PROCEEDINGS, Thirty-Eighth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 11-13, 2013
SGP-TR-198

A TECHNOLOGY ROADMAP FOR STRATEGIC DEVELOPMENT OF ENHANCED GEOTHERMAL SYSTEMS

John Ziagos[1], Benjamin R. Phillips[2,3], Lauren Boyd[3], Allan Jelacic[2], Greg Stillman[3], and Eric Hass[4]

[1]Lawrence Livermore National Laboratory, 7000 East Ave., Livermore, CA 94550
[2]SRA International, Inc.
[3]Geothermal Technologies Office, U.S. DOE, 1000 Independence Ave. SW, Washington, DC 20585
[4]U.S. DOE, 1617 Cole Blvd, Golden, CO 80401

E-mail: ziagos1@llnl.gov

ABSTRACT

Roughly 90% of the geothermal power resource in the United States is thought to reside in Enhanced Geothermal Systems (EGS). While realization of EGS development on the 100+ GWe scale would make geothermal a significant component of the renewable energy portfolio, hurdles to commercial development still remain in accessing and characterizing, creating, monitoring, operating, and sustaining engineered reservoirs. In August 2011 the Geothermal Technologies Office (GTO), U.S. Department of Energy (DOE), convened a workshop in San Francisco, CA, to outline opportunities for advancing EGS technologies on five- to 20-year timescales. Community input charted technology needs categorized within the functional stages of *Characterizing, Creating, and Operating* EGS reservoirs. In this paper we present technical paths—*identifying, creating, and managing fractures and flow paths; monitoring flow paths and fracture evolution; zonal isolation; drilling; models; and tools*—that encompass the underlying technology needs identified at the workshop as critical to optimizing and ultimately commercializing EGS. We develop the chronological evolution of these paths, tying the past and current status of each to the active GTO EGS research and development (R&D) portfolio, anticipating milestones that strategic initiatives could help to realize on a five-year timescale, and projecting to target capabilities for 2030. The resulting structure forms the basis for an EGS Technology Roadmap to help guide priorities for future GTO EGS R&D investments.

INTRODUCTION

A significant long-term opportunity for widespread power production from new geothermal sources lies in EGS, where successful technology development and deployment could facilitate access to a resource category estimated to be on the order of 100-500+ GWe (USGS, 2008). One of GTO's major long-term goals is to realize this potential through commercial, cost-competitive, EGS-based electricity generation in the U.S. In pursuit of this goal, GTO actively engages in R&D and field demonstrations to facilitate new, innovative technology deployment and validation to reduce costs and improve performance. The GTO's EGS Program (Program) investments consist of a mix of lab-scale research and development projects as well as field demonstration work. Currently, the Program supports applied research through an extensive research portfolio conducted by industry, academia and national laboratories; demonstration work through multiple EGS field demonstrations; and a proposed EGS field laboratory where EGS technology will be validated. This paper presents a roadmap informed by community and expert input that forms the basis for the current and future EGS R&D investment strategy. The roadmap illustrates technical research paths (tech paths) as they evolve over time: through past practices, current Program efforts and desired future capabilities and outcomes. It is intended that this EGS Technology Roadmap not only guide priorities for GTO investment, but also document and communicate the EGS Program R&D strategy to geothermal stakeholders, members of other subsurface science and energy sectors, and legislative and policy administrators.

State of EGS

Since the early 1970s, several large-scale EGS field projects reached varying degrees of success, though the majority of EGS developers and researchers would conclude that EGS has yet to be validated as an optimized technology on a commercial scale. Fenton Hill, Rosemanowes, Le Mayet, Hijiori, Soultz, and Cooper Basin (Wyborn, 2011) targeted granitic reservoir host rocks at depths in excess of 2 km to achieve temperatures sufficient for electric power production. With the exception of the Landau project in Germany, past projects have not successfully sustained commercial production rates (50-100 kg/sec). Note that the characteristics of Landau suggest that it is a stimulated hydrothermal reservoir and not a "green-field" EGS development (e.g., Baria and Petty, 2008). Each of these historic EGS projects, however, has played an integral role in informing the future direction of EGS research and development, having added significantly to our understanding of micro to macro-scale issues associated with EGS.

In addition to lessons learned from historic projects, recent successes within GTO's EGS demonstration portfolio have favorably positioned EGS technology for further advancement. In fiscal-year 2012, the first of several EGS demonstration projects funded by DOE has shown the potential to produce 5 MW from an engineered reservoir in a deep, impermeable, and unproductive rock body at The Geysers, with far greater additional potential at this site (M. Walters, personal communication, May 7, 2012).

Past experience dictates that challenges in EGS technology development require a broad-based, multidisciplinary approach. The large resource potential makes the challenge that much more enticing. EGS carries significant risk and uncertainty, but fundamental barriers to commercialization are surmountable. Critical to advancing EGS are technologies that facilitate characterization of local stress, chemical constituents, and thermal pathways prior to and during reservoir development. The second critical need is to achieve sufficient productivity for commercial EGS power generation without excessive pressure build up or localization of flow. This can be accomplished through the development of technologies and techniques to engineer reservoirs of sufficient scale and with an optimal distribution of permeable pathways. A final overarching hurdle is sustainable operation, which will require improved understanding of multi-decadal reservoir evolution and novel subsurface monitoring and management technologies.

The DOE's EGS research program is dedicated to addressing these key barriers through support of initiatives in the research and pre-commercial stages. Currently, GTO's portfolio can be characterized by R&D in three defining categories, which track the lifecycle of a successful EGS: reservoir characterization, creation, and operation.

GTO Roadmapping Goals

Roadmapping is commonly used by technology offices at DOE to craft R&D investment strategies that address complex barriers. Technology roadmapping is an important tool in developing and maintaining a successful and flexible research portfolio, and is the ideal mechanism through which GTO's EGS strategy can be developed, integrated, and communicated to geothermal stakeholders and the energy community. Many efforts within DOE's Office of Energy Efficiency and Renewable Energy (EERE) are "device oriented" due to an emphasis on improving performance of renewable technologies that are already commercially deployed at some level. The conceptual nature of EGS and the inherent focus on the subsurface separates EGS from these renewable programs. Furthermore, the state of understanding of the mechanisms that control EGS and its pre-commercial nature positions the technology at a different place on the development pipeline. Therefore, a different approach was necessary for this guidance document; traditional EERE roadmapping principles were modified accordingly to address the needs and constraints dictated by the uniqueness of EGS.

Since growing deployment through commercialization in a competitive energy market is an ultimate target of EERE investments, roadmaps are typically constructed around cost reduction strategies and culminate in "waterfall" charts, which delineate the development areas critical to meeting overall cost goals. In the case of GTO's EGS cost reduction strategy, resource characterization and well-field development account for almost half of total 2030 cost reduction targets (Figure 1). This includes reservoir stimulation activities, highlighting the importance of technology improvements in EGS characterization and creation.

DOE envisions this roadmap, built from community input, as technical and programmatic in nature. Its purpose is to inform future GTO technology investment decisions and outline a pathway to large-scale commercialization of EGS. Specifically, the document identifies technology advancements that

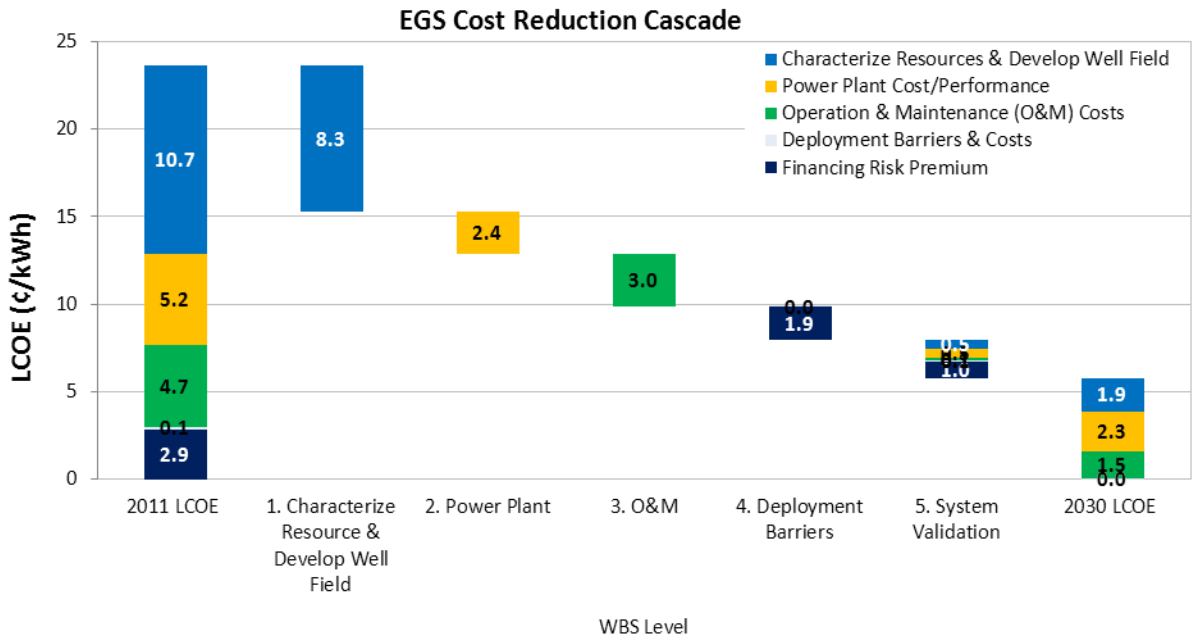

Figure 1: An example of GTO's cost-reduction cascade for a 20 MW binary EGS plant with a 175 ℃ resource at 3 km depth, calculated using the Geothermal Electricity Technology Evaluation Model (GETEM) (Mines, 2008), beta version updated September 27, 2012. Resource characterization and well field development, including reservoir creation, are the largest single component, contributing ~8 ¢/kWh to reductions from a 2011 levelized cost of electricity (LCOE) of ~24 ¢/kWh to a 2030 target of ~6 ¢/kWh. Operational cost reductions of ~3 ¢/kWh are also critical to meeting this goal.

can play a critical role in optimizing and commercializing EGS. In this roadmap, the state of the art in characterization, creation, and operation technologies/methodologies is assessed and pathways that outline advancements are extrapolated into the future. Critical to this roadmap is building upon lessons learned from past practices.

