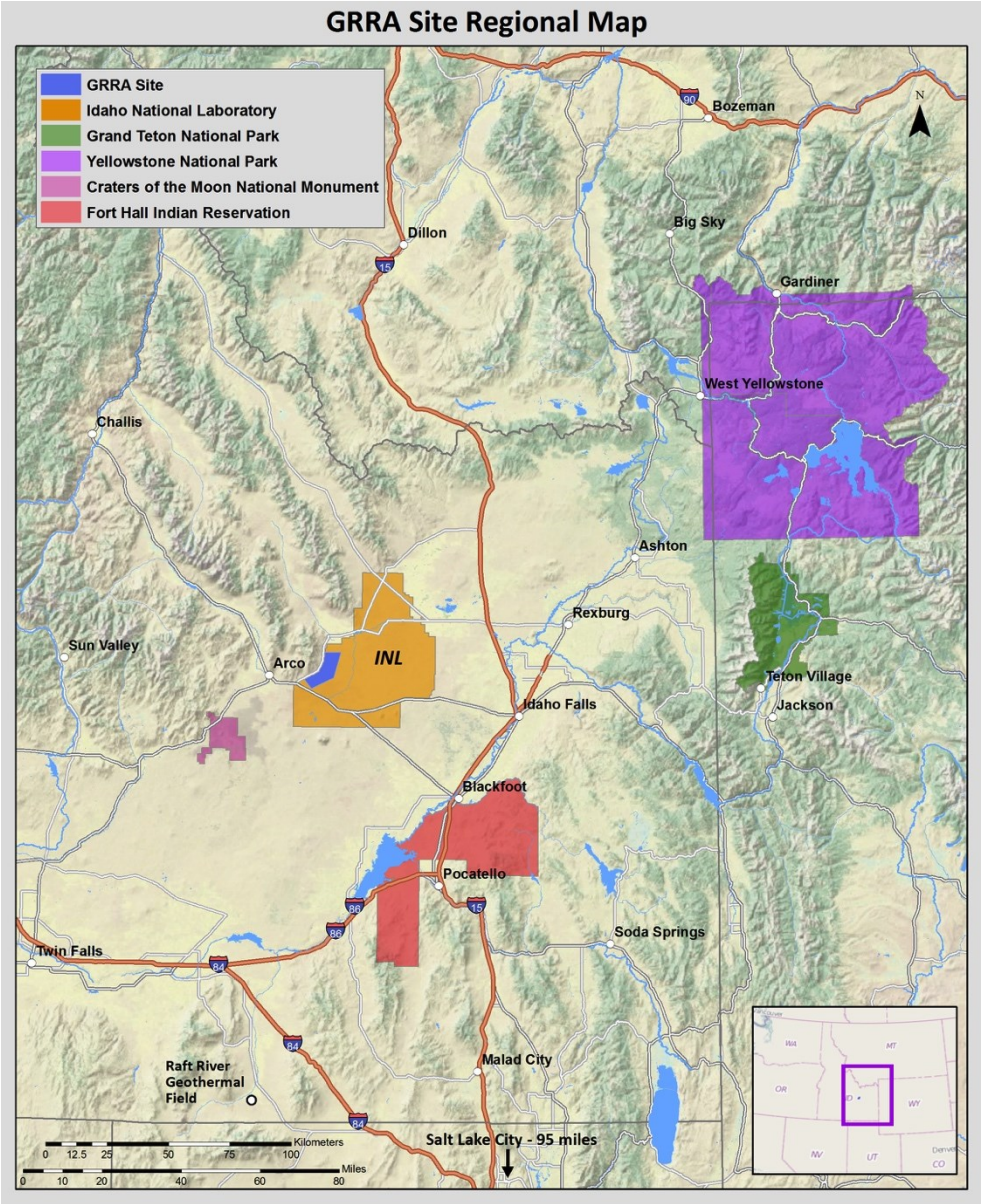


Figure 7. Locations of the INL Site, the Geothermal Resource Research Area (GRRA), and regional national parks, monuments, and the Fort Hall Indian Reservation.

