Title

GeoVision Analysis Supporting Task Force Report: Exploration

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Publication Date

2018-06-14

LBNL-2001120

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Exploration

June 2018

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[1] Now with Headwaters Bank

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List of Acronyms

(A)MT/CSEM	Audiomagnetotellurics/Controlled source electromagnetic
AHP	Analytical Hierarchy Process
AOI	area of interest
ARRA	American Reinvestment and Recovery Act
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
B&R	Basin and Range
BHTV	Borehole Televiewer
CCRS	Composite Common Risk Segment
CPG	CO_2 plume geothermal
CPUs	Central Processing Units
CRS	Common Risk Segment
CSMP++	Complex Systems Modeling Platform
CSRP	Central Snake River Plain
DAS	distributed acoustic sensing
DEGREe	Direct Electric Geothermal Resource Extraction
DOE	Department of Energy (United States)
DTH	down-the-hole
DTS	Distributed Temperature Sensor
EERE	Energy Efficiency and Renewable Energy
EGI	Energy & Geoscience Institute
EGS	Enhanced Geothermal Systems
EIT	Electric Impulse Technology
EIV	environmental information volume
EPB	Electro Pulse Boring
EPM	Effective Porous Medium

ERT	electrical resistance
ESMAP	Energy Sector Management Assistance Program
FDSP	Flowing Differential Self Potential
FLIR	Forward looking infrared
FORGE	Frontier Observatory for Research in Geothermal Energy
FPGAs	field-programmable gate arrays
GCS	geologic carbon sequestration
GeoRePORT	Geothermal Resource Portfolio Optimization and Reporting Technique
GEP	graphene-enriched product
GPUs	graphics processing units
GRRM	Geothermal Resource Reporting Metric
GTO	Geothermal Technologies Office
HADES	Hotter and Deeper
HTR	high-temperature reservoir
IDDP	Iceland Deep Drilling Project
IEA	International Energy Agency
IET	Innovative Exploration Techniques
IFS	iterated function system
INL	Idaho National Laboratory
kISMET	Permeability (k) and Induced Seismicity Management for Energy Technologies
LAFs	Large Aperture Fractures
LASEA®	LASEA® (Low Amplitude Seismic Emission Analysis
LBNL	Lawrence Berkeley National Laboratory
LiDAR	Light Detection And Ranging
MB	Mount Baker
MCMC	Markov Chain Monte Carlo
MEQs	micro-earthquakes

MSHSZ	Mount St. Helens Seismic Zone
MT	magnetotelluric
NASF	Naval Air Station Fallon
NEIC	National Earthquake Information Center
NEPA	National Environmental Policy Act
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
NUFT	Nonisothermal, Unsaturated Flow and Transport
ORNL	Oak Ridge National Laboratory
P-32	Prati 32
PCA	principal component analysis
PFA	play fairway analysis
POS	probability of success
PS-31	Prati State 31
PSInSAR	Permanent Scatterers Synthetic Aperture Radar Interferometry
PTS	pressure-temperature-spinner
QEMScan	Quantitative Electron Microscope Scanning
RD&D	research, development, and demonstration
RHS	Roosevelt Hot Springs
SEM	scanning electron microscopy
SIGMA-V	Stimulation Investigations for Geothermal Modeling Analysis and Validation
SNL	Sandia National Laboratories
SP	seismic profile
SP	Self-potential
SRP	Snake River Plain
SubTER	Subsurface and Engineering Research, Development, and Demonstration
SURF	Sanford Underground Research Facility

TA	Transportable Array
THC	Thermal Hydrologic Chemical
THM	Thermal Hydrologic Mechanical
THMC	Thermal Hydrologic Mechanical Chemical
TI	Technology Improvement
TZIM	thermally degradable zonal isolation materials
UCD	University of California at Davis
UGS	Utah Geological Survey
USGS	United States Geological Survey
VLF	Very low frequency
VOI	value of information
VSP	vertical seismic profile
WACC	weighted average cost of capital
WoE	weights of evidence
WRV	Wind River Valley
WSRP	Western Snake River Plain
ZTEM	Z-Tipper Axis Electromagnetic

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1 Introduction

The *GeoVision* study effort included ground-breaking, detailed research on current and future market conditions and geothermal technologies in order to forecast and quantify the electric and non-electric deployment potentials under a range of scenarios, in addition to their impacts on the Nation's jobs, economy and environment. Coordinated by the U.S. Department of Energy's (DOE's) Geothermal Technologies Office (GTO), the *GeoVision* study development relied on the collection, modeling, and analysis of robust datasets through seven national laboratory partners, which were organized into eight technical Task Force groups. These Task Forces and their respective principal leading National Laboratory are indicated in Table 1.

Table 1. Guide to GeoVision Task Forces providing the basis of the *GeoVision* analysis.

GeoVision Task Force	Lead National Laboratory
Exploration & Confirmation	Lawrence Berkeley National Laboratory (LBNL)
Potential to Penetration	National Renewable Energy Laboratory (NREL)
Thermal Applications - Direct Use	NREL
Thermal Applications - GSHP	Oak Ridge National Laboratory (ORNL)
Reservoir Maintenance and Development	Sandia National Laboratories (SNL)
Hybrid Systems	Idaho National Laboratory (INL)
Institutional Market Barriers	NREL
Social and Environmental Impacts	LBNL

The purpose of this report is to provide a central repository for the research conducted by the Exploration Task Force. The Exploration Task Force consists of four individuals representing three national laboratories: Patrick Dobson (task lead) and Christine Doughty of Lawrence Berkeley National Laboratory, Anna Wall of National Renewable Energy Laboratory, Travis McLing of Idaho National Laboratory, and Chester Weiss of Sandia National Laboratories. As part of the *GeoVision* analysis, our team conducted extensive scientific and financial analyses on a number of topics related to current and future geothermal exploration methods. A listing of our publications related to this effort is presented in Table 2.

Table 2. Exploration Task Force Publications related to *GeoVision* Study.

Reinsch, T., Dobson, P., Asanuma, H., Huenges, E., Poletto, F., and Sanjuan, B. (2017) Utilizing supercritical geothermal systems: a review of past ventures and ongoing research activities. *Geothermal Energy* 5, DOI 10.1186/s40517-017-0075-y.
Wall, A.M., Dobson, P.F., and Thomas, H. (2017) Geothermal costs of capital: Relating market valuation to project risk and technology. *Geothermal Resources Council Transactions* 41, 45–61.
Stimac, J., Wilmarth, M., Madeno, P.E., Dobson, P., and Winick, J. (2017) Review of exploitable supercritical geothermal resources to 5 km at Geysers-Clear Lake, Salton Sea, and Coso. *Geothermal Resources Council Transactions* 41, 806–835.
Dobson, P., Asanuma, H., Huenges, E., Poletto, F., Reinsch, T., and Sanjuan, B. (2017) Supercritical geothermal systems – A review of past studies and ongoing research activities. *Proceedings, 42nd Workshop on Geothermal Reservoir Engineering*, Stanford University, Feb. 13-15, 2017, 13 p.
Dobson, P., Wall, A., McLing, T., Weiss, C., and Doughty, C. (2016) The role of exploration in increasing geothermal deployment in the US Department of Energy *Geovision* study. *Proceedings 38th New Zealand Geothermal Workshop*, 5 p.
Dobson, P.F. (2016) A review of exploration methods for discovering hidden geothermal systems. *Geothermal Resources Council Transactions* 40, 695–706.
Wall, A.M. (2016) Future scenario development from disruptive exploration technologies and business models in the U.S. geothermal industry. *Geothermal Resources Council Transactions* 40, 787–793.
Wall, A.M., and Dobson, P.F. (2016) Refining the definition of a geothermal exploration success rate. *Proceedings, 41st Workshop on Geothermal Reservoir Engineering*, Stanford University, Feb. 22-24, 2016, 11 p.

The *GeoVision* Exploration Task Force complements the drilling and resource technology investigations conducted as part of the Reservoir Maintenance and Development Task Force. The Exploration Task Force however has focused primarily on early stage R&D technologies in exploration and confirmation drilling, along with an evaluation of geothermal financing challenges and assumptions, and innovative "blue-sky" technologies. This research was used to develop geothermal resource supply curves (through the use of GETEM) for use in the ReEDS capacity expansion modeling that determines geothermal technology deployment potential. It also catalogues and explores the large array of early-stage R&D technologies with the potential to dramatically reduce exploration and geothermal development costs, forming the basis of the *GeoVision* Technology Improvement (TI) scenario. These modeling topics are covered in detail in *Potential to Penetration* task force report. Most of the research contained herein has been published in peer-reviewed papers or conference proceedings and are cited and referenced accordingly. The sections that follow provide a central repository for all of the research findings of the Exploration and Confirmation Task Force. In summary, it provides a comprehensive discussion of Engineered Geothermal Systems (EGS) and associated technology challenges, the risks and costs of conducting geothermal exploration, a review of existing government efforts to date in advancing early-stage R&D in both exploration and EGS technologies, as well as a discussion of promising and innovative technologies and implementation of blue-sky concepts that could significantly reduce costs, lower risks, and shorten the time needed to explore and develop geothermal resources of all types.

2 Enhanced Geothermal Systems

The strict definition of an Enhanced Geothermal System is a high enthalpy, conduction-dominated geothermal resource located 3 kilometers (km) to 10 km deep in the earth's crust (other options for EGS include fluids co-produced from oil and gas wells, and geopressurized systems, but the discussion below centers on conduction-dominated systems). Rocks in potential EGS targets are usually incapable of sustaining fluid flow and require the creation of engineered fractured reservoirs to recover thermal energy. As shown in Figure 1, cool injected water warms as it moves through the fracture network to the production well. At the surface, the heat is extracted to generate electricity or for direct use and the cooled water is reinjected.

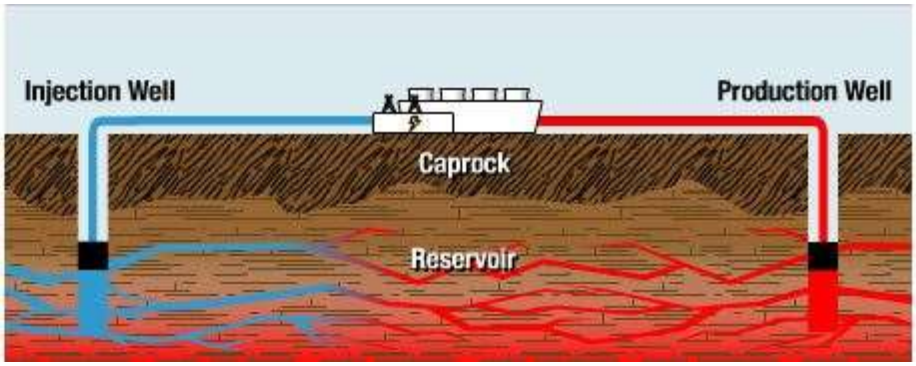


Figure 1. Schematic of EGS Operation (IEA, 2011)

Los Alamos National Laboratory first proposed EGS in 1970 as a means of recovering heat from hot tight formations. Field-testing for this effort started in 1973 at Fenton Hill, New Mexico. Since that time, no fewer than 30 significant field-scale tests have been conducted across the globe.

The high-enthalpy requirement can be met by locating the EGS in areas of high regional heat flow. Examples in the U.S. (Figure 2) include the Cascades, the Basin and Range and Snake River Plain provinces, the Rio Grande Rift and Colorado Plateau, the Salton Sea, the Clear Lake Volcanic Field, and east Texas and Louisiana. EGS sites are also envisioned near volcanic centers along the Aleutian Islands of Alaska and the Big Island of Hawaii. In order to augment natural permeability with an engineered fracture network, geologic information required are the state of stress and the rock type at depth, as these will affect key parameters such as the orientation and abundance of natural and created fractures, permeability and porosity, the rock strength and competence, and the thermal conductivity. Critical to assessing the EGS potential at any location is the development of a site conceptual model that incorporates and integrates all site characterization data.

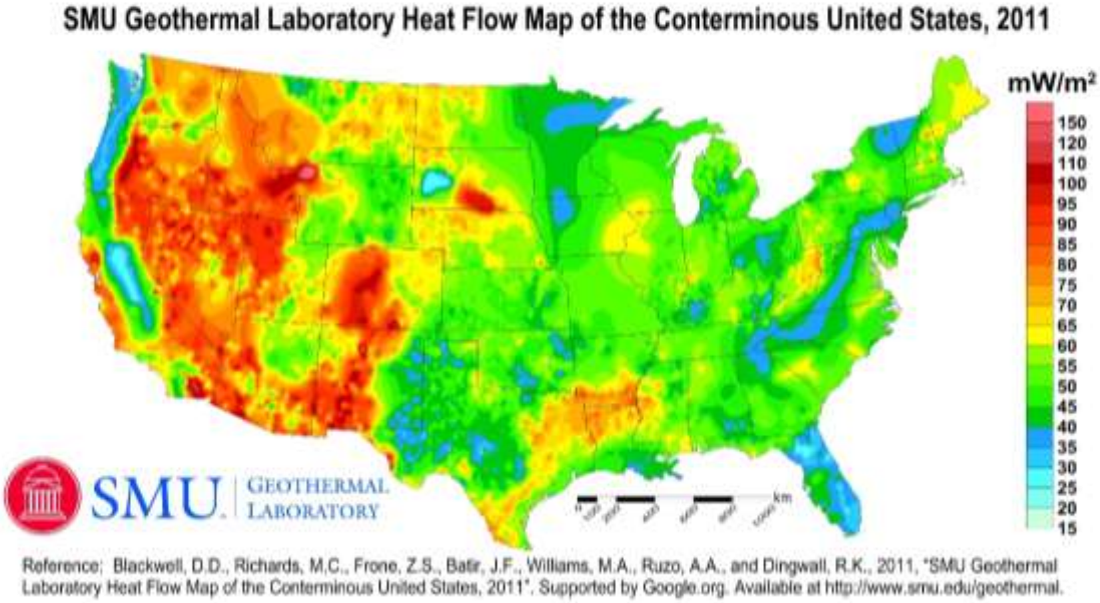


Figure 2. Heat flow map of the United States (Blackwell et al., 2011).

2.1 Hard-Rock EGS

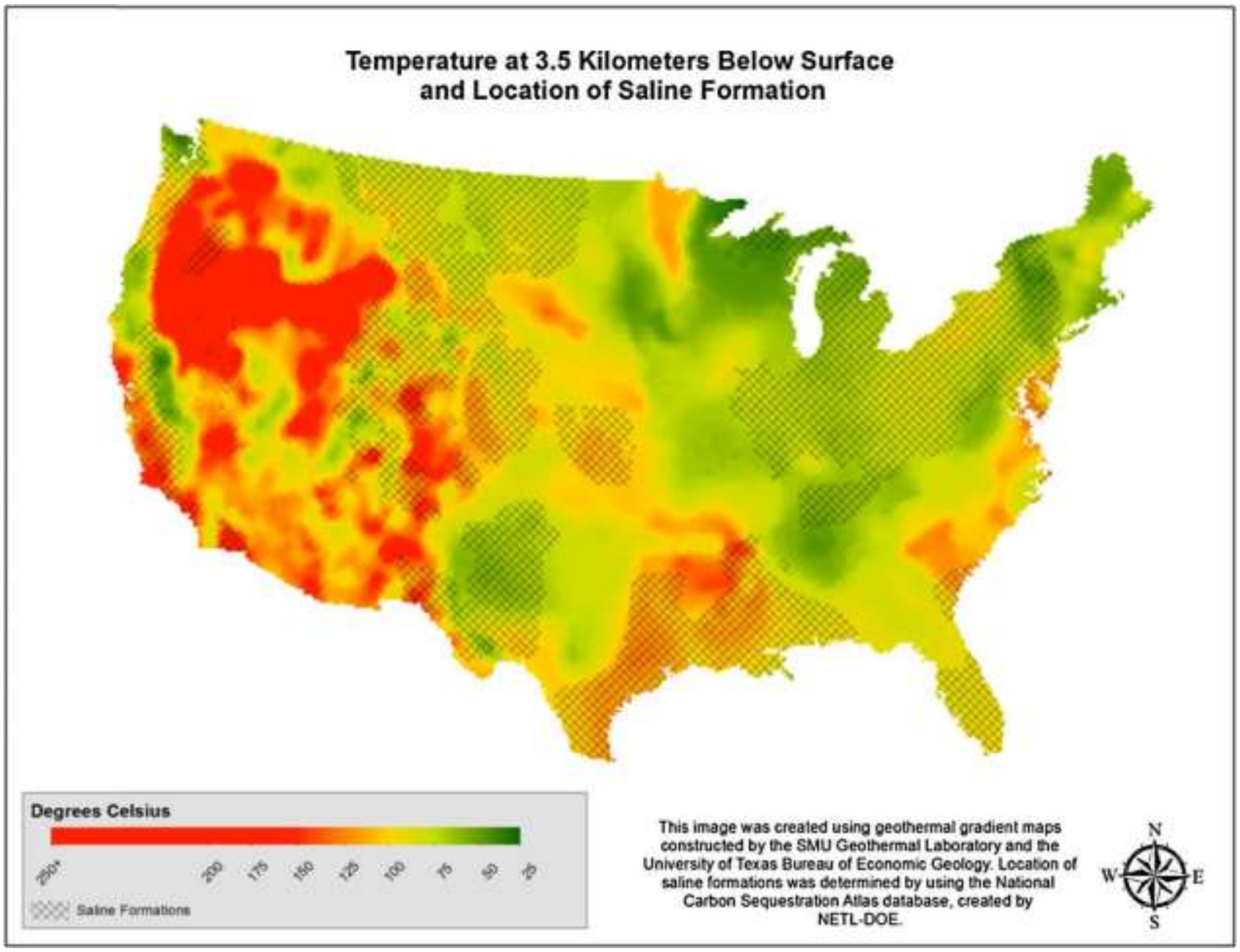
Initially, research into EGS has focused on low-permeability regions along the margins of existing hydrothermal fields located in hard rock where faults and fractures provided permeability. The most difficult technical aspect of EGS in such settings is creating fluid flow pathways with sufficient heat exchange area to economically recover the energy resource. The rate of water circulation through the hot rock mass is critical in determining this factor, and is controlled by the fracture flow paths between injection and production wells. Sufficient fracture density and size are needed to allow for short rock heat conduction pathways. However, extreme channeling resulting from flow through just one or a few high permeability fracture pathways between injection and production wells can reduce the useful recovered thermal energy. Developing an EGS with just the right amount of fracture connectivity is a current research challenge, and much more experimental and modeling work needs to be done to evaluate stimulation methods used to produce fractured reservoirs. The basic scientific issue is to understand the impact of fluid pressure on the behavior of fractured rocks under a variety of stress regimes. Methods of stimulation using variable injection pressure and injection at selective depth intervals need to be improved. Acoustic imaging methods can be employed to assess the extent and location of opened fractures resulting from stimulation, but tracer studies or analyses of the heat extracted are necessary to determine the volume of fractured rock through which fluid flows, which ultimately controls the amount of heat that can be extracted.

The primary parameters needed for estimating the cost of EGS reservoir development are the number of fractures needed to support the proposed power plant, and the total length of the horizontal boreholes that would be used to create and access those fractures. McLing (2017) illustrates how these critical values can be readily estimated from simple mathematical expressions. Gringarten et al. (1975) developed an analytical solution for an idealized EGS reservoir consisting of identical, equally spaced fractures, and quantified the heat transfer improvement achieved when flow is divided among multiple fractures rather than flowing through one fracture. Doe et al. (2014) considered less ideal fracture networks composed of fractures with different apertures, extents, and orientations, and showed that much of the advantage of multiple fractures found by Gringarten et al. (1975) disappears when the largest few fractures contain the bulk of the fluid flow. Grant and Garg (2012) examined the effect of preferential flow on recovery factor (heat extracted divided by original heat in place), and determined that the 50% to 70% recovery factors estimated from idealized models should be reduced by up to a factor of 20 for more realistic systems in which there is preferential flow. They explain why typical EGS recovery factors of less than 2% (Grant, 2016) are so much lower than hydrothermal recovery factors (~10%) by comparing the spatially extensive processes that create permeability in hydrothermal systems (formation porosity, natural fracturing associated with volcanic flows, tectonic movements, and hydrothermal alteration), with the essentially point processes used to create permeability in EGS (hydraulic, thermal, or chemical stimulation at the wellbore-fracture intersection). This comparison motivates the need for permeability enhancement in EGS to be as spatially extensive as possible (e.g., stimulating multiple zones, designing stimulation to occur at a distance from the wellbore).

In summary (Doe et al., 2014), in order to understand the feasible space of hard-rock EGS, one must recognize the key roles played by the geometry and properties of natural, induced, and reactivated fractures in controlling both the rate and quality of heat delivered from the EGS reservoir. EGS systems rely on a combination of conductive heat transport from the rock matrix to flowing fractures, and convective heat transport through these fracture networks to producing wells. The feasible space for EGS systems depends on the ability of fracture stimulation to produce rock masses providing a large amount of surface area for thermal conduction, and a relatively slow rate of flow in each fracture or stimulated volume to maintain the outlet water temperatures. Achieving economic total flow rates from the EGS system may require producing from multiple stimulated volumes.

2.2 Deep Sedimentary EGS

A second type of EGS is found in deep sedimentary basins, where porous media provide the permeability, which may or may not need to be enhanced. Figure 3 overlays a temperature map at 3.5 km depth with the locations of deep sedimentary basins in the U.S., and identifies many promising areas. Anderson (2013) studied 17 basins in the western U.S and used the innovative plotting approach developed by Porro et al. (2012) to categorize 15 of them by volume, depth, and temperature, as shown in Figure 4. Based on a minimum temperature of 125^{o}C and a maximum depth of 4 km, favorable basins are Denver, Great Basin, Williston, Fort Worth, Raton, and Sacramento. However, small volume would probably exclude the last three. Two other favorable basins based on temperature and depth are the Gulf Coast and Southern California’s Imperial Valley. Anderson (2013) then evaluated specific reservoir rock stratigraphy and quality, and produced the map shown in Figure 5, which adds porosity >10% and permeability >10–50 md to the depth/temperature criteria. The most promising basins are Denver, Great Basin, Gulf Coast, Imperial Valley, Fort Worth, and Sacramento. If the permeability criterion is eliminated (i.e., if permeability enhancement is to be used), then Williston and Raton can be added to the list.


Temperature at 3.5 Kilometers Below Surface and Location of Saline Formation

This image was created using geothermal gradient maps constructed by the SMU Geothermal Laboratory and the University of Texas Bureau of Economic Geology. Location of saline formations was determined by using the National Carbon Sequestration Atlas database, created by NETL-DOE.

Figure 3. Temperature at 3.5 km depth and the locations of deep sedimentary basins (from Pan et al., 2015).

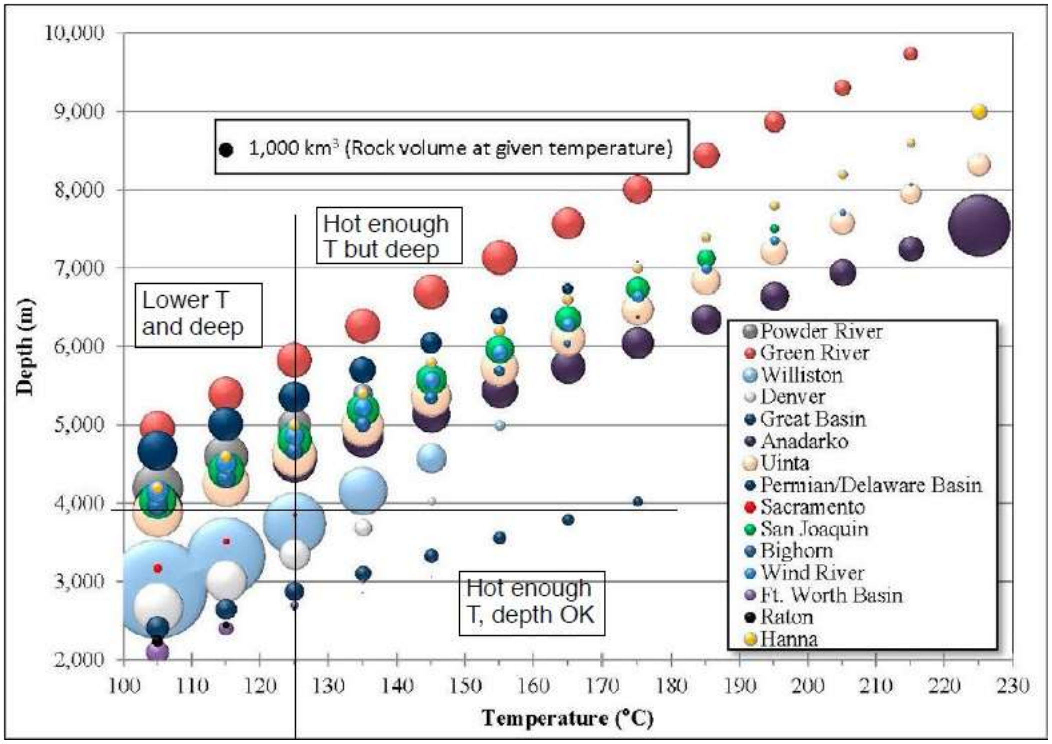


Figure 4. Categorization of 15 basins in the Western U.S. by rock volume, depth, and temperature (Anderson, 2013).

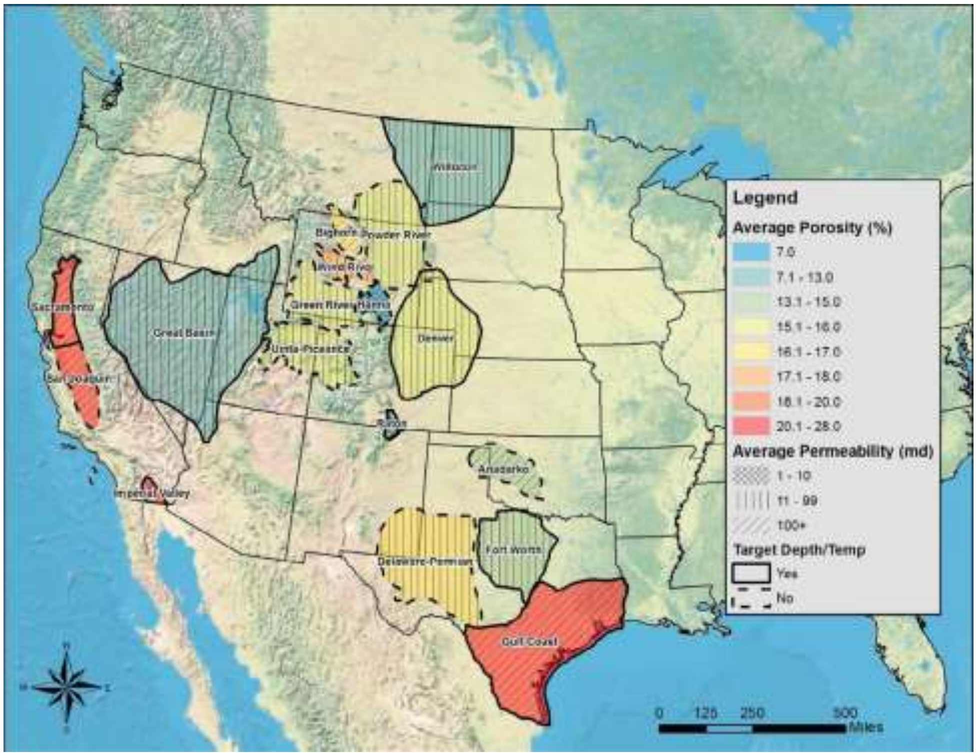


Figure 5. Map of 17 basins in the Western U.S., categorized by porosity (color), permeability (hatching), and depth/temperature criteria (outline) from Anderson (2013).

If natural permeability is adequate, then the "E" part of EGS means devising a circulation pattern through the reservoir to optimally extract heat. The simplest configuration is an injection/production well doublet, but more advanced schemes (e.g., Gringarten, 1978) have also been proposed to produce a more efficient heat sweep from the reservoir. Numerous studies of optimal well placement for environmental remediation and oil and gas recovery are also relevant. For simple well geometries, analytical solutions exist to predict fluid and heat flow and thermal breakthrough at the production wells (Gringarten, 1978), and for more complex geometries, numerical models may be used. Augustine (2014) used the Gringarten (1978) solution for an injection well/production well doublet to gain insights into how the reservoir will perform (e.g., how breakthrough time increases with reservoir thickness and the square of well separation, and decreases with flow rate) and do a cost analysis of sedimentary EGS.

If permeability needs to be augmented, then the discussion about optimal fracture spacing for hard-rock EGS applies generally. However, the character of flow in deep sedimentary basins will probably be somewhat different, with a small but significant fraction of flow occurring through the unfractured sedimentary rock. Thus, detailed specifications for reservoir stimulation will need to be tailored to particular sites.

2.3 Drilling Issues

The second major obstacle confronting EGS, either in crystalline rock or sedimentary basins, is the prohibitive cost of drilling deep wells. The cost of 3-6 km deep wells must decrease significantly if EGS is to become a viable energy option. The development of new drilling technologies for deep hydrocarbon targets by the oil and gas industry can be applied to the EGS field, especially for sedimentary basins. Geothermal wells tend to be more expensive than oil and gas wells of similar depth because of the need for larger diameter completions to accommodate high volumes of fluid flow, which requires larger drill rigs, drill bits, and casing. At EGS sites that are located near the margins of commercial geothermal systems, high heat flow would require significantly shallower wells, thus greatly reducing drilling and well completion costs. Many high-temperature drilling innovations developed for the geothermal industry (muds, mud chillers, bit design, cementing, casing) can also be used for EGS applications.

The time required for drilling deep wells is a major component to EGS well costs. Rates of penetration for hard rocks such as granites are typically quite low, resulting in long drilling times. New technologies such as improved drill bits, expandable tubular casing, and low clearance casing designs should reduce drilling and completion costs. Revolutionary changes in drilling (using methods such as projectiles, heat, lasers, or chemicals) may also improve rates of penetration for drilling deep wells needed for EGS systems. Further discussion of innovations in drilling can be found in Lowry et al. (2017).

Learning from drilling experiences should lead to a decrease in drilling problems, thus speeding up drilling and reducing costs. Technological advances will also lead to commercial development of deeper resources with time. Savings can also be realized by economies of scale. The generally more homogeneous geology and softer rock of deep sedimentary basins make drilling there less risky than for hydrothermal or hard-rock EGS.

One alternative technology currently being explored in Germany (Orzol et al., 2005) is the use of a single well for injection and production, which effectively halves the drilling cost for EGS. This well design injects fluid down an inner casing into the bottom portion of the well that is isolated by packers, with production occurring from a stratigraphically higher interval in the well through the annulus. Another single well concept is a closed-loop heat exchange system where the well has a wide U-shaped portion to facilitate conductive heat exchange – the working fluid for this system is CO_2 (Oldenburg et al., 2016a).

2.4 Technical Needs

A number of key technical needs have been identified by a major EGS review study conducted at Massachusetts Institute of Technology (Tester et al., 2006) that could enhance successful development of EGS resources. Assessment of the stimulated volume and heat transfer area within the reservoir using tracers, microseismic monitoring, or reservoir tomography could provide a better evaluation of the sustained energy generation potential of EGS reservoirs. Development and deployment of high-temperature logging tools and sensors such as SP, gamma, resistivity, sonic, density neutron, and bore hole imaging logs would enhance current downhole measurements (temperature, pressure, spinner logs) used routinely in the geothermal industry. Management of reservoir stimulation such as controlling the growth and extent of the fractured volume and mitigation of flow short circuits through the use of packers and controlled injection pressures is another key issue. Long-term performance data from EGS test sites is also needed to validate reservoir simulation models.

2.5 Energy Conversion Systems

Different energy conversion systems can be selected to optimize the energy extraction and economic viability of each geothermal resource. Binary power systems are well suited for lower enthalpy fluids ($T \leq 150°C$), such as those co-produced from deep oil and gas reservoirs. For fluids with temperatures around 200°C, a single flash plant may be the most efficient solution, while for higher temperature fluids ($\geq 250°C$), a double flash plant increases the efficiency of conversion of thermal to electrical energy. Potential geochemical effects associated with the residual brine such as scaling should also be considered.

Cost efficiencies are also achieved by using larger power plants. Another option is to use a cogeneration system, where the residual hot water could be used for area heating. Other options that could be considered include the use of supercritical fluids ($T > 374°C$) for power generation (Section 5.4), or the use of CO_2 as the circulating fluid (Section 5.5).

2.6 Lessons Learned from EGS Field Projects

Today, the portfolio of EGS studies and deployment include more than 30 projects spread across the globe. These projects range from greenfield hot dry rock research studies (Newberry, Oregon) to enhanced production at traditional hydrothermal locations (e.g., Raft River, Idaho). Table 3 summarizes key features of major EGS projects, taken from McLing (2017), who catalogued more than 30 EGS projects and identified key lessons learned. Examples of his findings for two projects are shown in Table 4 and the remainder may be found in McLing (2017). An assessment of specific successes and failures for the Fenton Hill project is presented in Kelkar et al. (2015), Kelkar et al. (2016), and McLing (2016).

Table 3. Chronological listing of major EGS field projects catalogued in McLing (2017).