Although integral to future DOE investment decisions, this roadmap also should act as a guide for the geothermal community. In order to grow our collective knowledge and expedite advancement of relevant technologies, DOE will rely on input from geothermal and other subsurface stakeholders to revisit and modify the plan as circumstances, outcomes, and budgets dictate.

EGS HISTORY

The concept of extracting the earth's heat with the creation of fractures in hot rock dates from the late 1960s when several proposals were made to use nuclear weapons as a means of fracture generation. The proposals were not adopted. In 1974, researchers at Los Alamos Scientific Laboratory received a patent for a "*Method of Extracting Heat from Dry Geothermal Reservoirs*" (Potter et al., 1974). The Los Alamos invention contained all the essential aspects of an EGS, and in fact those tasks have not changed over the ensuing years: a hydraulically stimulated fracture system in hot dry rock connected to the surface by injection and production wells (Figure 2). The bulk of the material in the following section was derived primarily from Tester, J.W., et al, 2006; hereafter referred to as the "MIT report").

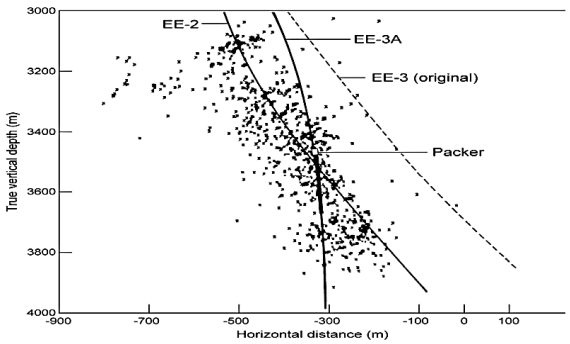

Figure 2: The Los Alamos' HDR project created the first EGS at Fenton Hill, NM. Elevation view showing locations of microseismic events in the Phase II reservoir (from Brown et al., 1987).

Foundational Projects

Fenton Hill

The Atomic Energy Commission funded Los Alamos to field a "hot dry rock" (HDR) system, and after several failed attempts to connect two wells, the first operational HDR circulation loop was established at Fenton Hill in 1977. Over the next three years multiple experiments were conducted to test and improve the circulation system, culminating with a continuous circulation experiment in 1980 lasting nine months. The experiment also included the first generation of electricity from an HDR system—a modest 60 kW using a binary turbine-generator.

The substantial success of this Phase I system led to the development of a larger Phase II system at Fenton Hill, with financial support by government agencies from Germany and Japan as well as backing by the DOE. The Phase II system never achieved its programmatic goal of a commercial-scale field demonstration. Well failures and completion problems, equipment design flaws, and funding shortfalls prevented the creation and long-term testing of a large-sized reservoir. However, a number of innovative techniques, equipment, and measurement tools were developed that enabled EGS technology to evolve.

Possibly the most telling lesson learned at Fenton Hill—bearing on the Project's success—was not to presume the stress field. The Fenton Hill experience taught that in situ stresses can vary with depth, and rocks may not fracture in predictable directions. The prudent approach to reservoir development involves drilling just one well prior to stimulation.

Rosemanowes

While Los Alamos led the world in HDR R&D, the Camborne School of Mines in the United Kingdom was not far behind (1977-1991). The British chose to develop the granite batholiths comprising western Cornwall. This area had some of the highest thermal gradients in the U.K., but the decision was made not to pursue higher temperatures at depth but rather to focus on developing equipment and techniques that could later be used for heat extraction.

Two deviated wells were drilled without incident to 2100 m depth, and hydraulic fracturing at 100 kg/sec, preceded by explosive fracturing, ensued with the intent of driving fractures vertically upward from the injection well to the production well. Remarkably, rather than migrating upward, the fractures moved downward as shown by microseismic events. The reservoir continued to grow in this manner for the next nine months of circulation with some events eventually reaching depths in excess of 4500 m. Downward growth was accompanied by high water losses (~70%) and high impedances to flow.

In view of the unsatisfactory results, a new production well was drilled to 2600 m beneath the first two wells and through the reservoir zone. Circulation was established at rates as high as 20-25 kg/sec. Testing of this loop continued for four years. But high water losses and large flow impedances continued. Viscous gel with sand proppant was used to stimulate the new well, and while water losses and impedances decreased, short-circuiting between the injection and production wells worsened. In an attempt to bypass the short-circuiting a packer assembly was used to stimulate the bottom of the production well. A good connection with the injection well was not attained. Subsequent analysis suggested that the new stimulation zone was parallel and independent of the earlier reservoir.

The British learned that rock failure at Rosemanowes occurred by shearing along pre-existing joint sets rather than through tensile fracturing from hydraulic pressurization. In fact, the creation of new fractures was almost irrelevant; the natural fracture system dominated the stimulation process. Artificial fractures only play a role in the immediate vicinity of the wellbore. Overstimulation at high pressures leads to runaway water losses and short-circuiting. The project goals, including sustained production at 50-100 kg/sec for five years with no thermal drawdown, were not achieved. The British government ended the Rosemanowes Project in 1991 and opted instead to support the new EU project at Soultz.

Hijiori

As its initial HDR project, Japan chose a site on the southern edge of Hijiori caldera, analogous in geologic complexity to Fenton Hill. Through its independent energy agency, the New Energy and Industrial Technology Development Organization (NEDO), Japan had participated in the Fenton Hill Project from 1981 to 1986. NEDO then undertook the development at Hijiori. Four wells, one injector and three producers were drilled to 1,800 m where temperatures reached 250° C. Attempts to stimulate and connect the wells were largely unsuccessful, even though the distances between wells were on the order of just 50 m. During circulation tests, water losses exceeded 70%.

The Hijiori experience reinforced the conclusion that EGS reservoirs result from the stimulation of natural fractures, and the geometry of the reservoir depends on the orientation of natural fractures relative to the in situ stress field. The Hijiori reservoir grew and

connectivity improved more during long-term, low-pressure circulation tests than during short-term, high pressure hydraulic fracturing. Clustering wells in a small spatial volume did not appear to offer any advantages for enhanced connectivity.

Ogachi

In 1990 the Japanese began a second HDR project, capitalizing on two early exploration wells drilled on the margin of Akinomiya geothermal field. The Ogachi project was the result of collaboration between the Central Research Institute of Electric Power Industry (CRIEPI), a research arm of the electric power industry, and Tohoku University. The target rock was a granodiorite with low permeability. The injection well was extended to 1,000 m where temperatures reached 230°C. The bottom of the well was stimulated, and subsequently a window was cut in the casing at 710 m followed by more stimulation. The second well was extended to intercept the stimulated zone. As at Hijiori, the wells were drilled within 100 m of each other. Despite their best efforts, the Japanese researchers could not establish a productive connection between the wells. Initially, water losses exceeded 90%, and improved to 75% after further stimulation. A third well, drilled to intersect the volume defined by acoustic emissions, improved the connection. Borehole televiewer logs were instrumental in determining fracture orientation. Over four years of tests, injection rates ranged from 8 to 17 kg/sec, while production rates did not exceed 2 kg/sec.

Soultz

In the mid-1980s, as interest in HDR grew, and spurred on by the work at Fenton Hill, the European Commission (EC) decided to support a large-scale HDR project in Europe. Eventually, the EC chose Soultz-sous-Forets, France, a site in the Rhine graben only a few kilometers from the German border. The Soultz Project was a collaboration of the EC and energy ministries from France, Germany, and the UK, and the onsite management team consisted of a representative from each of the three countries. Fenton Hill notwithstanding, Soultz was the first HDR project with the goal of generating commercial amounts of electricity.

To date, Soultz is the most successful of all the HDR/EGS demonstration projects. The extensional geologic structure of the Rhine graben has contributed to the success of this project, reinforcing the need to understand the structural constraints of a potential EGS site. The Soultz team was able to drill and stimulate at multiple depths without undue difficulty, the final HDR reservoir was the largest yet created and they were able to produce at the highest sustained flow rate (25 kg/sec). Injection testing suggested that fracturing was diffuse rather than concentrated in discrete fractures. The team showed that pumping the production well to maintain flow was a viable alternative to high-pressure injection. Soultz confirmed again that natural fractures are the controlling feature in reservoir formation.

Cooper Basin

By the late 1990s interest in geothermal development in Australia had begun to grow, fueled in large part by the entrepreneurial spirit of investors in new ventures. In fact, the Australian experience was unique in that the push to develop geothermal resources using EGS was driven almost entirely by the private sector. Initial government involvement in terms of funding support was minor. All previous HDR projects had relied heavily on government support.

Geodynamics, the first and foremost of the private companies, had established a land position in the Cooper Basin in the far northeast corner of South Australia. Like the area around Soultz, Cooper Basin had been an Oil and Gas (O&G) province with a substantial number of wells, some of which extended to the granitic basement. High temperatures from these wells led Geodynamics to drill Habanero-1, to 4,421 m with a bottom-hole temperature of 250°C. Surprisingly, Habanero-1 intersected highly permeable, over-pressured fractures at depth. Shut-in pressures of 35 MPa (5,000 psi) were measured.

If not for mechanical failures of several wells, Geodynamics' efforts at Cooper Basin would have succeeded well beyond initial expectations. The stress field and geology at 4 km depth were highly conducive to reservoir creation and growth. The horizontal geometry of the reservoir and the apparent ability to stack multiple reservoirs provide ideal conditions for massive heat extraction over a large area.

Summary and Lessons Learned

Since the 1970s at Fenton Hill, EGS technology has made significant progress. Experience gained in the last forty years at these EGS field projects has influenced, guided and further refined the EGS R&D investment strategy. The critical importance of understanding and mapping the natural fracture system and the in situ stress field painfully discovered at Fenton Hill, rediscovered at Rosemanowes, and reinforced at Hijori and Ogachi positively influenced the planning for Soultz and Cooper Basin. In addition, using low-pressure stimulation, hydroshearing, versus high-pressure hydraulic fracturing to increase reservoir growth and

connectivity, learned at Fenton Hill, Rosemanowes and Hijiori, was also incorporated into the Soultz and Cooper Basin project plans. Finally, trans-tensional environments (e.g., grabens) may be more amenable to successful manipulation than compressive stress regimes in EGS reservoir creation. Great progress has been made towards proving technical feasibility of EGS and these past experiences have been applied to the GTO-funded EGS demonstration projects as discussed in the next section.