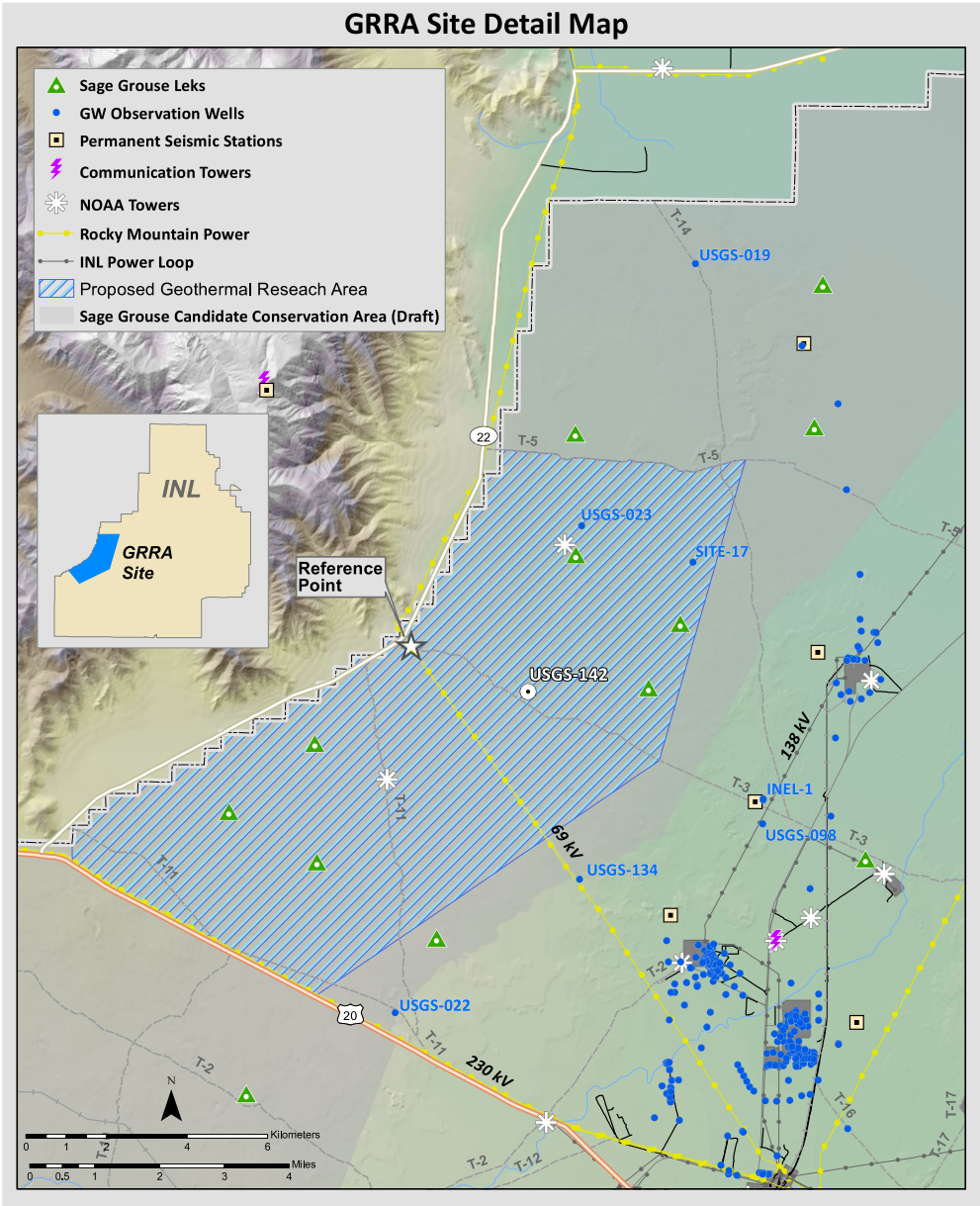


Figure 8. INL GRRA detail map showing existing transmission, roads, wells, seismic monitoring location, other infrastructures, and potentially sensitive areas. NOTE: "Reference Point" on the figure will be the basis for distances to other areas of interest in the region discussed herein.