Project Name	Years active	Location	Features
Fenton Hill	1974 - 1992	Adjacent to Baca geothermal field, New Mexico, USA	Intrusive crystalline rock; depth 4,400 m, 300°C; hydraulic fracturing, sheared joints self-prop
Falkenberg	1977 - 1986	Germany	Granite; depth 500 m; hydraulic fracturing
Geothermie-Pilotprojekt Bad Urach	1977 - 2008	Germany	Metamorphic rock; depth 4,500 m, 170°C; hydraulic fracturing
La Mayet	1978 - 1986	La-Mayet-de-Montagne, France	Granite; depth 800 m; hydraulic fracturing; multiple fracture zones
United Downs	1984 - 1992	Rosemanowes, England	Granite; depth 2,600 m, 79 – 100°C, hydraulic fracturing, explosives, viscous gel stimulation with proppants
Fjällbacka	1984 - 1995	Sweden	Granite; depth 70 to 500 m, 16°C; hydraulic fracturing and acid stimulation
Soultz-sous-Forêts	1984 - present	Upper Rhine Valley, France	Granite; depth 5,000 m, 200°C; hydraulic and chemical fracturing
Hijiori	1985 - 2002	Japan	Granodiorite caldera; depth 2,300 m, 270°C; hydraulic fracturing
Ocachi	1989 - 2002	Near Yamabushi volcano, Japan	Granodiorite; 228°C; hydraulic, thermal, and chemical stimulation
Altheim	1989 - present	Austria	Limestone; depth 2,300 m, 105°C; hydraulic and acid stimulation
GeneSys Hannover	2000 - 2007	Horstberg & Hannover, Germany	Sandstone and andesite; depth 3,800 m, 150°C at Horstberg; depth 2,900 m, 160°C at Hannover; hydraulic fracturing; single-well concept
Groß-Schönebeck	2000 - present	Germany	Sandstone and andesite; depth 4,300 m; reopened natural gas exploration well; hydraulic gel proppant and chemical fracturing
Berlin	2001 - present	El Salvador	Volcanic rock; depth 2,300 m, 179-196°C; hydraulic, thermal, and chemical stimulation

Coso	2002 - 2012	Coso geothermal field, Nevada, USA	Diorite, granodiorite, and granite; existing wells deepened to 2,950 m; 300°C; hydraulic, thermal, and chemical fracturing
Cooper Basin	2003 - 2013	Australia	Granite; depth 4,900 m, 278°C; hydraulic fracturing
Landau	2003 - present	Germany	Sedimentary rock; depth 3,300 m, 159°C; hydraulic fracturing; felt seismicity a problem
Unterhaching	2004 - present	Germany	Sedimentary rock; depth 3,350 m, 123°C; acid stimulation
Deep Heat Mining (DHM) Project	2005 - 2009	Basel, Switzerland	Granite; depth 5,000 m, 200°C; high historic seismicity, induced seismicity resulted in project termination
St. Gallen	2005 - 2009	Switzerland	Granite; depth 4450 m, 200°C; hydraulic fracturing; felt seismicity and lack of water resulted in project termination
Paralana Geothermal Energy	2005 - present	Flinders Rangers, Australia	Metamorphics and granite; depth 4,000 m, 170°C; hydraulic fracturing and acid stimulation
Insheim	2007 - present	Germany	Sandstone; depth 3,800 m; 165°C; hydraulic stimulation; induced seismicity an issue
South Geysers	2008 - 2009	The Geysers geothermal field, California, USA	Meta-sedimentary rock; depth 1,341 m; wellbore instability and seismicity concerns cancelled project
Desert Peak	2008 - 2015	Nevada, USA	Silicified rhyolite tuff and metamorphosed mudstone; depth 1,000 -1,800 m, 200°C; hydraulic and chemical fracturing
Brady’s	2008 - 2015	Brady’s Hot Springs, Nevada, USA	Altered rhyolite tuff; depth 1,320 m, 200°C; self-propping shear stimulation using both water and chemicals
Northwest Geysers	2009 - 2015	The Geysers geothermal field, California, USA	Intrusive crystalline rock; existing wells deepened to 3,400 m, 400°C; hydraulic and thermal fracturing
Raft River	2009 - present	Idaho, USA	Quartzite; depth 1,800 m, 275-300°C; hydraulic and thermal fracturing, sand proppant
United Downs	2009 - present	Redruth, England	Granite; hydraulic fracturing planned
Eden	2010 - present	St Austell, Cornwall, England	Granite; depth 4,000 m, 180-190°C; hydraulic fracturing
Newberry Volcano	2010 - present	Newberry caldera, Oregon, USA	Silicic volcanic rock; depth 3,100 m, 315°C; hydroshearing with cold water
Mauerstetten	2011 - 2012	Germany	Carbonate; 130°C; hydraulic and chemical fracturing
Bruchsal	2013 - present	Germany	Sandstone; depth 2,500 m, 130°C; operating power plant

Geostras	Planned for 2025	Strasburg, Germany and Kehl, France	Depth 4,000 - 5,000 m; will produce electricity and heat

Table 4. Two examples from McLing's (2017) catalog of EGS field projects.

Project Name	Fenton Hill
Location	Adjacent to Baca geothermal field, New Mexico
Type of Project	Research
Start date	1974
End Date	1992
Rock Type	Intrusive crystalline rock
Wells drilled	Phase I 1974-1980 Reservoir development and basic research. Wells drilled to 3,000 - 4,000 m encountered 200°C reservoir Phase II well EE-2 drilled to a depth of 4,400 m encountering 300°C rocks
Stimulation Type	Hydraulic fracturing (no proppants). Dominant stimulation process was shearing of natural joints; when frictional slippage occurred, it would self-prop along naturally rough surfaces
Seismicity	Low magnitude seismicity
Funding Source	U.S. Department of Energy
Lessons Learned:	• Crystalline basement rocks can be hydraulically fractured to create reservoirs. • Open fracture networks persist over time • Shift in stress field with depth occurred, causing the stimulated zone to be not where it was expected. Production wells had to be sidetracked to intersect simulated zone. • Reservoir productivity goals were not achieved • Flow rates and pressures were difficult to maintain • Drilling cost very high • Many operational problems attributed to using oil-field techniques that were not suitable for a geothermal environment • Microseismicity can be used to image reservoir creation • Regional stress and preexisting fracture are implicated in reservoir creation. • Thermal power can be produced over extended periods from EGS reservoirs • Long-term studies are important, funding needs to be reliable and consistent over time
Project Name	Soultz-sous-Forêts (European consortia)
Location	Soultz-sous-Forêts, Upper Rhine Valley, France
Type of Project	Research
Start date	1984
End Date	Continuing

Rock Type	Granite
Wells drilled	First well drilled to 3,600 m, three other wells for injection and production drilled to ~5,000 m. Reservoir rocks 200°C
Stimulation Type	Hydraulic and chemical fracturing
Seismicity	Seismicity could be felt at surface
Funding Source	Government (Agence Française pour la Maîtrise de l'Energie & Centre National de la Recherche Scientifique)

Lessons Learned:

- In EGS tests at the Soultz site, microseismic events generated in the reservoir during stimulation and circulation were large enough to be felt on the surface.
- Near-injection-well conditions are implicated in a large pressure drop across the reservoir, and can be mitigated somewhat by acidizing, the use of proppants, and stimulation.
- Stimulated fractures dominated the EGS reservoir. These fractures were part of the preexisting fracture network in the rock.
- Soultz demonstrated that EGS reservoirs could continue to expand during circulation. Therefore, pressures need to be controlled during circulation.
- Feed-in tariff motivated the project.

Ziagos et al. (2013) cautioned that the lessons learned from the “First Wave” of EGS studies, conducted in the 1970’s and 1980’s, should not be forgotten. These lessons were summarized as:

1. Understand and map the natural fractures at the EGS site.
2. Understand the stress field at the EGS site.
3. Low-pressure stimulation (hydroshear) is beneficial.
4. Sites in trans-tensional regimes tend to be more successful than sites in compressive regimes.

The wide range of geothermal conditions represented by the more recent projects listed in Table means that there is a large range of data and additional lessons learned that are available to researchers. These lessons learned will provide valuable information related to the research and technology needed to bring competitively priced EGS resources to the market place to help meet the energy needs of a global economy.

While each project has its own features and specific conditions, there are a few consistent lessons learned that are common across the projects. McLing (2017) summarizes these as:

- EGS technology can be applied across a wide range of geologic conditions across the globe.
- Many projects suffer from a lack of quality thermal output as defined by $P = \rho_f C_f Q(T_1 - T_O)$ due to insufficient reservoir productivity.
- Project indemnification (insurability) is crucial.
- Reservoir stimulation causes activation of existing fractures rather than creation of new fractures (i.e., without existing fracture networks, EGS stimulation is not possible).
- Seismicity is a double-edged sword.

  - Microseismicity is a very useful tool in imaging the stimulated volume of a reservoir and the location of fractures that can be used to connect injectors with producers.
  - Seismicity that can be felt at the surface can be a poison pill that is difficult or impossible for a project to overcome, and has resulted in the failure of several notable EGS projects. With the rise of induced seismicity associated with injection of produced waters in the oil and gas industry, seismicity may be the most significant issue that faces future EGS at any scale.
- Stimulation methods have varying degrees of success. The most problematic is hydraulic shearing below the critical zone. In some places, this works and in others less so. Coupling hydraulic shearing with more advanced oil-patch type stimulation such as chemical stimulation, acidification, viscous gels and the use of proppants seem to increase success. This is especially true in the cases where proppants are used.
- Most companies that are doing EGS are very small and have little operating capital. As a result, most projects are small and their applicability to large-scale (>100 MW) future efforts is limited. This issue illustrates the need for government funding to advance EGS to commercial success.
- Drilling issues are common at EGS sites. This can be mitigated to some degree with better characterization. However, given the small capital available to geothermal companies the availability of advanced oil-patch imaging technology is significantly limited.
  - Without a significant decrease in drilling cost (and risk), EGS cannot move forward at the scale needed to make a difference to the global energy market.
  - EGS needs access to larger drill holes, directional drilling, and sliding liners for multiple frack legs within a borehole.
  - When oil prices are high, drill rigs tend to be unavailable. Even though large rigs are readily available when oil prices are low, the operators have a minimum price threshold that must be met before a rig can be deployed (that is, the rigs will stay idle rather than deploy to a geothermal field at a loss).
- Control of corrosion and scaling requires a better understanding of water-rock interactions and associated geochemistry.
- Projects need downhole tools able to withstand high temperatures.
- Acoustic emissions method well suited for detecting fluid flow during reservoir stimulation.
- Use of downhole pump in production well to enhance flow rates may reduce risks of short-circuiting.
- Pumping under pressure in injection well can lead to induced seismicity.
- A better understanding of the influence of major fractures and faults as potential fluid conduits or barriers is needed.
- Financing is a major issue with geothermal energy in general and is even more so with EGS. In France and Germany, the countries have a feed-in tariff that makes geothermal energy more competitive. In the U.S., the absence of any financial incentives means that geothermal penetration into the market will not significantly increase. This is especially the case with EGS where development cost is significantly higher. However, there is hope: 20 years ago, producing hydrocarbon from shale formations was technologically and financially impossible. Due to government and industrial collaboration these technical issues were addressed through new drilling and completion technologies that today make these formations cost effective at a $/barrel price that seemed unavailable two decades ago.

3 Exploration Risks and Costs

The geothermal exploration process impacts project development timelines, costs, and overall perceived risk. However, the success in the exploration phase of a geothermal project—and the calculation of a success rate—is universally ill-defined. In previous studies, the success rate of a geothermal project has been loosely defined as the fraction of full-size production wells that meet sufficient performance criteria to result in commercially viable production. In contrast, Wall and Dobson (2016) focus on refining the definition of success for the exploration process to represent it as the combined probability of success of all stages in the project's workflow.

Figure 6 shows four stages of geothermal project development where each arrow labeled "pass" has an associated probability of success. The simplest approach is to assume that the probabilities are independent, so their product is the overall success rate. To test this method, the four stage probabilities [P(P) - permitting, P(EM) - exploration methods, P(D^E) - exploratory drilling, P(D^C) - confirmation drilling] have been determined by examining the development of selected geothermal projects in the western United States between 2005 and 2015:

P(P) = 87.5%

P(EM) = 60%

P(D^E) = 31%

If one can assume that projects move forward with development after finding successful production wells, regardless of the success rate in finding these wells, then P(D^C) can be roughly approximated 1 and the total conditional probability could be estimated as:

P = P(P and EM and D^E and D^C) = 87.5% 60% 31% = 16%

This value is somewhat lower than the 25% success rate typically quoted for greenfield development, so further refinement may be necessary. However, the framework of combining individual probabilities for each stage of development will be retained, as it promotes understanding of the geothermal exploration process.

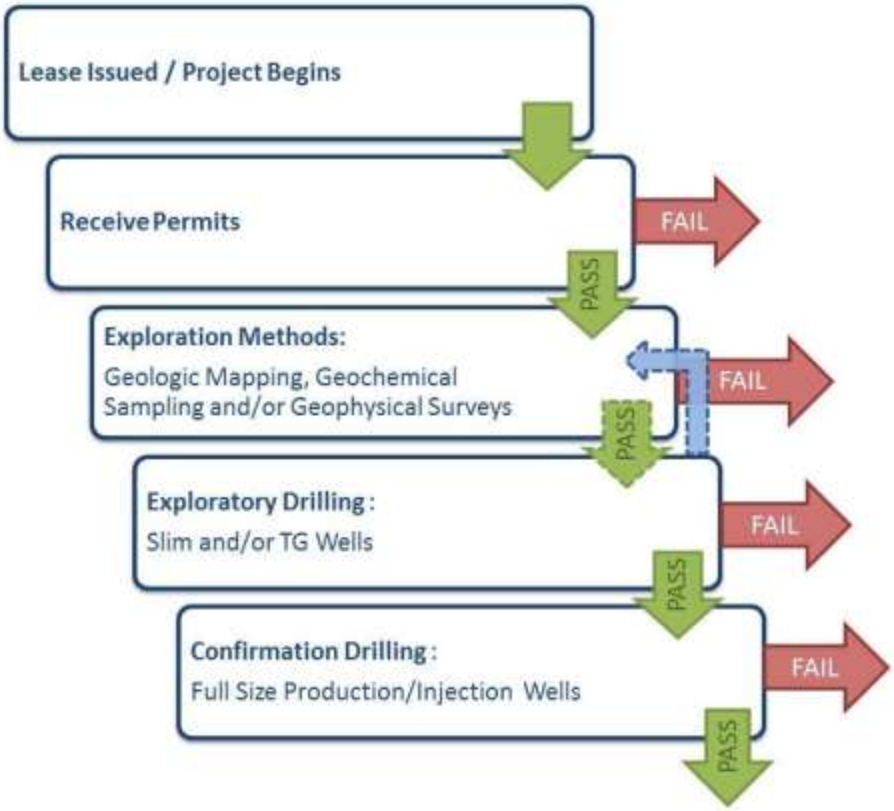


Figure 6. Diagram of decision nodes within a geothermal exploration project leading to resource production drilling. The option to abandon the project at each stage is depicted by the red arrows. The option to continue is represented by the green arrows. Options which may occur but which vary on a project by project basis (e.g., the choice to drill slimholes, or additional exploration after exploratory drilling) are represented by dashed arrows (Wall and Dobson, 2016, Figure 1).

In practice, the true measure of project success is a combination of the operational feasibility (discussed above) along with the likelihood of financial return. The preceding paragraphs do not directly address the financial decision process being made during geothermal exploration, such as the financial model that ultimately determines whether an area can support commercial geothermal power production. Financial issues are addressed in the following paragraphs.

Access to financing has frequently been noted as a barrier to geothermal project development, due to the high perceived risk during exploration and drilling. However, very little information has been made available to ascertain the costs of capital at stages of geothermal project development, and the sensitivity of these financing changes to the overall economics of a project. Here, the relationships between resource-related risks and variations in capital costs are charted with project progress (Wall et al., 2017). The primary focus is on two scenarios: the current “business as usual” scenario and a proposed “technology improvement” scenario, in which geothermal providers have advanced significant resource-focused technology breakthroughs from a confluence of current trends (see Sections 2.4 and 2.5), to increase confidence in exploration targeting and increase productivity of the projects chosen. Specifically, this scenario assumes that these technologies are all cost-effective and commercial by 2050.

In geothermal projects, the perceived risk of the project drops significantly as production drilling proceeds in line with the expectation of higher certainty about the project’s realization, based largely on progressive de-risking of the resource uncertainties (Figure 7). As a result, the types of financing available (i.e., equity or debt) and the hurdle rates necessary to invest are heavily tied to the stage of project feasibility, with 100% equity financing at the initial feasibility stage transitioning to 100% debt financing at the final operation stage, as shown in Tables 5 and 6, for the Business as Usual and Technology Improvement scenarios, respectively. A useful integrated measure is the WACC (weighted average cost of capital), which is a weighted average of the rates of equity and debt. The WACC can be defined for an individual stage of a project and for the total project. The total WACC for the Technology Improvement scenario (4.29%) is significantly lower than that for the Business as Usual scenario (as high as 19.4%), indicating that technological advances will greatly lower the financial barrier to geothermal project development

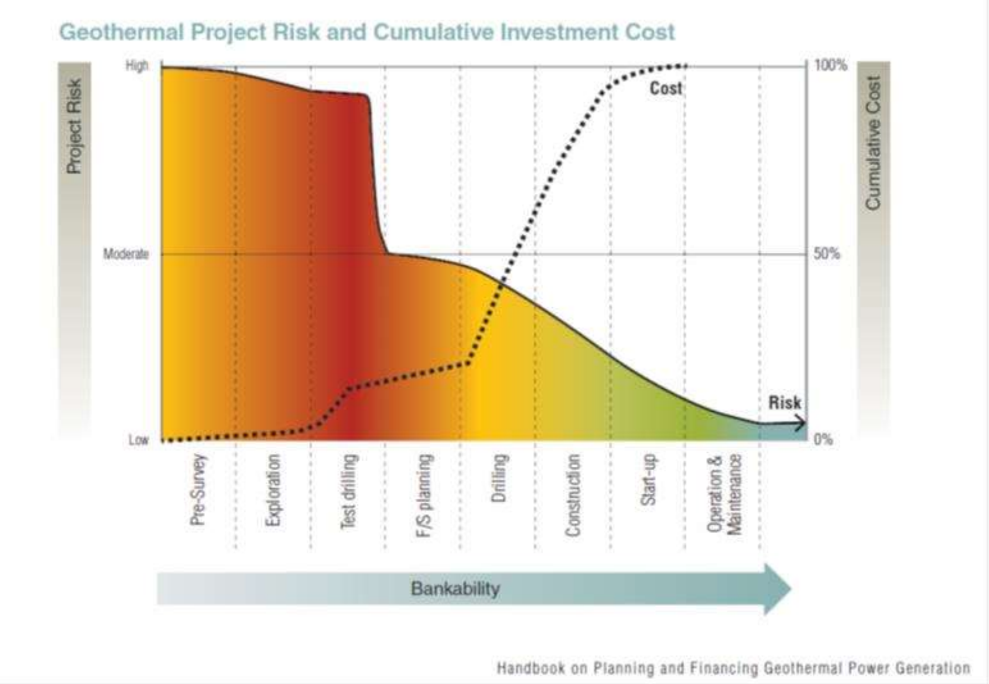


Figure 7. Diagram of cumulative investment costs and geothermal project risk over time (ESMAP, 2012). The test drilling stages of a project present the most significant barrier to geothermal development as the developer is typically confronted with a combination of high risk and high capital expenditures for confirmation activities. (Taken from Wall et al., 2017, Figure 1).

Table 5. Summary of assumed costs of capital for the Business as Usual scenario (Wall et al., 2017, Table 2), considering that the source of financing can be either external or internal to the geothermal company.

	External Financing				Internal Financing			
Project Stage	**Cost of Equity (%)**	**Cost of Debt (%)**	**Percent Equity Financing**	**Percent Debt Financing**	**Cost of Equity (%)**	**Cost of Debt (%)**	**Percent Equity Financing**	**Percent Debt Financing**
Exploration - Feasibility	35%	n/a	100%	0%	13%	n/a	100%	0%
Drilling/Well Field Development	30%	15%	40%	60%	12%	15%	40%	60%
Plant Construction and Startup	n/a	8%	0%	100%	n/a	5.3%	0%	100%
Total WACC	**19.4%**				**14.0%**			

Table 6. Summary of assumed costs of capital for the Technology Improvement future scenario (Wall et al., 2017, Table 6).

Project Stage	**Cost of Equity (%)**	**Cost of Debt (%)**	**Percent Equity Financing**	**Percent Debt Financing**
Exploration – Feasibility	8%	n/a	100%	0%
Exploration – Drilling	8%	n/a	100%	0%
Drilling/Well Field Development	8%	3%	15%	85%
Field Gathering System	n/a	3%	0%	100%
Plant Construction & Startup	n/a	3%	0%	100%
TOTAL WACC	**4.29%**			

4 Government Technology Research, Development and Deployment

The GTO has had a robust research, development, and demonstration (RD&D) portfolio since the 1970s, much of which has been dedicated to the development and deployment of improved geothermal exploration techniques that result in better subsurface characterization and reduced risk and costs for geothermal exploration efforts. Highlights of this early work is summarized in the DOE (2010) study: "A history of geothermal energy research and development in the United States: Exploration 1976-2006". The 2010 DOE retrospective study highlighted the major achievements of the first thirty years of DOE-funded research and development activities related to geothermal exploration. These included: (1) support of industry exploration and drilling activities, (2) cooperative programs with 26 states to help them assess their geothermal resources, (3) selected studies of hydrothermal systems (such as The Geysers and Dixie Valley), (4) geological technique development (such as field mapping, remote sensing, and the use of conceptual models), (5) geologic technique analysis (such as fluid inclusion, soil gas, and helium isotope studies), (6) geophysical technique development (such as potential field, seismic, electrical, gravity, and thermal methods, as well as borehole geophysical tools), and (8) exploration strategies, with a focus on the Basin and Range province.

This section describes three different recent and ongoing DOE GTO initiatives relating to the exploration of hydrothermal systems. The first provides a summary of the Innovative Exploration Techniques (IET) initiative, which was funded by the American Reinvestment and Recovery Act (ARRA) of 2009. The overall objective of the 25 IET field projects was to encourage testing and validation of new exploration concepts and methodologies, with the added benefit of helping confirm additional hydrothermal resources in the U.S. (Garchar et al., 2016). A wide variety of geological, geochemical, and geophysical techniques were tested in the field. While only two of the projects directly contributed to increases in production to existing fields (San Emidio and the NW Geysers), and thus far have not resulted in the development of any new fields, the projects provided several lessons learned that can be applied to future geothermal exploration efforts. One overall highlight is that combinations of different techniques that are strategically applied often provide the most useful results, such as the observation at San Emidio in developing a strategy and combination of methodologies best suited for identifying permeable structures at depth. Another useful observation was that each type of geothermal system type has its own characteristics and challenges, and that there is no "silver bullet" solution for identifying and characterizing geothermal systems.

The second area of focus is on the currently ongoing geothermal play fairway analysis program. This program (Weathers et al., 2015) was sparked by the concept that the play fairway analysis methodology that has been successfully applied to the oil and gas industry could be adapted for exploration of geothermal systems. The first phase of this effort focused on having each of the 11 funded teams utilize existing data from the regions they were evaluating to develop layers of evidence for key geologic, geophysical, and geochemical attributes that would be associated with the fundamental elements of geothermal systems encountered within the geologic environment(s) within the region. Akin to the elements associated with hydrocarbon systems (source rock, reservoir rock, seal, migration pathway, and maturation history), the key features associated with geothermal systems were identified as: (1) heat source, (2) permeable structures, and (3) reservoir seal. Each team developed its own way of associating regionally extensive geoscience data with these geothermal attributes, and created algorithms to produce Common Risk Segment (CRS) and Composite Common Risk Segment (CCRS) maps to identify areas with higher favorability that would be worthy of more focused study. Six of the initial 11 projects continued on to Phase 2, where the teams conducted field surveys of prospective areas identified from the results of the regional play fairway analysis – this work helped fill in data gaps and led to the identification of potential drilling targets for Phase 3, where additional field studies and thermal gradient and/or slimhole drilling is proposed to validate the play fairway methodology for geothermal exploration.

A final area of emphasis for the DOE GTO hydrothermal program has been to support the development of methodologies and techniques that improve the ability to discover and characterize hidden hydrothermal systems. The most recent assessment of moderate and high temperature geothermal resources in the U.S. (Williams et al., 2008) indicated that the resource potential for undiscovered (i.e., hidden) hydrothermal systems (30 GWe) is significantly greater that that associated with identified geothermal systems (9 GWe); and thus, discovery of hidden systems is critical if increased deployment of geothermal resources is to occur. Most developed hidden geothermal systems were initially identified by accident, i.e., while drilling for water, oil, or minerals (Dobson, 2016). Because hidden systems do not have, by definition, an obvious surface expression, their presence has to be inferred using other important indicators. The types of exploration methods for these systems will vary based on the geologic environment and geothermal play type. For the Basin and Range province, which has regionally extensive elevated heat flow, detailed structural analysis of over 400 geothermal systems in the Great Basin of the Western United States has led to the identification of favorable structural settings with enhanced permeability, such as fault step-overs, terminations, intersections, and accommodation zones. The presence of similar structural features in areas with no visible geothermal surface expression could help guide the exploration for hidden systems within this tectonic environment (Faulds and Hinz, 2015). Additional R&D efforts are needed to develop effective exploration strategies for hidden systems over a range of geologic settings. The play fairway methodology is one approach that could improve exploration success rates for hidden systems.

4.1 Innovative Exploration Techniques Initiative

The Geothermal Technologies Program has worked with the geothermal industry to develop and field test exploration tools and methodologies to reduce exploration, development, and deployment risk by improving the characterization of the subsurface in pre-drilling and preliminary borehole exploration technologies. Twenty-five Hydrothermal Resource and Confirmation (Innovative Exploration Technologies) field projects, funded through the 2009 American Reinvestment and Recovery Act (ARRA), have a key goal of advancing and sharing best practices for geothermal exploration including geologic research, remote sensing, geochemical, and geophysical techniques. The 25 project locations are shown in Figure 8 below.

Figure 8. Location of 25 IET projects (Garchar et al., 2016, Figure 1).

The IET field projects consisted of three phases: Phase I - Resource Evaluation, Phase II - Drilling, and Phase III - Well Testing. Phase I was envisioned to include geologic field work and interpretation, geophysical survey acquisition and processing, geochemistry sampling and analyses, geomechanical studies, drilling of temperature gradient wells, remote sensing, and any other appropriate surface studies, acquisition and reanalysis of previously collected data, and integration of the results. By the end of Phase I, awardees were expected to have selected target locations by incorporating innovative techniques for exploration, and to have identified the required permits to move forward. Phase II was contingent on complying with the National Environmental Policy Act (NEPA) regulations and envisioned to include site access and development, rig mobilization and de-mobilization, drilling, mud logging, casing and cementing, coring, running geophysical or production logs, limited flow testing, fluid sampling work, and other appropriate drilling/well-related activities and evaluations. By the end of Phase II, awardees were expected to evaluate the resource. Phase III was envisioned to include acquisition/rental of appropriate well and surface equipment for an extended flow test, appropriate logging, sampling and monitoring of the testing, interpretation of the test data, integration of the well test results with the previous geological, geothermal, and hydrological models, validation of innovative exploration technology/method, and final assessment of the site capacity for heat extraction from the geothermal resource. By the end of Phase III, awardees were to quantify the amount of additional resources discovered by drilling.

4.1.1 Synthesis of progress made and methods used

Garchar et al. (2016) analyzed all 25 projects awarded and found that about two-thirds (17) completed the work proposed in Phase I. Most (10) of these also completed Phase II; and only 4 projects completed work through Phase III. Awardees reported two main factors that prevented project progress: (1) company/market instability, and (2) unfavorable permitting circumstances.

Garchar et al. (2016) categorized the proposed technologies as shown in Figure 9 below.

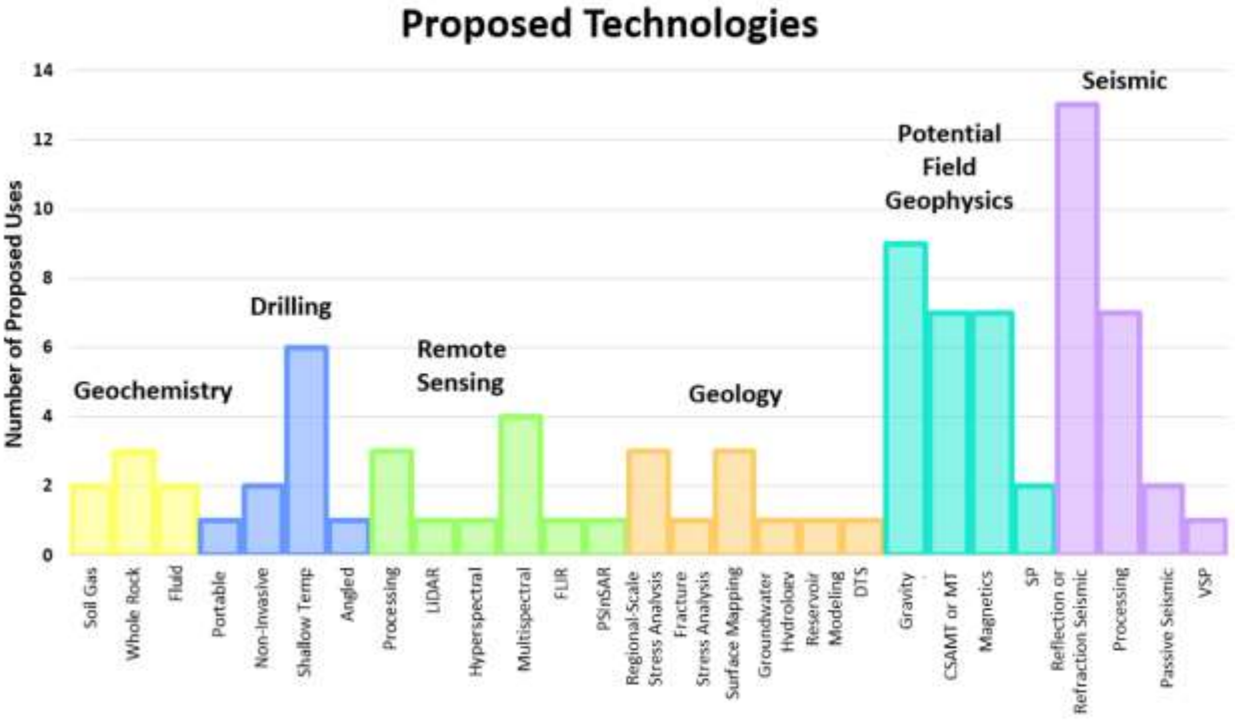


Figure 9. Proposed technologies for IET projects (Garchar et al., 2016, Figure 2).

The technologies used in the projects are shown in Figure 10, organized by degree of use (from Garchar et al., 2016).

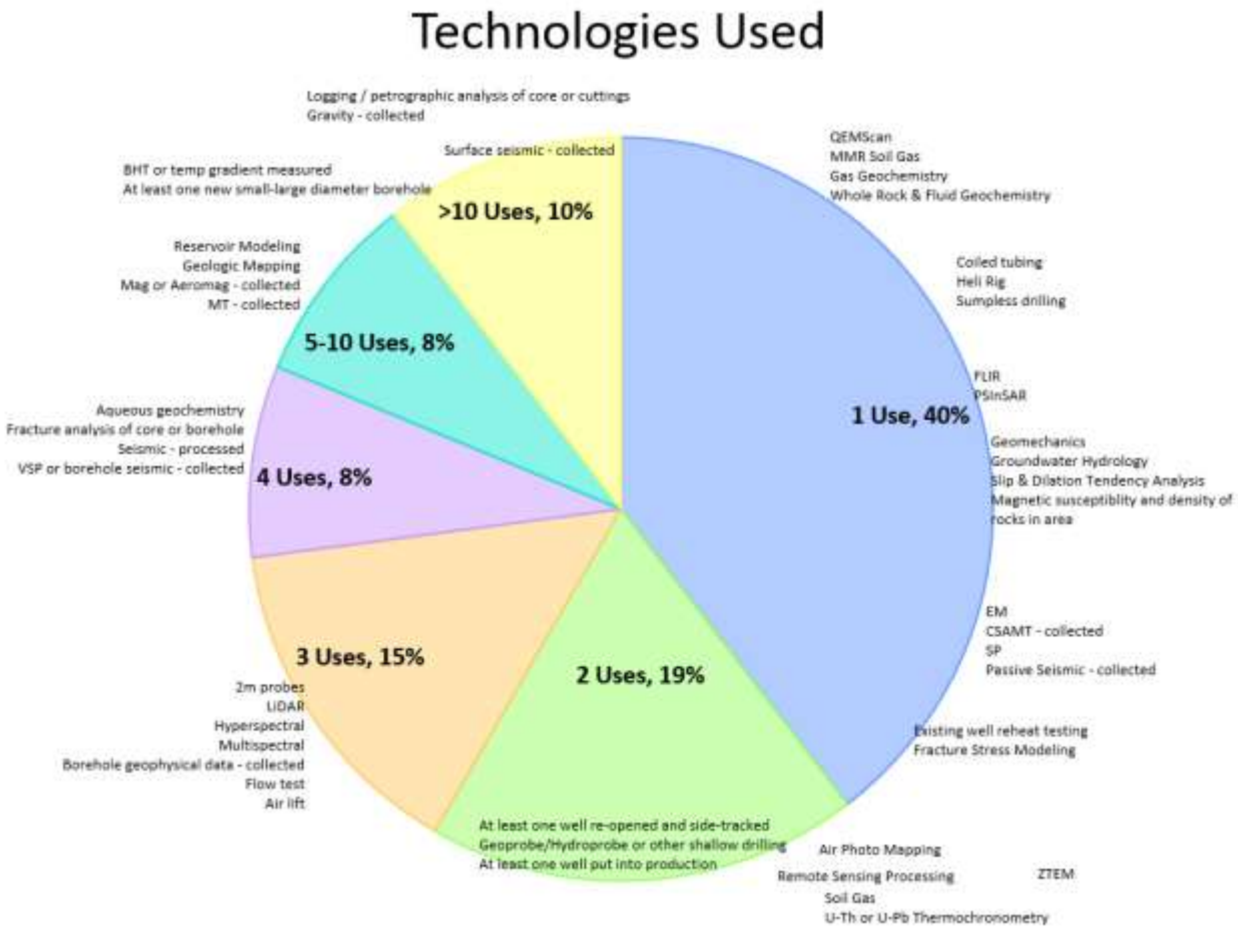


Figure 10. Technologies used in IET projects (Garchar et al., 2016, Figure 5).

4.1.2 Measure of success

The Geothermal Resource Portfolio Optimization and Reporting Technique (GeoRePORT), formerly known as the Geothermal Resource Reporting Metric (GRRM), being developed at NREL (Young et al., 2015 a; b; Badgett et al., 2016) is a tool that aims to capture the state of knowledge of a geothermal resource in terms of geologic, technical, and socio-economic categories. This metric provides a holistic view of a resource in terms of all the factors that could affect development: land access, permitting, transmission, energy demand, past drilling, drilling logistics, heat extraction technology, power conversion, resource temperature, reservoir permeability, reservoir volume, fluid chemistry, etc. The grades assigned by the metric may be visualized with a polar area chart that shows the grade and associated uncertainty (character, activity, and execution) for each Category, or by a Summary Resource Grade Chart, which shows character grades without depicting uncertainty, as shown in Figure 11.

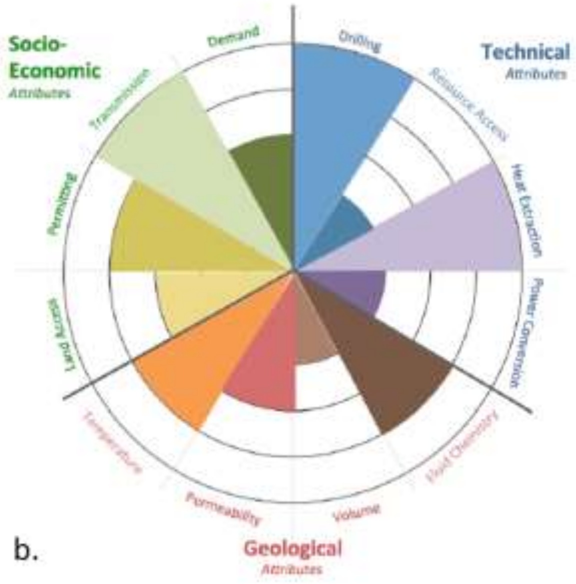


Figure 11. An example of a summary resource grade chart (Garchar et al., 2016, Figure 6b).

Garchar et al. (2016) applied the GeoRePORT metric before and after ARRA funding for 8 IET projects, as shown in Figure 12. Some initial takeaways include: (1) The ARRA funding advanced the state of characterization or certainty in some category for all projects that completed work; (2) some grades have improved, while others have downgraded; and (3) often awardees focused on reporting geologic information more than information that would fall into the Technical or Socio-Economic Categories.