GTO EGS Demo Portfolio Status

At present, there are four DOE funded EGS demonstrations projects located within or on the margins of hydrothermal fields and two projects in unexplored and undeveloped sites (although one is currently inactive and will not be described here). Promising results have been achieved to date at each of the sites that have initiated their stimulation phases.

Desert Peak

The Desert Peak demonstration project, run by Ormat Technologies Inc. is located northeast of Reno, NV, within the Hot Springs Mountain range. Existing hydrothermal production (12.5 MWe) at the site originates from a fractured zone located in the lower portion of a 760 m thick rhyolite unit, whose upper portion forms the reservoir cap.

In order to enhance the permeability of the target well (a tight well with temperatures up to 210°C) and develop connectivity between this well and the producing portion of the hydrothermal field, Ormat designed a stimulation program comprised of four unique phases. In August 2010, stimulation began at the Desert Peak site, where fluid was injected into the base of the Rhyolite Unit, between 914 and 1005 m. After an 8-month multi-stage stimulation that included shear (low volume), chemical, and high volume stimulation phases, the injectivity increased by several orders of magnitude and flow rate increased to hundreds of gpm. This represents a major improvement in the well permeability, in that both flow rate and injectivity were enhanced to within the range of a commercial well.

Lessons learned during this stimulation have allowed the team to re-evaluate certain methodologies or techniques; for example, the chemical stimulation increased injectivity temporarily, but it was determined that it later led to wellbore instability (Chabora et al, 2012). In addition, it was clear that shear stimulation was a necessary preliminary step to increase the stimulated volume away from the wellbore (Chabora, et al., 2012). Subsequent high volume stimulation also created additional permeability, although it remains to be seen if this permeability is sustainable. Finally, real-time microseismicity monitoring proved essential to validating the evolution of the stimulation, however, sub-surface geophones and modification of the detection algorithms were necessary to obtain the most pertinent data, which in this case, included small events (sub-zero magnitudes). To further increase injectivity, Ormat recently reworked the well to access deeper formations and initiated a high-volume, multi-zoned stimulation effort.

Brady's Hot Springs

In addition to the Desert Peak EGS project, in FY2008 Ormat Technologies Inc. was selected for an EGS demonstration award at Brady's Hot Springs, NV, 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. 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 (Benoit et al., 1982). Hydrothermal production at Bradys is generally associated with the Bradys Fault. 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. In general, the existing production wells range in depth from 600-1500 m and produce from near the fault zone. The Brady's EGS target well intersects a rhyolite unit where temperatures are in excess of 204°C and extensive fractures have been identified. Stimulation activities will occur in early 2013 and will be informed directly by successful operations at Desert Peak.

The Geysers

The Geysers EGS demonstration project, awarded to Calpine Corporation, is located west of the Basin and Range province in northern California at the largest steam geothermal field in the world. The Geysers reservoir is contained in greywacke sandstone that is capped by a mix of low permeability rocks and underlain by a crystalline rock body.

The objectives of this project were to augment production in an abandoned portion of the field by accessing and stimulating the low permeability, High Temperature Zone (HTZ) that lies beneath the producing Geysers hydrothermal reservoir. The HTZ has been estimated to reach temperatures of 280-

400°C and contain high concentrations of non-condensable gases (NCG). In 2011, Calpine initiated a year-long stimulation program comprised of step-wise injection of treated effluent water to enhance permeability through thermal contraction of the rock and shear-reactivation. The research team successfully created a new and discreet reservoir in the HTZ, which has been confirmed with geochemical data and by pressure responses to testing in respective wells (M. Walters, Personal Communication, April 5, 2012). Flow testing and power production estimates to date show the steam produced from this new portion of the reservoir has the potential to produce 5 MW. The operators are in the process of designing a new power plant to accommodate steam flow from the stimulated region.

Equipment failures that occurred during the re-completion of the injector and producer illustrate the need for advanced drilling technologies and temperature hardened reservoir interrogation tools. While re-opening and deepening the target wells into hard-rock formations, the rate of penetration decreased from 15-20 ft/hr to less than 10 ft per hour (Garcia, 2012). At ~3,300 m the bit was largely destroyed after less than 30 m of air drilling.

Furthermore, logging of the wells and downhole sampling under these high temperature conditions was problematic. Calpine commonly utilizes tools capable of operating at temperatures up to 360 C in field operations at The Geysers, however, those able to withstand the conditions in the HTZ don't currently exist. This proved problematic for obtaining true bottom hole temperatures and running other logging suites.

Limitations of current numerical modeling capabilities were also elucidated through Lawrence Berkeley National Laboratory's (LBNL) coupled thermal, fluid flow, and geomechanical modeling of the stimulation; TOUGH is not capable, at present, of simulating the movement of fluid through rocks at critical and supercritical conditions.

Finally, at the NW Geysers, it might be possible to discern the physical mechanisms involved in thermal versus pressure fracture creation by observing the microseismicity during stimulation. Increasing pressure triggered seismicity almost immediately after the start of the simulation, indicating that the seismicity was controlled by the injection rate, whereas fractures and seismicity triggered through thermal contraction or induced stress reduction appeared later. Slower acting thermal-induced seismicity tended to occur predominantly near the injection well while pressure-induced events were observed at a distance. Lastly, it was found that larger events are more likely to occur away from the injection point because larger magnitude events require an undisturbed and sizable rupture area, usually found away from the injection well and often associated with minor faults.

Newberry Volcano

The Newberry Volcano EGS demonstration project in central Oregon was funded through the American Recovery and Reinvestment Act of 2009. The project site, located on the flanks of the Newberry volcano, lies at the juncture of three geologic provinces: the Cascade Range to the west, the "high lava plains" portion of the Basin and Range province to the south and east, and the Blue Mountains to the north (MacLeod, et.al., 1981).

The Newberry demonstration project recently tested various innovative technologies to create an EGS reservoir by injecting cold fluid into the subsurface at pressure for approximately 40 days. The project utilized chemical and mineral diverter technologies, developed by AltaRock with CSI Technologies and funded in part by DOE, to temporarily plug zones of fluid loss so that new fractures could be reopened and extended (Bour et al., 2012). This facilitates access to a larger rock volume for heat extraction from a single wellbore. The diverters are comprised of non-toxic, biodegradable materials or naturally occurring minerals that temporarily seal fractures and eventually dissolve with time and heat. Analysis of seismic and injection data associated with the stimulation is currently underway; preliminary results indicate that the use of chemical diverters facilitated access to three distinct fluid exit points in the target wellbore during the stimulation.

In the spring of 2013, AltaRock will perform injectivity and flow testing to determine the characteristics of the stimulated zones. If the project passes through a routine decision point, production wells will be drilled to intersect the reservoir, about 1,500 feet away from the injection well. Once a connection between wells is made, the system will be flow-tested to determine if it is capable of supporting commercial production.

Raft River

Finally, the EGS demonstration located in Raft River, Idaho, was awarded to the University of Utah, Energy and Geoscience Institute. Raft River is located in south-central Idaho in the Raft River Valley, which is a north trending, down faulted basin. The known geothermal resource area is located in the southern part of the valley. At present, power is produced at the Raft River site via a conventional

geothermal resource that was developed as a result of a former U.S. Department of Energy geothermal demonstration project that operated from 1974 to 1982. As noted at many of the demonstration sites, the regional faults play an integral role in the geothermal potential of the site; at Raft River, geofluid is thought to circulate to depth and throughout the subsurface via the intersection of these faults.

The objectives of this demonstration project are to develop an EGS reservoir, at an estimated temperature of 130-200°C, to improve performance of the existing Raft River geothermal field. In order to increase production from the target well and connect it to the field, a staged stimulation program will be employed, starting with cool water injection to thermally fracture the rocks (50°- 70°C and 135°-140°C), followed by hydraulic stimulation. The stimulation phase will begin in early 2013.

Summary of Recent Advancements

Each demonstration was wholly informed by lessons learned from historic EGS/HDR projects and recent research focused on links between seismicity and permeability enhancement. As reservoir growth has been shown to be dependent predominantly on the shearing of natural joints aligned with principal stresses (Baria, 1999), natural fracture orientations and in situ stresses of target formations are measured or estimated and considered an integral part of designing each project's stimulation strategies. Historic data related to injection pressures and fluid volumes necessary to initiate shear associated with specific tectonic environments has also provided a starting point from which new methodologies can be tested, such as the feasibility of combining shear stimulation and fracture dilation by approaching and in some places surpassing the critical tensile stress. Research surrounding induced seismicity as a tool to track reservoir evolution, first utilized at Fenton Hill (NETL, 2007), has been critical for the current demonstration projects to locate stimulated fractures and track growth; each site is fully instrumented by Lawrence Berkeley National Laboratory per GTO requirements, and in some cases additional monitoring arrays have been deployed.

The implications of the success achieved to date at The Geysers and Desert Peak are far reaching; the ability to develop EGS reservoirs on the margins or in unproductive portions of existing hydrothermal fields at a relatively low cost can facilitate the build out of additional capacity in the short term. Furthermore, data from the stimulation at Newberry indicates that fractures were successfully opened and are taking fluid. With further analysis the degree of connectivity of these fractures will be clarified.

EGS PROGRAM STRATEGY

GTO's mission is to provide programmatic leadership, and fund key R&D technologies and focused demonstration projects to advance EGS technology while decreasing implementation costs. While achieving cost-competitive electricity generation from EGS is a long-term goal, in the near term, R&D and demonstration projects will move industry along the learning curve toward technological readiness. The economic viability of EGS depends on developing and improving critical enabling technologies. While these technologies are vital to the success of EGS, they also apply across the geothermal continuum. The ultimate goal of the EGS Program is to demonstrate the ability to create a 5MW reservoir by 2020, and ultimately lower the Levelized Cost of Energy (LCOE) to 6 ¢/kWh by 2030 (Figure 1).

GTO's current strategy for accelerating EGS demonstration successes involves a progression of EGS trials from near existing hydrothermal fields to undeveloped sites. Targeting demonstrations near existing hydrothermal fields in the short-term reduces costs and risk because existing infrastructure and subsurface characterization can be effectively leveraged. Heat and reservoir fluid have been confirmed from the hydrothermal activity nearby, hence, the main objective of these near hydrothermal field projects is to demonstrate effective permeability enhancement and sustained reservoir production over multiple years. Lessons learned and identified best practices for reservoir stimulation in near-field environments will be used to lower costs and risk for projects in undeveloped fields. In the long term, EGS technology development and demonstration will step out from the margins of existing hydrothermal development to 'greenfield' sites, where no previous hydrothermal development has occurred.