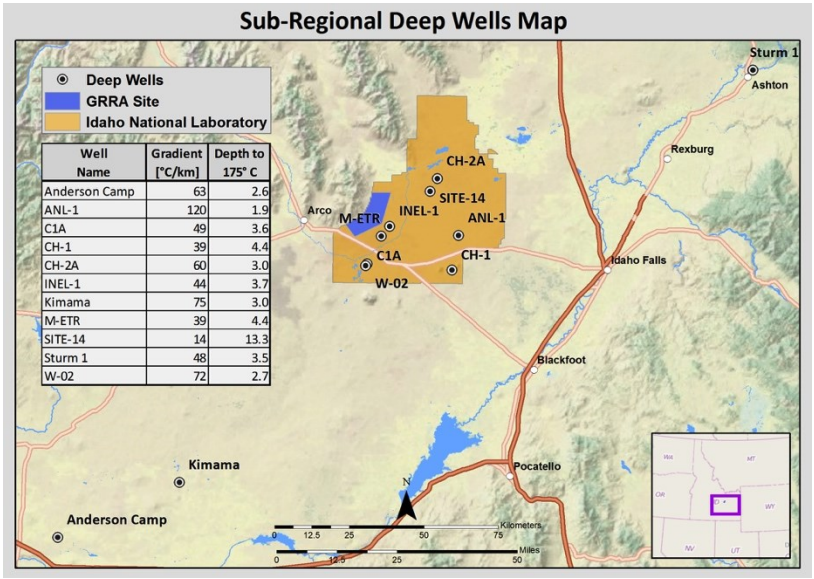
We expect the stratigraphy of the site to range from being similar to that encountered in the INEL-1 Geothermal Test Well (drilled in 1979) to potentially a series of caldera collapse structures and rhyolitic dykes. The sequence will likely contain highly-fractured basalt rocks and sediments from land surface to a depth of ~700 m (2,300 ft). Beneath the basalt, SRGC expects to encounter rhyolite with minor amounts of sediment to a depth of about 2,500 m (8,200 ft). Below the rhyolite, the INEL-1 well encountered dense rhyodacite ash flow that has been recrystalized and hydrothermally altered.

3.1 Reservoir Temperatures

A number of existing deep wells have intervals that extend below the base of the active, high-permeability groundwater system and into the regional low-permeability, thermally conductive controlled basement. These wells have been used to help develop the conceptual model of the deep subsurface of the INL and GRRA. Figure 9 shows the location of selected wells and the measured geothermal gradient.

An average gradient for the wells shown in Figure 9 is 54°C/km. The Kimama well has the maximum gradient of 74.5°C/km and well CH-1 has the lowest gradient of 39°C/km. Based on the bottom hole temperature of INEL-1 Doherty, McBroome, and Kuntz (1979); Mann (1986); Prestwich and Bowman (1980), and using the range of observed geothermal gradients, the maximum potential depth for the proposed FORGE location is expected to be 3.7 km. However, additional lines of evidence suggest the necessary reservoir

temperatures (175°C minimum) may be reached at shallower depths than those predicted based on INEL-1. For example, the water table temperature at INEL-1 is approximately 12°C, while groundwater temperatures underlying the GRRA as high as 20°C, suggests the subsurface temperatures are considerably higher in the area of the GRRA, In addition, results from recent geothermal gradient drilling in the GRRA look very promising.



Well Name	Gradient [°C/km]	Depth to 175° C
Anderson Camp	63	2.6
ANL-1	120	1.9
C1A	49	3.6
CH-1	39	4.4
CH-2A	60	3.0
INEL-1	44	3.7
Kimama	75	3.0
M-ETR	39	4.4
SITE-14	14	13.3
Sturm 1	48	3.5
W-02	72	2.7

Figure 9. Location map for several deep wells/borings in the Eastern Snake River Plain (ESRP), in which temperature data display a break in geothermal gradient that indicative of the bottom of the ESRP aquifer. Inset table shows geothermal gradients calculated from temperatures below the apparent break and the implied depth needed to reach a temperature of 175°C. Not shown are recent geothermal gradient drilling results.

3.2 Seismic Monitoring

Since 1972, INL has supported a seismic monitoring program and has monitored earthquake activity on and near the SRP. The INL seismic monitoring program provides earthquake data and staff to support nuclear operations through continuous monitoring of earthquake activity. Staff also develop seismic design criteria and perform assessments of seismic and volcanic hazards for existing and new facilities.