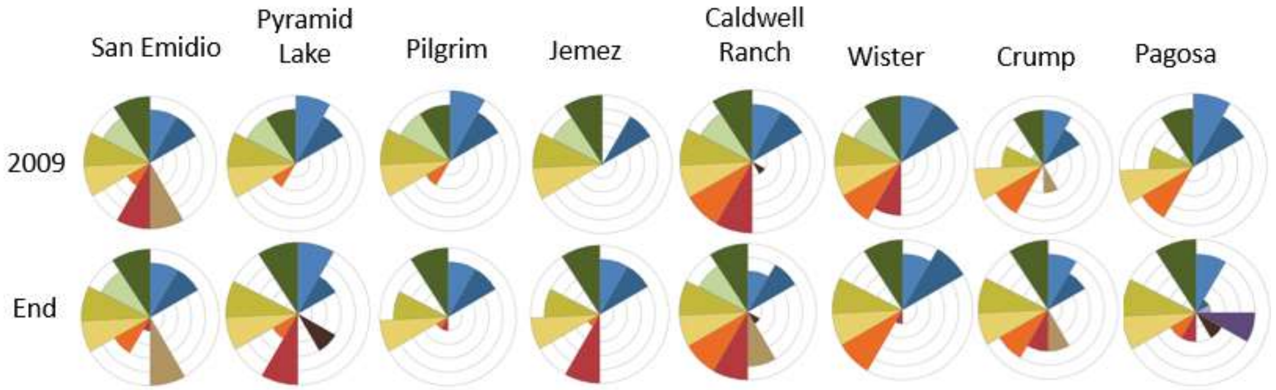


Figure 12. Summary resource grade charts for 8 IET projects before and after ARRA funding (Garchar et al., 2016, Figure 7).

4.1.3 Description and assessment of methods

Visser (2012) categorized the IETs as drilling techniques, remote sensing techniques, non-invasive (surface-based) geophysical techniques, invasive (borehole) geophysical techniques, geological techniques, and geochemical techniques. Below, individual IETs are described, and their success briefly assessed. For more details, see Visser (2012), but note that many of his conclusions were made before all the activities of the projects had been completed.

4.1.3.1 Drilling Techniques

- **Coiled tubing drilling (Alum, NV)**
    - The Alum project has achieved the first application of the coiled tubing drilling technique, wherein the drill string is reeled up (like a garden hose) in one piece on a large drum, to geothermal drilling, completing a slimhole well (26-19) to total depth of 1,475 meters and finding of 148°C fluid and a conductive geothermal gradient. The coiled tubing hole enabled acquisition of an extensive suite of scientific surveys including downhole geophysics, PTS logs, borehole image logs, lithologic logs, sidewall cores, and hydrothermal alteration mineralogy.
    - Results of the coiled tubing drilling experiment were mixed:
        - Mobilization cost was higher than comparable conventional rigs.
        - The coiled tubing technique struggled to achieve cost-effective rates of penetration. While the technique has been successful in flat-lying, non-faulted relatively soft sedimentary rock units, it was less successful in drilling dipping and faulted rocks with alternating hard and soft layers. Bit wander, borehole instability, and other problems prevented the coiled tubing technique from achieving the expected penetration rates and depths. Drilling of the well was ultimately completed with a coring rig (Garchar, 2015a).
- **Heli-lite drilling rig (Fort Bliss, El Paso, TX)**
    - The Heli-Lite® drill rig, proven for use in seismic surveys in exploration of oil and gas, had never before been utilized for geothermal exploration, particularly thermal gradient well drilling.
    - In the field, the demonstration of a low-cost, helicopter-transportable exploration drilling rig produced mixed results (Lear et al., 2016). The new rig met its portability goals and performed well in hard rock drilling. However, it would need additional improvements before it could function in the unconsolidated soils of the central basin. Because it was clear that the ability to penetrate hundreds of feet of alluvium would be essential, with the concurrence of DOE, the experimental drilling rig work was halted.
- **Slimhole diamond drilling with bottom hole temperature tool for real time temperature logs (Hot Spot, Snake River, ID)**
    - The project successfully drilled three slimhole wells:
        - Kimama well: 6,273-foot hole on the Snake River volcanic axis, through a section of basalt and sediment.
        - Kimberley well: 6,424-foot hole on a caldera margin, through a section of rhyolite, basalt and sediment.
        - Mountain Home well: 5,974-foot hole on the margin of a horst block, through a section of basalt and sediment.
    - The slimhole diamond drilling technique encountered several challenges related to the nature of the stratigraphy in the Snake River Plain, i.e., basalt flows with intercalated sediment horizons. Lost circulation (no mud returns) was common while drilling, the sediment zones often sloughed and bridged, and the drill string was stuck several times. The wells also experienced clogging of the bit and core barrel when penetrating the sediment breaks. One of the wells had such problems with the sedimentary section (created its own sidetrack) that the well was redrilled using a rotary bit down through this section (Shervais, 2014).

- **Direct push temperature gradient holes (Crump Geyser, OR)**
    - The Crump project completed a program of shallow direct-push wells designed to evaluate whether a basin-stepping structure east of the range-front could be channeling geothermal fluid. Ten holes were pushed to an average 27 meters depth before hitting material too hard to penetrate. The direct push data showed a clear trend of higher shallow temperatures in western locations closer to the range-front (Fairbank and Smith, 2015).
- **Geoprobes (Pilgrim Hot Springs, AK)**
    - The Geoprobe unit drives small-diameter sealed pipes into the ground without the need for circulatory fluids. The first series of holes penetrated 24 meters; subsequent smaller diameter pipes were able to penetrate deeper (up to 47 meters). Geoprobes were useful in delineating the location of the shallow outflow plume (Holdmann, 2015). One limitation was the inability to collect fluid samples using this method.
- **Sumpless drilling (Crump Geyser, OR)**
    - One TG slimhole was drilled to a depth of 1,036 meters, using sumpless drilling, a low-footprint drilling technology especially suited to environmentally sensitive areas.
    - Sumpless drilling was advantageous in terms of regulation, reduced expected disturbance, and drilling fluid waste (Fairbank and Smith, 2015).

4.1.3.2 Remote Sensing Techniques

- **Satellite thermal imaging (Pagosa Springs, CO)**
    - The Flint/Pagosa Verde project sought to confirm that satellite thermal imaging is a reliable and cost effective preliminary lead tool to identify thermally active areas, to reduce exploration costs and to increase the likelihood of commercial success (Pagosa Verde, 2016).
    - According to an expert involved in the project (Rick Zehner, Geothermal Development Associates) the technique didn't show much that was not already known, was heavily influenced by solar heating of the surface, and may not be worth further pursuit as an innovative exploration tool.
    - The project achieved limited success at finding ground confirmation of the remotely detected geothermal signatures. The methodology was reassessed as a result of ground confirmation results.
    - Temperature measurements using shallow (2-meter or 2m) survey revealed that several areas were falsely identified by remote sensing as prospective geothermal targets due to solar and topographic effects. To eliminate or reduce the solar and topographic effects, ASTER nighttime temperatures are calculated. The daily incoming solar radiation is computed (considering the surface orientation (slope, aspect, elevation, and atmospheric conditions) and converted to temperature. The temperature due to the solar radiation (with topographic effects) is then removed from the ASTER temperature, resulting in the temperature due to geothermal heat.
    - The technique was unable to detect geothermal signatures in the eastern half of Colorado where bedrock is masked by thick alluvium and sand.
    - At Pagosa Springs in Southwestern Colorado, where bedrock is much closer to the surface, three temperature gradient holes were sited using satellite thermal imaging, but did not produce high temperatures at depth.

  - The project recommends the following future technology enhancements: (1) encourage future satellite developers to increase the number of frequencies in the Far IR to collectively acquire images; (2) as the technology of optic manufacturing improves, determine if ASTER resolution might improve from its current 90 meters per pixel to 30 meters; and (3) after applying ASTER as the initial screening tool, engage organizations such as FLIR and hyperspectral imaging to conduct low level IR surveys from airborne platforms (fairly cost effective to cover a large area.)

- **Hyperspectral imaging (Alum, NV; Silver Peak, NV; Glass Buttes, OR)**

  - The Alum and Silver Peak projects utilized hyperspectral imaging to map thermal anomalies and geothermal indicator minerals (Kratt, 2011).

  - Hyperspectral imaging is a relatively mature technology. The survey identified hydrothermal mineral outcrops that are unlikely to have been found without extensively detailed and expensive ground field examination and sample analysis.

  - The downside of the technique is the inability to penetrate beyond the surface and to enable extrapolation of results to the subsurface. Hence, it is most useful when used in conjunction with other surface-based geophysical methods as it was at Alum and Silver Peak, where 2m probe thermal surveys were used in conjunction with hyperspectral data to develop a conceptual model (Kratt, 2011).

  - The technique may be useful in very lightly explored areas to reduce upfront surface mapping, sampling and analysis.

  - At Glass Buttes, hyperspectral data improved understanding of minerals present, but was not a significant factor in siting wells, especially following the interpretation that alteration predates the most recent volcanic flows (Walsh et al., 2015).

- **Light Detection And Ranging (LiDAR) (Glass Buttes, OR; Newberry, OR; Maui, HI)**

  - The Glass Buttes project used multiple high-resolution geological, geophysical and remote sensing methods (LiDAR, hyperspectral, gravity, magnetics, MT) to locate faults with permeability.

    - Surface fault expressions were mapped by LiDAR, together with geologic mapping and other geophysical surveys, increased the level of confidence in a subsurface model of mutually crosscutting NW and SE trending faults. Surface fault expressions were identified with 1-meter resolution LiDAR using variable illumination hill shading, elevation contouring, and slope analysis with the ArcGIS software (Walsh et al., 2015).

    - The highest measured geothermal gradients appear to be consistent with the interpreted fault intersections.

  - LiDAR imagery of Newberry Volcano allowed the technical team to see details of topographic features with a resolution that previously had been unavailable with aerial photography and topographic maps (Waibel et al., 2014). This new imagery should be the catalyst for much research on the volcano, ranging from surface lava flow boundaries to deep regional tectonic structures.

  - In Maui, locations and geometries of faults/fractures, vent zones, and dike intrusions within the Haleakala Southwest Rift Zone were inferred based on ground-based gravity coupled with heli-borne magnetics and LiDAR datasets (Fercho et al., 2015).

- **FLIR airborne thermal survey and automated processing of large thermal imagery datasets (Pilgrim Hot Springs, AK)**
    - The Pilgrim Hot Springs project used airborne thermal remote sensing (FLIR) imagery to detect thermal anomalies associated with low temperature geothermal systems in Alaska in a spring dominated environment (Holdmann, 2015).
    - The project utilized automated processing of the FLIR dataset.
    - Airborne optical and FLIR data acquisition, processing and analysis are complete. High-resolution mosaics of FLIR and optical data have delineated hot spots, vegetation anomalies, snow-melt anomalies and open water areas. Field temperatures matched well with FLIR temperatures.
- **PSInSAR (San Emidio, NV)**
    - The project has used PSInSAR (Permanent Scatterers Synthetic Aperture Radar Interferometry) for high-resolution assessment of surface deformation to help find Large Aperture Fractures (LAFs) that are prime drilling targets for the development of geothermal systems. LAF's in geothermal systems typically yield production wells of the highest productivity and lowest pressure drawdown within a given geothermal reservoir.
    - PSInSAR is able to map zones of subsidence indicating rapid ongoing dilational movement in the subsurface. A strong correlation was established between ongoing surface deformation and known LAF's. Ground deformation correlates with producing faults and indicates the direction of fault propagation (Teplow, 2015).
    - The highly productive fractures encountered in operating production wells 75-16, 75B-16 and 76-16 were clearly associated with rapid ongoing subsidence, a positive gravity residual, and a low seismic velocity zone that penetrated deeply through the entire Tertiary volcanoclastic section and into the Triassic phyllite (Nightingale Formation) basement.
    - These correlations formed the basis for siting slimhole exploration wells.
    - All seven exploration slimholes drilled to the south of the original field encountered commercial temperatures at the targeted depths ranging from 760 meters to 1,100 meters. Temperatures ranged from 275°F to 320°F (highest observed temperature in the field). Three of the four exploration holes encountered commercially exploitable permeability. Areal extent of the productive reservoir was increased by more than 0.5 miles to the south and west. Extension of the reservoir to depth was increased by 600 meters. The total productivity for three slimholes is estimated at ~4 MW net, approximately 50% of fluid requirements for the Phase 2 buildout.
    - While all of the targets drilled encountered permeable zones containing commercial temperature fluid, the target signature was not sufficiently unique to differentiate between zones of commercial and sub-commercial permeability or zones of minimal commercial temperature (270°F-280°F) and high temperature (>290°F).
    - PSInSAR data were dominated by ongoing production and injection whereas natural state areas had low signal to noise ratio. A new relationship was recognized between gravity and ongoing surface deformation as a product of production, injection, and natural state tectonics.

- **ASTER multispectral satellite imagery (Fort Bliss, El Paso, TX)**
    - Fault and hydrothermal mineralogy mapping, from ASTER multispectral satellite imagery analysis, augments geophysical surveys, including gravity, seismic, self-potential, and resistivity, to better characterize the geologic structure and the geothermal system (Lear et al., 2016).

4.1.3.3 Non-Invasive Geophysical Techniques

- **ZTEM vertical magnetic field survey (Alum, NV; Silver Peak, NV)**
    - The Alum and Silver Peak projects have used the Z-Tipper Axis Electromagnetic (TZEM) method, a relatively new technique and one of the first known applications to geothermal exploration (Shevenell and Zehner, 2011; Legault et al., 2011; Garchar, 2015a).
    - The ZTEM technique, together with a range of other tools, helped the identification and characterization of previously unidentified faults, better characterization of the Silver Peak-Lone Mountain detachment fault, and characterization of subsurface lithology.
    - ZTEM data collection was successful.
    - The downside of the technique is the limited depth resolution (1-1.5 km maximum depth) compared to ground-based magnetotellurics (MT).
    - ZTEM appears to be useful for early stage exploration projects with large areas with limited geologic and geophysical data.
    - A new refinement of the ZTEM (not used at Alum and Silver Peak) deploys a ground crew to collect ground-based measurements so the airborne ZTEM can be calibrated. Without this, ZTEM measures only relative resistivity, not absolute values, requiring modeling to be based on an assumed average ground resistivity.
- **Magnetotelluric Survey (Jemez Pueblo, NM; Newberry, OR)**
    - Jemez Pueblo
        - The Jemez Pueblo exploration project employed a 3D magnetotelluric survey along with detailed geologic mapping, high-resolution seismic data acquisition and processing tailored to steep and complex structure.
        - The “teacup” structure that was identified was somewhat counter to the conductive clay cap model that has been observed for most hydrothermal systems.
        - Drilling confirmed all structural elements and conductivity differences as determined by the geophysical surface surveys (Albrecht, 2015). The combination of structural information obtained through seismic and conductivity information obtained by magnetotelluric resulted in a solid conceptual model of the resource.
    - Newberry
        - At Newberry, magnetotelluric survey data were not able to contribute to identifying hydrothermal resources. Even with the discovery well drilled, the data could not be massaged to identify the location (Waibel et al., 2014).
        - The decades-old accepted and popular "mushroom" model provided no insight into the location of hydrothermal resources.

    - The quality of the shallow MT data was very good, however, and the final processing provided valuable structural and volcanology insight.

- **Gravity Survey (Newberry, OR)**
    - Gravity surveys, with a high density of stations on the western flank of Newberry Volcano, provided a key contribution to the geothermal exploration program (Waibel et al., 2014).
    - The combined results of all of the gravity surveys were integrated, providing a rather detailed view of location and geometry of density anomalies underlying the volcano.
    - Gravity data cannot uniquely be interpreted for heat content. The goal for using this tool was to look for structures and to look at the shape and boundaries of high density, probably plutonic rock related to the volcano.
    - Both of the two Davenport deep exploration well locations were picked based on temperature gradient and gravity data. Both of the wells intersected high heat, and one intersected active hydrothermal fractures.
- **Integrated Gravity and Magnetics (Pearl Hot Springs, NV; Maui, HI)**
    - At Pearl Hot Springs, integration of gravity and magnetic data with geological and structural mapping and fault kinematic analysis enabled a self-consistent surface and subsurface structural model (Stockli, 2015).
    - At Maui, locations and geometries of faults/fractures, vent zones, and dike intrusions within the Haleakala Southwest Rift Zone were inferred based on ground-based gravity coupled with heli-borne magnetics and LiDAR datasets (Fercho et al., 2015).
- **Reflection Seismic Tools: Coherency-First Arrival data processing, Full Waveform Inversion velocity model derivation, and 2.5D depth modeling (Hot Pot, NV)**
    - The Hot Pot project is using these reflection seismic techniques to: (1) define structure and stratigraphy in complex geologic environments including Paleozoic basement; (2) enable intermediate depth slimholes to target specific structures and/or potential reservoir formations in addition to their primary function of temperature gradient confirmation; (3) accelerate the development process by identifying high potential drilling locations early in the exploration phase; (4) facilitate conceptual model refinement; and (5) reduce the number of unsuccessful wells.
    - The objective of the seismic data processing is to develop a 3D velocity volume, through which reflectors are migrated to correct location.
    - Initial seismic images contained large areas of poor data. Some shallow high velocity zones were identified from mineral exploration well control. Velocity model was adjusted, lines reprocessed, and interpretable data obtained, even in Paleozoic basement to depth of approximately 5,000 feet. Seismic images suggest major low-angle structures in Paleozoic that could be pathways for geothermal system fluids (Lane et al., 2012; Oski Energy, 2013).
- **High resolution seismic data acquisition and processing tailored to steep and complex structure (Jemez Pueblo, NM)**
    - Elastic-wave reverse-time migration with a wavefield-separation imaging condition (from model to reality) has yielded interpretable data that has informed the subsurface model (Albrecht, 2015).

- **SeisOpt® seismic data analysis to create fault-plane images (Pyramid Lake Paiute, NV)**
  - The Pyramid Lake project employed these seismic tools for direct imaging of fault planes.
  - Operator claims that the tool enabled direct imaging of fault planes confirmed by drilling to 27-meter accuracy and resolution of the volcanic stratigraphy to 600 meters of depth with 10-meter accuracy.
  - Tertiary basalts were highly reflective; rhyolite dome interiors were less reflective.
  - Seismic imaging of the subsurface structure provided good targets for exploration drilling. The positions of the major seismically mapped fault zones are supported by the gravity data interpretations, but to identify where the faults actually provide conduits for upward flow of hot fluids, the mapped temperature gradient is needed (Pyramid Lake Paiute Tribe, 2013).
- **3-component geophone and 3-component Vibroseis to image steeply dipping faults and fractures (San Emidio, NV)**
  - The objective was to generate a detailed velocity model that can be correlated with known production zones from previously drilled wells.
  - The reflection profiles successfully imaged basement/tertiary volcanic contact, both depositional and faulted, defining individual range front fault blocks.
  - There was good 3D spatial resolution of target features, including Large Aperture Fractures (LAFs), both in reflection images and velocity models (Teplow, 2015).
  - The high cost of seismic survey resulted in too few profiles and large gaps between key profiles.
- **Active source reflection and refraction seismic (Pearl Hot Springs, NV)**
  - The successful use of low-cost auger drilling for shot hole drilling made the seismic work economical; successful deployment of “disposable” temperature probes attached to explosive charges in seismic shot boreholes enabled dual use as shallow thermal gradient holes.
  - The seismic data show that both the Paymaster Canyon Fault and Weepah Hills Detachment are very reflective. The high-amplitude reflectivity suggests that the faults are heavily mineralized and have slow seismic velocities, indications of geothermal fluid flow along the faults (Stockli, 2015).
- **2D active source seismic surveys of complex multilayered stratigraphy with density inversions, using long sweep times using both p-wave and s-wave methods to look for both pure p- and s-returns (Hot Spot, Snake River, ID)**
  - The Snake River project performed seismic imaging within interbedded basalts and sediments, a complex velocity/density medium with high impedance at shallow depths.
  - A 20-km 2D seismic line using a Vibroseis source was able to image through surface basalts and sediments.
  - At the Kimama drill site, the seismic survey successfully imaged the dominant seismic reflection at 0.2 second time matching the depth to a sediment interbed within the basalt-dominated sequence. An additional reflection at 1.0 second time also matches the depth to sediment interbeds (Shervais, 2014).

  - At the Kimberley drill site, the seismic survey successfully imaged the dominant reflection at 0.2 second time matching the depth to a basalt/sediment interbed within the rhyolite-dominated sequence.
  - Seismic resolution of the stratigraphy below 1.0 second was poor.
  - The depth to basement was much greater than predicted before drilling the Kimama and Kimberley wells. Because the seismic surveys were conducted after well drilling, they could not be used to predict depth to basement.

- **3-Dimensional–3-Component (3D-3C) reflection seismic survey, correlation with existing wells to identify fracture systems and permeable zones (Soda Lake, NV)**
  - The Soda Lake project undertook a 3D/3C seismic survey to better understand the geology and structures in the field and their control over the geothermal resource (Echols et al., 2011). A 1,500-2,000-foot thick near-surface sequence of sedimentary rocks at Soda Lakes offers one of the few places in Nevada where a seismic survey should be capable of providing quality data on subsurface structures associated with an extensively drilled geothermal system. Four 1970s-vintage 2D seismic lines showed that coherent reflectors are present in the Soda Lake area, making this a viable candidate field for a 3D-3C survey.
  - The 3D reflection seismic survey provided useful insights in unraveling the structural complexity of the Soda Lake field and the surrounding area and enabled the site selection of two drilled observation wells (44B-34 and 26-20A). The purpose of drilling the vertical 44B-34 and 46A-20 observations wells is primarily to demonstrate that temperatures above 320°F exist at depths above 4,000 feet to supply geothermal fluid to one or both of the existing Soda Lake power plants.
  - A mudstone layer encountered in the 44B-34 well below 760 feet was imaged by the seismic and enabled interpretation of the normal fault offsets that became the principal permeability targets for drilling.
  - Seismic time and depth sections indicating small-offset east dipping normal faults representing possible permeability were the principal basis for site selection of the 44B-34 well.
  - An east-west depth image passing through the 44B-34 well indicates that it successfully penetrated several east-dipping faults.
  - There was a strong correlation between the seismically imaged normal faults cut by the 44B-34 wellbore and the temperature profile and permeability encountered by the well.
  - Seismic mapping of the mudstone horizon reveals the regional tectonic setting that hosts the Soda Lake geothermal resource: a small extensional, pull-apart basin that has been active in the past few hundred thousand years.
  - A basaltic unit was anticipated to be the dominant reflector in the seismic survey, but over most of the developed field it failed to produce a strong or consistent reflection. In the central part of the field it is not recognizable in the seismic data without well control.
  - Below the basaltic unit at a depth of about 2,000 feet or a time of about 0.6 seconds the seismic results in the field area show few coherent reflectors.
  - One goal of the 3D seismic survey was to identify a “seismic signature” associated with production, either a structural relationship related to the orientation of the faults or through shear-wave anisotropy. Unfortunately, neither of these goals has been satisfied. The degraded quality of

    the data over the producing area introduced uncertainty in determining convincing orientations of faults.

    - Converted-wave processing has not yielded useful results. Shear-wave energy was under-sampled at the surface.
    - Understanding recent tectonics is critical to unraveling these geothermal systems.

- **3D-3C (converted shear wave) seismic survey to reduce exploration risk by characterizing fault and fracture geometrics to define open fractures (Wister, CA)**
    - The Wister project has explored whether 3D-3C seismic surveys could define open fractures in the Imperial Valley, which could greatly reduce exploration and development drilling risk.
    - The survey recorded very weak shear wave velocity and reflectivity. S-wave processing was unsuccessful, limiting the usefulness of the converted shear wave technique in finding open fractures in this environment (Matlick et al., 2015).
    - Both wells intersected seismically interpreted fractures but found little-to-no permeability and low injectivity. Structural dips were greater than expected.
- **High-precision geophysics for well targeting (Crump Geyser, OR)**
    - The project used very high-resolution seismic reflection/refraction, gravity, and magnetics to define a range-bounding fault in intercalated basalt flows and sediments (Fairbank and Smith, 2015).
    - Combined interpretation of the geophysics data was used to develop a 3D geologic model.
    - Fault interpretations from surface geology, aeromagnetic, seismic, and gravity data sets are in good agreement, illustrating two or more major range-bounding faults and buried northwest trending faults. The intersections of these fault systems provide the primary targets for drilling.
    - Drilling of two wells at the Crump project successfully located the targeted faults, but one well encountered an isothermal 200°F temperature to total depth indicating a hydrothermal outflow zone and the other found higher temperature (265°F), but low permeability.
    - Due to lack of permeable reservoir and fluid flow, planned Flowing Differential Self Potential (FDSP) and electrical tomography techniques were not tested.

4.1.3.4 Invasive (Borehole) Geophysical Techniques

- **2m Thermal Holes and Hydroprobe survey (McGee, NV)**
    - PI reports that the 2m survey and hydroprobe (also known as geoprobe) measurements at depths of 8 to 30 meters are in agreement.
    - Temperature measurements from both surveys have enabled the targeting of thermal anomalies, resistivity anomalies, and faulting at depth.
    - 2m survey and hydroprobe measurements delineate thermal targets at lower cost than temperature gradient drilling on a per-property and a per-site basis. The cost of both surveys together is approximately equivalent to one temperature gradient hole.
    - Both techniques were limited by penetration problems; the hydroprobe technique was limited to use on roads.

    - Results suggest that a successful and cost-effective exploration program should use 2m survey, hydroprobe, and temperature gradient drilling, in that order (Zehner et al., 2012).

- **DTS (distributed temperature sensing) measurements (Pyramid Lake, NV)**
    - Used along with borehole spinner log surveys with temperature probes to indicate that fracture inflows are relatively constant with isothermal temperatures ranging between 92 to 95°C along the exploration wells, indicating that the fracture network is well-connected and enables development of a shallow reservoir.
    - Monitored temperature during a long-term pumping test. The long duration of the test and the high-resolution monitoring of fracture inflow locations and borehole temperatures eliminate the possibility of preferential flow of geothermal waters exceeding 100°C (Reeves et al., 2012).

- **Use of groundwater temperature and water well temperature data, with geologic maps, to assess geothermal potential at depth (Hot Spot, Snake River, ID)**
    - The project gained valuable knowledge on the structure of the cold-water aquifers related to the modern Snake River drainage, as well as the underlying geothermal systems. The surface ground water temperatures provided little information regarding the deep temperature structure below this regional cold-water aquifer. The Kimama well encountered a much thicker cold-water aquifer than expected (960 meters) with a temperature gradient of 15-17°C/km, then 80°C/km below the aquifer. The Kimberley well encountered a warm water aquifer 1,250-meter thick with a temperature gradient of 55-60°C/km and a maximum temperature of 59°C at a total depth of 1,940 meters. The Mountain Home well encountered artesian flow at 160°C from an aquifer at 1,740 meters (Shervais, 2014).

- **Geophysical well logs in slimholes (Hot Spot, Snake River, ID)**
    - Borehole Televiewer (BHTV) was run in the Kimama and Kimberley wells (the temperature at the Mountain Home well was too high for the logging tool). The data were extremely valuable in providing fracture orientations. BHTV images correlate well with core obtained (Schmitt et al., 2012).
    - Hydrogen-index neutron and γ-γ density logs employing active sources were deployed through the drill string, and provide semi-quantitative information related to the ‘stratigraphy’ of the basalt flows and on the existence of alteration minerals.
    - Electrical resistivity logs highlight the existence of some fracture and mineralized zones.
    - Magnetic susceptibility together with the vector magnetic field measurements display substantial variations that, in combination with laboratory measurements, may provide a tool for tracking magnetic field reversals along the borehole.
    - Full waveform sonic logs highlight the variations in compressional and shear velocity along the borehole.

- **High resolution vertical seismic profile (VSP) to assess complex multilayered stratigraphy (Hot Spot, Snake River, ID)**
    - Downhole VSP data show low seismic attenuation, large seismic velocity contrasts at volcanic flow boundaries, and large near-surface static effects (Shervais, 2014).

  - Lithologic log comparison shows that low seismic velocity zones identified with the VSP match sediment interbeds, and these features correspond to slow velocity zones that relate to reflections on surface seismic profiles; this reflection pattern suggests flow volumes from the latest eruption can be estimated with surface seismic methods.
  - Downhole VSP and surface seismic results suggest seismic reflection methods are useful to image shallow flow boundaries.
- **2D VSP imaging with dynamic borehole cooling (Rye Patch, NV)**
  - The dynamic borehole cooling attempted at Rye Patch encountered problems, including uncontrolled steam/water flow, unrecovered VSP equipment, and only a partial run of the VSP (Ellis, 2011).
  - Select aperture mutes of VSP depth data highlighted and enhanced usable reflections, allowing interpretation of fault positions at depth, revision of the structural interpretation of range front, and identification of targets directly below and slightly east of existing wells 51-21 and 52-28.
  - Both VSP and surface profiles identified prominent east dip and an antithetic fault system (down-to-the-east) west of well field.
  - While difficult to interpret exact position/throw of antithetic fault on seismic, the integration of the seismic data with the dip reversal, gravity "low" and faults provide compelling and reasonably conclusive evidence.
- **Vertical Seismic Profile (VSP) (Soda Lake, NV)**
  - Vertical Seismic Profiles have limited applications in high-temperature geothermal wells. The windows of opportunity are currently limited to relatively cool wells outside of the thermal anomaly or immediately following periods of active cooling associated with drilling or injection testing. Full elastic coupling to the borehole or casing is vital for an acceptable signal-to-noise ratio. Unless a geothermal well is cased and cemented to near the zone of interest, the geophone array inside an uncemented liner will be reduced to a check-shot survey, where an expensive geophone array is not necessary.
  - One potential use of the VSP is to identify fluid-filled fractures adjacent to low permeable wells. Since a large part of the cost of a geothermal well is the large diameter hole to the casing point, it would be advantageous if a VSP could orient a redrill to permeability by use of directionally drilled laterals in multiple directions.
  - In addition to controlling wellbore temperatures and achieving full elastic coupling, the general volcanic geology of most geothermal resources will continue to be a challenge for this seismic method. In light of the experience with the 41B-33 VSP, this application could not be accomplished with a rig on stand-by. In this case, a Halliburton crew was mobilized from New Iberia, Louisiana. They arrived with 50,000 lb. vibrators, which were limited to travelling on hard-packed surfaces, even though it was clear that off-road source points were needed. The turnaround for a finished product is on the order of months, not hours. Results of the VSP conducted in 41B-33 did provide a depth conversion based on a velocity model, which was needed for the surface seismic survey conducted subsequently (Echols et al., 2011).

- **Downhole seismicity monitoring to detect fluid movement (Newberry, OR)**
    - The Newberry project is exploring for hidden hot plutons and geothermal systems in young volcanic terrain with a deep water table. The project is utilizing seismic monitoring to detect fluid movement.
    - Apex HiPoint has conducted a 4D passive seismic test using their patent pending LASEA® (Low Amplitude Seismic Emission Analysis) technology, using downhole sensors in shallow temperature gradient holes.
    - In some sense, the 4D seismic analysis appears promising. The technique imaged seismic energy in near vertical zone trending NNW-SSE at 5,000-10,000-meter depth. The analysis also discovered that the center of the Newberry caldera is not where the current lakes are located.
    - However, overall results are ambiguous and do not provide additional insights into the geothermal or fluid flow conditions. The results of both the southern and northern arrays have provided tantalizing interpretations that deserve future investigation. The results of this program, however, have not shown this technique is capable of uniquely identifying subsurface hydrothermal fluid movement (Waibel et al., 2014).

4.1.3.5 Geological Techniques

- **Use of groundwater temperature and water well temperature data, with geologic maps, to assess geothermal potential at depth. (Hot Spot, Snake River, ID)**
    - Existing geologic and geophysical data were used to define drilling targets.
        - Compiled geologic maps showing distribution of Quaternary volcanic centers and vents, ash flows, and flow directions.
        - Ground water temperatures to identify high thermal flux.
        - Existing water well logs to constrain stratigraphy.
        - New maps of faults and lineaments using 10-meter NASA Digital Elevation Model data.
        - New gravity and magnetic maps using existing data.
    - Drill sites were chosen to assess three distinct settings:
        - Kimama: Sub-aquifer high thermal flux along central volcanic axis of Snake River Plain, the locus of Quaternary volcanism.
        - Kimberley: Rhyolite caldera margin in area of high thermal flux.
        - Mountain Home: Faults related to buried horst-graben structures.
    - The axial Kimama well encountered a much thicker cold-water aquifer than expected. The surface ground water temperatures did not provide any information regarding the deep temperature structure below this regional cold-water aquifer (Shervais, 2014).
- **Detailed geologic mapping (Jemez Pueblo, NM)**
    - PI reports that detailed geologic mapping was useful in the development of subsurface model, seismic interpretation, structural style, etc.

- **Structural mapping and modeling (Pyramid Lake, NV; Glass Buttes, OR; Pearl Hot Springs, NV)**
    - Comprehensive 3D geological model at Pyramid Lake
        - 3D geologic framework model constructed from geologic map, surface fracture mapping, cross sections, topographic data, seismic data, and well data (Siler et al., 2012). Model allows plotting of any cross section and examination of the geometry of any fault intersection/interaction areas that may be controlling geothermal fluid circulation. Used as a basis for numerical reservoir model and is the centerpiece of the methodology for analyzing geothermal favorability for blind systems (Siler et al., 2016b).
        - Fracture stress modeling and associated analysis of optimally oriented fractures for fluid flow contributed value to integrated subsurface modeling.
    - Numerical reservoir model at Pyramid Lake
        - Sophisticated 3D model that simulates multi-phase, multi-component fluid flow, heat and mass transport in variably saturated geologic media (NUFT) and simpler MODFLOW model used for auxiliary calculations (Pyramid Lake Paiute Tribe, 2013).
        - Fracture network conceptualized as an Effective Porous Medium (EPM), which assumes that reservoir rock is highly fractured such that equivalent permeability tensors can be assigned to the reservoir volcanic rocks and the overlying alluvium.
        - Geothermal modeling exercises consisted of steady-state reservoir model calibration to field measurements and observations, to infer reservoir flow and transport properties, followed by exploitation scenarios to assess energy potential of the site.
    - Comprehensive 3D geological model at Glass Buttes
        - Leapfrog 3D software used to incorporate all geological and geophysical data sets into a comprehensive model (Walsh et al., 2015).
        - Created three-dimensional curvilinear fault planes to honor interpretations from all data sets.
        - Each well that is drilled will be used to revise and better constrain the model, further reducing risk for future wells (Walsh et al., 2015).
    - 3D earth model at Pearl Hot Springs
        - Geothermal resources in Clayton Valley are controlled by the interplay between low-angle normal faults and active deformation related to the Walker Lane.
        - 3-D Earth Model, combining all gravity, magnetic, seismic, geochemical data in an innovative approach combining classic work with new geochemical and geophysical methodology to detect blind geothermal resources in a cost-effective fashion (Stockli, 2015).
- **3D DEM mapping of fault locations (Fort Bliss, El Paso, TX)**
    - PI deemed the 3D DEM mapping as highly useful and contributed value to integrated subsurface modeling.