Bridging the existing field demonstrations, component R&D, and the long-term goal of 5 MWe from EGS are the Program's EGS Validation modeling effort and the proposed dedicated EGS field lab initiative. The EGS Validation effort is focused on informing possible conceptual approaches to EGS through numerical analysis of various EGS configurations; parameters governing the performance of such systems will be elucidated through this exercise. Suites of simulations will help identify ranges of key formation and stimulation parameters needed to engineer and sustain an EGS. The relationships of the formation to injection and production-hole characteristics and their effect on

flow rates and sustained power output will be examined. Lessons learned from this exercise and the current EGS demonstration projects and R&D portfolio will guide future GTO investments and activities including planning and execution of a DOE run field lab. The field lab will enable broad collaboration across subsurface science communities and will be structured around meeting key technology needs. It will also provide an opportunity for advanced technology testing that may be too risky or cost-prohibitive for private companies to undertake. The overall goal of this proposed five-year collaborative effort is to establish the technical and operational settings and parameters under which EGS can be commercially successful. This roadmap highlights the key technology areas that require immediate attention in the near-term, reinforcing the role that a dedicated field lab can play towards addressing goals in an expedited manner, and outlines the technical evolution necessary to meet GTO goals in the long term to ultimately establish the commercial viability of EGS.

Roadmap development history

The preliminary steps that eventually led to this technical roadmap began in September 2005 when DOE assembled an 18-member assessment 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." The panel's findings published in the MIT report were the first comprehensive assessment of EGS and concluded EGS can be a major U.S. energy source. Consequently, in June 2007, GTO held a workshop in Washington, DC "to clarify and evaluate the assumptions, analytical methods, and conclusions presented in the MIT report." Technical gaps were identified, as summarized in a report of workshop results (DOE, 2007).

Three other workshops were held in 2007 focusing on major aspects of EGS: Reservoir Creation (San Francisco), Reservoir Management and Operations (San Francisco), and Wellfield Construction (Houston). These workshops (results accessible here: http://www1.eere.energy.gov/geothermal/egs_worksh ops.html) brought together panels of industry, academia and national laboratory experts to identify technical challenges and hurdles to EGS. It was noted that understanding of EGS subsurface processes would benefit from the ability to model systems more realistically. Further, the workshop attendees agreed that drilling technology improvements and development of high temperature and pressure tools are essential to the advancement of both the EGS and the larger geothermal industry. In 2008, an *Evaluation of Enhanced Geothermal Systems Technology* report was published as a summary of all previous workshop results (DOE, 2008a). This report extended, reorganized, and summarized the lists of technical barriers, and developed R&D necessary to advance. Topical areas were identified that required additional research, culminating in a comprehensive list of technologies within functional categories.

These research categories were further expanded and refined in the concurrently developed *Multi-Year Research, Development and Demonstration (MYRD&D) Plan* (DOE, 2008b). The *MYRD&D Plan* also describes the intended research, development and demonstration activities for geothermal technologies through 2015, with additional information on potential Program activities through 2025. The *MYRD&D Plan* presents the development of an EGS project as a logical, multi-step decision process, with the overall goal of generating energy which meets certain defined performance parameters including economic operation. More importantly, technical hurdles, possible solutions, and critical research areas were listed along with metrics to track research progress. *Finding the site, site characterization, exploratory well and reservoir confirmation, creating the reservoir: injection well, creating the reservoir: stimulation and operating the reservoir* were among the *MYRD&D* suggested research topics.

A final EGS community roadmapping activity was held with a select group of EGS expert volunteers at the *EGS Technical Roadmapping Workshop* held in August of 2011 in San Francisco, CA. Previous top-level research topics were reviewed and condensed into three categories: *characterize, create, and operate.* Tech paths that provide details on the steps necessary to *characterize*, *create* and *operate* were identified and proposed, including: zonal isolation techniques, improved HT logging tools, improved flow, temperature and pressure instruments, a comprehensive crystalline rock database for the U.S., new fracture imaging techniques, technology to create/enhance flow paths, advance drilling technology, develop methods to identify flow paths, develop innovative stimulation techniques, new methods to maintain fluid flow rates, further monitoring tools and sensors, and techniques to track fracture evolution, control fluid flow, and advance applied reservoir modeling.

In February 2012 at the Stanford Geothermal Workshop, public and community input were requested through three one-page summary sheets of the results obtained from the 2011 San Francisco workshop. Subsequently, further input was gathered

from the geothermal community and discussions were held regarding the direction of the roadmap.

Finally, a series of EGS Roadmapping Meetings were held at DOE headquarters starting June 2012 with EGS Program staff to streamline, organize input, and develop the final roadmap. Activities included reducing tech paths from sixteen to eight, mapping proposed technology solutions to these paths, and developing metrics and technology evolution descriptions. The results of this work are presented here. The original concepts and technology needs developed by the expert participants have been maintained, but the research topics, tech paths, and evolution timelines were condensed and further refined to better communicate GTO's Program goals with potential stakeholders and EERE management.

EGS PROGRAM ROADMAP

Three high-level EGS R&D topics, *Characterize, Create,* and *Operate;* and eight unique tech paths capture and communicate EGS research needs as identified by the geothermal community. The eight tech paths are presented in Figure 3, reflecting the action-oriented theme set in the *MYRD&D Plan*. The tech paths are *Identify Natural Fractures and Flow Paths, Create New Fractures and Flow Paths, Monitor Flow Paths, Zonal Isolation,* and *Manage Fractures and Flow Paths*. The three crosscutting tech paths, *Drilling, Modeling,* and *Tools* are critical for all three EGS research topic areas. *Monitor Flow Paths* and *Zonal Isolation* are common to *Create* and *Operate*.

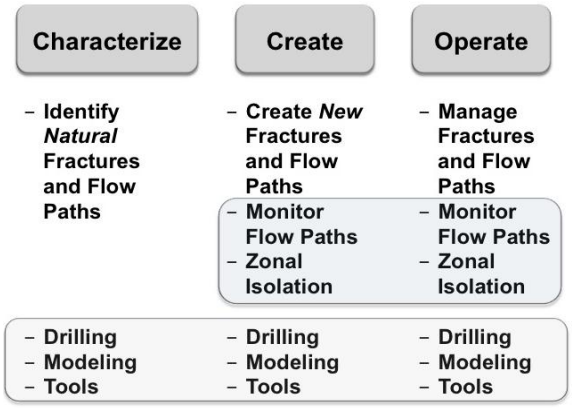

Figure 3: The relationship between high-level EGS Technical R&D topics and their tech paths is shown. Drilling, Modeling and Tools are crosscutting in that they are necessary to all of the topic areas, though depending on the topic they have different components and emphases. The Monitor Flow Paths and Zonal Isolation tech paths are common to Create and Operate.

Identified technology areas

The categories *Characterize*, *Create* and *Operate* were selected as a starting point for this roadmap as they clearly reflect the distinct technologies associated with the stages of implementation of an EGS. These topics were derived from previous planning efforts as described above.

EGS site characterization technologies bear significant overlap with conventional hydrothermal exploration technologies. See Phillips et al. (2013) for an overview of this R&D space. In this paper we focus on the subsurface properties most critical to EGS, such as the state of stress, and fracture aperture, extent, fill material, orientation, and distribution. In the EGS setting, efforts go beyond non-invasive characterization to detailed down-hole and core investigations, and associated modeling (e.g., Hickman and Davatzes, 2010; Cladouhos et al., 2011). Also, a distinction is drawn between potential EGS sites that may fall along the continuum of EGS: ranging from ubiquitous "green fields," to the outskirts of existing hydrothermal fields, and finally to unproductive portions within operational hydrothermal fields (Robertson-Tait and Lovekin, 2000). The latter applications comprise the majority of the current EGS demo Program.

Conversely, technologies necessary to create an EGS reservoir are different from those employed at conventional hydrothermal sites and creation is one of the greatest technical challenges to the commercial success of EGS. Fracture creation and reactivation technology or "fracing" is not new, however, and continues to be a major component in O&G production as well as a key technology responsible for the success of shale gas development (e.g., King, 2010). Technology advances in multi-stage fracturing, among other improvements, have been critical to the exponential growth of both conventional and unconventional resource development in the last decade. Fracturing techniques available at present in the O&G sector are well summarized by Angeles et al.,2009 and include: cemented liners with plug-and-perf (e.g., Blanton and Mackenzie, 2006), coiled-tubing conveyed annular fracturing (Hari et al., 2010), open-hole systems with external mechanical or swellable packers and ball-actuated sliding sleeves (e.g., Lohoefer et al., 2006;Snyder and Seale, 2011), high-velocity sand-jet stimulations (e.g., McDaniel and Surjaatmadja, 2009; Itibrout et al., 2010) as well as the Just In Time Perforating (JITP) process (Tolman et al., 2009; Angeles et al., 2012). Each method was developed to improve technical and economic aspects of resource development; the ability to place and initiate fractures more accurately and efficiently facilitates better

utilization of resources through increased production per well, which in turn improves economics. The extent to which advanced fracturing technologies from the O&G industry can be adapted to EGS application deserves close attention.

Similarly, the EGS community seeks greater control over fracture location and initiation. To this end, DOE-funded EGS demonstration projects have developed or utilized zonal isolation technologies to perform multi-zone stimulations, ultimately increasing the surface area of the created reservoir and improving the business case via an effective single well stimulation. Chemical diverters, developed by AltaRock and partners temporarily seal fracture zones to facilitate stimulation of a new fracture set from the same wellbore (Petty et al., 2011). This methodology could potentially reduce costs of power production by 40% by stimulating more of the wellbore (Petty et al., 2011). Mechanical isolation devices, such as open-hole packers, have also been effectively demonstrated for multi-zone stimulations in EGS wells and are used widely in hydrothermal operations, however temperature-resistance of open-hole packers currently available (Polsky et al., 2008) limits widespread use in EGS environments.

In addition to fracturing methodologies, GTO and partners are currently pursuing opportunities to bring other successful research and experimentation surrounding shale gas to bear on the EGS problem. This is a rich R&D space that covers rock mechanics (e.g., Lutz et al., 2010), geochemistry (e.g., Portier et al., 2009), and thermodynamics (e.g., Zhou et al., 2009), and could carry the geothermal community in novel directions such as the application of energetic and other non-aqueous fracturing technologies (e.g., Rogala et al., 2013).