The INL seismic monitoring program currently operates 32 permanent seismic stations to determine the time, location, and size of earthquakes occurring in the vicinity of the INL Carpenter, Payne, Hodges, and Berg (2011). Seismic stations are located within and around the INL near potential seismic sources that include major range-bounding normal faults and volcanic rift zones. The seismic network within INL Complex boundaries has an average station spacing of 20 km and a detection threshold of approximately magnitude 0.1. There are seven seismic stations that surround and are located within 10 km of the proposed FORGE site (see Figure 8). Global Positioning System (GPS) receivers are collocated at 16 seismic stations to determine rates of crustal deformation and locations of active seismic regions. Three GPS receivers are located at seismic stations that are within 10 km of the GRRA. Figure 10 shows the location of seismic stations used by the INL monitoring program.

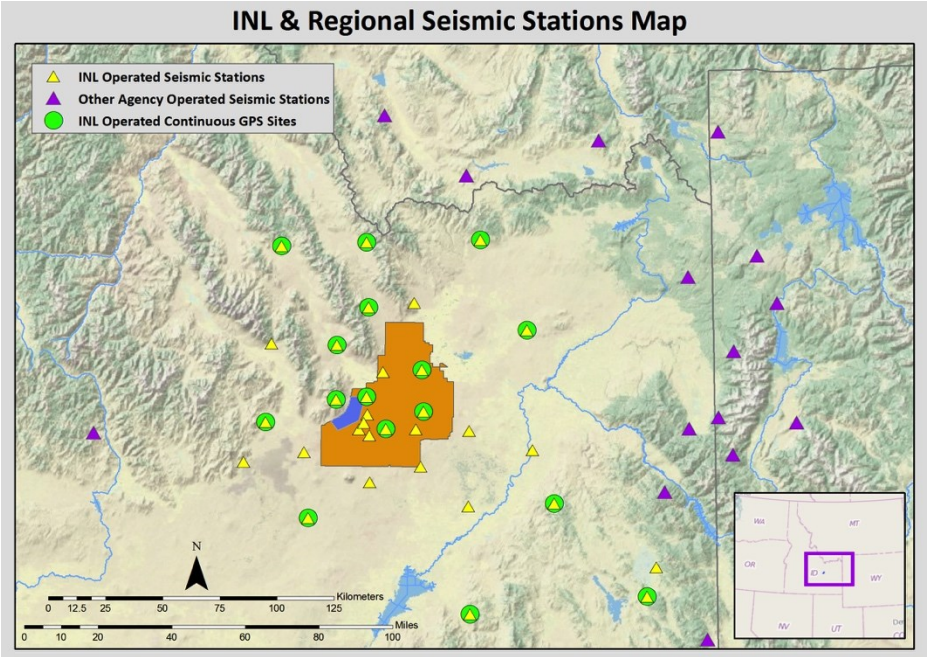


Figure 10. Locations of INL seismic stations and stations monitored by INL that are operated by other institutions Carpenter et al. (2011).

The INL Seismic Monitoring program also operates 31 accelerometer sites for the purpose of recording strong ground motions from local, moderate, or major earthquakes. Eight of the accelerometers are located within INL buildings to determine the response of these buildings to ground motions in the event of a large earthquake. The others are located at "free-field" sites (not within buildings) at INL facility areas and seismic stations. The free-field data are used to determine the levels of earthquake ground motions at the ground (rock or soil) surface and to assess crustal attenuation of small to large magnitude normal faulting earthquakes.

This network, and the decades of existing data, is a real benefit to establishing and operating FORGE. We have a verifiable baseline that is unparalleled and quiet seismic conditions, which will provide a rigorous framework to assess FORGE activities.

3.3 Groundwater Aquifer

The Eastern Snake River Plain comprises a complex sequence of volcanic materials that record the passage of the Yellowstone hotspot beneath the western North American plate beginning in early to middle Miocene time Brott, Blackwell, and Mitchell (1977) . Fractured and highly permeable basalt lava flows of Pliocene and younger age, intercalated with minor amounts of fine to coarse eolian, fluvial and playa sediments, hosts an active, fast-flowing aquifer in the uppermost part of the basalt section Smith (2004). Total basalt thickness approaches 2 km in the central portion of the basin, but secondary mineralization has reduced porosity and permeability by orders of magnitude in the deeper basalts (see e.g., Morse and McCurry (1997)) and created an effective hydraulic base to the ESRP aquifer. This restricts active ground water flow to the uppermost ca. 100 to 500 meters of the basalts in the vicinity of the INL (see e.g., McLing, Smith, Blackwell, Roback, and Sondrup (2014)). Underlying this mineralized aquifer base are more than 3 kilometers of ignimbrite, welded tuff, rhyolitic and granitic basement (hereafter collectively referred to as "rhyolite") that reflect the pervasive silicic volcanism and caldera collapse that occurred in the wake of the hotspot's passage.