- **Kinematic Structural Analysis (detailed fault mapping and direction of slip) (San Emidio, NV)**
    - Kinematic Structural Analysis uses detailed geologic mapping, slip orientation on exposed fault surfaces, regional tectonics and kinematic analysis to identify specific faults and zones of maximum dilational tendency.
    - The San Emidio project used kinematic structural analysis to help find Large Aperture Fractures (LAFs) that are prime drilling targets for the development of geothermal systems. LAF's in geothermal systems typically yield production wells of the highest productivity and lowest pressure drawdown within a given geothermal reservoir.
    - Kinematic structural analysis was used to conduct detailed fault and slip direction mapping with finite element analysis based on observed slip direction. The resulting map shows fault segments with maximum dilational tendency that increase the likelihood of LAFs and permeable hydrothermal reservoirs (Teplow, 2015).
    - Known LAF occurrences correlate with a specific fault orientation relative to region stress that generates maximal dilational tendency.
    - Seven exploration slimholes encountered commercial temperatures at the targeted depth intervals. Temperatures ranged from 275°F to 320°F (highest observed temperature in the field). Three of the four exploration holes encountered commercially exploitable permeability. Areal extent of the productive reservoir was increased by more than 0.5 miles to the south and west. Extension of the reservoir to depth was increased by 2,000 feet. The total productivity for three slimholes is estimated at approximately 4 MW net, about 50% of fluid requirements for the Phase 2 build out.
    - While all of the targets drilled encountered permeable zones containing commercial temperature fluid, the target signature was not sufficiently unique to differentiate between zones of commercial and sub-commercial permeability or zones of minimal commercial temperature (270°F-280°F) and high temperature (above 290°F).
    - Kinematic structural analysis is highly dependent on surface fault exposures that show slip direction. Lack of faulted outcrop in southern exploration area introduces uncertainty in fault locations and geometry.

4.1.3.6 Geochemical Techniques

- **Soil gas survey (McCoy, NV; Pagosa Springs, Co)**
    - McCoy
        - A soil multi-gas survey was collected from a depth of 1 meter along seven lines. The results of this survey were highly suspect. The primary disappointment is that the control station, sampled once daily for calibration of the results, showed wildly varying gas concentrations. The only conclusion that can be reached with these is the control sampling data points could not be reproduced with reasonable accuracy. Given that both the magnitude and the variability of the sample points are within error of the control points, the rest of the survey has no value to McCoy (Garchar, 2015b).
        - As a general observation, it seems to make little sense to run a soil gas survey in an area where there is no particular reason to expect a high flux of gases.
    - Pagosa Springs

        - Ten sites in the east region and nine sites in the west region were sampled for their soil gases and three geothermometers were calculated for each site: CO_2/CH_4, CO_2/N_2, and H_2/Ar (Pagosa Verde, 2016).
        - The CO_2/CH_4 geothermometer consistently returned results dramatically higher than those of the CO_2/N_2, and H_2/Ar samples, as well as the geothermometers calculated from the water samples. The CO_2/CH_4 results are considered inaccurate at these locations.
        - Although the average and median temperatures of the eastern data points are 15°C higher than the western, scatter among measurements is large and with only ten data points taken for each region there is a significant risk in using this method to infer a temperature anomaly or geothermal resource potential.

- **Targeted CO_2 flux and isotopic measurements (Maui, HI)**
    - The Maui project conducted a targeted CO_2 flux survey, helium and targeted carbon isotope sampling across geophysically defined structures at both the Puna geothermal field and the Ulupalakua exploration area (Fercho et al., 2015).
    - Geochemical survey results have been mixed. Soil CO_2 flux measurements typically did not reveal upflow of magma-derived CO_2 to the surface. The lack of observed CO_2 flux at known fracture and volcanic centers at Puna may be explained by 'scrubbing' of CO_2 by the significant groundwater transport through the southeast flank of Kilauea; isotopic data bears this out. The lack of CO_2 flux on the Haleakala SW Rift Zone (with one notable exception) could be a function of: (1) probable low overall flux in this dormant system, (2) similar groundwater scrubbing, and (3) biogenic exhalation swamping magmatic flux.
    - After comparing results from Maui, Puna and Kona, groundwater geochemistry is deemed to be a more successful indicator of magmatic fluid upflow than soil CO_2 flux measurement in areas with high groundwater flow, relatively deep vadose zone, and/or dense vegetation that may mask upflow of magmatic volatiles to the surface.

- **Chemostratigraphy (Fort Bliss, El Paso, TX)**
    - The Quantitative Electron Microscope Scanning (QEMScan) system at the Energy & Geoscience Institute (EGI) is an automated scanning electron microscope that allows rapid collection and analysis of quantitative mineral abundances with unprecedented precision and accuracy.
    - Well RMI 56-5 was drilled from May 17 to June 23, 2013 to a depth of 924 meters below ground level. The well was drilled with flooded reverse circulation, which produced an exceptionally large and complete cuttings record.
    - Chemostratigraphic Analyses (utilizing QEMScan) of available cuttings allows the quantitative evaluation of minerals by scanning electron microscopy (SEM). Automated mineralogy and petrography providing quantitative analyses of minerals.
    - Chemostratigraphy enables regional lithologic and age correlations, mineralogic correlations, fracture/microfracture evaluation for fluid movement.
    - The PI deemed chemostratigraphic correlation as moderately useful in determination of the geothermal source, migration pathways and a regional flow model. Chronostratigraphic correlation was of limited use in this project (Lear et al., 2016).
    - Preliminary results indicate:

        1. Post-lithification fractures are the dominant transport pathways for hydrothermal fluids;

        2. The main reservoir for the hydrothermal system is the limestone/dolomite formations;

        3. Some of the dolomite units are characterized by unfilled or re-formed vuggy porosity; and

        4. Fracturing and brecciation within the Tertiary intrusive formations indicate deformation and compression during the emplacement of the porphyritic sills.

- **U-Th/He thermochronometry and geothermometry (Pearl Hot Springs, NV)**
    - Extensive fluid sampling was conducted concurrent with geological and structural mapping. All completed analytical data (ages) have been compiled in map form and shown to spatially coincide with the 2m shallow thermal anomaly (Stockli, 2015).
    - The co-location of the anomaly with a mineralized outflow sheet and our discovery of actual steam exhalations (fumaroles) suggest that there is a surface manifestation of the hydrothermal plume.
- **Whole-rock and fluid geochemistry to understand the hydrothermal reservoir volume and thermal structure (Caldwell Ranch, CA)**
    - Well testing and geochemistry of well fluids and cuttings allowed the characterization of three compartments within the geothermal reservoir.
    - Commercial potential confirmed and exploited – 7.4MW (estimated 12MW potential) added to power plant output (Garchar, 2015c).

4.1.3.7 Summary

Visser (2012) rated the methods as highly useful, moderately useful, or of limited use. It is important to note that most of the projects lie in one tectonic province (see project location map above). Therefore, the findings may be skewed to that environment. For drilling techniques, the most useful IET was slimhole diamond drilling with bottom-hole temperature tool, which was rated highly useful. Moderately useful drilling techniques included direct push temperature gradient holes and dynamic borehole cooling.

For remote sensing, LiDAR and FLIR airborne thermal survey were highly useful, and direct confirmation of geothermal resources by remote sensing and ground investigations, hyperspectral imaging, and PSInSAR were moderately useful. Many noninvasive geophysical techniques were rated moderately to highly useful, including gravity, ZTEM vertical magnetic field survey, 3-component geophone and 3-component vibroseis to image steeply dipping faults and fractures, active source reflection and refraction seismic, 3D-3C reflection seismic survey, innovative re-processing of existing surface seismic data.

Invasive geophysical technique rated moderately to highly useful included geophysical well logs with acoustic televiewer to assess fracture distribution, porosity, and permeability with use of petroleum industry modeling tools, 2m thermal holes, hydroprobe survey, and VSP. For geological techniques, detailed geologic mapping, improving the structural model, and doing a kinematic structural analysis, which included detailed fault mapping and direction of slip, were all rated moderately useful. Of the geochemical techniques, chemostratigraphy was rated moderately useful.

Lessons Learned

Assessing the IET projects both individually and as a group revealed important lessons.

- Drilling

  - Lack of standardization/best practices in drilling methodology and protocols meant that every project had different results. This variability in results is further complicated by the various rigs, bits, tools, materials, contractors, and plays explored—no two projects are similar enough to control for specific variables.
  - Paucity of datasets related to drilling methods and parameters make it difficult to improve or develop best practices for a given situation.
  - Shallow temperature probe surveys at McCoy, Pyramid Lake, Silver Peak, Alum, Pilgrim, and Crump Geyser received positive reporting from awardees.
- Remote Sensing
  - Utility of Remote Sensing for geothermal exploration is mixed.
  - Surface thermal anomalies imaged at Pilgrim and Pagosa have not translated to the discovery of a geothermal resource
  - At Glass Buttes, hyperspectral data improved understanding of minerals present, but was not a significant factor in siting wells, because alteration is interpreted as predating the most recent volcanic flows
  - LiDAR has proven to be an extremely valuable exploration tool. At Glass Buttes and Newberry, LiDAR identified many geologic features not previously identified, and more importantly improved ability to quantify fault interactions and improves the insight into possible relationships between surface topography and models of subsurface geophysics. Glass Buttes operator has already significantly increased its use of LiDAR around the world based on the perceived value of these results.
  - The resolution of PSInSAR at San Emidio did not allow imaging of small-scale structures such as individual fractures
- Potential Field Geophysics
  - Awardees considered potential field data to be useful, but recognize that it is most valuable when combined with other datasets.
  - Variability and ambiguity in how various surveys were prioritized, designed, interpreted, incorporated makes comparison among applications difficult.
  - Adequate resolution often not obtained with original survey design, suggesting an iterative approach would be useful.
  - Few teams had a staff geophysicist—lack of capability/expertise in geothermal applications.
- Seismic
  - Mixed results were obtained. Some awardees considered seismic invaluable (Rye Patch, Hot Pot, Jemez Pueblo, Pyramid Lake, San Emidio, Pearl Hot Springs), while others concluded it was not suitable for geothermal applications (Soda Lake, Wister).
  - While seismic is generally successful at identifying faults, it does not necessarily indicate whether or not faults are high-permeability conduits for flow.

  - At Jemez Pueblo, drilling confirmed all structural elements and conductivity differences as determined by the geophysical surface surveys (Albrecht, 2015). The combination of structural information obtained through seismic and conductivity information obtained by Magneto-Telluric resulted in a solid conceptual model of the resource. Each survey method alone would not have been able to provide a comparable resource model.
  - Frequent frustration was experienced with processing data, such as lack of capability and expertise in geothermal applications. Processing is a non-trivial task, and practices standard for the oil and gas industry are not necessarily applicable to the geothermal industry. The time and effort involved in planning, permitting, processing, and interpreting the seismic data is great. U.S. geothermal companies are not properly staffed or equipped to efficiently and routinely conduct and interpret such seismic surveys. Most seismic supporting services are centered in Texas, far from the locations of all geothermal companies.
  - A 3D survey conducted early in the development cycle of a field could eliminate typical surface noise associated with operating power plants, an active well field, and the drilling of new wells, leading to greatly streamlined processing.
- Geology
  - Many awardees reported that continuously updating conceptual model was important, but did not always demonstrate this behavior. This could be related to lack of capability/expertise/familiarity with 3D modeling.
  - 3D geologic modeling was at an early stage at the outset of the IET project at Glass Buttes. Since that time and partly driven by the value demonstrated, especially in conveying results to management, operator now creates 3D models of most exploration and development fields. The correlation between features observed on the surface with those identified by geophysics and previous temperature gradient drilling drive recommendations for first drilling targets.
- Geochemistry
  - Soil Gas surveys at Pagosa, McCoy, and Maui were inconclusive and not useful. Highly variable results represented other environmental factors more than faults and/or thermal upwelling.
  - Fluid and rock geochemistry were useful for developing conceptual models.

4.2 Play Fairway Analysis

A major barrier to the development of the large geothermal resources in the United States is the difficulty in locating blind hydrothermal systems, along with the great expense of exploratory drilling. The DOE Geothermal Technologies Office has made a priority of advancing the state of the art in exploring for blind hydrothermal systems, and key among these technologies is the concept of play fairway analysis (PFA).

A play fairway is the area in a basin or region where examples of an individual play type are projected to exist and is defined by the geologic characteristics of the basin and of the play type. A play fairway analysis incorporates basin-wide evidence for the occurrence of the requisite geological factors of a particular play type, and plots the probability of finding the play over the entire area of study. This allows for rigorous quantification of exploration risk; areas with the highest probability of success are highlighted as fairways on the resulting maps and are the main focus in subsequent stages of exploration. Already successfully used in the oil and gas sector, play fairway analysis can be a key tool for decision making in any exploration project.

In oil and gas parlance, a petroleum ‘play’ is a group of fields or prospects that are controlled by the same set of geological circumstances. Similarly, a geothermal play would be a set of potential geothermal systems sharing the same geologic setting or origins. A play fairway then is the portion of a study area with a high probability of encountering a particular play, based on high confidence in the presence of the geologic factors required for the formation of the play. A typical play fairway analysis would follow a process similar to the steps shown in Figure 13 to determine where the fairways are located.

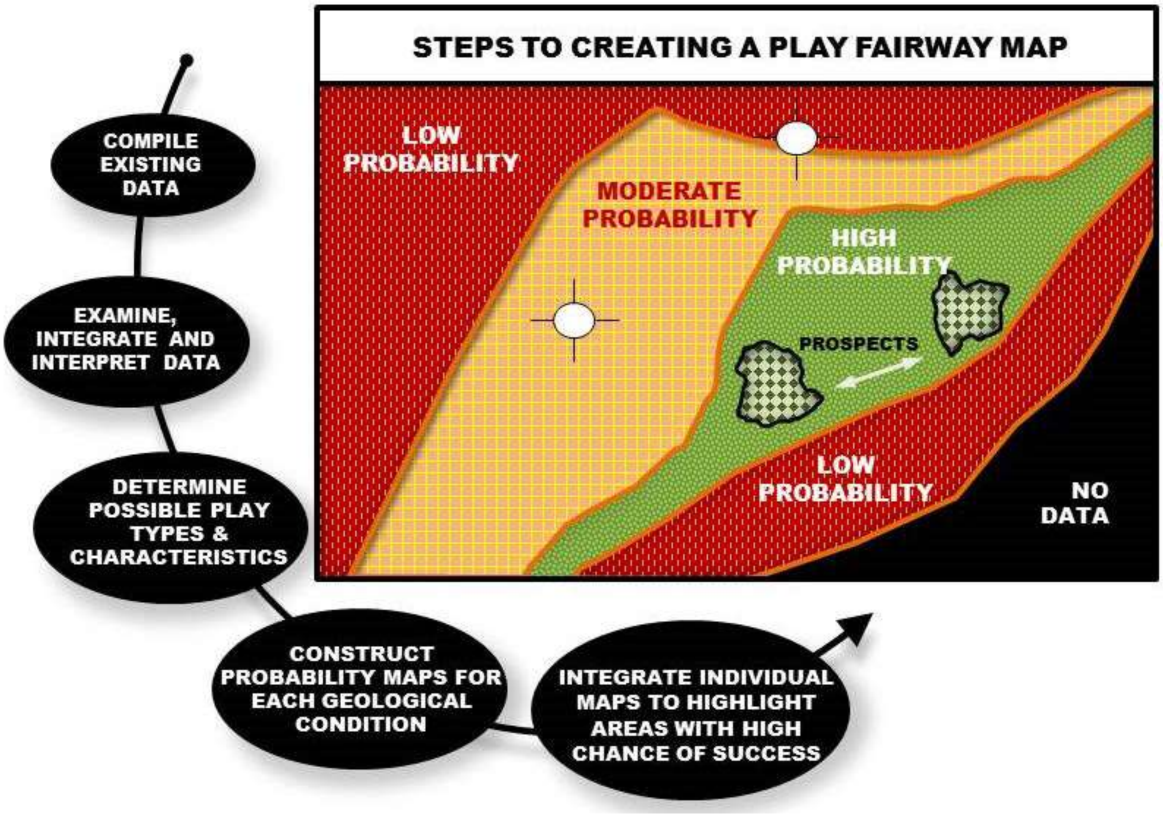


Figure 13. General process of creating a play fairway map. Note that critical to the process is determining the type or types of possible resources in the region of study. Not all the individual probability maps might be used in the creation of each play fairway map (Weathers et al., 2015, Figure 1).

For oil and gas exploration, the commonly used geologic (or play fairway) factors are reservoir facies, a sealing cap rock, and source rock. Early efforts in geothermal exploration focused mostly on heat flow, but currently the commonly used play fairway factors for geothermal exploration are: (1) a heat source, (2) reservoir permeability, (3) a reservoir seal, and (4) presence of geothermal fluids. The specific data used to assess these attributes depends on the particular geologic setting. Geothermal resources show a much greater driving force toward the surface than do oil and gas resources, making surface manifestations more likely to be useful components of a play fairway analysis. However, hidden geothermal systems, where surface manifestations are lacking or minimal, are also amenable to play fairway analysis, by emphasizing regional-scale surface-based geophysics methods such as MT (Dobson, 2016). On the other hand, McClain et al. (2015) point out that geothermal systems do not have the same level of basin-wide coherence as oil- or gas-bearing formations, whose sedimentary reservoirs tend to be horizontal, but rather are often controlled by very localized characteristics, such as the vertical upflow of geothermal fluids from great depth along a fault. As such, play fairway analysis for geothermal may be more challenging than for oil and gas.

Eleven projects were selected for a DOE-sponsored play fairway analysis in 2014 (Weathers et al., 2015). The primary goals for the projects were to demonstrate methods for rigorously quantifying project risk, thereby aiding in project finance, and to identify high-grade potential drilling areas to reduce the number of unsuccessful wells that are drilled. The projects, located in the five areas shown in Figure 14, were selected in order to:

- Focus on under- or unexplored regions (play analysis is early-stage exploration, and not intended to step out from existing known resources);
- Be at a basin- or regional scale;
- Consider a wide range of possible geothermal resources, including traditional hydrothermal, blind hydrothermal, EGS, and low-temperature geothermal resources;
- Apply innovative analysis methods to extract new value from existing public and/or private data; and
- Develop methodologies to couple multiple data types.

These projects developed geothermal fairway maps utilizing a wide range of data, including observation of subsurface temperatures and structural and tectonic settings, as well as chemical and isotopic data, rock mechanics, and hydrologic and basin history. For areas that looked promising, a plan to further characterize the geothermal resource was developed in a second project phase.

Figure 14. Areas of the United States being studied through Play Fairway Analysis (Weathers et al., 2015, Figure 2).

Table 7 and the succeeding paragraphs provide details from the eleven project teams. Most of the projects chose similar play fairway factors, but the types of data available for analysis varied with play type. There were a variety of approaches used to extrapolate data to cover the study area, and to combine different data types to create favorability maps. A key question for combining different data types is how to weight the different data types, and in particular whether to let the data dictate the weights or to use expert judgment. The sparser the data coverage is, the more likely it is that expert judgment is needed. All the projects felt that the PFA they conducted in their particular region greatly improved the prospects for efficient geothermal exploration.

Table 7. Summary of Phase 1 projects by title, region, and organization. Projects shown in bold continued on to Phase 2.

Project Title	Region	Organization (PI)	Play Fairway Factors	Approach to combine data types	Weights
Low-Temperature Geothermal Play Fairway Analysis for the Appalachian Basin	Appalachian Basin	Cornell University (Jordan)	Heat source, permeability (indirect, existence of reservoirs), seismic risk, heat demand	Sum, product, minimum	From data
Discovering Blind Geothermal Systems in the Great Basin Region: An Integrated Geologic and Geophysical Approach for Establishing Geothermal Play Fairways	Basin and Range	Nevada Bureau of Mines and Geology (Faulds)	Heat source, permeability	Common Risk Segment-like with benchmarks	From data and expert opinion
Geothermal Play Fairway Analysis of Potential Geothermal Resources in NE California, NW Nevada, and Southern Oregon: A Transition Between Extension-Hosted and Volcanically-Hosted Geothermal Fields	Basin and Range	University of California, Davis (McClain)	Heat source, permeability, fluid availability, a reservoir unit, cap rock (first two used here)	GIS with fuzzy logic	From data and expert opinion
Structurally Controlled Geothermal Systems in the Eastern Great Basin Extensional Regime, Utah	Basin and Range	University of Utah (Wannamaker)	Heat source, permeability	Common Risk Segment	Expert opinion
Geothermal Potential of the Cascade and Aleutian Arcs with Ranking of Individual Volcanic Centers for their Potential to Host Electricity-Grade Reservoirs	Pacific and Cascades	ATLAS Geosciences, Inc (Shevenell)	Heat source, permeability, fluid composition, cap rock; add surface features and degree of exploration	Various: product, average, maximum, fuzzy logic	From data and expert opinion
Geothermal Play-Fairway Analysis of Washington State Prospects	Pacific and Cascades	Washington Division of Geology and Earth Resources (Norman)	Heat source, permeability	Analytical Hierarchy Process	Expert opinion

Comprehensive Analysis of Hawaii’s Geothermal Potential Through Play Fairway Integration of Geophysical, Geochemical, and Geological Data	Pacific and Cascades	University of Hawaii (Lautze)	Heat source, permeability, fluid	Bayesian	Expert opinion
Structurally Controlled Geothermal Systems in the Central Cascadia Arc-BackArc Regime, Oregon	Pacific and Cascades	University of Utah (Wannamaker)	Heat source, permeability	Common Risk Segment	Expert opinion
The Convergence of Heat, Groundwater, and Fracture Permeability: Innovative Play Fairway Modelling Applied to the Tularosa Basin	Rio Grande Rift	Ruby Mountain, Inc (Nash)	Heat source, permeability, fluid	Common Risk Segment and weights of evidence	From data and expert opinion
Hydrogeologic Windows: Regional Signature Detection for Blind and Traditional Geothermal Play Fairways	Rio Grande Rift	Los Alamos National Laboratory (Middleton)	Heat source, permeability, fluid	Integrated framework with spatial association analysis; prospectivity approach	From data
Geothermal Play Fairway Analysis, Snake River Plain, Idaho	Snake River Plain	Utah State University (Shervais)	Heat source, permeability, caprock	Common Risk Segment with training sites	Expert opinion

4.2.1 Appalachian Basin

Cornell University: Low-Temperature Geothermal Play Fairway Analysis for the Appalachian Basin

This DOE-funded effort applied the Play Fairway Analysis (PFA) approach to low-temperature geothermal exploration and potential development of direct-use geothermal plays in the Appalachian Basin portions of New York, Pennsylvania, and West Virginia (Jordan et al., 2016). Broad regions of the basin in all three states have heat fluxes in excess of 50 mW/m^2. The four “Play Fairway” risk factors analyzed in this study are: (1) thermal resource quality, (2) natural reservoir quality, (3) induced seismicity, and (4) utilization opportunities. Uncertainty analyses considered the estimated precision in the geologic risk factors (1-3) and estimated the uncertainty in the combined index. The assumed use scenario investigated on a basin-wide scale was that of district heating systems.

The quantitative analysis was based on pre-existing data from sources inclusive of: (1) previous national and state research efforts; the National Geothermal Data System; (2) the Midwest Regional Carbon Sequestration Partnership; (3) New York, Pennsylvania and West Virginia State geologic, oil and gas well data provided by the State Geological Surveys and by their oil and gas regulatory bodies; (4) NOAA Climate data; NEIC and EarthScope (TA) seismicity data; (5) a regional-scale magnetic grid; (6) regional-scale gravity data; (7) the World Stress Map; U.S. Census Bureau population data; and (8) Energy Information Agency power consumption data.

Several techniques were used to compute the combined risk metric at each location using a grid resolution of 1 km^2. These methods included using the sum of individual risk factor favorability ratings, the product of individual favorability ratings, or the minimum (least favorable) value of the four risk favorability ratings. There is value in considering the outcomes of each of these methods:

1. The summation approach highlights areas that appear favorable overall, but does not inform a decision maker if any given risk factor is unfavorable at a location.
2. The minimum value approach highlights the most unfavorable rating of the four risk factors, but does not inform a decision maker of how much more favorable are other risk factors.
3. The product approach highlights those few areas that are favorable in all four risk factors, but highly down-weights those areas that are even slightly less favorable.

Overall, the summation approach rapidly identifies areas for which additional study to reduce risk related to any one of the risk factors is most warranted. The minimum value approach highlights the fact that there is no place where the existing results warrant immediate investment in commercialization. While it is almost impossible for analysts to say which method is the best, the information conveyed by these methods is useful for the decision makers to consider in assessing their site, or when comparing sites for development. Where all three PFA methods are favorable, these sites are most robust as potential plays; however, uncertainty in each metric should also be considered while making a decision. Each individual risk is accompanied by a map of the uncertainty, which was then included as part of the final PFA. The set of PFAs that combine all four risk factors highlight the spatial layout of existing population centers. Areas of low population density are matched by low favorability ratings, irrespective of their geological resources.

The following five highest-priority Play Fairways are recommended for further investigation. The Corning-Ithaca Play Fairway (mostly in New York) includes locations with especially favorable overall scores and small degrees of uncertainty, and warrants investigation to better determine the full costs of heat delivery as well as to determine the spatial extent of the high-quality reservoirs. The Morgantown-Clarksburg Play Fairway (West Virginia), the Meadville–Jamestown Play Fairway (mostly in Pennsylvania) and the Charleston Play Fairway (West Virginia) also have favorable scores for most of the four risk factors, and deserve more in-depth analysis than was within the scope of this Phase 1 project. The Pittsburgh Play Fairway is a region of very few deep wells and therefore scant data for the subsurface depths at which the temperature exceeds 50°C. Given the large utilization potential near the city of Pittsburgh, a more focused study of the deepest wells is recommended in order to better evaluate the potential for deep natural reservoirs.

Major uncertainties remaining at the end of this analysis are especially large regarding characterization of reservoirs to flow hot water, and regarding the three-dimensional spatial distribution of reservoirs because the data are biased by the hydrocarbon industry source of data. In addition, although the general spatial patterns of the heat resource variations appear to be robust, the accuracy of the temperature-depth profiles at given locations of interest could be improved significantly if new equilibrium temperature and thermal conductivity data were acquired.

As a follow-up step, the subsurface costs for a set of case study scenarios should be analyzed as well as the surface infrastructure costs, to facilitate Levelized Cost of Heat discussions with potential user groups at favorable locations. The methodologies developed in this project may be applied in other sedimentary basins as a foundation for low temperature (50-150°C) direct use geothermal resource, risk, and uncertainty assessment.

4.2.2 Basin and Range

Nevada Bureau of Mines and Geology: Discovering Blind Geothermal Systems in the Great Basin Region: An Integrated Geologic and Geophysical Approach for Establishing Geothermal Play Fairways

The Great Basin currently hosts about 24 geothermal power plants with more than 600 MW of capacity, but estimates suggest that the region is capable of producing much greater amounts of geothermal energy, primarily from fault-controlled geothermal reservoirs. Considering that most of the geothermal resources in this region are blind, it is imperative that the favorable characteristics for geothermal activity be synthesized and techniques perfected for the discovery of new viable systems. At this time, no single tool can define the detailed structural framework of a geothermal area and fault segments that host fluids. Therefore, a multi-disciplinary approach was utilized to synthesize nine geologic, geochemical, and geophysical parameters to produce a new detailed geothermal play fairway map of a large transect across the Great Basin region (96,000 km^2) from west-central to eastern Nevada, with the primary objective of facilitating discovery of commercial grade, blind geothermal fields (i.e., systems with no surface hot springs or fumaroles).

The play fairway factors employed were permeability and heat (Faulds et al., 2016). As adequate fluids are generally present in the subsurface in the Great Basin, the third factor of fluid availability was not utilized. Permeability was categorized as: (1) regional permeability (regional strain and stress), (2) intermediate-scale permeability (distribution of Quaternary faults), and (3) local permeability (favorable structural settings). The types of data analyzed included: (1) structural settings (i.e., patterns of faulting), (2) age of recent faulting, (3) slip rates on recent faults, (4) regional-scale strain rates, (5) the tendency of faults to slip or dilate based on their orientation in the regional stress field, (6) earthquake density, (7) gravity data, (8) temperature at 3 km depth, and (9) geochemistry from springs and wells. Local permeability was deemed the most critical component of the fairway model in the Great Basin region, because the geothermal gradient and regional setting are generally conducive for geothermal activity throughout the region. Thus, the most critical variable was local permeability as dictated primarily by the makeup of the local structural setting.

A major challenge was developing appropriate weightings of individual data types to best predict permeability and overall geothermal potential. A total of 34 benchmarks of known relatively high-temperature (>130°C) geothermal systems in the region were employed to help determine the weights of each parameter. Both weights determined from weights of evidence and from expert opinion were utilized.

The fairway model produced in this study is a significant improvement over previous models, because compared to past efforts, it incorporates a greater dimensionality of input data (greater diversity of data types); uses more up-to-date and more accurate data (e.g., earthquakes and Quaternary fault slip and age data); and marks the first comprehensive inclusion of structural data, which is critical given its key role in controlling systems in the Great Basin region and elsewhere. The modeled fairway is a target-rich model, with numerous favorable locations identified in a variety of settings throughout the study area. As evidenced by comparing the fairway map with the benchmarks, the model predicts geothermal potential well.

In Phase 2 of this study (Faulds et al., 2017), 24 of the most promising sites, including both known undeveloped systems and previously undiscovered potential blind systems, were appraised with field reconnaissance, limited reconnaissance-level shallow temperature measurements in key areas, limited geochemical analyses, and review of existing geologic, geochemical, and geophysical data. Several criteria were employed to rank these sites, including: (1) type of favorable structural setting with the more complex settings receiving higher rankings; (2) extent of available geological, geochemical, and geophysical data; (3) proximity to Quaternary faults with evidence for rupture in the past approximately 750 ka; (4) quality of exposure; (5) evidence of thermal anomalies from 2-meter temperature surveys; (6) observation of surface geothermal features: (7) presence of thermal or non-thermal springs and wells with anomalous geothermometry; (8) distance from an electrical transmission power corridor; and (9) land status including percent of area considered primary sage grouse habitat. These criteria were semi-quantitatively combined to broadly estimate potential for geothermal development. Five of the most promising sites were selected for detailed studies: Granite Springs Valley, Sou Hills, southern Gabbs Valley, Crescent Valley, and Steptoe Valley. Multiple techniques, including detailed geologic mapping, shallow temperature surveys, detailed gravity surveys, LiDAR, geochemical studies, seismic reflection analysis, and 3D modeling, are being employed in these areas.

University of California, Davis: Geothermal Play Fairway Analysis of Potential Geothermal Resources in NE California, NW Nevada, and Southern Oregon: A Transition Between Extension-Hosted and Volcanically-Hosted Geothermal Fields

Teams of scientists from the University of California at Davis (UCD) and the Lawrence Berkeley National Laboratory (LBNL) focused on a rural region of northeastern California (Modoc and Lassen Counties), northwestern Nevada, and southern Oregon. The region is the site of two geological environments that can increase temperatures at shallow depths within the earth. To the west is a volcanically active area known as the Modoc Plateau. Already some communities in the region use geothermal waters for space and industrial heating. To the east is a broad region known as the Basin and Range that extends from eastern California to Utah. The Basin and Range is an extensional tectonic province, allowing hotter rocks from deeper in the earth's crust to rise closer to the surface. Several geothermal power plants in Nevada and California exploit this shallow source of heat. However, the area to be studied by the UCD/LBNL team has only seen limited use of geothermal energy thus far.

The project involved three main tasks: (1) gathering existing data sets; (2) placing the combined data into a GIS software platform that allows enhanced analysis; and (3) developing a fuzzy-logic PFA procedure and applying it to assess the potential for the development of geothermal resources in the region (McClain et al., 2015). Ultimately, there will be five play fairway factors: a heat source, permeability, fluid availability, a reservoir unit, and a cap rock, but the data collected so far inform the first two only. Six different datasets are utilized as proxies for heat: the age and composition of Quaternary and younger volcanism, four different types of subsurface heat/temperature measurements (heat flow, temperature gradient, measured well temperature, and smoothed heat flow interpolation), and geothermometry data from three different chemical geothermometers. Seven different datasets are utilized as proxies for permeability: The total mapped fault length, the age of the youngest faulting, the stress state of mapped faults (dilation tendency and slip tendency), the existence of favorable structural settings, the strain rate, and the total seismic moment released during earthquakes.

Fuzzy logic is described as "formalizing reasoning in natural language" (Zhang et al., 2016). It has the advantages of utilizing expert knowledge, combining multiple data types, making use of sparse data, and providing uncertainty estimates along with results. The fuzzy-logic analysis included two key steps: (1) formulation of fuzzy rules that relate data attributes to play fairway factors, and (2) assignment of membership functions in order to apply these rules.

A typical example of a fuzzy rule used by Zhang et al. (2016) is, "If a fault at a location is LONG, and YOUNG, and the fault stress is HIGH, then the fault is FAVORABLE to permeability." Then, the membership function for fault length to be LONG is defined as

- 0 for faults whose log-length is less than 3.5
- 1 for faults whose log-length is greater than 4.0
- Linearly varying from 0 to 1 over the log-length range 3.5 to 4.0.

Analogous rules are given for fault length to be MEDIUM and SHORT, and for all the other data attributes that impact play fairway factors permeability and heat source. The entire study area is discretized into 2 km by 2 km grid blocks, and these rules are then applied to each grid block, yielding favorability scores for permeability and heat source, which are then combined to yield an overall favorability score.

High overall favorability with moderate risk is found at nine known and developed geothermal areas, validating the method. The results identify five geothermal prospects where there is sufficient data coverage, quality, and consistency that the exploration risk is relatively low (Siler et al., 2017). These unknown, undeveloped, and under-developed prospects are well-suited for continued exploration efforts. The results also indicate to what degree the two ‘play-types,’ i.e., Cascade arc-type or Basin and Range-type, apply to each of the geothermal prospects, a useful guide in exploration efforts. More details of the procedure and results are provided in Zhang et al. (2016) and Siler et al. (2017).

Energy & Geoscience Institute at the University of Utah: Structurally Controlled Geothermal Systems in the Eastern Great Basin Extensional Regime, Utah

In the Eastern Great Basin extensional tectonic regime of western Utah, active Basin and Range (B&R) extension with volcanism having a N-S strike is superimposed upon pre-existing E-W belts of plutonic rocks and large-scale structural lineaments. Cumulative heat flow along the N-S strike of the state totals approximately 5 GWt above background stable interior. Three electricity-producing power plants currently exist, with potential for greatly increasing this number. An advantage of this PFA region is the relative abundance of existing data, related to a substantial history of geothermal exploration in the region.