Successful reservoir creation also relies on improved imaging methods and technologies to characterize the state of permeability enhancement in the subsurface. Advancing downhole seismic monitoring (e.g, Maxwell et al., 2010) and further developing smart tracers (e.g., Nottenbohm et al., 2012) are of great interest here.

The distinction between reservoir creation and management is somewhat artificial; the *Operate* research topic has considerable overlap with the *Create* topic (Figure 6). However, there are some significant differences that warranted a separate category in this roadmap and specific technology requirements for reservoir operations remain ambiguous due to limited experience.

Current EGS R&D related to the *Operate* topic is generally focused on developing and improving economic models (e.g., Entingh, et al., 2006; Lowry, et al. 2010). Initial work on comprehensive, real-time, subsurface monitoring and modeling is in its infancy, but will play a critical role in the success of EGS. Research activities associated with operations and sustainability of EGS reservoirs culminate in the ability to optimize reservoir productivity in real-time, which is directly linked to reservoir sustainability and economic vitality.

EGS Technology Pathways

The above technology areas were divided into tech paths as presented in Figure 3. The tech paths were further developed into timelines that depict technology evolution from the past through 2030. There is considerable overlap in the technology development process—past practices remain while innovation continues. Reservoir characterization techniques, reservoir creation methods and operational practices have evolved. Past practices are modified through experience, discovery, and invention into current practice. Future capabilities envisioned by the Program will evolve similarly. Together these research topics along with Program goals and metrics comprise the EGS Technology Roadmap.

Characterize the Reservoir

Figure 4 shows technology evolution timelines for *Characterize*. The EGS R&D tech path for the *Characterize* topic evolves from s*imple inference to using observations, to specific site workflows,* and finally to *generalized play workflows.* The proposed EGS field lab estimated completion date in 2018 was incorporated into the roadmap as a target end date for the development for many of the tech paths, as seen in Figure 4. The EGS field lab is an important component of the EGS R&D strategy to accelerate the implementation and commercialization of EGS technology.

The *characterize* topic contains one unique tech path (*Identify Natural Fractures and Flow Paths),* and three crosscutting tech paths *(Drilling, Modeling, and Tools)* (Figure 4). The techniques for *Identifying Natural Fractures and Flow Paths* evolves from *inferring from shallow temperature depth profiles, geothermometry and geologic setting,* to *remote sensing techniques, structural setting and regional tectonics,* to *borehole televiewer, core analysis and inter-well correlation,* to *joint inversion of geology and geophysics correlated with wellbore fracture density,* and finally to the ideal method for accurately identifying and characterizing fractures: *complete 3D reservoir, stress and fracture models, constrained by*

all observations. The crosscutting tech paths are discussed below.

As mentioned above, a thorough understanding of the target reservoir's fractures, in situ stresses, and permeability (flow paths) is essential, therefore, the tech path was developed to incorporate associated technology needs, and is titled: *Identify Natural Fractures and Flow Paths*. *Drilling*, *Modeling* and *Tool* improvements are critical aspects of fully 'characterizing' a reservoir, but these research categories have been identified as crosscutting, and will be discussed together in a subsequent section.

In the past, geothermal characterization research focused upon improving and modifying tools and techniques for high-temperature and pressure conditions, application of standard geophysical exploration techniques such as reflection seismology, heat flow, gravity and electrical methods, as well as qualitative inverse methods. This roadmap considers new ideas such as ambient noise tomography and novel methods to measure and understand in-situ elastic rock properties. Furthermore, the need for techniques to measure fracture orientation and stress magnitude were identified as critical to successful EGS reservoir development. The entire list of technologies generated at the 2011 EGS Roadmapping meeting in San Francisco is presented in the Appendix.

EGS-specific Characterization technology is early in the R&D process but evolving quickly. Most of the techniques are not new but rather adapted to address EGS focused problems, where knowledge of the subsurface stress field and in situ fracture distribution is critical. Past practices inferred subsurface conditions such as in situ temperature, stress, fracture location, and permeability through surface geophysical measurements guided by simple geologic models. In current EGS characterization practice, observations are normally qualitatively and occasionally quantitatively coupled, but infrequently constrained by geologic models. In many cases, more complex geologic and geophysical models are hypothesized but are mainly unconstrained. Often numerical models are utilized to replicate the subsurface conditions, but largely in the forward sense. Current research and improved technology for characterization of the subsurface includes building optimized geologic model workflows for individual sites in conjunction with more formal inverse and statistical modeling methods that permit uncertainty analyses.

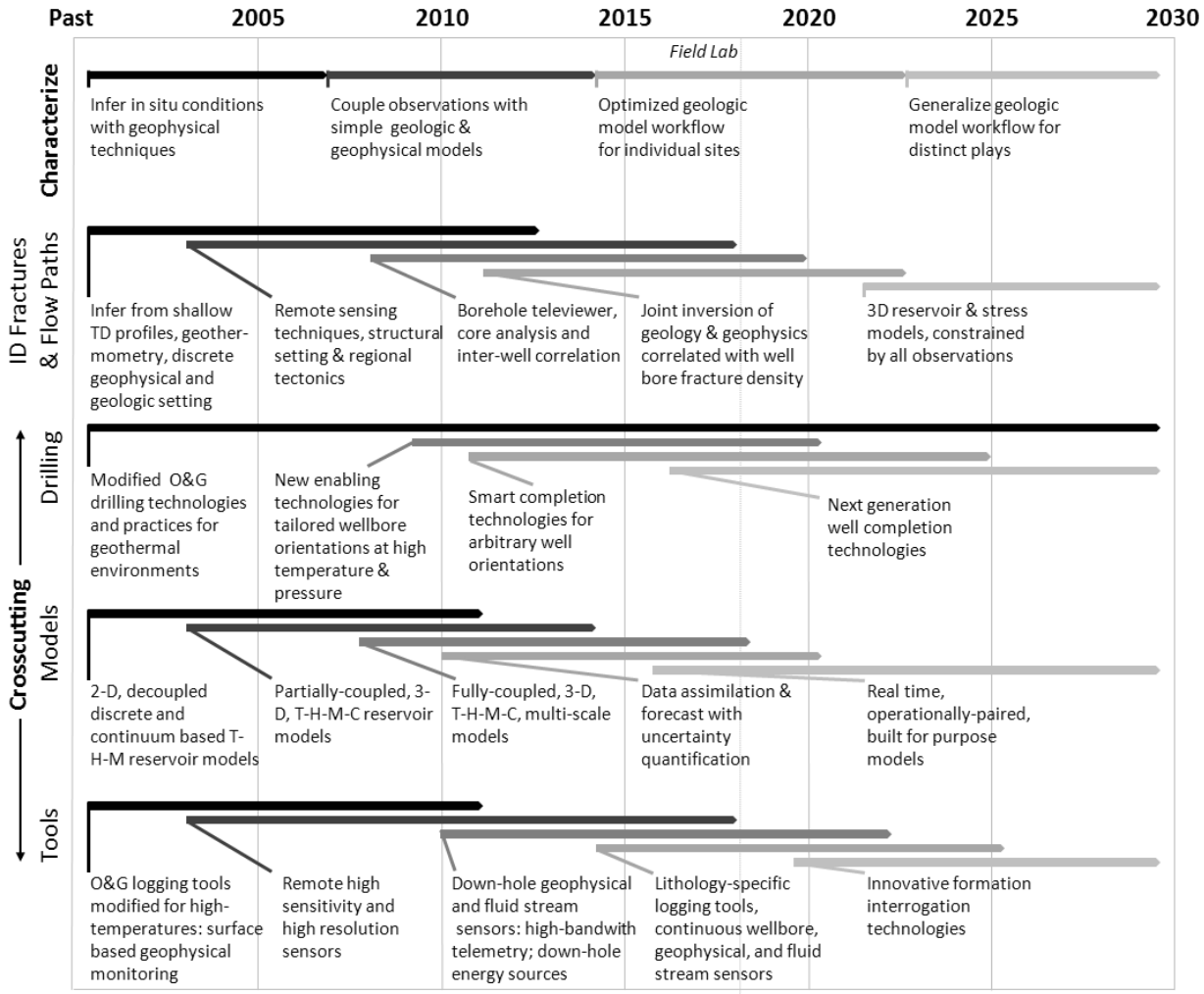

Figure 4: Characterize technology evolution timelines through 2030. The top-level arrows summarize the proposed progression of GTO investment in this area. Specific timelines for Identify Fractures & Flow Paths and the three crosscutting tech paths are shown below in more detail. The beginning and terminus of arrows reflect the time period over which GTO investments focus on the stated technology space. The vertical dotted line is for 2018; coincident with the targeted completion of a proposed EGS field lab effort.

These research activities and their technology evolution culminate in the ability to build and execute generalized geologic models and workflows for distinct EGS play types. This will constrain uncertainty in project development and thereby lower risk and cost. The overall goal for *Characterize* is to fully understand the conditions in the subsurface such that reservoir development and operation can be optimized to maximize heat extraction. Therefore, the metric established to summarize the goals of the suite of technologies encompassed in the *Characterize* topic is "viable play risk." It is assumed that as characterization technologies advance the risk associated with the viability of an EGS play will decrease (Figure 5).

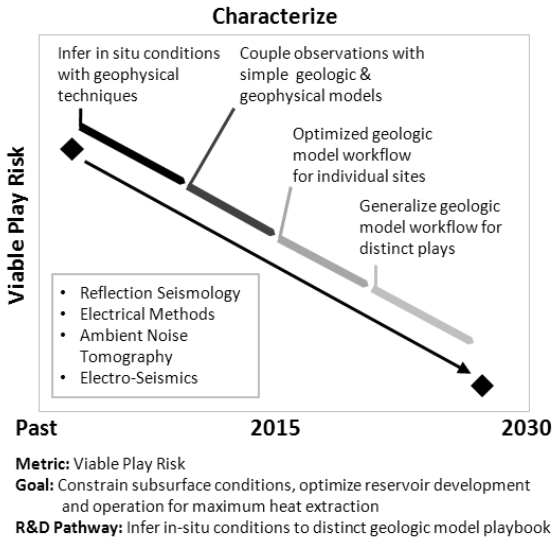

Figure 5: The Characterization EGS Research topic with technical evolution timeline, metrics, and goal. Listed are some of the critical technologies identified.

Crosscutting Technology Paths:

It was decided that R&D in *Drilling, Modeling and Tools*, with some noted top-level specific differences, were required for each topic. Here we discuss the technical evolution for *Drilling, Modeling and Tools* as pictured in the *Characterize* strategy (Figure 4).