4.0 KEY FEATURES OF THE INL SITE

INL occupies a significant amount of land in southeastern Idaho and employs approximately 3,800 people. As such, a significant amount of equipment and trained operators are on-site and available to support FORGE operations. INL has and supports its own stand-alone power grid and a full-time electrical transmission staff, with capabilities ranging from power pole installation and line installation to transmission load and capacity forecasting. These capabilities will support establishment of FORGE on the INL Complex. In addition to the INL complex equipment, the SRGC partner institutions bring significant equipment and capabilities to FORGE.

4.1 Permitting

INL has been operating as a nuclear test site for nearly 70 years, and has also been required to perform environmental restoration activities as a result of past operations. Over the years an extensive number of environmental evaluations and permitting activities have been performed in support of the INL mission, and the FORGE project will benefit from a large amount of accumulated site data and the expertise of existing staff.

4.2 Power

A 69-kV Rocky Mountain Power transmission line runs from a substation located at INL CFA through the project area. Power will be available for purchase to operate FORGE. Rocky Mountain Power's parent company, PacifiCorp Energy, is engaged with the project and is a member of the SRGC Advisory Panel.

4.3 Water

INL has reserved approximately 125 l/s (4.5 CFS) of its 2250 l/s (80 CFS) groundwater right for FORGE activities. If needed, additional water is available because INL currently uses only approximately 10 percent of its water rights for all of its activities. Water usage has never been curtailed on INL due to water right seniority issues.

4.4 Roads

The project area is accessible year round. Idaho Highway 22/33 is adjacent to the area and maintained by the Idaho Transportation Department. INL Complex interior roads run from the highway through the GRRA and are maintained by INL.

As shown on Figure 7, the location selected for FORGE on the INL Complex is remote. The nearest airports are located in Idaho Falls and Sun Valley/Hailey. Approximate drive time from either airport is 90 minutes. The nearest international airport is located in Salt Lake City, UT, approximately a 3-½ hour drive.

5.0 THE SNAKE RIVER GEOTHERMAL CONSORTIUM TEAM

To meet the challenges and drive the solutions for EGS, the Snake River Geothermal Consortium, a research partnership focused on advancing geothermal energy, was established. The SRGC is comprised of national laboratories, academic institutions, federal/state agencies, and private industry partners. National laboratory partners include Idaho National Laboratory (INL), the National Renewable Energy Laboratory and Lawrence Livermore National Laboratory, which support the full spectrum RD&D on energy technologies. In addition to the national laboratories, six academic institutions are SRGC partners, including the Center for Advanced Energy Studies (University of Idaho, Idaho State University, Boise State University, University of Wyoming), University of Utah, and University of Oklahoma; they add diversity of research innovation and network to the broader STEM educational functions and outreach that will be instrumental in helping secure the long-term goals for EGS. Also, six private partners participate as SRGC members and bring key perspectives to the research team and provide a context for commercializing the research outcomes; they include Mink GeoHydro, Baker Hughes, Geothermal Resource Group, Chena Power, Campbell Scientific, and US Geothermal. The team also has participants from federal and state agencies, including the USGS, Idaho Department of Water Resources, and the Idaho Geologic Survey.