In Phase I of the PFA (Wannamaker et al., 2016a), pertinent data were assembled for the eastern Great Basin region. These included: (1) a large number of MT site response functions; (2), earthquakes from the Utah Seismic Network for clustering analysis; (3) fault locations and orientations from the USGS and Utah Geological Survey (UGS) active fault databases and the literature; (4) major element and isotopic compositions of spring fluids from the USGS and UGS databases and published/unpublished literature; (5) heat flow from the SMU database greatly augmented by temperature gradient holes culled from industry records; and (6) volcanic distributions from the UGS database. Subsequently, data were processed using state-of-the-art modeling approaches to obtain modern 3D geophysical images, an updated active fault database, identification of critically stressed zones from potential fields and aerial photography, updated heat flow from numerous industry thermal gradient wells, and a re-evaluation of chemical geothermometry. The conceptual model of geothermal resources in this region that emerged from this analysis shows fluid upflow from deep magmatic sources through steep, low-resistivity crustal fault systems to high-temperature geothermal resources.

Common Risk Segment maps for heat and permeability in the eastern Great Basin were derived, using kriged probabilities and person-defined weights. These maps were then combined to produce an overall favorability map. Two east-west conductive lineaments, one coincident with the Cove Fort transverse zone and one nearby to the north, which is named the Twin Peaks-Meadow zone, appear to be controlling structures for several local fluid and heat upwellings such as Cove Fort, Twin Peaks, and several previously unnamed prospects. Areas of particular interest that emerge are the northern Cinder Knoll areas on the northeast flank of the Mineral Mountain, Twin Peaks rhyolitic volcanic center, and a northward extension of the Cove Fort field.

Under Phase 2 (Wannamaker et al., 2017), new MT surveying is concentrated around Crater Knoll and Twin Peaks, and provides near continuous denser coverage westward from Cove Fort. Additionally, coarse MT site coverage was extended south past the Roosevelt Hot Springs producing area. A geothermal fluid origin for low resistivity MT upwelling structures is being tested using Nodal passive seismic surveying that seeks presence of seismic swarms. New structural analysis in the area will exploit Google high-resolution DEM data that has become available for the state of Utah. Gravity fill-in is being accomplished to improve resolution of possible cryptic subsurface structures. Approximately 160 thermal gradient wells, 8 deep wells and 20 water wells with thermal information are being analyzed and the data show a cumulative heat loss west and north of Cove Fort exceeding 100 MWt, approximately twice that of the Roosevelt Hot Springs producing system. Promising geophysical and geological structures will be profiled for magmatic source input using new passive ^{3}He detectors developed at the University of Utah.

4.2.3 Pacific and Cascades

ATLAS Geosciences, Inc.: Geothermal Potential of the Cascade and Aleutian Arcs, with Ranking of Individual Volcanic Centers for their Potential to Host Electricity-Grade Reservoirs

The U.S. leads the world in geothermal power production, yet neither the Cascade nor Aleutian arcs currently support electricity production. However, outside the U.S. much of the world's geothermal power comes from active arc settings. As part of a DOE-funded project on geothermal play fairway analysis, data compiled from the Cascades and Aleutians are compared to geologic, geochemical, and geophysical information from geothermally productive volcanic arc centers in the other parts of the world.

The first stage of the work (Shevenell et al., 2015; Stelling et al., 2016) involved evaluating trends and correlations of volcanic characteristic- and surface manifestation-data with existing geothermal power production sites in subduction zone volcanic settings, worldwide. A database was developed that describes key geologic factors expected to be indicative of productive geothermal systems in a global training set, which includes all 74 subduction zone volcanic centers world-wide with current or proven geothermal power production capability. Findings show a strong correlation between the presence and size of active flank fumarole areas and installed power production. Additionally, the majority of volcanic characteristics, including long-held anecdotal correlations related to magmatic composition or size, have limited to no correlation with power production potential. Notable exceptions are correlations between greater power yield from geothermal systems associated with older (Pleistocene) caldera systems than systems hosted by Holocene calderas or non-caldera volcanic centers. Power-hosting volcanic centers that have erupted within the last 160 years supply 50% of the global installed geothermal power in subduction zones, and nearly all of these systems are generally mafic (basaltic or andesitic) in average composition. Volcanic centers erupting between 160 and 900 years ago are dominated by felsic volcanic systems, and provide 47% of the global power from volcanic arcs. Only 3% of geothermal power produced in subduction zones comes from fields that are hosted by volcanic centers erupting more than 900 years ago.

Compared to worldwide values, generally lower temperatures are found in Cascades and Aleutian arc volcanoes, and the U.S. arc systems typically display a smaller areal extent of fumarole manifestations, with the exception of the Lassen volcanic field, which has hot springs and fumaroles issuing over a relatively large area.

The second stage of the work (Hinz et al., 2015) evaluated local structural and tectonic settings associated with permeability fairways in the Aleutian and Cascade arcs, and found the following:

- In terms of type of structure and overall structural complexity, shear strain that is focused along major strike-slip faults (arising from stress on thick, strong, continental crust) can translate to high extensional strain across pull-apart structures. In contrast, shear strain distributed across many structures (arising from stress on thin, weak, oceanic crust) will yield a lower slip rate per individual structure.
- Extensional strain is better than compressional strain.
- High strain rate (an active system) is better than low strain rate. Favorable structures include intersections of major faults, pull-aparts along strike-slip faults, step-overs between normal faults, fault terminations of normal or reverse faults, displacement transfer zones, accommodation zones, and dense networks of nascent faults or fault intersections.

Volcanic-characteristic, structural, and tectonic-setting data were combined into predictive geothermal models using a play fairway concept (Coolbaugh et al., 2015) with four play fairway factors: heat source, permeability, fluid composition, and cap rock. Potential volcanic arc play types of conventional arc systems, strike-slip pull-apart systems, extensional basin systems, and other fault dominant systems were incorporated into a single play fairway model using weighting factors appropriate to the specific structural setting of each.

Subsequent to creation of the fairway models, direct evidence in the form of spring and well temperatures and geothermometry, as well as occurrences of fumaroles and surface mineral deposition (e.g., silica sinter) were used to refine the predictions. Degree-of-exploration was also incorporated by applying negative weights for the lack of positive direct evidence at volcanic centers where exploration was considered to have been significant.

The resulting fairway and favorability models predict elevated geothermal potential in several clusters of the central to western Aleutian Arc, the largest of which corresponds to the transition from oceanic crust to continental crust. In the Cascades, the best geothermal potential is predicted in the southern half of the arc, where transtensional to extensional tectonic process are more operative and Basin and Range extension overlaps with the active arc.

Washington Division of Geology and Earth Resources: Geothermal Play-Fairway Analysis of Washington State Prospects

Unlocking the geothermal resource of the Pacific Northwest requires innovative methodologies that address complex patterns of crustal deformation, dense vegetation, glacial veneers, extreme precipitation that erodes heat at very shallow depths, and surficial alteration. Analysis of a previous Washington statewide geothermal resource assessment (Boschmann et al., 2014) revealed areas with elevated heat and permeability, within close proximity to transmission lines, and at elevations reasonable for development, defining three promising plays along the central axis of the Cascade magmatic arc in Washington State: Mount St. Helens Seismic Zone (MSHSZ), Wind River Valley (WRV), and Mount Baker (MB). Natural permeability along faults and associated fractures can provide vertical pathways capable of tapping deep heat sources related to magmatism and can access large fracture networks that could serve as geothermal reservoirs. The MSHSZ and MB are associated with active volcanism although in both cases there is significant horizontal separation between the magmatic heat source and the potential drill sites. The WRV heat source is a stalled, shallowly emplaced intrusion that underlies the potential drill site.

This project (Forson et al., 2015; 2016) goes beyond the existing statewide model by improving the assessment of the heat and permeability necessary to support commercial geothermal operations. Potential permeability is assessed through geomechanical modeling of the deformation that can generate and maintain reservoir porosity and permeability. Metrics to inform permeability potential include: (1) slip and (2) dilation tendency on mapped and seismically inferred faults; (3) maximum shear strain; (4) dilational strain at the surface; (5) modeled fault displacement distribution; (6) fault displacement gradient; (7) shear; and (8) tensile fracture density. Metrics to inform heat potential include: (1) temperature-gradient well data: (2) Quaternary volcanic vents: (3) Quaternary intrusive rocks; (4) spring temperature; and (5) reservoir temperature inferred from geothermometry. Permeability and heat maps are then combined into geothermal favorability maps by normalizing each of the input layers, and assigning them weights according to expert opinion using the Analytical Hierarchy Process (AHP) (Saaty, 2008). The AHP is a valuable tool for complex decision making that works by completing a series of pairwise comparisons. The AHP tests the consistency of the decision makers' evaluations, which is useful for reducing bias in the decision-making process. The AHP was used as a way to compare and ultimately weight the value of the many heat and permeability input parameters at multiple stages of the modeling process to produce a fully integrated prediction of resource potential.

Geothermal favorability maps were generated for each of the three play areas at both 200 meters depth (typical for drilling a temperature-gradient well) and 3 km depth (typical for drilling a production well) slices at each of the three sites. These maps identify favorable locations within developable land for more detailed research in Phase 2. The work in Phase 1, described in detail in Forson et al. (2015) and Norman et al. (2015), resulted in three distinct products: (1) geothermal favorability models; (2) maps of uncertainty in these models (which illustrate where the data used in the favorability models are high quality and spatially accurate, or where there is a lack of data and favorability mapping is solely based on interpolation); and (3) maps of development risk (which are calculated by taking the difference between the favorability maps and the uncertainty maps).

Phase 2 focuses on specific geothermal area of interest (AOI) identified from the favorability and risk maps from Phase 1, at each of the three sites. The AOIs are located on land that can be permitted for geophysical exploration and developed for geothermal production if future exploration proves promising. Phase 2 activities include geophysical surveys (magnetotelluric, magnetic, gravity, electrical resistivity, and passive seismic) that have been tested and used extensively in oil and gas, mineral, and geothermal exploration, and also includes geological and geochemical analyses that will add critical data to the areas where data are sparse (geologic mapping, LiDAR analysis, field surveys, and geochronology). Each of these methods are designed to address a specific issue influencing resource potential or uncertainty identified in the Phase 1 analysis; therefore, the data types vary by site reflecting both differences in existing data and analysis sensitivities. In general, these geophysical and geological methods focus on refining the geometry of known faults, testing for hidden faults, better understanding the local geology, and detecting areas with low resistivity that may be associated with hydrothermal alteration and geothermal fluids.

University of Hawaii: Comprehensive Analysis of Hawaii's Geothermal Potential through Play Fairway Integration of Geophysical, Geochemical, and Geological Data

The state of Hawaii's unique geologic setting makes it an exceptional candidate for geothermal resource development. As a remote island state, Hawaii is more dependent on imported fossil fuel than any other state in the U.S., relying on oil for approximately 90% of the state's energy. The only known geothermal resource in Puna (on Hawaii Island's active Kilauea volcano) is a region of exceptionally high geologic risk. This project offers the opportunity to study and analyze other regions where probable resources exist but lack adequate assessment. An assessment of geothermal resources in 1983 had promising findings statewide, but little geothermal exploration has been done in the past three decades, indicating that there is a clear need to reassess geothermal resources in Hawaii, and provide a new successful methodology to stakeholders that can reduce the risk in exploration and development.

Phase 1 of the play fairway analysis of geothermal resource potential across the State of Hawaii considered play fairway factors of subsurface heat (H), permeability (P), and fluid (F) (Lautze et al., 2017a). This study: (1) identified and compiled all legacy and current data relevant to Hawaii's geothermal resource; (2) ranked these datasets in terms of their relevance to subsurface H, P, F; (3) developed a Bayesian statistical method to incorporate the data and their rankings, and produce a statewide resource probability map; (4) developed a method to assess confidence in the probability values; and (5) assessed what is termed 'development viability' in resulting areas of interest across the state. The study's datasets include: surface geologic mapping data (calderas, rift zones, volcanic vents, dikes, faults), groundwater data (water table elevation, recharge, temperature, chloride: magnesium, SiO_2,) and geophysical data (gravity, magnetotelluric, seismic, geodetic strain). Ito et al. (2017) summarize their impact on H, P, and F, and describe the details of the statistical methodology. The final products of this work include a statewide geothermal resource probability map, a map of confidence in this probability, an assessment of the viability of development in areas of interest, and a prioritized list of recommended future exploration activities.

Overall, it is found that the likelihood of abundant of geothermal resources is highest on the youngest island of Hawaii, but groundwater indicators suggest there may also be resources on the other, older islands, with a total of ten locations identified as warranting further exploration. Probability decreases primarily with shield volcano age, being relatively moderate in select locations on Maui and Lanai, relatively low on Oahu, and minimal on Kauai. The higher demand for renewable energy on the more populated islands of Maui and Oahu, as well as a high viability of development on Lanai, also motivate further exploration on these islands. The difficulties of interisland power transmission mean that even areas with moderate to low probabilities are worth investigating on islands with population centers.

The two main Phase 2 field activities currently ongoing (Lautze et al., 2017b) are: (1) geophysical (electromagnetic and gravity) surveys on Lanai and Haleakala's SW rift zone (Maui)—to explore for heated fluid and intrusive rocks; (2) a groundwater sampling and analysis campaign in the ten locations of interest—to validate groundwater indications of geothermal activity and improve knowledge of groundwater flow paths. The latter activity is important because groundwater indicators provide one the most direct ways to detect present-day heat, and groundwater models have large uncertainties due to the variable spatial distribution of well data used to constrain the models.

Energy & Geoscience Institute of the University of Utah: Structurally Controlled Geothermal Systems on the Central Cascadia Arc-BackArc Regime, Oregon

A research team with membership from the University of Utah/EGI, the Oregon State University, and Lawrence Berkeley National Laboratory has carried out a play fairway analysis (PFA) for geothermal resources in the Central Cascades arc-backarc volcano tectonic regime of central Oregon (Wannamaker et al., 2015; 2016b). This is a unique region for geothermal exploration because active Basin and Range (B&R) extension is superimposed upon and contemporaneous with subduction arc magmatism. Cumulative heat flow along the N-S strike grows from negligible values at the north end to >300 MW in the space of approximately 100 km concentrated in the northern portion of the PFA area. Perhaps surprisingly then, no geothermal resources leading to construction of an electricity-producing power plant have yet been identified in the U.S. Cascades.

Play fairway risk is assessed using a simple Common Risk Segment analysis that emphasizes the downweighting of a potential prospect if any play element is deemed of high risk. A challenge in this PFA region is the paucity of existing data, presumably related to the lack of historical geothermal development as well as some non-trivial access. Due to data scarcity, a mixed approach is taken, based upon probability kriging and conceptual global models based on experience in other environments. Furthermore, weighting factors are human-defined, based on expert judgment. However, the weighting factors considered are not wide-ranging and experiments with changing relative values yield only minor changes in the map views of favorability.

The two PFA factors for establishing a geothermal resource are sources of heat and permeability in the region. Criteria selected for establishing heat potential include: (1) direct heat flow measurements in boreholes, (2) magnetotelluric (MT) low resistivity anomalies, (3) fluid geochemistry, and (4) proximity to recent volcanic eruptions. Permeability is established by: (1) fault density, (2) propensity of faulted sub-regions for slip or dilation, and (3) MT low resistivity anomalies. Of the four data types informing heat source, fluid geochemistry data was found to be too sparse to be useful, and silicic volcanics were preferred to mafic. For permeability, this project exploits the extensive coverage of the region by LiDAR data, which has the ability to image fine scale, distributed structure through forest canopy, to determine fault density. A favorable stress state exists region-wide, minimizing its value as a criterion. Note that MT low resistivity anomalies inform both heat source and permeability factors, as they represent the upwelling of hot fluid from depth, which requires both factors to be present.

Heat source and permeability potential are expressed in terms of their individual common risk segment maps, and then combined to form an overall favorability map. Higher weighting is given to heat source, to enable the potential for EGS to be recognized. When land and transmission access is also considered, results suggest that prospective areas may lie along a NW-SE fault trend passing from the Breitenbush Hot Springs area through the Mt Jefferson volcanic edifice into the backarc area, as well possibly as areas nearby to the north of Mt. Jefferson.

4.2.4 Rio Grande Rift

Ruby Mountain Inc.: The Convergence of Heat, Groundwater, and Fracture Permeability: Innovative Play Fairway Modelling Applied to the Tularosa Basin

Tularosa Basin is located in the southern Rio Grande Rift. This extension basin reaches from El Paso, Texas, near its southern boundary, northwardly for about 270 km. It is a sparsely populated region within the Chihuahuan Desert that is home to several military installations, which cover approximately one half of the land area, and which would benefit greatly from geothermal energy development to help meet their Net Zero Energy goals.

The Tularosa Basin Geothermal PFA project (Nash et al., 2016) uses heat, fault-related permeability, and ground water as play fairway factors for geothermal exploration using CRS development. Quantitative geothermal exploration models have also been developed in the past, but their use has been limited. One such model is created through the application of the weights of evidence (WoE) method, which considers the correlation of evidence layer values with those of training sites located at known geothermal systems and hot springs. This project tested the WoE method alongside the deterministic petroleum industry PFA method to compare the effectiveness of both techniques within the study area. Supporting data for both PFA analyses consisted of heat flow, temperature gradients, and quartz geothermometers (heat CRS), Quaternary faults and zones of critical stress (fault-related permeability CRS), and wells that penetrate ground water and springs (ground water CRS).

For the petroleum industry logic PFA, these data were integrated into a final GIS vector based model that identified eight plays. WoE used raster input data and produced a probabilistic raster output, which identified ten plays. Of the 12 total identified plays, six were identified by both methods, two were unique to the deterministic method, and four were unique to the WoE method. Complimentary deterministic and probabilistic certainty maps were produced to help prioritize plays. The highest priority play was the McGregor Range at Fort Bliss in Otero County, New Mexico, which was identified by both methods. This play contains the only known geothermal system in the basin. A medium-high priority play was gleaned from the WoE identified plays and a medium priority play from those produced by the deterministic method. Both methods allowed the delineation of geothermal plays. However, most were low certainty, which was primarily due to data paucity. WoE identified the greatest number of plays; however, it is unknown if its apparent greater sensitivity is real. Play veracity will require additional work. Of the medium to high priority plays, economic analysis indicates that development could take place with reasonably low risk.

Phase 2 activities include (1) geologic reconnaissance will be done on each play, (2) detailed geologic mapping and outcrop fracture analysis will be done for high priority plays, (3) water well sampling and temperature logging will be done on each play, (4) a shallow temperature survey will be done in an area suspected of having surface temperature anomalies, (5) gravity survey infill will be done for high priority plays, and (6) a magnetotelluric survey will be done on the highest priority play. It is expected that this additional work will help determine the viability of the plays and lead to the re-prioritization of plays for additional temperature gradient work, which is sparse or missing over most of the plays.

Los Alamos National Lab: Hydrogeologic Windows: Regional Signature Detection for Blind and Traditional Geothermal Play Fairways

The goal of this project is to develop a methodology to identify blind geothermal systems associated with “hydrogeologic windows” across the Rio Grande Rift and southern Basin and Range Provinces using a wide range of geologic, geophysical, geochemical, and hydrologic data that contain signatures of geothermal upflow zones. Hydrogeologic windows are zones where regional or local aquitards are breached by faulting, erosion, or fractured igneous intrusions, allowing relatively rapid vertical discharge flow from advective geothermal systems, which may be as deep as 4 - 8 km, toward the surface (Person et al., 2015). In many cases, the outflow plume associated with active hydrogeologic windows is hidden below shallow fine-grained facies in the basin fill or by deep static water tables, resulting in a blind system. Examples of these systems in New Mexico include the Rincon (T > 100°C), Radium Springs (T > 60°C), Truth or Consequences (T > 40°C), and Socorro (T > 40°C) geothermal systems. Presently, no formal approach exists that can identify hydrologic windows in blind geothermal systems. They are typically discovered serendipitously during well drilling.

This Geothermal Play Fairway Analysis project sought to develop new ways to analyze geologic, geochemical, and geophysical data to reduce the risk and increase the prospects of successful geothermal exploration and development. Data from southwest New Mexico were collected, organized, and analyzed in the context of an integrated framework that combines the data for various signatures of a geothermal resource into a cohesive analysis of the presence of play fairway factors: heat source, fluid, and permeability (Bielicki et al., 2016). Data types included structural characteristics (earthquakes, geophysical logs, fault location and age, basement depth), topographic and water table elevations, conservative ion concentrations, and thermal information (heat flow, bottom hole temperature, discharge temperature, and basement heat generation). These data were combined to create maps that summarize structural analysis, slope, geothermometry, and heat. Discharge areas were also mapped (to constrain elevations where groundwater may be discharged through modern thermal springs or paleothermal springs). Subcrops, which are possible erosionally- or structurally-controlled breaches in regional-scale aquitards that form the basis of our hydrogeologic windows concept, were also mapped. These two maps were particularly useful in identifying known geothermal systems and narrowing the search for unknown geothermal prospects. We further refined the "prospectivity" of a geothermal resource in the regions within the subcrops and discharge areas by developing and applying a new method for spatial association analysis to data on known and inferred faults, earthquakes, geochemical thermometers, and heat flow. This new methodology determines the relationships of the location and magnitudes of observations of these data with known geothermal sites. The mean prospectivity value for all regions with positive prospectivity was 1.83 (standard deviation = 0.75), whereas this mean prospectivity for known geothermal sites was 3.07 (standard deviation = 0.90). The prospectivity approach also substantially decreases the search area and increases the number of known geothermal resources per km^2 (from 0.004 at prospectivity > 0 to 0.016 at prospectivity > 3), suggesting that limiting an exploration area to regions with high prospectivity scores could reduce exploration costs. These results suggest that the prospectivity analysis using our integrated framework and the hydrogeologic windows concept is useful for identifying known and potential geothermal resources.

4.2.5 Snake River Plain

Utah State University: Geothermal Play Fairway Analysis, Snake River Plain, Idaho

Although the Snake River Plain is part of the highest heat flow anomaly in the US, it has experienced very little geothermal exploration. The project team believes that this results from the lack of obvious high temperature manifestations (except for Yellowstone) and the dominantly basaltic nature of the province. This project addresses systems that are related to basalt magmatism and basalt differentiates, as well as the young rhyolite domes. A particular emphasis is placed on blind resources that may be overlooked using traditional approaches to geothermal exploration.

The play fairway parameters, that is, the three critical resource parameters for exploitable hydrothermal systems in the Snake River Plain are heat source, reservoir and recharge permeability, and cap or seal. Data included in the compilation for heat were heat flow, the distribution and ages of volcanic vents, groundwater temperatures, properties of thermal springs and wells, helium isotope anomalies, and reservoir temperatures estimated using geothermometry (Neupane et al., 2017). Permeability was derived from the analysis of stress orientations and magnitudes, post-Miocene faults, and subsurface structural lineaments based on maximum horizontal gradients of magnetic and gravity data (Glen et al., 2017). Data for seal included the distribution of impermeable lake sediments and clay-seal associated with hydrothermal alteration below the regional aquifer. These data (and the corresponding uncertainty) were used in ArcGIS to compile CRS maps for heat, permeability and seal, which were combined to create a CCRS map for all of southern Idaho that reflects the risk associated with geothermal resource exploration and helps to identify favorable resource tracks (DeAngelo et al., 2016). PFA made use of two training sites, where known geothermal resources exist: Mountain Home and Raft River. Detailed numerical modeling of the Mountain Home site, including coupled fluid flow, heat flow, and geochemical reactions, provides insights into heat source emplacement and cooling (Nielson et al., 2017) and the natural (i.e., pre-production) state (Garg et al., 2016).

The Phase 1 PFA assessment (Shervais et al., 2016) indicates that important undiscovered geothermal resources may be located in several areas of the Snake River Plain (SRP). The results identify eight areas with multiple prospects, each of which may contain resources that equal or exceed the system associated with the 10

MWe Raft River geothermal plant. Four of these areas are in the Western Snake River Plain (WSRP) and include blind systems, two are in the Central Snake River Plain (CSRP), and two are Basin-and-Range play types in eastern and southeastern Idaho. The training site in the WSRP (on Mountain Home Air Force Base) is a blind resource similar in temperature to Raft River. The identified prospects exhibit higher favorability and broader regional extents on CRS and CCRS maps than either of the training sites. Phase 2 activities focused on conducting field studies to better characterize two of these prospective regions: Camas Prairie and Mountain Home (Neupane et al., 2017; Glen et al., 2017; Shervais et al., 2017).

4.3 Discovering Undiscovered (Hidden) Geothermal Resources

The 2008 USGS assessment of geothermal resources in the western United States (Williams et al., 2008) noted that among moderate and high temperature resources, undiscovered hydrothermal systems (which are typically hidden systems with no surface thermal manifestations) have three times the resource potential than identified hydrothermal systems. Conventional identified geothermal systems and hidden geothermal systems have many attributes in common – what separates them is the absence of thermal features at the surface for hidden systems. Given that both types of systems have permeable flow pathways at the reservoir level that are in many cases associated with faults, certain conditions must prevail to prevent the rise of hot, buoyant geothermal fluids to the surface. These may consist of the following factors:

1. Hidden systems may have thicker, better-developed seals.
2. Faults associated with hidden systems may not reach the surface (being buried by younger rocks), or may be sealed by prior hydrothermal alteration.
3. The systems may have depressed water tables that result in no surface thermal manifestations.
4. The systems may be obscured by an overlying cold-water aquifer.
5. The systems may be smaller than identified hydrothermal systems in the same geologic setting. If a system is large and vigorous, it has more opportunity to leak to the surface.
6. The systems may be deeper than their identified geothermal counterparts. A deeper system would make for a longer flow path to the surface and the potential for more impermeable layers to block the upward flow of fluids.

Dobson (2016) reviewed hidden geothermal systems that have been discovered and developed in the Imperial Valley and Basin and Range provinces, and summarized the different exploration methods that were utilized in these efforts, as shown in Table 8 and Table 9.

Table 8. Hidden geothermal fields in the Imperial Valley

Field	Surface features	Initial discovery methods	Field exploration methods	Installed capacity* (MWe)	Resource notes
Heber, CA	None	Oil exploration well drilled in 1945 found hot water	Gravity, reflection seismic, electrical resistivity, SP	142.5 (179.8)	Capping clays above reservoir, with matrix permeability in upper portion of reservoir, fracture permeability in lower part. 100-150 m deep temperature gradient holes most effective way to define resource. Field marked by gravity high.
Brawley, CA	None		Gravity, MT, temperature gradient wells	64 (50)	Temperature gradient wells most effective in delineating resource. Shallow, moderate temperature (315-366°F) reservoir with matrix permeability; deep, high temperature (525°F) reservoir with hypersaline fluids and fracture permeability.
East Mesa, CA	None	Petroleum exploration wells found hot water	Gravity, electrical resistivity, temperature gradient, microseismic, reflection seismic, structural and stratigraphic studies	111.2 (115.4)	Porous sedimentary formation confined by thick clay cap, upflow associated with active fault.

***Installed capacity** - (2014 data) https://www.eia.gov/electricity/data/eia860/; Boyd et al. (2015) values in parentheses.

Table 9. Hidden geothermal fields in the Basin and Range

Field	Surface features	Initial discovery methods	Field exploration methods	Installed capacity* (MWe)	Resource notes
Desert Peak, NV	Minor areas of hydrothermal alteration and small, widely scattered calcareous and siliceous mounds	Investigated due to proximity to Brady's H.S.; regional temperature gradient wells (100 m deep)	Temperature gradient/ stratigraphic wells, electrical resistivity, detailed structural mapping	26 (24.7)	Temperature gradient and deep wells most useful in delineating resource, productive area associated with a normal fault step-over with multiple strands that produce a subvertical conduit of high fracture density.
McGinness Hills, NV	Hydrothermal alteration, silica sinter, and silica-cemented Quaternary alluvium	Minerals exploration boreholes encountered hot water	Field mapping, water chemistry, electrical surveys, gravity survey, 3D GIS modeling, temperature gradient holes	52 (52)	Fault-controlled permeability in reservoir. Field upgraded to 72 MWe in 2015.
Blue Mountain, NV	Hydrothermal alteration in faults, quartz veins and stockworks, intense silicification, silica sinter, moderate to advanced argillic and acid-sulfate alteration	Shallow (< 150 m) gold exploration drilling encountered geothermal fluids at 190°F	Geologic mapping of alteration and structures, temperature gradient wells, electrical resistivity, SP surveys	63.9 (49.5)	Associated with Battle Mountain heat flow high.
Soda Lake, NV	Hot ground with surface alteration 3 miles to NE	A water well drilled in 1903 encountered boiling water	Temperature gradient wells, resistivity, seismic reflection, gravity, aeromagnetic surveys	26.1 (23.1)	Defined by TG wells, in Carson Sink by Holocene maar eruptions, upper km of unconsolidated Quaternary basin fill overlying basalts, andesites, volcaniclastic sediments, and Mesozoic intrusive and metamorphic rocks. Fluid flow controlled by N-NE striking normal faults.
Stillwater, NV		A shallow water well drilled in 1919 hit hot water	Temperature gradient wells, gravity, magnetics, and MT surveys	47.2 (47.3)	Bulk of production from a poorly consolidated Quaternary sandstone, with some production from underlying fractured Tertiary basalts. NS fault zone provides conduit for deep recharge to system.

Raft River, ID	Warm seep (38°C) in The Narrows and altered alluvium by the Bridge well that marks the site of a former hot spring	Boiling water encountered in two 120-150 m deep irrigation wells	Shallow temperature gradient wells, geologic mapping, gravity & magnetics, reflection seismic, resistivity, SP, well geochemistry	18 (15.8)	Original deep exploration wells sited based on location of shallow hot wells. Reservoir is fracture-controlled and hosted in the Precambrian basement, with some production in overlying silicified Tertiary lacustrine deposits and volcanic tuffs and flows. Narrows structure appears to represent a barrier that separates high and low salinity waters. Deep (≥5km) conductor may indicate deep source to system.
Lightning Dock, NM	None	Four agricultural water wells drilled in 1948 found boiling water at a depth <30 m	Temperature gradient wells, gravity, magnetics, electrical resistivity, MT, seismic refraction, CO_2 soil gas, geologic mapping	4 (4)	Geothermal anomaly located over a small, buried, Neogene horst block, with upflow controlled by the intersection of four regional tectonic features; reservoir reported to be hosted in silicified conglomerate and rhyolite ash flow tuff.
Rye Patch Humboldt House, NV	Sinter deposits with hydrothermal alteration; near Florida Canyon gold deposit	Shallow temperature gradient wells identified thermal anomaly	Temperature gradient wells, seismic reflection, gravity & magnetics, LiDAR & hyperspectral imaging	12.5 MWe plant built but never put online (Benoit, 1994)	Two aquifers encountered: one near Tertiary-Mesozoic unconformity, and other within sequence of Mesozoic sediments (limestone, phyllite, siltstone and sandstone). Newest model consists of a dilational, pull-apart block. Key challenge is encountering permeability.
Tungsten Mtn., NV	Minor argillic alteration, carbonate tufa, chalcedony along the range-front fault	Gold exploration drill holes encountered hot water and steam	Temperature gradient wells, 2 m temperature survey, gravity, structural mapping	24 MWe plant	Field began commercial operation in Dec. 2017.

***Installed capacity** - (2014 data) https://www.eia.gov/electricity/data/eia860/; Boyd et al. (2015) values in parentheses.

Many of the systems shown in Table 8 and Table 9 were initially identified by accident, i.e., exploring for water, oil and gas, or minerals. However, the actual discoveries in most cases were made through the use of a comprehensive suite of normal geothermal exploration tools. Key exploration methods include the following:

1. Heat flow and temperature gradient methods: Traditional heat flow studies utilize >100-meter deep temperature gradient wells; shallow thermal anomalies found using 2-meter holes have identified a number of hidden geothermal prospects in the Basin and Range province.

2. Electrical and magnetic methods: The DC resistivity and MT techniques map out the subsurface distribution of low-resistivity cap rocks that form as a result of argillic alteration, defining the top and margins of the geothermal reservoir, while the seismic profile (SP) method can identify zones of enhanced permeability.

3. Gravity surveys: Gravity highs associated with geothermal systems may indicate the deposition of secondary mineral phases by circulating hydrothermal fluid, the presence of elevated temperatures, and the emplacement of magmatic intrusions beneath these systems.

4. Field mapping of structural geology: In addition to requiring a heat source, hidden hydrothermal systems also need to have the appropriate structural setting to facilitate convective fluid flow in the reservoir. For example, in the Basin and Range province, hydrothermal activity is often associated with intersecting faults or a normal fault step-over.

5. Identification of surface alteration features: Often, surface alteration is associated with the active system below, and resulted from the previous circulation of hot fluids that reached the surface.

6. Development of conceptual models/data integration: Utilizing multiple geologic, geophysical, and geochemical tools to look for the key traits of geothermal systems, such as a heat source and zones of elevated permeability, and integrating them into a coherent conceptual model is called geologic framework modeling.

7. Soil gas surveys: Anomalous quantities of Rn, Th, He, H_2, O_2, N_2, Hg, CO_2, CH_4, and H_2S in soil gas have been used to identify underlying geothermal systems, as have isotopic signatures.

8. Reflection seismic and microseismic monitoring.

9. Remote sensing: LiDAR and hyperspectral surveys.

10. Geochemical analysis of well waters.

11. Deep exploration drilling.

Based on this review, several recommendations are made that might reduce the risk associated with exploration of hidden systems:

1. Data mining of diverse data sets can identify overlooked clues to the presence of hidden systems. Comprehensive screening of all classes of wells and boreholes can help identify prospective areas with thermal anomalies. Hydrothermal alteration features such as tufas and sinters can also indicate fairly recent thermal activity.

2. Conceptual models for hidden system play types need to be developed for distinct tectonic settings. Careful evaluation of case studies of discovered and developed hidden systems for the Imperial Valley and the Basin and Range regions can help in the creation of these models. Once the diagnostic features of these systems have been identified, this can provide information on which exploration methods are most effective for each specific play type (see play fairway analysis in Section 4.2 above).

3. Utilization of an already discovered class of hidden systems—sedimentary basins. There is extensive information on these basins from oil and gas exploration and development efforts (e.g., Porro et al., 2012; Anderson, 2013; Allis et al., 2013). Many oil and gas wells produce significant amounts of hot water—utilization of these coproduced fluids constitutes a low risk approach to exploit these extensive medium temperature resources.

4.4 EGS Techniques

DOE has a long history of supporting RD&D related to Enhanced Geothermal Systems (EGS), dating back to the Fenton Hill project, where groundbreaking field studies were conducted between 1970 and 1995 (Kelkar et al., 2016). In 2005, DOE assembled a panel “to evaluate the technical and economic feasibility of EGS becoming a major supplier of primary energy for U.S. baseload generation capacity by 2050” (Ziagos et al., 2013). The resulting report (Tester et al., 2006) provided a comprehensive review of past EGS projects as well as an assessment of EGS resources in the U.S., and concluded that EGS could provide a significant (100 GWe) contribution to the U.S. energy supply by 2050, provided that appropriate RD&D efforts were conducted to help reduce the costs associated with drilling, power conversion, and reservoir technologies needed for commercial, large-scale deployment of these resources.

Over the past decade, DOE's Geothermal Technologies Office (GTO) has initiated several major EGS research initiatives to address the key research questions associated with characterization, reservoir creation, sustainability, and operation of EGS. These include the following:

1. EGS field demonstration projects at The Geysers, Desert Peak, Raft River, Brady's, and Newberry.

2. The SubTER crosscutting research projects, which were conducted in conjunction with other DOE programs, focused on adaptive control of the subsurface. Several of these projects addressed fracture creation, subsurface monitoring, stress measurements, and permeability enhancement.