As seen in Figure 4, the technical evolution path for *Drilling* technology begins with Modified *O&G drilling technologies and practices for geothermal environments*, moves to *new enabling technologies for tailored wellbore orientations at high temperatures and pressures*, to *smart completion technologies for arbitrary well orientations*, and finally reaches *next generation well completion technologies.*

Temperatures in the wellbore can be significantly lower than in situ reservoir temperatures due to circulation of fluids downhole. This often permits the utilization of currently available logging and reservoir interrogation tools, most of which can operate up to approximately 175°C (Polsky et al., 2008). But because potential EGS resources are estimated to be largely in the 150-300°C range, temperature hardening is the most immediate modification required for drilling technology today..

Aside from temperature limitations, formation type is another consideration that limits the ability to successfully access an EGS reservoir. EGS wells may encounter hard, igneous formations, but in some cases only in the final interval(s) at depth. This leaves room to develop innovative drilling methodologies that incorporate O&G techniques for the upper portions of the well (where formations common in O&G plays are present) with new techniques relegated to the deeper, basement rock formations. The O&G sector's experience in complex well completions (as a result of annual footage drilled) indicates the need for technology transfer from this community. Sandia National Laboratories (SNL) has initiated this transfer through recent field-testing of commercially available PDC bits during the drilling of a geothermal exploration well in the Chocolate Mountains of California (Raymond et al., 2012). Although originally developed for geothermal use, PDC cutters have seen little adoption by the geothermal industry. However, the Sandia work demonstrated that, if properly run, PDC bits can be used in drilling hard-rock formations common in geothermal environments and can contribute to lower well construction costs because of superior rate-of-penetration and bit life (Raymond et al, 2012).

Technology adaption is not limited to downhole elements alone; surface equipment (e.g., fit for purpose rigs) and O&G methodologies should be examined for application to the geothermal sector if they can bring efficiency gains and cost savings. Drilling process improvements and optimizations will also have economic benefits for EGS well construction. For example, using surface and down-hole data to make adjustments to the drilling operation in real-time can increase rates of penetration and improve wellbore quality. SNL and a geothermal developer are working together to increase the use of drilling related data to increase the efficiency of the drilling process.

Current O&G technologies for directional drilling use down-hole motors that rely on elastomeric seals in their power sections. These seals are temperature limited; cooling through drill fluid circulation can prevent failure of seals at higher temperatures but alternative technologies for down-hole power sections/motors that do not rely on elastomeric seals are essential to completely resolve these constraints. The ability to steer a drill bit in a high temperature environment will also require advancements in high temperature sensors and electronics as well as their supporting components (e.g., Polsky et al., 2008) and high rate data telemetry methods. Semiconductor technology is moving away from silicon to wider band-gap materials that are inherently more stable at higher temperatures (e.g. silicon carbide, see Casady and Johnson, 1995). Advancements in semiconductor materials must be pursued in conjunction with higher reliability packaging and components.

The drill bit's position, orientation, and trajectory must be communicated to the surface operator in order to accurately control the well profile. This will likely require advancements in data telemetry for deep and hot wells, and becomes increasingly necessary as the geothermal industry moves toward logging-while-drilling applications. Data telemetry is currently accomplished by mud pulsing, electromagnetic (EM) wave propagation, or wired drill pipe. Wired pipe offers the highest data transmission rates but is expensive to deploy. Mud pulse telemetry is limited to about 20 bits per second at depth shallower than 20,000 feet (increasing depth decreases data transmission rates) (Wassermann et al., 2008). Data encoding and signal processing techniques can improve data transfer rates from these systems. EM telemetry is also subject to deterioration with increasing depth; magnetic/conductive properties within the formation can interfere with the propagation of the EM waves. Wave repeaters along the drill string and encoding/processing techniques provide improvements.

Advances in drill fluids may be required to construct certain well profiles within high temperature reservoirs. The ability of drill fluids to clean and lift drill cuttings becomes compromised in deviated boreholes where high temperatures will alter fluid chemistry and rheology. Similar advancements may also be required for cements in high temperature, highly deviated wells.

Smart completion technologies can facilitate precise control of the evolution of an EGS reservoir by allowing continuous measurement of production parameters and flow control within sections of production and injection wells. Permanently installed sensors can monitor fluid temperature, pressure, chemistry, and flow rate at various wellbore intervals. Furthermore, down hole valves can also isolate production and injection flow to specific areas of a wellbore, controlling which fractures are produced/injected into at various times.

Hydrothermal wells are commonly completed open hole to facilitate unrestricted access to natural productive fractures. EGS well completions need to be optimized for the most effective stimulation and production/injection strategies and to lower costs. Leaner casing designs, for example, or the elimination of casing stings can have a significant impact on well cost (Augustine et al., 2003).

Next generation wellbore construction technologies encompass a broad range of potential advancements and are presented here as an open ended evolution. Research on field-ready hybrid mechanical and non-mechanical rock reduction mechanisms will likely be available in the future. This category also includes other technological advances such as casing-while-drilling systems that may reduce the cost of wells along with advances in automation, data synthesis, and artificial intelligence.

The technical evolution path for *Modeling* technology starts with past practices of *2-D, decoupled discrete and continuum based T-H-M (Thermal-Hydro-Mechanical) reservoir models,* to *partially-coupled, 3-D, T-H-M-C (T-H-M plus Chemical) reservoir models,* to *fully-coupled, 3-D, T-H-M-C, multi-scale models,* to *data assimilation and forecast with uncertainty quantification*, and finally *real time, operationally-paired, built for purpose models.* Challenges to moving along this trajectory include the development of models that can deal with the disparate length and time scales of discrete fracture growth to continuum reservoir evolution; faithful parameterizations of realistic and even non-aqueous fluids; and next-generation thermodynamic and rock mechanics data to constrain ever-refined models (e.g. Ingebritsen et al., 2010; Fairley et al., 2010). Critical to successful model development is careful validation. A number of subsurface communities have recently undertaken such code comparison efforts, including for geologic CO_2 disposal (Mukhopadhyay et al., in press), gas hydrates (Anderson et al., 2011), and dynamic earthquake rupture (Harris et al., 2009). GTO has just initiated support for a code comparison effort for geothermal reservoir modeling, with results expected over the next couple of years (PNNL, 2013).

Tool technology uses past practices beginning with *O&G tools modified for high-temperatures along with surface based geophysical monitoring, and advances* in *remote, high-sensitivity, high-resolution sensors*. The topic includes *down-hole geophysical and fluid stream sensors: high-bandwidth telemetry, down hole energy sources, lithology-specific logging tools, and continuous wellbore, geophysical, and fluid stream sensors.* The pathway finally evolves to i*nnovative formation interrogation technologies* to enable EGS reservoirs to be effectively characterized, created, and sustained.

Similar to drilling components, the availability of diagnostic tools for use in downhole geothermal environments is largely limited by temperature. Recently, advancements have been made in critical areas related to tool development through GTO investment, for example the recent development and field testing of Baker Hughes' 300°C acoustic televiewer. Utilization of wellbore and formation

evaluation tools from the O&G sector will continue, again, aided by development of deeper plays in hotter environments. Challenges related to material availability and costs remain; high-temperature scintillator materials, for example, are extremely limited and thus neutron based logs remain elusive for EGS.

Geophysical monitoring techniques have historically been limited to surface based measurement largely because of temperature constraints of the sensor elements. This is rapidly evolving where high temperature geophysical sensors (e.g., accelerometers) can be deployed down hole, in multi-string systems that deliver data over fiber optic cable. This is critical for fracture and flow path identification as resolution improves with decreased distance between sources and receives. Advancements continue into areas such as 9-component (3 axis + 3 rotation directions about each axis), high-temperature, down-hole accelerometers.

Data transmission for wireline logging tools can also utilize fiber optics; however standard conductor cable has cost advantages. Data encoding and signal processing techniques can improve the data transmission rates of this cost effective telemetry method. Wireless telemetry is also a logical advancement, especially for long-term or permanent sensor installations. Similarly the ability of a sensor to store and/or generate energy downhole would be advantageous for long-term wellbore and formation monitoring. Fiber optics can be used for data communication and serve as the sensor element (e.g. distributed temperature sensing, or DTS). High temperature data telemetry with fiber optics would benefit from temperature hardened down-hole modulators and/or lasers. Optic fiber, in geothermal wells, is subject to high signal attenuation overtime due to chemical alteration (both reversible and irreversible) by hydrogen. This 'darkening' has had significant impact on fiber optic DTS, where attenuation is highest in the ~1390 nm wavelength, an area in the spectrum critical to fiber optic temperature sensing. Attenuation compensation methods have been developed but a true solution to 'darkening' of the fiber has not been developed.

Fluid stream sampling is currently performed at the wellhead by taking flow aliquots at a given time interval. It would be advantageous to sample the fluid stream at various depths within a production well such that geochemical data can be correlated (e.g. tracer and isotope data) with fracture and flow zones, as opposed to integrated wellhead samples. If such sensors could be permanently installed, chemical signatures indicative of fracture surface cementation or dissolution could be monitored continuously and reservoir operations adjusted to optimize heat extraction or interventions deployed to prevent short circuit development. Similarly, permanently installed seismic sensors could accurately image fracture evolution as the reservoir stress state changes from production due to cooling and pore-pressure changes, which would aid in the long-term fluid management of an EGS.