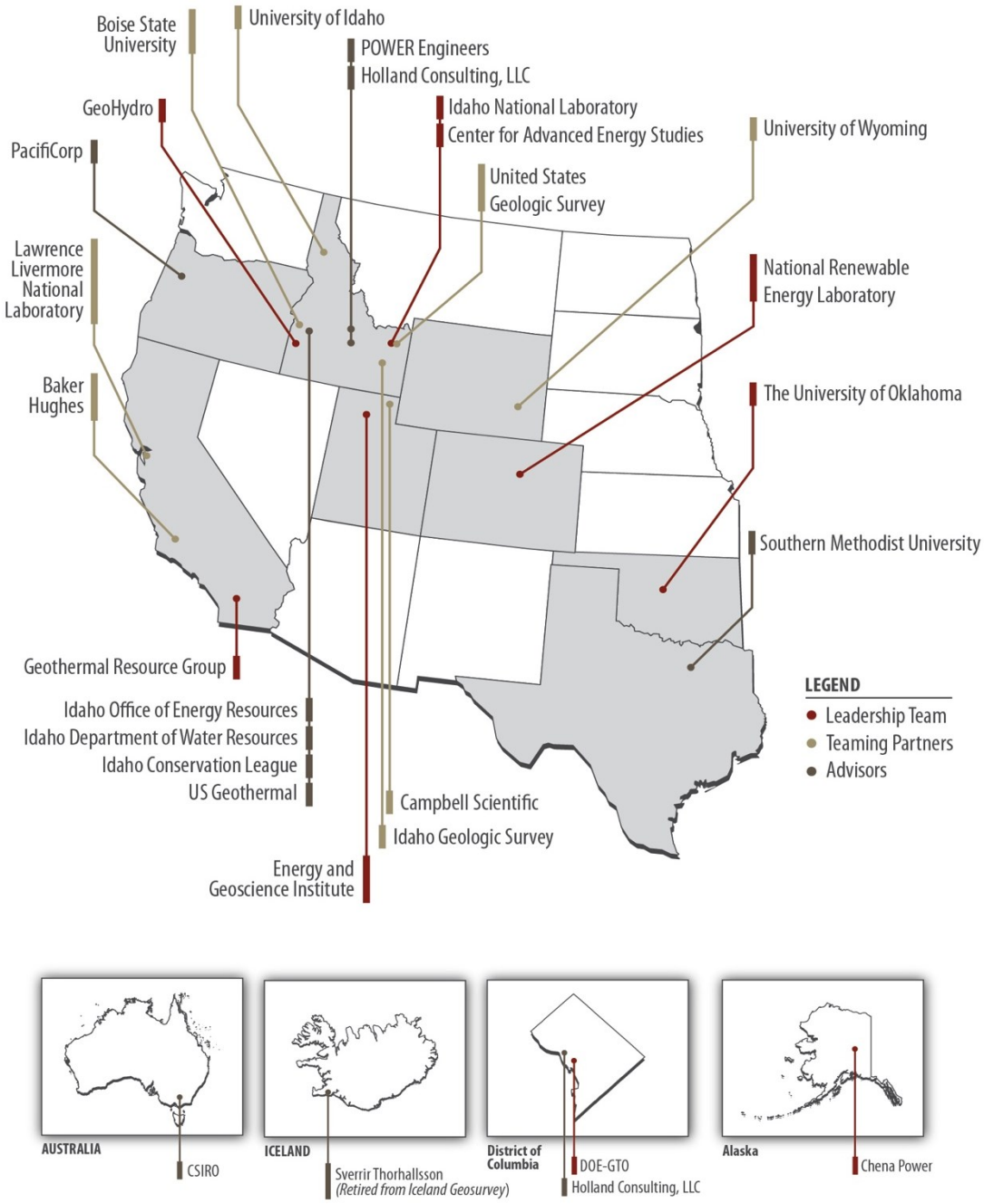


Figure 11. Location of the Snake River Geothermal Consortium teaming members and Advisory Panelists.

Table 1 below summarizes a number of detailed presentations from the SRGC team that provide more information about the characteristics of the INL GRRA and the potential FORGE location on the Snake River Plain.

Lead Author	Affiliation	Title
Bakshi	Univ of Oklahoma	Geomechanical characterization of rock core from the proposed FORGE Laboratory on the Eastern Snake River Plain, Idaho
Grana	Univ of Wyoming	Rock physics modeling for the potential FORGE site on the Eastern Snake River Plain, Idaho
McCurry	Idaho State Univ	Geologic Setting of the Idaho National Laboratory Geothermal Resource Research Area
Plummer	INL	Modeling Heat Flow in the Eastern Snake River Plain Aquifer
Plummer	INL	Effects of Groundwater Flow on Groundwater Temperature Profiles and Impacts on Their Interpretation
Welhan	Idaho Geologic Survey	Thermal and Geochemical Anomalies in the Eastern Snake River Plain Aquifer: Toward a Conceptual Model of the EGS Resource in the FORGE test area

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