3. The EGS Collab project, a suite of integrated field and coupled process modeling experiments designed to help understand and predict permeability enhancement and evolution in crystalline rocks at intermediate scales (10-20 m), including how to create sustained and distributed permeability for heat extraction from an EGS reservoir.

4. The Frontier Observatory for Research in Geothermal Energy (FORGE), a dedicated field site that will host R&D activities focused on innovative drilling techniques, reservoir stimulation techniques and well connectivity and flow-testing efforts.

This section provides descriptions of DOE's recent and ongoing EGS research initiatives listed above. The EGS field demonstration projects provided some important lessons and created some key technology advances regarding well stimulation and monitoring activities. The highlights include the following:

1. The response of a well to differing stimulation methods (hydraulic, chemical, and thermal) varied from site to site, and each location needs to be evaluated based on the rock types, the preexisting fracture network (i.e., the distribution and orientation of fractures) and the stress conditions when designing a stimulation program. In all of the field experiments, more than one stimulation phase was applied, and in most cases, more than one stimulation approach was utilized. In some cases, significant increases in permeability were observed right away, while in others, incremental improvements in permeability occurred as long-term stimulation was carried out. Additional evaluation of the field test data is needed to gain a better understanding of why the stimulation methods were effective in some sites, and less so in others.

2. Each field project developed their own site-specific Induced Seismicity Mitigation Plan to meet the DOE protocol. Microseismic monitoring was utilized in all field sites, but it had varying degrees of success in tracking the stimulation of fractures associated with reservoir creation. For some locations, such as the Geysers and Newberry, abundant microseismic activity could be clearly linked with injection, whereas at other sites, such as Desert Peak and Raft River, very little induced seismicity could be detected even with very large volumes of fluid being injected (over 800 million gallons at Raft River). Location of the micro-earthquakes (MEQs) depends on having a robust velocity model of the site. This is critical for accurately locating the stimulated reservoir volume so that a production well could be precisely targeted to intersect this region.

3. All of the field sites used "wells of opportunity," i.e., existing wells with low permeability, for the injection projects. As such, they were not drilled nor completed in a way that would be optimized for EGS. Almost all existing geothermal fields have similar "failed" wells with low permeability, so development of effective well stimulation methods would allow many such wells to be converted into

commercially viable injection or production wells. This methodology would allow for utilization of infield EGS within low permeability zones of conventional hydrothermal systems.

4. The Newberry EGS project was the only true “green field” EGS demonstration project. One important technology that was utilized successfully at this site was a thermally degradable zonal isolation material (TZIM), designed to temporarily isolate zones that were stimulated initially so that additional stimulation could shear other fracture sets, resulting in multiple zones with enhanced permeability (Cladouhos et al., 2016).

Another recent DOE R&D initiative is the Subsurface and Engineering Research, Development, and Demonstration (SubTER) crosscut. This initiative, supported by multiple DOE programs, is focused on adaptive control of subsurface fractures and fluid flow, and has four main areas of research: (1) wellbore integrity and drilling technologies, (2) subsurface stress and induced seismicity, (3) permeability manipulation and fluid control, and (4) new subsurface signals. Two of the SubTER projects directly addressed the challenges faced by EGS: (1) the kISMET project (Oldenburg et al., 2017), which focused on subsurface stress characterization and hydraulic fracture stimulation in crystalline rock at a depth of approximately 1.5 km in the old Homestake Mine in Lead, SD; and (2) the Blue Canyon Dome project (Knox et al., 2016), which focused on imaging explosively generated subsurface fractures using seismic and electrical tomography methods. Both projects were able to test innovative methods to monitor fracture initiation and growth.

One of the latest GTO initiatives is the EGS Collab project, which is establishing a collaborative experimental suite of intermediate-scale (~10-20 m) field test beds coupled with stimulation and interwell flow tests to constrain and validate coupled process models. The first phase of this project is being conducted by a diverse team of national lab and university researchers at the Sanford Underground Research Facility at a depth of approximately 1.5 km, in a location close to the kISMET experiment. Data on fracture permeability enhancement mechanisms (e.g., slip on existing fractures, new fracture generation, and mixed-mode fracturing) will be gathered through carefully designed and closely monitored fracturing and fluid-flow experiments, and will elucidate the basic relationships between stress, induced seismicity, and permeability enhancement. The proposed stimulation and fluid flow experiments will create a rich data set that will be used to validate the capabilities of predictive models that will be employed to support FORGE (Dobson et al., 2017b).

DOE’s flagship R&D EGS project is the FORGE. This dedicated field site will be used to test innovative technologies and methods to improve the subsurface characterization, reservoir access (drilling), reservoir creation (stimulation), and sustainability of an EGS. Phase 1 of this project evaluated five distinct sites for FORGE and two of these locations (Fallon, Nevada, and Milford, Utah) are undergoing further evaluation as part of Phase 2. Research boreholes drilled at these sites during Phase 2 will further evaluate the suitability of these sites (appropriate temperature, lithology, and permeability), and a down-select process in 2018 will result in the selection of the final FORGE location. Phase 3 activities will include the use of directional drilling, testing of new techniques for reservoir stimulation and zonal isolation, addressing ways to increase production well flow rates without developing short circuits, and identifying ways to maintain productivity in an EGS reservoir with minimal thermal drawdown and water losses. The overarching goal of FORGE is to achieve needed technology advances that would make large-scale commercial deployment of EGS in the U.S. possible.

4.4.1 In-field Expansions of Current Hydrothermal Systems

4.4.1.1 Northwest Geysers

An EGS demonstration project is currently underway in the Northwest Geysers (Garcia et al., 2016; Rutqvist et al., 2016), a vapor-dominated geothermal field sited within the San Andreas fault system in northern California. The project goal is to demonstrate the feasibility of stimulating a deep high-temperature reservoir (HTR) (depth greater than 2,700 m, temperatures up to 400°C) that has high non-condensable gas contents. The host rock for the HTR is metagraywacke, the same rock as for the overlying hydrothermal reservoir, except that it has been thermally altered. Two previously abandoned wells, Prati State 31 (PS-31) and Prati 32 (P-32), were reopened and deepened to be used as an injection and production doublet to stimulate the HTR. The deepened portions of both wells had conductive temperature gradients of 182°C/km, produced connate native fluids and magmatic gas, and the rocks were isotopically unexchanged by meteoric water (Lutz et al., 2012).

Injection into P-32 began on October 6, 2011. A one-year stimulation injection was conducted, systematically injecting cool water at carefully designed injection rates, keeping the bottom-hole pressure much below fracturing pressure, aiming at a gentle but pervasive stimulation of the existing fracture network. Thereafter, monitoring and analysis of the long-term sustainability of the system during continuous injection and production from the EGS occurred. Monitoring methods included microseismic (Lawrence Berkeley Induced Seismicity EGS), pressure-transient, non-condensable gases, chlorides, stable isotopes, and satellite-based ground surface deformation. The ambient-temperature meteoric water injected into these hot dry rocks evidently created a permeability volume of several cubic kilometers as determined by microseismic monitoring. Preliminary isotopic analyses of the injected and produced water indicated that 50 - 75% of the steam from the created EGS reservoir is injection-derived.

Injection in P-32 resulted in a substantial reservoir pressure rise in the area compared to values observed in the 1980s. The stimulation has also caused an increase in the flow rate at neighboring well P-25 and a considerable reduction of the NCG concentration in the P-25 steam. Pressure transient analysis of PS-31 flow rate indicates that following stimulation the permeability-thickness product approximately doubled from the value found when the well was re-opened. This increase is considered small but it is an indication that permeability has increased at the EGS site, albeit at a low rate.

Comprehensive seismic data collection and analysis (e.g., Jeanne et al.; 2014a; 2014b; 2014c; 2015a) have been an integral part of the EGS demonstration project. A seismicity cluster began to develop almost immediately after P-32 water injection was initiated, and data analysis indicates: (1) the opening of new permeability zones defined by seismicity that are confined in time/space; (2) preferential water movement NNW (N130) trending along tilted zones of permeability; (3) limited water flow to the southeast and northeast which correlates with surface faulting; (4) the downward progression of seismicity indicating deeper permeability stimulation; and (5) increased seismicity associated with an injection rate increase, followed by a significant decrease in event frequency. The linear alignment of seismicity hypocenters (representing hydraulic discontinuities) correlate very well with other constraints such as lithology logs, well pressure measurements, well temperature measurements and previous surface mapping.

A coupled thermal, hydraulic, and mechanical (THM) model was developed as part of the pre-stimulation phase of the EGS demonstration project (Rutqvist et al., 2015). Model simulations were conducted to investigate injection strategies and the resulting effects of cold-water injection upon the EGS system; in particular to predict the extent of the stimulation zone for a given injection schedule. After the actual injection began, pre-stimulation model predictions were compared with MEQ monitoring data over the first few months of the one-year stimulation period. The results show that the predicted extent of the stimulation zone (defined as a zone of high MEQ density around the injection well) compares well with observed seismicity.

In general, the creation of an EGS reservoir may be achieved by two methods: (1) high pressure hydraulic fracturing to create new fractures over a very short period of time (hours), or (2) the shear reactivation of pre-existing fractures at relatively low pressures just high enough to cause shear failure over a long-time period (months). At the Northwest Geysers, modeling indicates that shear reactivation of pre-existing fractures is triggered by the combined effects of injection-induced cooling around the injection well and rapid (but small) changes in steam pressure as far as half a kilometer from the injection well (Rutqvist et al., 2015).

Pressure-monitoring data at adjacent wells and satellite-based ground surface deformation data (Vasco et al., 2013) were also used to validate and further calibrate reservoir-scale hydraulic and mechanical model properties (Rutqvist et al., 2015). The pressure signature monitored from the start of the injection was particularly useful for a precise back-calculation of reservoir porosity. The first few months of reservoir pressure and surface deformation data were useful for estimating the reservoir rock permeability and elastic modulus. Finally, although the extent of the calculated stimulation zone matches the field observations over the first few months of injection, the observed surface deformations and MEQ evolution showed more heterogeneous behavior as a result of more complex geology, including minor faults and fracture zones that are important for consideration in the analysis of energy production and the long-term evolution of the EGS system.

Therefore, for an interpretive analysis of the one-year stimulation campaign, two sets of vertical shear zones were included within the model: (1) a set of more permeable NW-striking shear zones, and (2) a set of less permeable NE-striking shear zones (Rutqvist et al., 2016). Overall, the integrated monitoring and modeling of microseismicity, ground surface deformations, reservoir pressure, fluid chemical composition, and seismic tomography depict an EGS system hydraulically bounded by some of the NE-striking low permeability shear zones, with the more permeable NW-striking shear zone providing liquid flow paths for stimulation deep (several kilometers) down into the HTR. The modeling indicates that a significant mechanical degradation (damage) inferred from seismic tomography (Jeanne et al., 2015b), and potential changes in fracture porosity inferred from cross-well pressure responses, are related to shear rupture in the stimulation zone driven by both pressure and cooling effects.

4.4.1.2 Desert Peak

Following an integrated study of fluid flow and geology (Zemach et al., 2010), fracturing and stress (Hickman and Davatzes, 2010), and rock mechanics (Lutz et al., 2010), silicified rhyolite tuffs and metamorphosed mudstones were hydraulically and chemically stimulated in Desert Peak well 27-15 as part of an Enhanced Geothermal System (EGS) project (Chabora et al., 2012). Well 27-15 is located on the margins of the Desert Peak geothermal field located in western Nevada, in the Basin and Range province. For the initial portion of the project (2010 - 2012), the stimulated zone was at a depth from 914 to 1,067 m, denoted the shallow zone. The stimulation zone was then deepened to extend from 914 to 1,770 m, denoted the extended zone, for stimulations in 2013. Well 27-15 was chosen because it showed poor initial potential as either a producer or injector, was close to the existing infrastructure, had favorable bottom hole temperatures (about 200°C at 1,000 m depth), and demonstrated hydraulic connectivity to nearby injection wells.

Stimulation in the shallow zone began in September 2010 with a long period of shear stimulation that was carried out at low fluid pressures (less than the least horizontal principal stress, S_{hmin}). This stimulation was intended to promote the propagation of shear displacement along existing fracture planes, ideally resulting in self-propping dilatation that yields permanent gains in permeability after fluid pressures are reduced. This shear stimulation increased injectivity by more than one order of magnitude, but it was not permanent. In February 2011, chemical stimulation with chelating agents and mud acid treatments was used to dissolve mineral precipitates and open partially sealed fractures. This chemical stimulation phase temporarily increased injectivity, but led to increased wellbore instability and collapse. After wellbore clean-out, a large-volume hydraulic fracturing operation was carried out in April 2011 at high pressures (exceeding S_{hmin}) and medium to high injection rates, to promote fluid pressure transfer to greater distances from the borehole, resulting in an additional four-fold increase in injectivity. The injectivity gains were consistent with hydraulically induced mechanical shear (for $P < S_{hmin}$) and tensile (for $P > S_{hmin}$) failure in the surrounding rock. Subsequent injections at high pressures were conducted in May-June and October 2011. In November 2012, the stimulation zone was deepened to 1,770 m. Stimulation at a pressure comparable to S_{hmin} was conducted in January 2013 and at a pressure less than S_{hmin} during February-March 2013.

A multi-faceted monitoring program included wellhead and downhole pressure monitoring and periodic pressure-temperature-spinner (PTS) surveys in the injection well 27-15, tracer monitoring in nearby production wells, and the real-time observation of MEQs through an in-field multi-component seismic monitoring array (Lawrence Berkeley Induced Seismicity EGS) with the goal of tracking the progress of the stimulation.

Induced seismicity played a key role in identifying a large northeast-trending normal fault structure located approximately 400 m below the shallow injection interval that coincides with the locations of most of the observed micro-seismicity. This structure may provide a hydrologic connection between EGS well 27-15 and injection/production wells further to the south–southwest. Identification of this structure during the analysis of the shallow-zone simulations motivated the deepening of the stimulation zone.

Real-time observation of MEQ events during shallow-zone stimulations proved to be a valuable tool, but the project team recognized several areas where improvements were needed. First, the location of the geophones required further optimization with respect to the stimulation target and possible sources of noise. Second, excessive surface noise observed throughout the operations highlighted the need for more geophones to be deployed below the ground surface in dedicated boreholes. Finally, the detection algorithm would need to be further refined in order to filter false triggers more effectively and identify small events ($Mw < 0$) generated by the stimulation. These issues were addressed when the microseismic monitoring array was upgraded prior to the extended-zone stimulations.

Thermo-hydrologic mechanical (THM) modeling played an integral role in interpreting all the stimulation tests, providing important insights into the permeability change processes activated for given sets of injecting conditions. Benato et al. (2013) and Dempsey et al. (2015) modeled the low-pressure shallow-zone stimulations as shearing along existing faults, and both models predicted the observed lack of MEQ for the lowest pressure tests. Benato et al. (2016) found that the high-pressure, medium-flow shallow-zone stimulation could instigate tensile failure close to the injection interval and shear failure at greater depths on the fault structure. Benato and Taron (2016) examined medium- and high-flow shallow-zone tests and all extended-zone tests, and concluded that matching the observed well-head pressure responses differentiated between tensile failure (slow, steady pressure decline) and shear failure (irregular, rapid pressure decline). Thermo-mechanical and hydro-mechanical processes (tension) were found to govern permeability enhancement during the main stimulation phases of the shallow zone of well 27–15. The development of permeability related to these processes is limited to rock mass volumes near the wellbore (~6 to10 m), as fluid pressure drops below S_{hmin} at a small distance from the open interval. In contrast, shear failure processes developing on the deeper fault structure seem to control most of the permeability gain produced during the well 27–15 extended-zone stimulations.

4.4.1.3 Brady's

The geothermal field at Brady's Hot Springs, NV, is adjacent to the Desert Peak site. The stratigraphy at Brady's is similar to that of Desert Peak; both sites possess sedimentary rocks overlying Tertiary volcanic rocks and metamorphic basement rock of varying lithologies. At both sites, heat and permeability are controlled by regionally high heat flow and Basin and Range-style Miocene to Recent extensional faulting. Geological, geophysical and log data collected at Desert Peak have proven beneficial to the overall understanding of the geological environment at Brady's Hot Springs and for developing the EGS project. Research indicates, however, that the Brady's and Desert Peak heat sources are independent thermal plumes (Ziagos et al., 2013). Fluid flow at Brady's is controlled by a left step-over in the west-dipping, north-northeast-striking Brady's fault zone (Queen et al., 2016). Wells that are deeper than the rest of the production field were drilled recently in order to intercept the fault at greater depths and higher temperatures. Equilibrated down-hole fluid temperatures at Brady's have been measured as high as 207°C. In general, the existing production wells range in depth from 600-1,500 m and produce from near the fault zone. The Brady's EGS target well (15-12 ST-1) extends to 1,525 m depth and intersects a rhyolite unit some distance from the fault zone, where permeability is low but temperatures are in excess of 204°C and extensive fractures have been identified, making it an excellent candidate for stimulation.

The EGS demonstration project is divided into three phases. Phase 1: Characterization of the Target Well to Prepare for Stimulation Activities; Phase 2: Well Stimulation and Collection/Analysis of Stimulation Monitoring Data; and Phase 3: Long-Term Testing of the System.

During Phase 2, a series of stimulations were conducted at well 15-12 ST-1, beginning with low injection rates and well pressure below S_{hmin}, and continuing with increasing injection rates and well pressure above S_{hmin}. Injectivity was observed to increase throughout the series of stimulations, until during the subsequent Phase 3 long-term injection, injectivity showed a 30-fold increase compared to the baseline injectivity (Drakos and Akerley, 2015). An array of eight shallow (30 m) borehole three-component seismic monitoring stations was installed at Brady's Hot Springs to monitor seismic activity prior to and during EGS activity at the Brady's site (Lawrence Berkeley Induced Seismicity EGS).

4.4.1.4 Raft River

An EGS demonstration project is taking place at U.S. Geothermal's Raft River Field in Idaho. The Raft River Valley is located in Cassia County, southwestern Idaho, on the northeastern edge of the Basin and Range province and on the southern side of the Snake River Plain (Ayling and Moore, 2013). The wells at Raft River pass through nearly 1,500 m of discontinuous Tertiary and Quaternary volcanic and volcanoclastic rocks that overlie metamorphic Precambrian basement rocks. Fluid is primarily produced and injected back into the Elba Quartzite, located in the Precambrian basement. Fluid flow is fracture- and fault-controlled. The average resource temperature of the produced fluid is 150°C, but geochemistry suggests temperatures may be as great as 260°C in deeper portions of the resource (Ayling and Moore, 2013).

Since the summer of 2013, a DOE EGS stimulation program has injected almost 1 million cubic meters of sub-reservoir temperature water into the well RRG-9 ST1, which intercepts the Elba Quartzite between depths of 1,600 m and 1,800 m, in an attempt to increase permeability of existing fractures by a combination of hydraulic and thermal effects (Bradford et al., 2015; 2016). The water source alternated between the geothermal plant (T = 34°C) and colder well water (T = 10-12°C). These stimulations have led to a significant improvement in the performance of the well. Over time, injection rates have increased from near zero in June 2013 to 3,546 Lpm (937 gpm) in February 2016, at constant or decreasing wellhead pressures. This injectivity improvement was achieved through a combination of three hydraulic stimulations accompanied by thermal contraction of the surrounding rocks. At the shortest timescale, distinct jumps in injectivity occurred following the two high-pressure injection tests in August 2013 and April 2014. These jumps suggest that near-well permeability increases have occurred via hydroshearing of fractures or mitigation of well skin effects developed during drilling.

Geologic, water chemistry, microseismic activity, and borehole imaging data have been used to develop a conceptual model describing possible flow paths of injected water from a highly fractured zone connecting well RRG-9 ST1 to a Northeast striking shear zone known as the Narrows, then through the Narrows to producing wells. The well stimulation program was simulated numerically using an Idaho National Laboratory reservoir simulation code, FALCON, a flow and transport code in which permeability can be adjusted to represent the effects of hydraulic and thermal stimulation (Bradford et al., 2016). These simulations indicate a significant increase in the permeability of connecting fracture pathways occurred after each stimulation event.

The increased injectivity arising from the stimulations has enabled well RRG-9 ST1 to be converted into a commercial injection well. The team's success at the Raft River EGS demonstration shows the importance of low-pressure thermal stimulation as the primary mechanism for improving the injectivity of the EGS well. Since injection began in June 2013, only 180 microseismic events have been recorded field-wide, some of which appear to be related to injection into other wells.

Broad collaboration on this EGS demonstration project has contributed significantly to its success to date. Lawrence Berkeley National Laboratory's (LBNL) Distributed Temperature Sensor (DTS) array, deployed in the wellbore during injection activities, was instrumental to the monitoring efforts and analysis associated with the stimulation. Additionally, LBNL deployed the microseismic array used to monitor the EGS activities (Lawrence Berkeley Induced Seismicity EGS). Also, Idaho National Laboratory (INL) is providing critical insight to the evolution of the geothermal reservoir via modeling of the thermal and hydraulic behavior of the reservoir in response to the well stimulation (Plummer et al., 2015). Breakthrough techniques in this field are advancing the field of well injectivity, ultimately contributing to the adoption and large-scale deployment of EGS.

4.4.2 Greenfields: Near-field and Deep EGS

The Newberry Volcano EGS Demonstration is a five-year field project in central Oregon, located at the intersection of three geological provinces: the Cascade Range, the High Lava Plains of the Basin and Range, and the Blue Mountains, which is designed to demonstrate recent technological advances for EGS development. Advances in reservoir stimulation and monitoring are being tested in a hot (>300°C), dry well (NWG 55-29) drilled in 2008, at depths around 3,000 m.

In support of the field experiments, a petrophysical and geomechanical characterization program focusing on the rock mechanical properties of welded tuffs from Newberry volcano was conducted (Wang et al., 2016). Petrographic thin sections were prepared and used to describe rock texture and mineralogy, a high-resolution X-ray CT scanner was used to provide 3D images of the rock pore structure, rock porosity and permeability were measured, and triaxial compression tests were performed to determine Young's modulus, Poisson's ratio, and failure envelopes. In particular, multistage triaxial compression tests were carried out to determine deformation and failure properties, and to establish relationships between petrophysical and mechanical/failure properties. In addition, multistage triaxial shear tests were performed to determine the mechanical properties and shear strengths of the fractures developed in triaxial compression tests. The data set obtained in this study is very useful for stimulation design and interpretation of observed microseismicity in relation to permeability enhancement.

Well stimulation is via hydroshearing, wherein water at pressure below the minimum principal stress is injected, to cause existing fractures to dilate and slip in shear. After shear-slip, irregularities along the natural fracture surfaces cause the fractures to remain self-propped, creating lasting permeability enhancement. This ability to enhance permeability without the use of proppants, which may not last at high temperatures, is another benefit of hydroshearing. Well stimulation carried out in 2012 indicated that casing repairs were needed; confirmed by further wellbore logging and analysis in 2013. Repairs were completed in August 2014, and the well was re-stimulated in the fall and 9,500 $m^{3\,(}$2.5 million gallons) of groundwater were injected at a maximum well-head pressure of 195 bar (2850 psi) over 4 four weeks of hydraulic stimulation.

A key feature of the Newberry project is the use of thermally degradable zonal isolation materials (TZIM), which enables stimulation of multiple fracture sets in a single well, by hydraulically isolating each fracture network after it has been stimulated (Cladouhos et al., 2013a; 2016). After the stimulation of the first fracture set, a pill of TZIM is mixed and pumped to temporarily seal the fracture network stimulated in the first stage from accepting additional fluid. Additional pressure is then applied to the well and a second set of fractures, which had a higher minimum hydroshearing pressure than the fractures stimulated in the previous stage, are stimulated. After multiple fractures are stimulated, injection is discontinued and the well bore is allowed to reheat to the original well temperature. This causes the TZIM material to thermally degrade, leaving all fractures open for circulation and flow during the operation of the EGS reservoir.

Multiple monitoring methods were deployed during the Newberry stimulation, including pressure and flow rate to infer injectivity changes, thermal profiles (DTS) (Petty et al., 2013), tracers (Dean et al., 2013), flow back, and microseismicity (Cladouhos et al., 2013b; Matzel et al., 2014; Templeton et al., 2014). Injectivity increases indicate that fracture permeability in well NWG 55-29 was enhanced. The fifteen-station microseismic array located 398 events in 2014, ranging in magnitude from M 0 to M 2.26, identifying a fracture extent of at least 200 m (Lawrence Berkeley Induced Seismicity EGS). Temperature logs run after injection of TZIM showed that at least two flow zones were blocked and one or two new zones opened because of the injected TZIM. Breakdown products of TZIM were detected in flow-back fluids, indicating that the material degraded as predicted. An overlying groundwater aquifer that provided water for the stimulation was monitored for pressure and geochemistry (Grasso et al., 2013) and no adverse effects were found.

Coupled Thermal Hydrologic Chemical (THC) modeling of the natural state at Newberry and coupled Thermal Hydrologic Mechanical Chemical (THMC) modeling of the stimulation processes were conducted (Sonnenthal et al., 2012; 2015). A 3D model was developed using low-pressure injection tests in 2010 and 2013 and the 2012 stimulation test. The model was used to evaluate processes and for planning the 2014 stimulation test. The model captured the approximately four-fold increase in injection rates obtained in the 2014 stimulation test quite closely, as well as the spatial distribution of permeability increases and pressure changes.

This work demonstrates the viability of large-volume low-pressure stimulation coupled with non-mechanical zonal isolation technology and microseismic monitoring for reservoir mapping.

4.4.3 SubTER Field Experiments/Laboratories

4.4.3.1 kISMET: Permeability (k) and Induced Seismicity Management for Energy Technologies

The kISMET SubTER project was led by Lawrence Berkeley National Laboratory, with participation by multiple national laboratories, universities, and industry partners throughout the U.S. The two-year project was concluded in October 2016.

The overall focus of the kISMET project was to investigate stress measurement and fracture stimulation with borehole monitoring to characterize relations between stress, induced fractures, and rock fabric. The kISMET research and development efforts are aimed at providing major contributions to the SubTER Crosscut pillars: (1) Wellbore Integrity & Drilling Technologies; (2) Subsurface Stress & Induced Seismicity; (3) Permeability Manipulation & Fluid Control; and (4) New Subsurface Signals.

The specific objectives of the kISMET project were to:

1. Investigate the relationship between fractures (natural and induced) and stress field, rock fabric, and stimulation approach to inform EGS stimulation

2. Investigate microseismicity arising from fracturing as an analog for deep basement rock induced seismicity underlying a deep injection site

3. Establish a SubTER field observatory.

The approach taken to meet these objectives consisted of the following:

1. Drill and core five boreholes at SURF (Sanford Underground Research Facility, located in the former Homestake Mine in Lead, South Dakota) for fracture stimulation and monitoring

2. Characterize the site

    - Lithology, rock fabric, structure, hydrology

    - Stress state (local and mine-wide)

    - Existing fractures (map orientations, size, aperture, etc.)

3. Instrument the site and surroundings to monitor fracturing, seismic response, and to characterize and image the resulting fracture(s)

4. Carry out hydraulic fracturing in the borehole for stress measurement and for stimulating fractures

5. Analyze seismic, ERT, and induced seismicity data to characterize fracture(s).

The kISMET project findings are detailed in Oldenburg et al. (2016b; 2017) and are summarized as follows.

A field test facility was established in a deep mine, where the large overburden stress σ_v is representative of typical EGS sites, and in situ hydraulic fracturing experiments were designed and carried out in the crystalline Precambrian schist and other metamorphic rocks, to characterize the stress field, understand the effects of rock fabric on fracturing, and gain experience in monitoring using geophysical methods. The project also included pre- and post-fracturing simulation and analysis, laboratory measurements and experiments, and an extended analysis of the local stress state using previously collected data.

Currently, the orientation of the stress field is being used to interpret a large number of borehole breakouts recorded in nearby boreholes at SURF to generate a more complete picture of the stress field and its variations at SURF. The efforts on the project have prompted recommendations for a host of additional follow-on studies that can be carried out at the kISMET site.

4.4.3.2 Blue Canyon Dome

Efficient reservoir enhancement, whether it is applied to tight shale gases or geothermal reservoirs, requires both effective stimulation and real-time feedback. It is easy to imagine a system where an initial stimulation would occur and real-time feedback could drive all subsequent stimulations. This would enable a well to be stimulated safely until no further economic benefit could be realized. For the present project (Knox et al., 2016), coupling novel energetic stimulations (i.e., explosions) with multi-disciplinary geophysical change-detection techniques provides an avenue under which this system is realized.

The work was conducted at the Blue Canyon Dome in Socorro, NM. The field site, which is comprised of a series of shallow boreholes, is situated on a ridge on Socorro Peak. The ridge itself is unbounded on three sides (making it approximately stress free) and consists of a two-layer geologic system. The uppermost layer (approximately top 10 m) is comprised of weathered (i.e., highly fractured) rhyolite. The second layer is un-weathered rhyolite with sparse near-vertical natural fractures that have been mineralized.

During the initial phase of this project, a series of high-energy stimulations in the wells were conducted, the effects of which were evaluated with high resolution seismic imaging campaigns designed to characterize induced fractures. The high-energy stimulations used a novel explosive source that limited damage to the borehole, which is paramount for change detection, seismic imaging, and re-fracturing experiments. The time-lapse crosswell seismic campaign interrogated the fracture set from all sides at close offsets and with very closely spaced source and receiver positions. This technique, which is commonplace in non-destructive testing of civil structures, utilizes logging equipment rather than traditional hydrophone arrays and single seismic sources, which would be cost prohibitive for the large number of measurements required to achieve detailed time-lapse imaging. This work provided evidence that the high-energy stimulations were generating self-propping fractures and that these fracture locations could be imaged at inch scales using high-frequency seismic tomography.

While the seismic testing certainly provided valuable feedback on fracture generation for the suite of explosives, it left many fracture properties (i.e., permeability) unresolved. The methodology for the second phase of the project involves developing and demonstrating emerging seismic and electrical geophysical imaging technologies that have been designed to characterize: (1) the 3D extent and distribution of fractures stimulated from the explosive source, (2) 3D fluid transport within the stimulated fracture network, and (3) fracture attributes through advanced data analysis. Monitoring techniques include real time electrical resistance (ERT) and seismic tomography, campaign-style high resolution seismic tomography, the use of a novel contrasting agent, continuous recording on a fiber optic cable (i.e., Digital Acoustic Sensing and Digital Temperature Sensing) array, traditional pressure decay tests, and traditional borehole logging techniques for imaging fractures. Analysis of the resulting data sets will include implementation of joint inversions, passive seismic interferometry, and change detection techniques. Focus is being placed upon advancing these technologies toward near real-time acquisition and processing in order to help provide the feedback mechanism necessary to understand and control fracture stimulation and fluid flow.

4.4.4 EGS Collab (SIGMA-V): Stimulation Investigations for Geothermal Modeling Analysis and Validation Project

The EGS Collab project is a multi-national laboratory and university collaborative research project supported by the DOE Geothermal Technologies Office. The project is led by Lawrence Berkeley National Laboratory and brings together some of the world's most skilled and experienced scientists and engineers in the areas of subsurface process modeling, monitoring, and experimentation. The project focuses on intermediate-scale EGS reservoir creation processes and related model validation at crystalline rock sites. Cooperative research under the three-year EGS Collab project began in early 2017 and will be focused on a field site at SURF (see description of the kISMET project above). It will build on the understanding gained from the kISMET project and provide a foundation of knowledge and modeling capability that form a bridge to meeting the challenges of FORGE. While kISMET focused on fracture creation, fracture monitoring, stress measurement, and induced seismicity, EGS Collab focuses on fracture connectivity, fluid flow between boreholes, and validation of coupled process models (Dobson et al., 2017b).

The EGS Collab project provides researchers the ability to address and meet the fundamental challenges of understanding and predicting permeability enhancement and evolution in crystalline rocks including how to create sustained and distributed permeability for heat extraction from the reservoir by generating new fractures that complement existing fractures. The scale of the EGS Collab project stimulation and fluid flow experiments will allow proximal monitoring through multiple boreholes with separations on the order of 10 m, leading to high-resolution geological and geophysical characterization of the rock mass before, during, and after stimulation. Modelers will assist in the design of field tests aimed at providing the key perturbation-response feedback information needed to constrain mechanistic models of coupled THMC processes, e.g., the degree to which shear offset on an existing fracture increases permeability of the fracture. Data on fracture permeability enhancement mechanisms (e.g., slip on existing fractures, new fracture generation, and mixed mode fracturing) will be gathered through carefully designed fracturing and fluid-flow experiments executed by the leading national lab and university field teams. Variability in fracture characteristics and related micro-seismicity as a function of in situ stress and stimulation processes will be monitored using multiple approaches during monitoring campaigns in the high-density borehole arrays feasible at intermediate scale. The fate and distribution of injected fluids in generated and natural fractures will be assessed. These measurements will provide the THMC modeling community with a rich data set that can in turn be used to validate the capabilities of predictive models that will be employed to support FORGE.

4.4.5 FORGE: Frontier Observatory for Research in Geothermal Energy

The FORGE project is designed to test and report on techniques needed to make EGS a commercially viable electricity generation option for the United States. The objective of FORGE is to establish and manage a dedicated underground laboratory where the scientific and engineering community can research, develop and test new technologies and improve upon existing technologies in an environment that is well characterized and well instrumented, and has optimal target reservoir temperature, depth, lithology, and permeability for EGS.

The FORGE initiative is comprised of three phases. The first two phases focus on selecting both a site and operations team, and preparing and fully characterizing the FORGE site. In Phase 1, teams performed analysis on the potential of five proposed sites and developed plans for Phase 2. Two of the five sites were selected to continue on to Phase 2, during which recipients work to fully instrument, characterize, and permit candidate sites. Phase 3 involves full implementation of FORGE at a single site guided by a collaborative research strategy and executed via annual research and development solicitations designed to improve, optimize, and drive down the costs of deploying EGS. In this phase, partners from industry, academia, and the national laboratories will have ongoing opportunities to conduct research and development projects at the site enabling testing and evaluation of new and innovative EGS science, technology, tools, and techniques in critical research areas such as reservoir characterization, creation, and sustainability.

The requisite site characteristics for FORGE are temperatures of 175-225°C at depths of 1.5-4.0 km, crystalline rocks with low permeability, a favorable stress regime for permeability generation through well stimulation, and a location where there is not an existing hydrothermal system. The five sites selected for Phase 1 are summarized in Table 10.

Table 10. Phase 1 sites for FORGE. Sites selected to continue on to Phase 2 are shown in bold.