An understanding of formation stress state and characteristics of the natural and engineered fracture system are critical to successfully commercializing EGS. The tools that can collect this type of information must be developed and be deployable at low cost. Part of this includes incremental advancement of O&G tools into high-temperature application but the community must also pursue innovative subsurface interrogation methods

Create the Reservoir

Creating the reservoir remains, by far, the most formidable EGS undertaking in the EGS development lifecycle to date. After decades of research and field demonstrations EGS reservoir creation technology is still immature. The correct mix of technique and technology that the shale gas industry has benefited from, e.g., horizontal wells and slick water injection, eludes EGS. The *Create* topic encompasses the technology developments the community sees as necessary to advance EGS and can be further described by three additional tech paths (Figure 6): *Create New Fractures and Flow Paths, Monitor Flow Paths, Zonal Isolation* and three crosscutting. The *Create* R&D tech path evolves from *traditional O&G fracing*, to *staged hydroshearing*, to i*nnovative reservoir geometries*, and finally to *real time optimization.*

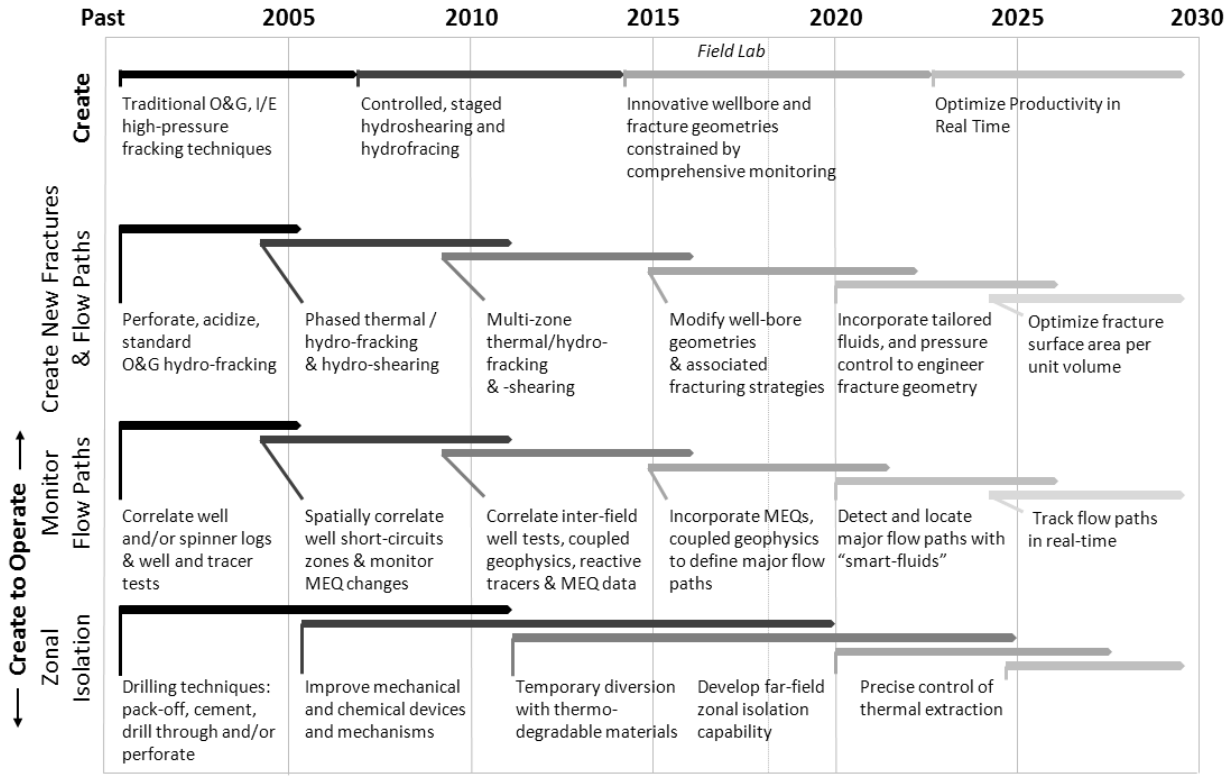

Figure 6: *Create technology evolution timelines. The overarching evolution, specific timelines for Create New Fractures & Flow Paths, and the two tech paths shared with Operate are all shown. Crosscutting tech paths as shown in Figure 4 are also relevant here.*

At Fenton Hill, HDR reservoir creation relied upon, then standard, O&G fracing techniques modified for HDR-specific goals as well as unusually high-temperature and pressure conditions. Monitoring techniques developed by HDR continue to be used today. Zonal isolation consisted of O&G-developed standard drilling technology such as cement plugs, packers, and perforations. Variations on standard O&G techniques have been attempted at multiple EGS projects with varying levels of success, but based on collective knowledge from past EGS projects both domestic and international, 'hydro-shearing' as opposed to hydraulic fracturing is considered the most promising and efficient methodology for EGS reservoir creation. Zonal isolation also shows promise as a means to enable multi-zone stimulations, thereby reducing well costs and associated risks. Recent success of the diverter technology developed by AltaRock and partners (Petty et al., 2011; Bour et al., 2012) indicates that this is an area that warrants further investigation. This roadmap also considers new ideas such as alternative fracturing methods, advanced hydraulic stimulation techniques, geothermal specific viscosifiers, diverters, and innovative packer designs.

These research activities and their associated technology evolutions culminate in the ability to optimize reservoir productivity in real-time while reservoir creation is underway. This will facilitate lower costs in the long run and significantly lower risk. The overall goal for this topic is to reduce costs and optimize reservoir extraction to maximize heat extraction. Therefore, the metric established for the suite of technologies included in the *Create* topic is "enthalpy out per volume of reservoir rock over operational lifetime". These concepts are summarized in Figure 7.

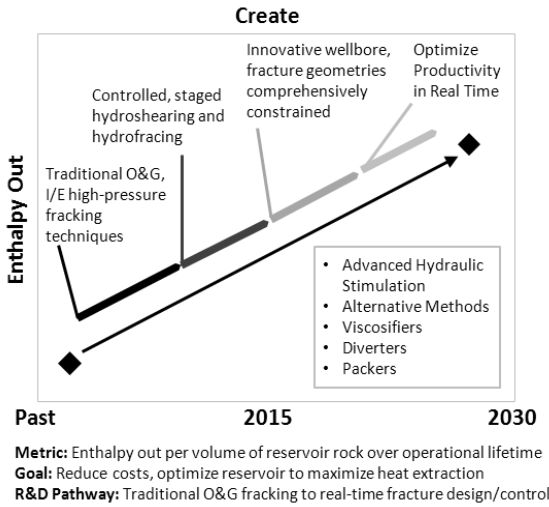

Figure 7: The Create EGS Research topic with technical evolution paths, metrics, and goal.

Operate the Reservoir

Many of the historic EGS projects underwent long-term circulation testing (measured mostly in months), but none were operated commercially for an extended period of time. Thus, a clear understanding of, and a repeatable strategy for, addressing long-term EGS operations barriers is necessary. Fortunately, the *Operate* research topic has considerable overlap with the *Create* topic as noted above (Figure 6) and despite decades of experience with long-term operations of hydrothermal systems, EGS brings new challenges to this area, due mainly to the man-made nature of the reservoir. We attempt to outline and address these important distinctions in this roadmap. As shown in Figure 8, the *Operate* tech path develops from past practices of *no injection*, to current schemes involving simple *injection*, to *informed injection*, to *monitoring and feedback* and eventually realize the goal of *real-time feedback monitoring and model operations.*

Specific technology requirements at this stage of EGS reservoir development remain uncertain due to limited operating experience. The longest period of continuous performance was at the Rosemanowes project in the U.K. where fluids were circulated for three years, during which time production temperatures fell from 80°C to 55°C. This temperature decline suggested to some experts that a short circuit was present in the reservoir. Technology solutions to address short-circuiting, like other concerns with long-term operation, will require a much larger and broader experience base.

The MIT study assumes a conservative reservoir lifetime of six years after which the reservoir would require re-drilling and/or re-stimulation in new thermally undisturbed rock. EGS reservoir lifetimes and other parameter values have been estimated in various studies since the MIT report was published, using economic models based on input from operating hydrothermal fields, for example the Geothermal Electricity Technologies Evaluation Model (GETEM) model (Entingh, et al., 2006) and GT-Mod (Lowry, et al. 2010)

To address these concerns, the *Operate* topic is subdivided into six tech paths (Figure 8): a unique *Manage Fractures and Flow Paths*, together with operations-centric *Monitor Flow Paths*, and *Zonal Isolation* represented in Figure 6. Again, the three crosscutting *paths (Drilling*, *Modeling*, and *Tools)* as shown in Figure 4, but modified for operations, are also included. Because the EGS field must continuously mine the reservoir for heat, technologies and approaches included in the *Create* section are very important to operations. In fact, all of the technologies considered in the *Create* R&D topics are applicable to *Operate*; the major difference is in managing the reservoir over decades.

Comprehensive, real-time, subsurface monitoring and modeling in conjunction with current geothermal operations is rare and cutting-edge. However, EGS operations will be more dependent on this monitoring feedback than hydrothermal operations. For example, thermal break-through caused by a lack of understanding of reservoir flow paths and exacerbated by overproduction or injection might be detected and managed with such technologies.

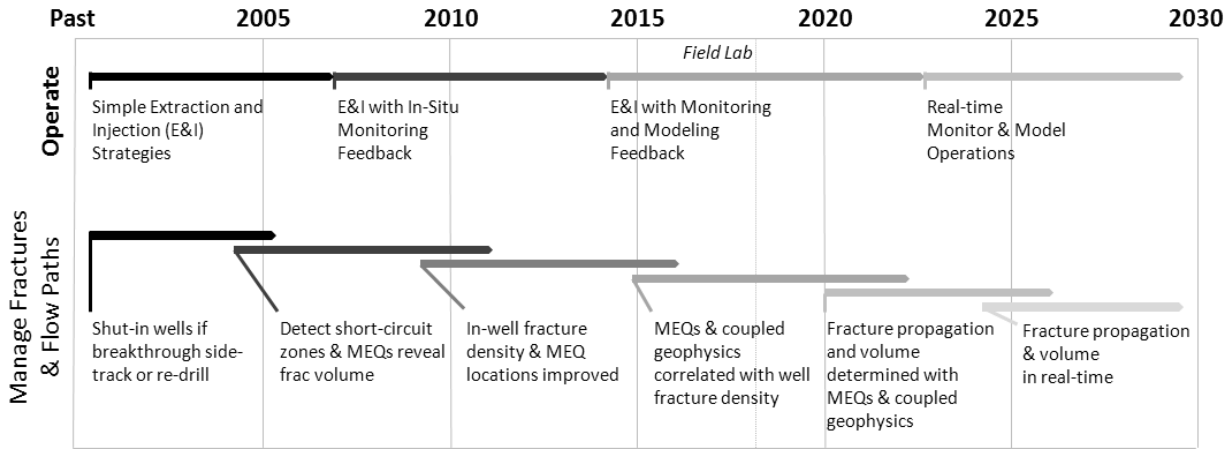

Figure 8: *Operate technology evolution timelines. The overarching technical evolution and specific timelines for Manage Fractures & Flow Paths are shown. Crosscutting tech paths as shown in Figure 4 and the two tech paths shared with Create as shown in Figure 6 are also relevant here.*

At this point in the development and demonstration of EGS technology, the community is focused primarily on creating an extensive and efficient reservoir, with site operation over 30 years as a longer-term goal. Therefore, current EGS R&D related to the *Operate* topic is focused on improving economic and physical models. This roadmap considers a more technical approach to operations and sustainability, focused on innovative ideas to manage the reservoir such as: fracture permeability evolution, chemical injection and zonal isolation, field expansion/wellbore modification and technologies to maintain enthalpy or reservoir expansion techniques. Again, the full list of technologies generated at the 2011 EGS Roadmapping meeting in San Francisco is included in the Appendix.