Site	Location	Geological Setting	Depth (km)	Temperature (°C)	References
West Flank	Just west of Coso Geothermal Field, Eastern California	Crystalline granitic basement in volcanically, seismically, and tectonically active Coso Range at the boundary between the Sierra Nevada (Sierran) microplate and the Basin and Range province	1.5	>175	Siler et al., 2016a
Eastern Snake River Plain	Geothermal Resource Research Area, Idaho National Laboratory complex, Idaho	Ignimbrite, welded tuff, rhyolitic and granitic basement that reflect the pervasive silicic volcanism and caldera collapse that occurred in the wake of the Yellowstone hotspot's passage	3.7 - 4	175 - 200	Podgorney et al., 2016; Welhan, 2016
Fallon	Naval Air Station Fallon (NASF) directly southeast of the town of Fallon, West-Central Nevada	Jurassic felsic metavolcanic rocks, metaquartzite, and Cretaceous granitic intrusions in the Mesozoic basement in the Carson Sink area of the Great Basin region	1.5 - 3	>175	Faulds et al., 2015; Siler et al., 2016c; Blankenship et al., 2017
Newberry	On the northwest flank of Newberry Volcano, Central Oregon	A variety of volcanic rocks resulting from millions of years of volcanic activity emanating from multiple eruptive centers, situated near the juncture of several geologic provinces: the Cascade Range and volcanic arc to the west, the Columbia River Basalt Plateau to the northeast, and the Basin and Range to the southeast	2 - 3	200 - 320	Bonneville et al., 2016
Milford	West of Roosevelt Hot Springs, Southwestern Utah	Precambrian gneiss and Tertiary granitic plutons inside the southeast margin of the Great Basin, a region of extensional faulting, sporadic magmatism, and zones of anomalously high heat flow	3.8	230	Allis et al., 2016; Simmons et al., 2016; Gwynn et al., 2016

In the current (second) phase of the project, of two years duration, two sites are under consideration. The site in Fallon, Nevada, is being investigated by a team led by Sandia National Laboratories. Fallon was selected for a potential FORGE site due to its extensional tectonic setting, abundance of available data, existing infrastructure, and documented temperatures, permeability, and lithologic composition of potential reservoirs. During the four-month Phase 2A segment, the focus is on providing an environmental information volume (EIV), an assessment of existing infrastructure available in support of FORGE operations and R&D

technology testing and evaluation, implementation of public communication, outreach and stakeholder engagement, and deployment of a telemetered seismic monitoring array (Lawrence Berkeley Induced Seismicity EGS). Phase 2B is a one-year operation involving further site characterization activities. Although substantial geologic, geochemical, and geophysical data have previously been amassed for the Fallon area, several key data gaps preclude comprehensive characterization of some important aspects of the site. These data gaps relate to the following major themes: (1) delineating the precise location of EGS targets such that all FORGE criteria are satisfied; (2) establishing the mechanical and hydrologic attributes of these potential targets; (3) obtaining baseline data sets critical for evaluating the effects of stimulation experiments; and (4) minimizing uncertainties in interpretations and decisions.

The site in Milford, Utah is being investigated by a team led by the University of Utah. Analysis of the extent of the low-permeability thermal anomaly adjacent to the Roosevelt Hot Springs hydrothermal system demonstrates why developing techniques to extract the heat is so important to future geothermal power development. The area of apparently tight rock with a temperature of over 150ºC could be about 100 km^2, and is more than 10 times the area of the hydrothermal system. The volume of this rock at less than 4 km depth is at least 100 km^3. The power potential here could be as high as 1 GW if this rock can be successfully fractured. Recent re-evaluation of thermal data from over 100 wells drilled mostly during the 1970s and 1980s in the area of Roosevelt Hot Springs (RHS) has refined earlier interpretations of the thermal regime. These data have been combined with pre-existing gravity and magnetotelluric data to construct a 3D model of the area as part of the site characterization phase.

In summary, FORGE's mission is to enable cutting-edge research, along with advanced drilling- and technology-testing, to allow scientists to identify a replicable, commercial pathway to EGS. In addition to the site itself, the FORGE effort will include a robust instrumentation, data collection, and data dissemination component to capture and share data and activities occurring at FORGE in real time. The innovative research, coupled with an equally innovative collaboration and management platform, is truly a first-of-its-kind endeavor.

All R&D activities at FORGE will focus on strengthening understanding of the key mechanisms controlling EGS success; specifically, how to initiate and sustain fracture networks in basement rock formations. This critical knowledge will be used to design and test a methodology for developing large-scale, economically sustainable heat exchange systems, paving the way for a rigorous and reproducible approach that will reduce industry development risk and facilitate EGS commercialization. R&D activities may include, but are not limited to, innovative drilling techniques, reservoir stimulation techniques and well connectivity and flow-testing efforts. The site will also require continuous monitoring of geophysical and geochemical signals.

Additionally, dynamic reservoir models will play an integral role in FORGE by allowing the site operator to synthesize, predict, and verify reservoir properties and performance. R&D activities will have open participation, via competitive solicitations to the broader scientific and engineering community.

As advancements in EGS are made over the course of FORGE's operation, R&D priorities are likely to shift and change in response. As a result, FORGE will be a dynamic, flexible effort that can adjust to and accommodate the newest and most compelling challenges in the geothermal energy frontier.

5 Innovative Technologies and Blue-Sky Concepts

The key to accelerating deployment of geothermal resources over the next few decades in the U.S. will be the development of innovative technologies and implementation of blue-sky concepts that could significantly reduce costs, lower risks, and shorten the time needed to explore and develop geothermal resources of all types. These types of changes have occurred in the oil and gas industry, where the development of directional drilling and multistage stimulation revolutionized the utilization of unconventional oil and gas resources (e.g., Warpinski et al., 2009). This section describes some of the critical technologies and blue-sky concepts that could have a dramatic impact on the future of geothermal resource utilization. These include: (1) innovative drilling technologies, (2) next-generation geophysical imaging methods, (3) big data analysis, interpretation, and utilization, (4) supercritical geothermal resources, (5) alternative working (heat extraction) fluids, and (6) alternative methods for thermal mining (solid state heat exchanger).

As highlighted in the MIT report (Tester et al., 2006), lowering drilling costs is critical for achieving widespread commercial deployment of EGS in the U.S. Efforts are being made to move beyond current rotary drilling methods and to develop new techniques that could result in faster drilling penetration rates at lower costs. Such techniques include new hammer drilling, projectile drilling, thermal spallation drilling using downhole combustion, hydrothermal and laser jets, electrical plasma, and microwaves, and chemical drilling methods. Many of these approaches are currently in early developmental stages – one or more of these methods could lead to a major breakthrough in drilling.

Advances in geophysical imaging and monitoring techniques will also play a significant role in accelerating geothermal resource deployment. One of the main challenges to geothermal exploration and development efforts is the high risk associated with exploration—this results in failed projects, higher costs, and increased financing rates. Improved geophysical methods to better characterize the subsurface could result in improved well targeting of permeable features, both natural (conventional hydrothermal) and stimulated (EGS). Such methods could include time-lapse multi physics methods, novel tracers or tagged proppants to image fracture and fluid flow networks, interpretation of geophysical data through the use of statistical representation of fractures, use of ambient noise and other anthropogenic “signals” to image the subsurface, improved borehole sensing and monitoring techniques, and full waveform seismic imaging.

One of the benefits and challenges of the digital age is the explosion in the quantity of information now at our disposal (e.g., Weers and Anderson, 2016). New approaches are needed to store, organize, analyze, and interpret these vast amounts of data. Data mining techniques will be critical to utilize relevant data obtained from a wide variety of sources, such as water well records, oil and gas and mineral exploration data, and a wide range of geoscience information. New joint inversion methods could provide improved resolution data for subsurface imaging. Optimization methods will also allow for creation of conceptual and numerical models of geothermal systems with higher fidelity, and help identify what data elements are most uncertain and most influential on model interpretation. Value of information analysis can lead to prioritizing and determining which types of studies will have the most impact on exploration efforts. Finally, developing methodologies that facilitate better decision-making will result in this information being used in the most effective manner.

One blue-sky concept is the utilization of supercritical geothermal resources, which are very high temperature geothermal systems that are located at depths near or below the brittle-ductile transition zone in the crust where the reservoir fluid is assumed to be in the supercritical state, e.g., for pure water temperature and pressure are respectively in excess of 374°C and 221 bars (e.g., Dobson et al., 2017a). These systems are often associated with magmatic centers, and may underlie conventional hydrothermal systems. Several research groups around the world are actively evaluating this potential resource—the most prominent is the Iceland Deep Drilling Project, which has drilled two deep wells and encountered fluids at supercritical conditions. One of the main attractions for this type of resource is that much higher enthalpy fluids would be produced, resulting in well productivities several times higher than conventional wells. To achieve this objective, high temperature tools, casings and surface production systems need to be developed to withstand the elevated temperatures and corrosive fluid chemistry. In addition, the presence of long-term permeability near the brittle-ductile transition zone needs to be demonstrated. However, this resource base could represent a more energy intensive and shallower EGS target with a significant EGS resource potential. Initial conservative resource estimates (for depths down to 5 km) of just three of the potential supercritical systems in the U.S. (Geysers-Clear Lake, Salton Sea, and Coso) total more than 2 GWe (Stimac et al., 2017). International collaboration between different research teams could lead to improved understanding of these systems and future commercial development of such resources.

Another potential game-changing development would be to fundamentally alter the way thermal energy is transported to the surface for power generation. Currently, water/geothermal brine is circulated through a fracture network to extract heat from the hot rocks in the subsurface. One proposed system is to use supercritical CO_2 as a working fluid for EGS reservoirs (Brown, 2000). This would also serve an alternative benefit of sequestering volumes of CO_2 in the subsurface. Another proposal is to use solid-state heat exchangers, such as highly conductive graphene fibers, to bring geothermal heat to the surface. An even more novel idea is to develop a way to generate electricity in the subsurface using thermometric materials. Such innovations could completely revolutionize the way geothermal resources are utilized.

5.1 Innovative Drilling

Significant advances in drilling technology have been made since the advent of large-scale geothermal drilling in the 1970s, including adaptation of techniques from the oil and gas industry and techniques developed to address issues specific to geothermal drilling such as great depths, high temperatures, and hard rock. High temperatures require advanced control mechanisms; hard rock greatly slows the rate of penetration and accelerates bit wear, which are serious limitations considering the great depths involved. Advances that are becoming more commonly used include directional drilling and multi-lateral wells (Tester et al., 2006); mud motors, long-life bits, automated pipe handling, large-diameter wells, barefoot well completion, balanced (aka underbalanced) drilling to keep well pressure low, so cuttings do not flow into the reservoir and block flow paths (Thorhallson, 2006); and casing-while-drilling, expandable tubulars, percussion drilling, controlled pressure drilling (Vollmar et al., 2013). Randeberg et al. (2012) advocate seeking both technological advances and also organizational improvements to the drilling process, including minimization not only of time spent drilling (rotating time), but also time spent not drilling (tripping time), increased automation, and integrating all aspects of the drilling operation under one control system.

Novel, but less thoroughly tested, concepts to improve drilling include:

- Extending the concept of using fewer casing intervals (Tester et al., 2006) to using only one, creating a single-diameter well (Thorsteinsson et al., 2008).

- Developing an improved casing material such as an advanced polymer or resin that coats the well wall while drilling and is strong and stable enough to act as permanent casing (Thorsteinsson et al., 2008).

- Percussive drilling using down-the-hole (DTH) mud hammers (Wittig et al., 2015), which use drilling mud to drive the hammer rather than the traditional compressed air (for shallow holes) or clean water (for deep holes). Mud weight can be tailored for the depth of operation.

- Projectile drilling (aka particle-impact drilling), which consists of projecting steel balls at high velocity using pressurized water to fracture and remove the rock surface. The projectiles are separated and recovered from the drilling mud and rock chips (Curlett et al., 2002; Geddes and Curlett, 2005). In addition to fast rock cutting rates, projectile drilling results in straight boreholes because the mechanically decoupled drilling method eliminates the mechanical contact forces, reactions, and dynamics normally associated with rotary-mechanical drilling methods that tend to cause well bore tortuosity and deviation. Furthermore, the non-contact bit shape is expected to be much more durable than standard rotary-mechanical drill bits, providing a major reduction in tripping requirements normally associated with worn mechanical parts.

- Thermal spallation drilling, which uses various means of rapidly increasing the rock temperature, inducing a steep temperature gradient and thermal stresses, causing the rock to fracture or "spall." Such a system can also be used to melt or evaporate non-spallable rock. This method is also a mechanically decoupled (i.e., non-contact) drilling method and has the advantages described for projectile drilling above. As an added benefit, it under-reams the borehole. Methods of heating the rock include:
    - High-temperature downhole combustion: For shallow depths, a supersonic flame jet can be created in an air-filled borehole (Potter and Tester, 1998), with spalls cleared from the hole by the hot, high-velocity exhaust gases. For typical EGS depths, air-filled boreholes can be unstable and, therefore, water-filled holes are preferred. At depths greater than about 2.3 km, where the downhole conditions render water supercritical ($T > 374°C$, $P > 221$ bars), gases such as O_2, N_2, CO_2, and H_2, as well as non-polar organic compounds, such as methane, ethane, and benzene, are completely miscible with water, forming a single homogeneous phase that can be ignited and combusted, producing luminous flames known as hydrothermal flames (Augustine and Tester, 2009).
    - Hydrothermal jet (Potter et al., 2010; Wideman et al., 2010): A heated jet of water impacts the rock formation and addition of chemicals to the jet can enhance rock breakup (Hillson and Tester, 2015). The greater density of the water compared to gas used in shallower wells not only enhances borehole stability, but also increases buoyancy forces for carrying spalls to the surface.
    - Laser jet (Jamali et al., 2016): A water jet acts as a wave guide for a laser beam that heats and spalls the rock.
    - High-energy electrical plasma (Kocis et al., 2015): An electrical arc with temperatures up to 10,000 Kelvin heats the rock surface directly. The arc creates an area-wide, relatively homogeneous heat flow over the rock surface, and also creates electrohydraulic phenomena, generating shock waves for the destruction and transport of the disintegrated material. The system uses electrical and optical characteristics of the arc/rock interaction to derive indirect sensory information (e.g., online spectroscopy for logging while drilling).
    - Voltage difference between electrodes: In EIT (Electric Impulse Technology, Anders et al., 2015), a high voltage electrode (up to 500 kV), and a ground electrode are placed on the rock. Rock and electrodes are surrounded by liquid (water, drilling mud, etc.). The fluid acts as an insulator, so the electrical discharge occurs in the rock, where very high pressures and temperatures are generated in the plasma channel, leading to failure of the rock structure. A big advantage of this technology compared to mechanical drilling is that work is done against the tensile strength of the rock, which is about one tenth of the compressive strength. In EPB (Electro Pulse Boring, Scheigg et al., 2015), voltage is applied as a pulse, with a pulse frequency of 10 Hz.
- Laser drilling: It relies on pulses of laser transmitted through fiber optic cable to heat the rock surface. Fractures, cracks, and spalls are created, greatly weakening the rock, which is then easily drilled with a traditional drill bit. Significant technical obstacles had to be overcome to deliver the laser energy to the drilling location (Zediker, 2014).
- Microwave-assisted drilling: Microwave energy induces inter-granular and trans-granular cracks in the rock in order to reduce its strength prior to mechanical drilling (Hassani et al., 2008). Microwaves have a good penetration rate into rock and different minerals have different transparencies to microwave radiation—some minerals will heat up and some will not. Thus, microwaves create strong thermal gradients and thermal stresses that weaken and crack the rock.

- Chemical drilling: This involves the use of hot aqueous fluid to dissolve the rock and has the potential to be used in conjunction with conventional drilling techniques (Polizzotti et al., 2004). The heated aqueous fluid comprises water and hydroxides of Group I elements of the Periodic Table of Elements and mixtures thereof.

- Using microholes (boreholes with diameter less than 10 cm) to enhance fluid flow and heat exchange within an EGS: Multiple microholes are drilled as sidetracks off of injection or production wells (Bracke and Wittig, 2011). Because microholes can be spread widely, thus intersecting a larger portion of the fracture network, the use of microholes increases the rock volume that is accessed by the circulating working fluid, therefore extracting more heat from the geothermal reservoir (Finsterle et al., 2013). Additionally, if some of the microholes miss the stimulated fracture zone, the circulating fluid will self-regulate and flow through the remaining microholes that intersect the fracture zone. Thus, using a microhole array reduces the possibility of a failed design. Drilling microholes requires advanced drilling methods, such as the mechanically decoupled methods described above. Additionally, drilling the many holes needed can be expedited by using a coiled tubing drilling technology (Wittig and Bracke, 2011), wherein the drill string is reeled up (like a garden hose) in one piece on a large drum.

5.2 Game-Changing Technologies for Geothermal Energy Resources: A Geophysics Perspective

The following discussion is restricted to technologies that minimize uncertainty on our knowledge of the state of the subsurface in intrinsically complex geothermal systems, under the premise that it is precisely this uncertainty that ultimately drives the upstream cost of exploration and production of geothermal energy. Discussion of drilling and other hardware technologies whose goal is to minimize the cost of *accessing* the energy resource will be deferred to a separate section of this report and will not be discussed here. Generally stated, the “game changing” geophysical technologies surrounding uncertainty minimization can be grouped into six broad categories: time-lapse multi-physics experiments integrating large volumes of disparate geophysical data; geophysical methods that exploit “tagged” proppants or contrast agents to detect the presence and changes to a fracture system; realistic and computationally economic methods for statistical representation of fractures; methods that accommodate or even exploit the anthropogenic infrastructure surrounding a developed geothermal resource; borehole sensing and monitoring techniques; and full-waveform seismic imaging. Some bias toward electromagnetic methods is present in the discussion that follows because of their particular sensitivity to subsurface fluids, and more importantly, how the fluids are hydrologically connected.

5.2.1 Time-Lapse Multi-Physics Experiments

Bowles-Martinez et al. (2016) have recently taken the first steps toward time-lapse multi-physics in their work at the Newberry EGS site, where they have implemented continuous (A)MT/CSEM monitoring of temporal changes in MT response functions and inversion for temporal changes in resistivity. This has been combined with repeat or continuous microgravity, ground-based true aperture radar interferometry and satellite InSAR, and Thermal-Chemical-Mechanical modeling. By co-registering all of the above observables, changes in permeability can be isolated from other effects, since changes in density can be determined from microgravity, and changes in porosity from ground deformation observations. The changes in resistivity can be attributable more to changes in permeability than the other usual factors. Microseismicity somewhat constrains the volume over which these changes take most obvious form. Similar multi-physics studies are also currently underway at Brady Hot Springs NV, where an integrated dataset was collected in March 2016 from active seismic sources. The response was recorded simultaneously across temperature-resistant fiber-optic cables for distributed acoustic sensing (DAS) to 400-meter depth, 240 surface seismometers and 9 km of DAS cable, and 5 pressure sensors in observation wells. Co-registered with these data are distributed temperature sensors to 400-meter depth, continuous geodetic measurements at 3 GPS stations, and at least one InSAR acquisition every 11 days. Initial results on ground deformation analysis and microseismicity have already been reported (Ali et al., 2016; Cardiff et al., 2018).

Such an approach is ambitious from the perspective of uncertainty quantification using classical geophysical inverse theory, as it is not immediately clear how each of the geophysical observables should be co-registered: whether through a site-specific rock physics model or some ad-hoc constraint, such as cross gradients (Gallardo and Meju, 2004). Given the difficulty of this problem, exasperated by the large volume of data involved, it may turn out that machine learning algorithms prove useful for both economically sifting through the data and for revealing *data driven relationships between fundamental material properties* sensed by geophysical methods. If successful, the data mining approach may provide the necessary efficiency for new concepts in coupled hydro-chemical-physical rock interactions to evolve. Advances in machine learning would be a natural extension to present-day work in Bayesian data fusion (e.g., O'Callaghan et al., 2013; McCalman et al., 2014) which quantifies, in a statistical sense, the confidence one may place on estimates of earth properties, such as fracture location and temperature.

It is interesting to note that in the oil and gas industry there is a growing enthusiasm for machine learning technology, an enthusiasm that is fueled by two key observations. In the last 10 years, despite a steady development of computer technology (multi-core CPUs, GPUs, FPGAs, etc.) and algorithm development (e.g. full-waveform inversion) the decision time between acquisition of a 3D or 4D seismic array and action in the field has not decreased significantly. Furthermore, the acquisition of ever-larger seismic data volumes has exceeded the ability of seismic interpreters to fully explore them, and hence, approximately 40% of seismic data goes unused. The feeling within the oil and gas industry is that data analytics is the key to maximizing the value of these data. If left unchecked, the geothermal industry may find itself in a similar situation at some future time if exuberance for executing "large N" or "big data" experiments goes unchecked in the present.

5.2.2 Tagged Proppants

Development of geophysical methods that sense the state (or changing state) of a fracture system through tagged proppants, "smart tracers" or contrast agents would certainly be game changing. For example, one might consider micro/nanoparticles that emit detectible acoustic pulses or multiple temperature-sensitive dyes with different characteristic decay curves versus temperature that allow one to determine the maximum temperature reached along a fluid flow path. Another example, again taken from the oil and gas industry, is to engineer ceramic proppant that is both tolerant of extreme physiochemical conditions but also endowed with elevated electrical conductivity. A subtle, but important difference between tagged proppants/geofluids and microseismic hypocenter clusters is that the former is a direct indicator of open fractures—admittedly a challenge—or engineered permeability whereas the latter is not. Recent field tests by CARBO Ceramics, Inc., (Aur et al., 2016) using engineered proppants in a Marcellus Shale hydrofrack operation, show a detectable electromagnetic signature, even in the presence of considerable anthropogenic noise. Similar results were reported by Wilt et al. (2016) using saline tracers in an unconventional oil play. Also, Knox et al. (2016) report successful use of zero-valent iron as a tracer for monitoring fluid flow using electrical resistance tomography, including a dual inversion approach to integrate ERT data with multi-level continuous active source seismic monitoring (Daley et al., 2007; 2011; Ajo-Franklin et al., 2011).

5.2.3 Efficient Statistical Representation of Fractures

Statistical or other methods for describing fracture systems and geologic texture that enable useful predictive modeling/inversion without requiring excessive model complexity, commonly correlated with extreme amounts of computer resources, would be extremely valuable. One promising approach taking hold in hydrogeophysics is characterization of geomaterial/system through heavy-tailed distributions (Meerchaert et al., 2013), with a resulting advective/diffusive flow model that incorporates fractional derivatives to economically describe fluid transport therein (Benson et al., 2013; Major et al., 2011a; 2011b). Weiss et al. (2016) and Beskardes et al. (2017) demonstrate how similar concepts of statistics and fractional calculus can be applied to the diffusion of electromagnetic fields in the subsurface; Zhu and Carcione (2014) show how seismic anelasticity can be accommodated by the same mathematical formalism. The key point is that the fractional calculus framework is a rapidly developing and novel approach in which the fundamental governing equations of multiple geophysical methods are being re-evaluated and re-cast so that ensemble system behavior can be modeled with an economy of computational resources. Furthermore, the order of the fractional derivative is directly related to the statistical complexity of the geosystem—hence, inversion for geophysical data (perhaps even through machine learning algorithms) for the *order* of the fractional derivatives gives a novel and compact way of describing the underlying geocomplexity. If successful, the constraints provided by fractional derivative analysis could then be integrated with other, more technically mature, lines of analysis, such as digital rock physics (e.g., Sain et al., 2014), multipoint statistics (Silva and Deutsch, 2014) and Bayesian inference (Martinelli et al., 2013).

5.2.4 Exploiting the Anthropogenic Infrastructure

Geophysical data acquisition and interpretation methods should fully embrace the anthropogenic/infrastructure clutter of a geothermal resource site. For several years, seismologists explored how ambient seismic noise can be exploited as a source for subsurface imaging. Similar efforts have tentatively been explored in the field of electromagnetics (e.g., Shamsalsadati and Weiss, 2010; Slob and Weiss, 2011; references therein), with much of theory now in place but also a notable absence field data and examples—due in part to a poor understanding of how the method will perform in practice rather than under ideal conditions. Also poorly understood is how anthropogenic signals from infrastructure (e.g., powerlines, cathodic protection systems, etc.) can be exploited as a source to illuminate subsurface fractures, either in an exploration sense or later when the fracture is subjected to secondary stimulation, possibly with the tracers and contrast agents cited earlier. There is some precedent for exploiting natural electromagnetic sources (e.g., the "radio" MT method, or VLF soundings), but nothing focused on the particulars of a geothermal energy facility. Doing so naturally requires that all of the electrically conducting infrastructure of a geothermal energy facility be modeled accurately and with an economy of computing resources (as discussed in the preceding paragraph). Hence, many of the numerical techniques commonly used by engineers to model the electromagnetic scattering of structures and devices will need to find a home in the geophysical modeling toolkit. This task is well suited to expertise in the national weapons laboratories due to their long history with predictive modeling under the stockpile readiness and border security programs. A recent issue of The Leading Edge (March 2013) illustrated many of the technical problems associated with conducting geophysics in cluttered environments—far from pristine in both the presence of noise and the presence of man-made targets and scatterers—where the technical problems just raised are illustrated with examples from the geotechnical community. While the scale of operations between urban near-surface geophysics is 10 to 100 times smaller than that in geothermal, many of the underlying problems remain. Hence, an integrated approach to modeling and exploiting the "engineered" man-made environment for geophysical exploration is a grand challenge and will likely provide the type of step-change benefit to reducing upstream geothermal energy costs.

5.2.5 Borehole Sensing and Monitoring

For most characterization and monitoring tools, subsurface access is the key to improving resolution because overburden heterogeneity typically obscures the reservoir. An example is slimhole drilling combined with fiber-optic sensing. Multiple wells drilled only to deploy a slim fiber cable could multiply the available well control and spatial distribution of sensors. Current fiber optic seismic sensing can have sensor sampling at 1 m intervals along the entire length of the cable/well on a 0.25-inch cable—requiring only a 1-inch hole size. Low cost drilling and cable deployment is the enabling technology to achieve thousands of subsurface sensors. Advances in fiber technology could allow electrical and chemical detection, along with seismic and strain sensing.

5.2.6 Full-waveform Seismic Imaging

A transformative means to subsurface characterization of permeability-controlling features in geothermal fields is full-waveform seismic imaging using dense receiver arrays, broadband sources and receivers, and multiply scattered waves. While 3D surface seismic reflection imaging has transformed oil and gas exploration in marine environments by utilizing advances in dense, broad-band, wide-aperture receiver arrays to achieve high-spatial resolution images of the subsurface, seismic imaging in geothermal environments has not experienced a similar transformation. The challenge in geothermal environments is the complex scattering of seismic waves resulting from strong material contrasts encountered in faulted and fractured rock. Conventional seismic imaging approaches are based on single, weak scattering assumptions that are not valid under these conditions (Valenciano and Chemingui, 2015). New seismic imaging approaches that utilize multiply-scattered seismic waves, including conversions between compressional and shear waves, have the potential to significantly improve the quality and spatial resolution of seismic imaging. These approaches will require advanced wave physics-based inversion approaches and high-performance computing.

The six areas just described encompass a broad view of the potential game changers for lowering upstream geothermal costs. Geophysical methods that faithfully and economically represent full complexity—natural and manmade—of the geothermal field sites are needed. Seeding the subsurface with tracers and smart sensors has the potential to enhance our understanding of the permeability field and therefore directly feeds decisions on how best to manage the resource. Lastly, no diminishment in the desire to collect more and more data is foreseen—with good reason—but the full utility of these data will be unrealized without some automated approach for data synthesis, such as machine learning. Doing so is needed to justify these large data volumes, and from a scientific perspective, to unlock the new science within.

5.3 Smart-Data Use

5.3.1 Effective Decision-Making in Uncertain Conditions

Making effective exploration and development decisions in uncertain conditions is important for the success of a geothermal project. The ability to make good decisions relies on the capability to forecast the performance of the proposed facility. In particular, the uncertainty and high cost of drilling makes forecasting the performance of a proposed well a key geothermal expertise; the probability of success (POS) can succinctly express that forecast, when based on a clear definition of success. Two examples of good decision making in uncertain conditions, presented by Melosh (2017), are described below, along with the characteristics of the successful forecasters.

1. Unocal, including its geothermal division, had a remarkable record on well costs. In spite of using the same drilling technology and tools as other operators, Unocal oil and gas and geothermal well costs were typically around 50% of its competitors (Unocal Corporation, 1999) during the period from about 1995 through 2010. Unocal drilling performance was strongly facilitated by a team process including forecasts of decision impacts and designs, detailed review of data, and multiple critical opinions in advance and in review in an empowered setting. The Unocal drilling team process involved open-minded and critical interaction, testing of ideas and equipment, and detailed engineering before and after drilling events to forecast and review results. The team process was supported by a trustful environment among team members that allowed challenging communications and full empowerment by the company. Part of the drilling decision work included geothermal well targeting using multiple targeting and conceptual models.

2. An international study of forecasting involved a tournament of forecasts of world political events by individuals and teams with participation of about 20,000 people (Tetlock and Garner, 2015). Forecasts were checked against actual results over five years. During the study, it became clear that certain groups were consistently much better forecasters than others. Mellers et al. (2015) showed that the best teams consistently produced forecasts that were roughly 50% more accurate and showed strong learning improvements. These teams are referred to as super-forecasters. A lot of analysis went into showing that this was not pure luck and to identify what helped create the differences in performance.

   One study of the contrasts between the best forecasters and teams and others revealed a style of thinking that was consistent with better performance (Tetlock and Garner, 2015). People and teams that achieved more frequent successful forecasts were self-critical, detail-oriented, open minded, and accountable.

   Successful forecasters were also more likely to believe that they could acquire skills to become better forecasters, i.e., that it was not just talent or intelligence or better information. Part of being accountable involved committing to a numerical probability for an event. Review showed that precision in estimating the probability of an event correlated to the score of the forecast (Tetlock and Garner, 2015).

One approach used by both groups is to develop multiple conceptual models. The thinking process behind developing multiple specific and detailed models helps fully explore and visualize possible outcomes of multiple data sets, and requires all four of the characteristics of super-forecaster thinking cited above. According to Melosh (2017), one of the advantages of using multiple models is that it frees up the thinking from “what is the right model?” to become “what could the model be?” This is practical since in uncertain geothermal conditions, especially during exploration, a single model is very likely to be wrong.

For a particular activity, such as drilling a well, each conceptual model must have an associated POS (to be accountable). Beyond informing the decision about whether and where to drill, estimates of the POS can be used to compare relative expected values of well designs. Although expected value comparisons are simplistic, they provide a monetary value context that supports good team-based well design decisions.

5.3.2 Big Data/Data Integration at the Pre-drilling Stage of Exploration

Use of big data and data integration are two means to improve the pre-drilling stage of geothermal exploration, in order to reduce the risk of drilling unproductive wells. These techniques can be applied at the initial stage of investigating existing information about a region or site, and at the subsequent stage of surface-based site characterization. Another means to minimize risk is to do site characterization followed by deep drilling in incremental stages rather than all at once. All information obtained from drilling the first set of wells should be used to improve the conceptual model of the resource and the interpretation of observation data, in order to inform the choice of locations for the next set of wells.

Preliminary screening using existing information: The most common situation for geothermal exploration is to be looking for a resource in a region where other known resources are already present. Understanding the tectonic stress state, geologic, and hydrogeologic setting that fosters the known resources is critical for successful exploration. A useful first step is to inventory known geothermal resources and look for common features in geologic setting. Faulds et al. (2011) did this for the fault structures associated with known geothermal fields in the Great Basin. They found that geothermal systems are rare along displacement-maxima zones or mid-segments of major range-front faults, but are more commonly associated with locations where multiple faults intersect, especially in extensional stress regimes that tend to cause intersecting faults to remain open. Play fairway analysis, described in Section 4.2, is another means of doing a preliminary screening. Attributes associated with known resources are mapped and locations where the attributes overlap are selected for further investigation.

Site Characterization: Once a particular site has been chosen for further investigation, a suite of surface- or near-surface-based methods may be used to characterize the site on a local scale, which will ultimately lead to determining locations for deep drilling. This is an intrinsically difficult problem. Multiple site characterization methods are available, each of which has strengths and weaknesses, and provides useful, but incomplete, information about the subsurface. Therefore, it is beneficial to analyze the output of different methods jointly, which requires careful treatment of different data types and generally complicates the analysis. Moreover, inferring subsurface structure, parameters, and fluid and heat flow distributions from surface measurements is an ill-posed inverse problem, meaning that multiple solutions may equally well fit the observed data. It is therefore important to make use of knowledge of geologic setting to develop a conceptual model of fluid and heat flow when interpreting site-characterization data, in order to eliminate spurious results. Additionally, the optimization algorithm used to find candidate solutions during the inversion must be chosen with care. Each of these topics is described briefly below and in more detail in Doughty (2016).

- **Developing a conceptual model for fluid and heat flow:** Rather than choosing drilling locations based on targeted anomalies (e.g., a zone of resistivity below a certain cutoff), which is the direct result of an electrical geophysical method, Cumming (2009a; 2009b) recommended to develop a conceptual model of fluid and heat flow in the subsurface that integrates all available information. At the outset of site characterization activities, available information is limited to regional and local geology, hydrology, structure, and surface manifestations including geochemical analysis of geothermal fluids, and evidence of hydrothermal alteration. Hence, the initial conceptual model will likely be rather simple. As site characterization data is obtained, it should be interpreted in the context of the conceptual model, which greatly constrains possible data interpretations, but also enables the conceptual model to be improved and refined. This closely-coupled iterative approach to conceptual model development and interpretation of site characterization data is a key feature to improve the success of geothermal exploration. As more data is collected, the conceptual model should be translated into a numerical model of the thermophysical and chemical processes controlling the natural state of the geothermal reservoir. In addition to helping site drilling locations, such a model will be valuable for estimating reservoir production capacity and determining optimal exploitation strategies.

- **Surface and near-surface data collection methods**: In contrast to hydrocarbon resources, geothermal resources have a strong upward driving force, which makes shallow subsurface (temperature) and surface (geochemistry of spring fluids containing geothermometers) measurements useful indicators of temperature conditions at depth. Surface-based geophysical measurements are useful for identifying caprocks and possibly other reservoir structures. Below is a list of useful surface and near-surface based site-characterization techniques. Note that there are multiple interpretations for some data types, indicating the need for joint inversion of multiple data types in the context of the conceptual model (geologic framework modeling).
    - **Surface**
        - Electromagnetic geophysical methods: DC resistivity and MT are used to identify low-resistivity zones, which are associated with clay and indicate low-permeability cap rocks (Dobson, 2016). MT is said to identify fluid (McCalman et al., 2014) and could provide images of fracture networks or fault zones. Self-potential (SP) is associated with permeability. Magnetics can identify regions with different magnetic susceptibility, which could help identify resource structure.
        - Gravity surveys: Gravity highs can indicate deposition of secondary minerals, high temperature, magmatic intrusions, and faults.
        - Seismic reflection: While not as pervasively used as in oil and gas exploration, seismic reflection data can provide useful information on reservoir structure.
        - Soil gas methods: Soil gas may contain isotopic or other fingerprints of deeper geothermal activity.
        - Geothermal fluid analysis: Hot springs and other surface manifestations are the most commonly used identifier of subsurface geothermal activity. Geothermal fluids often include geothermometers, chemical compositions by which the maximum temperature at depth may be estimated.
        - Hydrothermal alteration: In the absence of active surface manifestations (hidden geothermal systems), hydrothermal alteration observed at the surface may be indicative of a previous era when there were active surface manifestations.
    - **Near-Surface**
        - Shallow wells (only a few meters deep) can provide useful information on the subsurface temperature distribution, and hence the heat flow.
        - Unproductive wells, or wells previously drilled for other purposes, can also provide useful temperature information, and can even be used for various geophysical logging methods.

    - Slim holes can be drilled to investigate reservoir conditions at a fraction of the cost of full-scale wells.

- **Joint inverse analysis of multiple datasets:** As mentioned above, the incomplete or even contradictory information about reservoir structure and parameters obtained from different geophysical methods means it can be most beneficial to analyze them together. This becomes a joint-inverse problem, in which all the observed data from two or more geophysical methods are used to constrain different possible models of the subsurface. While this is straightforward in principle, it requires careful coordination of different forward models (e.g., to model gravity and MT response), including assuming correlations between properties of different models based on rock physics (Sain et al., 2014), and weighting schemes so that widely different magnitude data types can be compared fairly. McCalman et al. (2014) describe an analysis that is done in a Bayesian framework, whereby the overall framework of the geological setting is considered known, but the parameters that control the detailed geometry of geologic structures (e.g., layer thickness, intrusive body size and location) is inferred by matching trial solutions to the observed data. Equally valuable is the inclusion of uncertainty throughout the analysis, thus rather than providing a single answer (e.g., for depths to reservoir layers and basement), a probability density function is given, indicating not only the depth estimates, but the uncertainty associated with the estimates. When comparing answers obtained by using different subsets of the surface-based geophysical data, much insight into the sensitivity of various model structures and parameters to different types of data is obtained.

- **Advanced optimization algorithms for site characterization**: Using inverse analysis to infer hydrogeological properties is common. In the simplest, most idealized cases (e.g., using pressure-transient data to infer the permeability in a homogeneous aquifer), only a few parameters are needed to characterize the system, and a unique answer may be obtained, either from an analytical solution, or from a local optimization algorithm that uses a simple steepest descent search through the parameter space to reach a minimum—that is, where the mismatch between the observed data and the model results is minimized. However, the complex geology/hydrogeology typical of a realistic geothermal resource requires many parameters to characterize the structure and flow. This creates an ill-posed inverse problem, in which the parameter space is many-dimensional and contains many local minima, where only some aspects of the observed data are matched. Global optimization algorithms are required to search such parameter spaces, to avoid getting trapped in local minima. Numerous global optimization techniques have been developed over the past 25 years, mostly devised to match well-test, tracer-test, or production data from existing wells, in order to optimize reservoir performance. However, the principles apply to surface-based observations also, and hence can be useful at the pre-drilling site-characterization stage.

  There are two key principles of advanced optimization algorithms. The first is the desire to characterize subsurface heterogeneity using as few parameters as possible. Generally, the more parameters there are, the more forward simulation must be done, each varying different parameter, in order to find a model that is consistent with all the data. For joint inversions, each forward simulation requires solving for the gravity response, the MT response, the seismic response, etc., thus each is computationally expensive. Additionally, more parameters generally mean a more ill-posed inverse problem, with more distinct parameter sets matching the observed data equally well. The second key principle is to use an intelligent search algorithm through parameter space that enables local minima to be escaped and converges at the global minimum, thus returning a parameter set that best matches all observation data.

    - **Characterizing subsurface heterogeneity with few parameters:** A fixed-structure model is one in which the structure of heterogeneity is specified a priori and the inverse method searches only for property values within that structure. It requires very few parameters. This method is appropriate if very little is known about a system, and only one or a few parameters are sought to provide an average picture of the system. It is also appropriate if a detailed conceptual model of the system is available, so that the locations of key features are known with certainty. However, neither of these conditions is met for pre-drilling site characterization, so inverse models in which both the structure of heterogeneity and the value of properties are unknown parameters are necessary.

Generally, the more information that can be incorporated about the geological setting and the conceptual model for fluid and heat flow, the fewer parameters are needed. Usually this information is based on observations of geologic forms (such as the orientation of fracture sets or typical dimensions and spacing between intrusive bodies), but it can also arise from a process model. One example is a fracture genesis algorithm (Hestir et al., 1998), in which the flow model is created by a stochastic fracture growth process that is based on fracture mechanics principles. Random numbers within the growth algorithm are varied in order to match well-test data. The resulting fracture network honors both the fracture genesis process and the well-test data.

One simple way to produce complex heterogeneity with few parameters is by using geostatistics, wherein only a few parameters specifying a variogram are needed, and a great deal of variability in heterogeneous systems is generated by drawing different realizations from probability distributions. One drawback of variogram-generated heterogeneity is that it does not honor realistic relationships between facies. This shortcoming is addressed in T-Progs (Carle and Fogg, 1996), a powerful geostatistical method wherein the juxtaposition of multiple facies, based on a training image, is honored in all randomly drawn realizations.

A new approach, based on principal component analysis (PCA) for the representation of complex geological models in terms of a small number of parameters is presented by Vo and Durlofsky (2014; 2015). The basis matrix required by the method is constructed from a set of prior geological realizations generated using a geostatistical algorithm, which enables the inclusion of bound constraints and regularization, which are shown to be useful for capturing highly connected geological features and binary/bimodal (rather than Gaussian) property distributions.

The iterated function system (IFS) inverse method (Doughty et al., 1994) uses fractals to represent heterogeneity structure, enabling highly heterogeneous systems to be represented with only a few parameters. It is primarily applied to fracture flow, or highly heterogeneous sedimentary systems that can be represented in a binary manner (e.g., sand and shale). The IFS method of generating fractals is very flexible, and able to capture geologically realistic patterns of flow channels or barriers. As the parameters are varied, flow channel or barrier continuity is altered, producing distinctly different flow patterns.

- **Intelligent optimization algorithms:** Traditional local optimization algorithms, which attempt to move towards minima in parameter space, such as Levenburg-Marquadt or downhill simplex, do not work well when the number of parameters is large, as described above. The original solution to this problem was Monte Carlo simulation, in which alternative models using parameters drawn at random were successively used to simulate a problem, until a reasonable match to observed data was obtained. This method was extremely inefficient, and has been supplanted by some variation of Markov Chain Monte Carlo (MCMC), wherein each entry in a sequence of Monte Carlo models changes one thing from the previous model, then is compared with the previous model and either accepted or discarded with a probability based on the change in mismatch between the model and the data, scaled by a steadily decreasing parameter, known as the “temperature.” If the mismatch is smaller for the new model, it is always accepted, but if the mismatch is bigger for the new model, it is accepted with a probability that decreases as temperature decreases. Thus, early in the inversion, when temperature is large, a wide variety of models are accepted, which enables the optimization algorithm to escape local minima. Later in the inversion, when the temperature is small, fewer models are accepted, and the results are more stable, but efficiency decreases. The basic algorithm is known as the Metropolis algorithm (Metropolis et al., 1953).

- **Value of information analysis for geophysical data:** A methodology, known as value of information (VOI), objectively quantifies the value of a particular information source by appraising its relevance and reliability. VOI provides a metric that derives from the field of decision analysis and declares that an information source has value if it can improve a decision maker's probability of making decisions with higher valued outcomes.

  Earth scientists inherently see the value of geophysical data; they appreciate that knowledge, although imperfect due to noise, resolution limitations, the challenges of inversion, etc., is gained over the previous incomplete state of information. Geophysical surveys provide spatial coverage that sparse, expensive wells cannot. In many situations; however, it may be difficult to objectively quantify and demonstrate to decision makers if knowledge has been (or can be) gained, thus motivating a VOI analysis. When performing a VOI analysis on geophysical data, some special considerations are necessary (Trainor-Guitton et al., 2014). The methodology must recognize that often the raw data from a geophysical source are not useful for spatial decisions (i.e., decisions related to spatial exploration such as "where to drill?"). Thus, the geophysical "information" will typically consist of the data, the inversion, and the interpretation to link the geophysical attributes to a parameter that would directly affect a decision outcome (e.g., a geologic horizon or unconformity). In particular, the VOI assessment must include how the spatial distributions or locations of reservoir parameters may be distorted by the effects of noise, data sampling, model parameterization, and regularization (smoothing), on the inverse image.

  VOI is a powerful technique that can be used to justify the costs of collecting the new, proposed data. With a flexible framework that includes the spatial uncertainty in the decision and the information itself, this methodology can be applied to multiple subsurface resource decisions and geophysical techniques to assess the possible gain of knowledge.

In summary, there are two major recommendations for geothermal exploration, which focus on the pre-drilling stage of site characterization.

1. *Develop a conceptual model for fluid and heat flow as early as possible in the site-characterization process.* Use it to help interpret site-characterization data, and use site-characterization data to improve and refine the conceptual model. This closely-coupled iterative approach to conceptual model development and interpretation of site-characterization data is a key feature to improve the likelihood of developing a sound model of the geothermal resource, which enables making an optimal choice of drilling location. Multiple models can be developed to test working hypotheses and guide future exploration efforts.

2. *Make use of sophisticated data interpretation approaches to jointly analyze different forms of site-characterization data that honor the conceptual model.* The inherent difficulty of developing a detailed and correct enough model to determine successful drilling locations from surface-based data cannot be overstated. All available capabilities should be employed.

5.4 Supercritical Geothermal Systems

Supercritical geothermal systems are very high temperature geothermal systems that are located at depths near or below the brittle-ductile transition zone in the crust where the reservoir fluid is assumed to be in the supercritical state, e.g., for pure water temperature and pressure are respectively in excess of 374°C and 221 bars. These systems have garnered attention in recent years as a possible type of unconventional geothermal resource that could yield much higher well productivities due to their very high enthalpy fluids. Supercritical conditions are often found at the roots of volcanic-hosted hydrothermal systems. Additionally, supercritical geothermal resources could exist under the ocean floor, associated with mid-ocean ridges (see Section 5.4.6), mantle plumes such as in Hawaii, island arc volcanoes, and back arc volcanoes. Arc volcanoes are relatively common in the western Pacific Ocean, particularly around the Philippines, Indonesia, the Marianas and New Zealand, and in the Mediterranean Sea. Deep wells drilled in geothermal fields such as The Geysers and Salton Sea, United States; Kakkonda, Japan; Larderello, Italy; Krafla, Iceland; and Los Humeros, Mexico, have encountered temperatures in excess of 374°C, and in some cases, have encountered fluid entries. These very high-enthalpy fluids are often very corrosive and abrasive. All wells experienced serious issues with regards to the rock-physical properties as well as physical and chemical fluid conditions, leading to problems related to drilling (e.g., violent blow outs, cave ins, blockages), completion (e.g., unsuccessful cement jobs, casing damage), and fluid handling (e.g., corrosion and scaling of surface facilities). Innovative drilling, completion, and fluid handling techniques, including borehole cooling during drilling and fluid scrubbing, were developed to deal with the extreme temperatures and aggressive fluid chemistry compositions of these systems.

5.4.1 Physical Conditions of Supercritical Systems

The transition to supercritical conditions occurs near the brittle-ductile transition zone, where magmatically dominated fluids are found in the lower, hotter plastic rock, and hydrothermal fluids circulate through the overlying cooler brittle rock (Fournier, 1999). One key aspect of this environment is that quartz develops retrograde solubility—this might result in sealing of any fractures that would be generated (Fournier, 1991; Tsuchiya and Hirano, 2007; Saishu et al., 2014). However, laboratory experiments on fractured granite (Watanabe et al., 2017) suggest that there is not a step-function decrease in permeability associated with the brittle-ductile transition, and that potentially exploitable resources may occur in nominally ductile granitic crust at temperatures of 375-460°C and depths of 2-6 km. These laboratory findings are supported by field observations of fractured rock producing fluids at temperatures above 374°C (Dobson et al., 2017a). These fluids also have high rates of mass transport because of their much higher ratios of buoyancy forces relative to viscous forces in the supercritical state (Elders et al., 2014).

5.4.2 Current Research Efforts

Research is underway in Japan, Italy, Iceland, Mexico, New Zealand, and the United States to investigate supercritical systems, as summarized in Table 11. Further details may be found in Dobson et al. (2017a), Stimac (2017), Stimac et al. (2017), and Reinsch et al. (2017). These projects provide an unprecedented opportunity for international collaboration to help solve the technical challenges associated with characterizing, drilling, and developing these high temperature systems, which include:

- Exploration methods for better resource assessment
- Laboratory experiments to investigate in-situ fluid as well as in-situ rock physical properties
- Adapted drilling and completion technologies
- Logging and monitoring instruments and strategies
- Numerical simulation tools capable of handling supercritical conditions
- Field laboratories to gain more knowledge about downhole conditions and test technological approaches along the entire development chain.

Table 11. Current efforts to investigate supercritical geothermal systems.

Country	Project Name	Site	Depth (km)	Temperature (°C)	Pressure (bars)	Comments
Italy	DESCRAMBLE	Larderello	3.5 planned	450 expected	250 expected	Goal: improve drilling methods and develop better ways to physically and chemically characterize deep crustal fluids and rocks
Iceland	Deep Drilling Project (IDDP)	Reykjanes peninsula	4.6	427	340	Permeability encountered below 3 km; plan hydraulic fracture stimulation with cold water injection
Japan	Beyond Brittle	TBD in Tohoku area of north Honshu	3 - 5	400-500 expected		Region has shallow magma chambers, site search now underway for EGS at brittle-ductile transition
New Zealand	Hotter and Deeper (HADES)	Taupo	5 - 7	>400 expected		Goal: use passive seismic to image brittle-ductile transition
Mexico	GEMex	Acoculco (EGS) and Los Humeros				Goal: generate electricity and heat with high environmental standards and social acceptance
U.S.	*GeoVision*	The Geysers-Clear Lake	5	374 - 650 expected		890 MWe estimated at 50% confidence
U.S.	*GeoVision*	Salton Sea	5	374 - 650 expected		1,259 MWe estimated at 50% confidence
U.S.	*GeoVision*	Coso	5	374 - 500 expected		59 MWe estimated at 50% confidence

5.4.3 Numerical Simulation Studies

There has been extensive work conducted by a number of researchers on the topic of numerical simulations of supercritical geothermal systems. These range from conceptual and numerical models linking magmatic and hydrothermal systems (e.g., Fournier, 1999; Gunnarsson and Aradottir, 2015), to treatment of the supercritical regime as a complex dynamical system whose behavior is likely chaotic (Norton and Dutrow (2001), to extensions of water Equation of State packages to temperatures and pressures above the critical point (e.g., Yano and Ishido, 1998; Croucher and O'Sullivan, 2008; Magnusdottir and Finsterle, 2015). Driesner et al. (2015) developed a new modular numerical simulator platform, known as Complex Systems Modeling Platform (CSMP++), to simulate geological processes such as fluid flow and heat transfer while also capturing geo-mechanical and geochemical processes. In addition to coupled process modeling, additional work has focused on developing improved geophysical models that capture the changing physical properties associated with the brittle-ductile transition zone. One mechanism for facilitating the testing and validation of these codes is to develop benchmark tests and code comparison efforts, as has been done by DOE's GTO, to evaluate the ability of numerical simulators to accurately model coupled thermal, hydrologic, mechanical, and chemical (THMC) processes associated with EGS (e.g., White and Phillips, 2015; Fu et al., 2016), and the international DECOVALEX project (www.decovalex.org), initiated in 1992, which is focused on coupled process in geological systems related to radioactive waste disposal.

When data is limited, a simpler approach to supercritical geothermal potential is reasonable, and is illustrated for The Geysers-Clear Lake, Salton Sea, and Coso areas for depths of up to 5 km below ground surface (Stimac et al., 2017). All three areas show evidence for relatively recent (≤50,000 years) shallow intrusion of magma resulting in supercritical conditions at this depth. The accumulated wisdom of relevant data and interpretations regarding the supercritical domain available through public sources, with some data from field operators, is employed to develop temperature maps, from which supercritical reservoir volumes are estimated. Then conservative recovery factors ranging from 0.1% to 4% are used to estimate their power production capacity using the volumetric heat capacity (heat-in-place) and power density methods, yielding the values shown in Table 11 above.

5.4.4 High Temperature Instrumentation and Method Development

One critical challenge confronting the commercial utilization of supercritical geothermal systems is the need for drilling systems, well completions, power plants, and logging tools and characterization methods that can withstand the high temperatures and aggressive fluids associated with such systems. Several projects focused on developing high temperature tools and methods for characterizing and exploiting supercritical geothermal systems (e.g., Ásmundsson et al., 2014). These technologies were deployed on traditional production wells, as well as deeper wells, where the pressure may be as high as 150 bars and temperature can exceed 400°C. They include all aspects of the well completion process, such as optimization of cementing and sealing procedures, selection of materials and coupling of casings, temperature and strain measurements in wells using fiber optic technologies to monitor well integrity, and development of risk assessment methods.

5.4.5 Collaboration

It is important to note that research activities along the entire geothermal value chain are underway in all regions worldwide where people try to utilize supercritical geothermal systems. A number of research areas are common to multiple groups, and would benefit from international collaboration:

- Exploration methods for better resource assessment:
    - Geophysical exploration methods
    - Field stress measurements
    - High temperature geothermometers
    - High temperature tracer tests
- EGS reservoir characterization and stimulation:
    - High temperature logging and downhole monitoring tools, including optical methods
    - Microseismic monitoring methods
    - Soft stimulation methods
- High temperature drilling and completion methods:
    - Improved drilling methods for high temperature systems
    - Improved well completion methods for high temperature systems
- Surface systems:
    - Scrubbing and fluid handling strategies for dealing with supercritical fluids and corrosive gases

    - Optimized designs for surface fluid handling, power conversion, and cooling systems for supercritical fluids

- Modeling and laboratory characterization of supercritical systems:
    - THMC modeling of supercritical systems
    - Geologic and geophysical modeling of brittle-ductile transition zone
    - Calibration of models using laboratory measurements of rock and fluid properties
- Enabling international collaboration:
    - Data sharing
    - Lessons learned from field experiments
    - Workshops
    - Exchange opportunities for students, postdocs, and researchers

5.4.6 Mid-Ocean Ridges as Source (Iceland and Others)

A particular subset of supercritical systems that holds extreme promise, at least theoretically, is those associated with mid-oceanic-ridge spreading centers, also known as oceanic rift zones (Orcutt and Shnell, 2014). A much higher level of energy is available in the ocean floor, as compared with the continents, because the crust in the continents is, on average, approximately 30 km thick, while the crust under the ocean is, on average, approximately 5 km thick, and is thinner still in the oceanic rift zones where magma arises to repave the seafloor as the lithosphere spreads away from the rifts. Accordingly, while mantle heat flow measurements beneath thermally stable continental areas average approximately 15 mW/m^2 (and may be as low as 10 mW/m^2), and beneath young, perturbed continental areas might be as much as 60 to 70 mW/m^2, suboceanic heat flows average several hundreds of mW/m^2 at mid-oceanic ridges, as shown in Figure 15. These mid-oceanic ridges extend 67,000 km around the world, providing a huge potential resource.

Two strategies are envisioned to tap into the mid-ocean ridges' heat source: one is to capture hot fluid emitted by oceanic hydrothermal vents (Hiriart et al., 2010), and the other is to extract fluid by drilling into the ocean floor (Shnell et al., 2015).

To investigate the vent approach, Hiriart et al. (2010) report that of the 67,000 km of mid-oceanic ridges, 13,000 km have been studied, and 30% have vents. Thus, an estimation of 3,900 km of active vents was used for preliminary calculations, in which a submarine generator uses the hot source (the vent) and the cold sink (surrounding ocean) to run an organic Rankine cycle thermal plant located at the sea floor. Detailed calculations and results of a reasonable efficiency for every part of the cycle show that an overall efficiency for a vent of 4% (electrical power generated over the thermal power of a vent) is a reasonable conservative value for such an installation (Hiriart et al., 2010). Applying this efficiency to an equivalent hypothetical case of a vent with a 3,900-km length with a slot of 10 cm and a discharge velocity of 1 meter per second showed that using only 1% of this equivalent vent to generate electricity, without any drilling, 130,000 MW of electricity could be generated. The main conclusion is that the available (supposedly reasonable) geothermal power that could be generated from well-known hydrothermal vents along mid-ocean ridges is of the same order of magnitude as the EGS geothermal power that can be produced world-wide.

As large as this amount of energy from vents is, it is small compared to the amount of energy estimated from drilling into mid-oceanic ridges. Based on projections from available data, Orcutt and Shnell (2014) report that drilling into oceanic rift zones could provide enough geothermal energy to generate five times as much electricity as the world consumed in 2011.

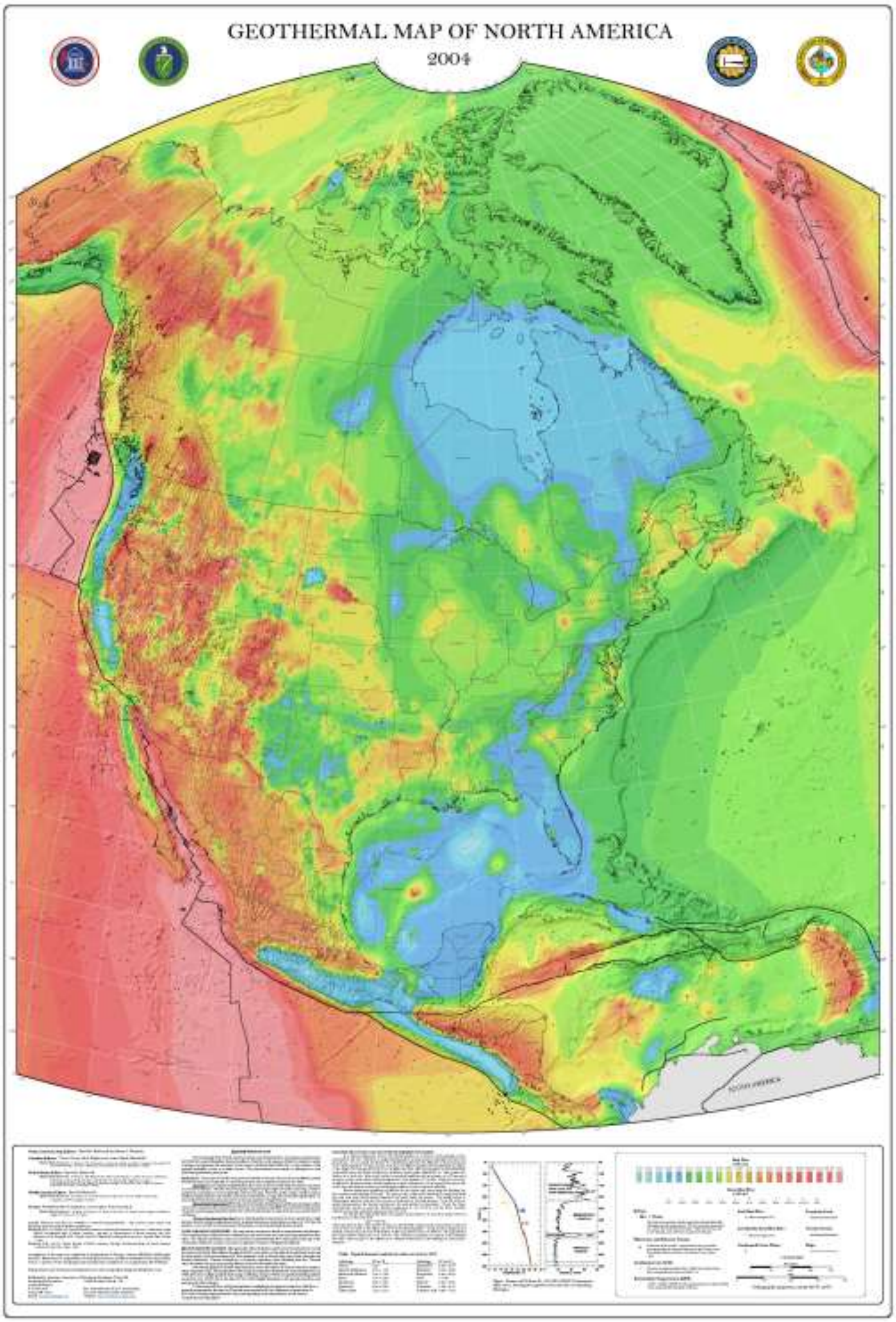


Figure 15. Geothermal heat flow map of the North American continent, including heat flow along two mid-oceanic rift zones: The East Pacific Rise off the western continental boundary and a portion of the Mid-Atlantic Ridge off the eastern edge of Greenland that contains Iceland (Blackwell and Richards, 2014).

One of the concerns that have been expressed concerning the drilling approach has been skepticism about the permeability of the crust, and whether water would circulate through the crust readily enough to permit power plants to access enough brine rapidly enough, particularly at the very high temperatures and pressures that are anticipated. Many types of rock become ductile at temperatures and pressures below those of the oceanic rift zones, which would cause the closing of the cracks that would otherwise allow the brine to circulate. It has been determined; however, that the gabbros in oceanic rift zones will fracture and crack at temperatures as high as 700°C to 825°C (Orcutt and Shnell, 2014). Accordingly, hydrothermal fluids could circulate through oceanic basalt crust down to depths of 6 to 8 km, and supercritical fluids might be expected at depths of 4 to 6 kilometers. Moreover, not only is basalt able to fracture at such temperatures; frequent, small earthquakes in the rift zones should cause movements on the fractures and maintain good permeability. If necessary, standard EGS techniques could be used to augment permeability, expedited by the unlimited supply of brine available at the sea floor.

The drilling challenges described in the previous section on supercritical systems hold here also, but the technology for offshore drilling to the depths contemplated by this approach has already been developed in drilling for the oil and gas industry, albeit for the softer sedimentary rocks that host oil and gas reservoirs.

To use the geothermal energy under the ocean floor, a new approach will be needed to generate electricity. Too much energy would be lost by bringing geothermal fluid to the surface of the ocean through a pipe surrounded and cooled by ocean water for two thousand meters or more of its length. One possible innovation (Shnell et al., 2015) uses a self-contained, submersible, remote-controlled geothermal-powered electric generating station that sits on the sea floor and uses a supercritical CO_2 turbine coupled to a generator to convert geothermal energy to electricity. The electricity is then transmitted as DC current through a cable to the electrical grid on land.

5.5 CO_2 as a Working Fluid

Carbon dioxide has been proposed as an alternative to water as a working fluid to produce geothermal electricity (Brown, 2000). In the past, replacing water with CO_2 has been hampered by the lack of widespread naturally occurring CO_2 sources. The widespread adoption of geologic carbon sequestration (GCS), where fixed CO_2 sources such as power plants and ethanol processing facilities add a capture process and store the captured CO_2 underground, would drastically increase the availability of CO_2. The primary benefits cited for using CO_2 as a replacement for water are: (1) its large compressibility and expansivity, which can lead to creation of a natural thermosiphon, wherein CO_2 circulates between injection and production wells without the need for external pumping; (2) lower viscosity; and (3) reduced chemical interaction with rock minerals. While CO_2 has a smaller heat capacity than water, when considered in light of its lower viscosity, the greater mobility leads to a net overall increase in efficiency (Pruess, 2006). Using CO_2 as a working fluid has been proposed for both traditional EGS in fractured rock and for EGS in deep sedimentary basins (e.g., Garapati et al., 2014; Buscheck et al., 2016; Xu et al., 2016a), where it is sometimes referred to as CO_2 plume geothermal (CPG).

Pruess (2006) performed detailed numerical reservoir simulations of a classical five-spot well pattern comparing CO_2 with water, assuming realistic thermophysical parameters for fractured rock. His results show that there is a broad range of pressures and temperatures at which there is a significant benefit in using CO_2. Pruess (2006), however, simplified the physics of heat and fluid flow in the wells, considering them under isenthalpic and gravitationally static conditions to produce estimated wellhead conditions. This ignores the heat transfer between the wells and the surrounding formation, as well as frictional and inertial forces. Considering the great depth of typical geothermal reservoirs, flow and transport through the wells are expected to have a significant impact on overall system performance.

Pan et al. (2015) developed a fully-coupled reservoir, wellbore, surface power plant model for a deep (3 km) sedimentary reservoir. The wellbore model includes heat transfer between the fluid in the well and the surrounding formation, in addition to frictional, inertial and gravitational forces. Therefore, complex interactions between the wellbore processes and the reservoir processes can be investigated. A simplified representation of CO_2 turbomachinery for a surface plant optimized for direct use of supercritical CO_2 is also included. Simulation results show that the production-wellhead pressure remains much higher than the injection-wellhead pressure after a short kick-off period. This implies that it is possible to establish a thermosiphon mechanism for geothermal heat extraction using CO_2 as the working fluid, eliminating the need to pump the wells. Furthermore, it is easier to set up a thermosiphon system for a higher flow rate than for a lower flow rate. This unique feature is related to the strong dependence of CO_2 density on temperature. In a higher flow-rate injection well, the higher velocity and greater inflow of cold CO_2 makes the lateral heat gain from the surrounding caprock less important. This makes the overall CO_2 temperature lower than it would be in a lower flow-rate injection well. As a result, the CO_2 in a higher flow-rate injection well is colder and denser than in a lower flow-rate injection well, which requires a smaller wellhead pressure to maintain the given well-bottom pressure for driving flow into the reservoir. For a similar reason, the CO_2 in a higher flow-rate production well is warmer and lighter than in the lower flow-rate case, which results in a higher production-wellhead temperature in the higher flow-rate case. However, when the flow rate goes too high, both the pressure loss due to friction to the well wall and the reservoir pressure drop due to widespread cooling would become dominant and destroy the benefit of smaller lateral heat exchange obtained for the higher flow rate. Thus, there is an optimum flow rate that maximizes system performance, which depends on reservoir conditions and well configurations. Tubing diameter similarly has an optimal value, i.e., a small diameter tube has higher friction and momentum pressure loss, whereas a large diameter tube has greater lateral heat loss to the caprock.

The reservoir model in these simulations is highly simplified, i.e., it is homogeneous and fully saturated with supercritical CO_2. In a more realistic reservoir (e.g., multiple layers, heterogeneity, and the coexistence of CO_2 and brine), both the wellbore processes and the reservoir processes are more complicated. This was demonstrated by the results of a thermosiphon field test conducted at Cranfield, Mississippi (Freifeld et al., 2016). At the Cranfield Site, a sedimentary reservoir at 3-km depth has been under near continuous CO_2 flood since December 2009 as part of a DOE demonstration of CO_2 sequestration. A thermosiphon was briefly established between an injection/production well pair separated by 100 m, but it was not sustainable. While a simplified model of the field test (Freifeld et al., 2016) predicted a sustainable thermosiphon, a detailed numerical model (Pan et al., 2018) was able to reproduce the actual field behavior, and in a series of sensitivity studies, factors were identified that could potentially contribute to the failing of a sustainable thermosiphon. These factors can be categorized as two types: (1) factors that increase the resistance to flow, and (2) factors that increase the heat loss of the working fluid. The lessons learned can be applied to both future modeling and to achieving CO_2-based geothermal reservoir exploitation.

5.6 Graphene Replacing Pipes and Geothermal Fluid Due to Its High Thermal Conductivity

The distribution of geothermal energy has been traditionally through the use of a medium, typically liquid water or steam, or more recently CO_2 (see Section 5.5). In the novel concept described below, graphene cables replace the working fluid in a hydrothermal reservoir or EGS (Richter, 2015; Bhargava, 2015).

The use of liquid or gas to distribute heat has several disadvantages. Liquid or gas media require containment vessels such as pipes in order to be effective media for distributing heat. The pipes require strong seals to prevent leakage. Additionally, the pipe must be strong enough to withstand the pressure of the contained medium. Generally, thick walled pipes are used, which are heavy and bulky, or alternatively, lighter and expensive materials are used.

Additionally, in order to move the traditional medium sufficiently through the distribution system, some type of propulsion is required. A pump is typically used to move the liquid or gas through the distribution system. Pumps generally require their own mechanical or electrical energy to operate, further reducing the total efficiency of the system. Further, pumps generally require periodic maintenance and replacement. Traditional media moving through pipes at high pressure are also subject to frictional losses and turbulence due to the interior surfaces of the pipes. These losses further reduce the efficiency of the traditional system. A more efficient system to conduct heat energy that overcomes these disadvantages is desirable.

Graphene is a recently-developed material that has many advantageous properties: it is chemically very stable, flexible, a hundred times more tear-resistant than steel and, at the same time, very light. Most important for geothermal applications; however, is its very high thermal conductivity when compared to traditional materials. Graphene is an allotrope of carbon in the form of a two-dimensional, atomic-scale, hexagonal lattice in which one atom forms each vertex. It is the basic structural element of other allotropes, including graphite, charcoal, carbon nanotubes and fullerenes. Graphene is typically manufactured in the form of thin sheets, one atom thick. A graphene-enriched product (GEP) has at least one layer of graphene adjustably affixed to at least one of its surfaces. For example, a cylindrical conduit can have multiple layers of graphene affixed to its surface with or without a substrate layer separating them. Energy, including but not limited to heat energy, can be conducted through the layers of graphene affixed to the conduit. Due to the high thermal conductivity of graphene and its unusual conductivity properties (thermal conductivity logarithmically increases as a function of the size of the graphene samples; energy is transferred through graphene from end-to-end without any heat remaining in between), very little heat is lost to the environment. Thick insulation, typical of other media that conduct heat to prevent radiant heat energy from escaping, is not needed. Generally, a protective outer layer covering the graphene protects the graphene layers from damage. Since graphene is a solid material, the containment issues of liquid or gas mediums are eliminated. Expensive containment vessels, seals, gaskets, and other equipment required with traditional liquids or gases are not required. Pumps are also not required, as the heat energy is conducted linearly through graphene due to the inherent properties of the material.

Using graphene cables instead of a traditional working fluid in geothermal systems is still at a highly speculative state. Actual efficiencies of heat transfer for real-world geothermal conditions have yet to be worked out, and manufacture of graphene-based fiber is an active research area (e.g., Meng et al., 2015; Xu et al., 2016b).

5.7 Direct Electric Geothermal Resource Extraction (DEGREe)

Rather than pulling hot fluid up from the earth and converting it to electricity in a power plant, the Direct Electric Geothermal Resource Extraction (DEGREe) concept is to just bring up electricity. That is, one would make a solid-state heat exchanger in the subsurface and then couple that with thermometric materials to make electricity. The installation would be expensive, but after that the solid-state electricity source would last for the lifetime of the heat and materials. It would take a new generation in materials, but it would also totally change the geothermal landscape (P. Nico, personal communication). Such thermoelectric generators are currently in testing in the laboratory to optimize power generation (Chen et al., 2017), and there are plans to conduct small-scale field testing of such units in China in the near future (K. Li, personal communication).

Acknowledgments

Many people in the geothermal community have generously shared their ideas and insights with our team. In particular, we wish to thank the members of the *GeoVision* Visionary team and the DOE GTO staff for their assistance in this effort. In particular, we would like to thank Jeff Winick for his leadership and Morgan Smith (BCS, Incorporated) for integrating our report sections in to a more seamless document. Major contributions to this summary were derived from unpublished analysis of GTO-funded R&D that were conducted by Charlie Visser (NREL) and Laura Garchar (DOE GTO). This work was supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Geothermal Technologies Office (GTO) under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory, No. DEAC02-05CH11231 with Lawrence Berkeley National Laboratory, No. DE-AC07-05ID14517 with Idaho National Laboratory, and DE-AC04-94AL85000 with Sandia National Laboratories.

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