Research activities associated with operations and sustainability of EGS reservoirs culminate in the ability to optimize reservoir productivity in real-time, which is directly linked to reservoir sustainability. The overall goal for the *Operate* topic is to reduce costs and optimize reservoir extraction to maximize heat extraction. Therefore, the metric for *Operate* is "maximize reservoir sustainability." It is assumed that as technology advances the ability to extract enthalpy while sustaining the reservoir will improve. These ideas are summarized in Figure 9.

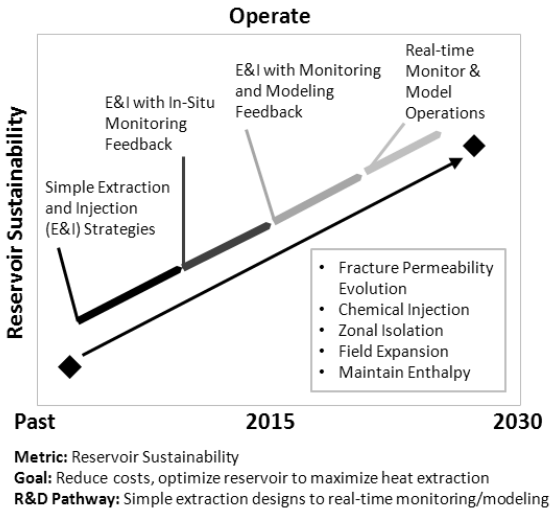

Figure 9: The Operate EGS Research topic with tech paths, metrics, and goal.

CURRENT EGS R&D PORTFOLIO

The current EGS R&D portfolio consists of 130 projects and five active field demos. Scientists and engineers in industry, at universities and national labs conduct this research. Projects were funded over several years through different funding instruments (e.g., FOA, ARRA, RFP, etc.) and the current portfolio is a combination of varied strategic approaches, drivers and goals. The majority of the projects (83%) are performed with industry (36%) and at the national labs (47%). University conducted research comprises only 17% of the projects. EGS projects maybe accessed here: http://www4.eere.energy.gov/geothermal/projects.

If we look at the distribution of projects among the three top-level EGS Technology Roadmap topics

with consideration for one project potentially impacting multiple research topics, we find that 44% of the projects are broadly focused on reservoir creation, 39% on technologies to advance reservoir operations and 17% are improving characterization technologies. The similarities in technologies and goals between the *Create and Operate* topics are illustrated in the statistics on GTO's R&D portfolio. *Characterization*, however, encompasses a different technology base. EGS experience dictates that knowledge of the in situ stress conditions and fractures distributions are critical to creating a successful reservoir.

If we look at the current project portfolio breakdown by tech path an interesting trend is observed, namely, the majority of the projects (71%) are the crosscutting tech paths *Drilling*, *Modeling and Tools*. Not surprisingly, *identifying, creating and managing fractures and flow paths* comprise just 11% of the projects for these are the new emerging technologies. Note, the number of projects in a given category is not indicative of the programmatic impact and does not represent current Program emphasis.

KEY PRIORITIES AND CONCLUSIONS

The purpose of this roadmap is to present a strategy for promoting technology advancements necessary to optimize EGS, such that this new resource class can be effectively exploited to meet projected capacities on the order of 100+ GWe. The technology pathways as presented here chart an ambitious course of technical progress, building upon past and recent successes, over a relatively short period of time. Current practices in unconventional O&G development demonstrate that rapid technology advancement correlates with sector growth by improving project economics and decreasing risk (e.g., NETL, 2007). Although there are fundamental differences between the O&G and geothermal sectors, the exponential growth in development realized as a result of technology development and optimization, such as horizontal wells and advanced fracturing fluids (e.g., King, 2012), should be considered a model for the EGS industry.

GTO, in partnership with the geothermal community, seeks to drive this technology revolution through targeted R&D, accelerated by implementation and testing at the proposed EGS field lab. In the near term, Program priorities will focus broadly on characterization and creation of EGS, guided by the technology evolution timelines established in this roadmap. Integral to success in these phases are improved methods for identifying natural and induced stress states, fractures, and flow paths. As described earlier some of the technology space associated with reservoir operations overlaps with the two preceding phases. The potential to effectively manage the permeability structure realized through stimulation activities should be considered through targeted investments in reservoir modeling and laboratory investigations of long-term fluid-rock interactions, factoring sustainability into EGS design. Furthermore, emphasis will be placed on improving existing and developing novel reservoir creation methodologies that allow larger volumes of rock to be accessed from a given well.

Technology breakthroughs in the above areas will facilitate progress on longer-term challenges associated with operations. Future GTO investments are likely to address real-time monitoring, modeling, and operations feedback, and broader well-field evolution aspects such as re-stimulation and site rotations.

On an annual basis and as necessary this EGS Technology Roadmap and all its parts will be re-evaluated with regards to relevance to national needs and DOE/EERE priorities, alignment with current knowledge and research outcomes, and focus on new and innovative ideas. GTO expects to reach out to the EGS community every five years to gather input to inform updates to this strategic plan.

ACKNOWLEDGEMENTS

The GTO EGS Program wishes to thank all the EGS Team members and other Office staff who contributed to this effort including Bill Vandermeer, Elisabet Metcalfe, Jay Nathwani, Brittany Segneri, Joshua Mengers, Daniel King and Doug Blankenship. In addition, a special thanks is extended to the August 2011 EGS workshop participants as well as those that have provided written and oral input to the previous drafts.

INFORMATION

If you have any questions or comments concerning this paper please contact:

Lauren W.E. Boyd
Geothermal Technologies Office
Office of Energy Efficiency and Renewable Energy
U.S. DOE
O: 202.287.1854
M: 202.297.8798

REFERENCES

Anderson, B., Hancock, S., Wilson, S., Enger, C., Collett, T., Boswell, R. and Hunter, R. (2011), "Formation pressure testing at the Mount Elbert Gas Hydrate Stratigraphic Test Well, Alaska

North Slope: Operational summary, history matching, and interpretations," *Marine and Petroleum Geology*, **28**, 478-492.

Angeles, R., Tolman, R., Ross, K., Burnham, H., El-Rabaa, W. (2012), "First Application of Just-In-Time Perforating in a Horizontal Well," paper SPE 152100 presented at *SPE Hydraulic Fracturing Technology Conference*, The Woodlands, Texas, 2-6 February.

Augustine, C., Jefferson, T., and Anderson, B. (2003), "A comparison of geothermal with oil and gas well drilling costs," *Proceedings, Thirty-First Workshop on Geothermal Reservoir Engineering, Stanford University*, Stanford, California, SGP-TR-179.

Baria, R., Baumgartner, J., Gerard, A., Jung, R., and Garnish, J. (1999), "European HDR research programme at Soultz-sous-Forêts (France) 1987–1996," *Geothermics*, **28**, (4–5), 655–669

Baria, R., and Petty, S. (2008), "Economic and Technical Case for Geothermal Exploitation of EGS," *Proceedings, Thirty-Third Workshop on Geothermal Reservoir Engineering, Stanford University*, Stanford, California, January 28-30, 2008, SGP-TR-185.

Benoit, W.R., Hiner, J.E. and Forest, R.T. (1982), "Discovery and geology of the Desert Peak geothermal field: A case study,". Nevada Bur. Mines Geol., Bull. 97.

Blanton, E., and Mackenzie, G. (2006), "Hydraulic Pump-Down Frac Plug and Subsequent Coiled-Tubing Removal Increases Client Efficiency in Barnett Shale Play," paper SPE 100139 presented at the SPE/ICoTA Coiled Tubing Conference & Exhibition, The Woodlands, Texas, 4-5 April.

Bour, D., Nordin, T., Watters, J., Sutton, J., Combs, K., and Aphblett, A. (2012), "Development of Diverter Systems for EGS and Geothermal Well Stimulation Applications," *Proceedings, Thirty-Seventh Workshop on Geothermal Reservoir Engineering Stanford University*, Stanford, California, January 30 -February 1, 2012, SGP-TR-194.

Brown, D. W., Franke, P. R., Smith, M. C. and Wilson, M.G (1987), "Hot Dry Rock Geothermal Energy Development Program, Annual Report, Fiscal Year 1985," *Los Alamos National Laboratory Report*, LA-11101-HDR, Los Alamos, New Mexico, 87545, USA.

Casady, J.B. and Johnson, R. W. (1996), "Status of silicon carbide (SiC) as a wide-bandgap semiconductor for high-temperature applications: A review," *Solid-State Electronics*, **39** (10) 1409-1422.

Cladouhos, T. T., Petty, S., Callahan, O., Osborn, W., Hickman, S. and Davatzes, N. (2011), "The Role of Stress Modeling in Stimulation Planning at the Newberry Volcano EGS Demonstration Project," *Proceedings, Thirty-Sixth Workshop on Geothermal Reservoir Engineering Stanford University*, Stanford, California, January 31 - February 2, 2011, SGP-TR-191.

DOE (2007), "Workshop for Enhanced Geothermal Systems Technology Evaluation, June 7-8, 2007, Washington, DC," *U.S. Department of Energy Report*, online: http://www1.eere.energy.gov/geothermal/pdfs/enhanced_geothermal_systems.pdf.

DOE (2008a), "An Evaluation of Enhanced Geothermal Systems Technology," *U.S. Department of Energy Report*, online: http://www1.eere.energy.gov/geothermal/pdfs/evaluation_egs_tech_2008.pdf.

DOE (2008b), "Geothermal Technologies Program Multi-Year Research, Development and Demonstration Plan, 2009-2015 with program activities to 2025, Draft" *U.S. Department of Energy Report*, online: http:// www1.eere.energy.gov/geothermal/pdfs/gtp_myrdd_2009-complete.pdf.

Entingh, D. J., G. L. Mines, et al. (2006). "DOE Geothermal Electricity Technology Evaluation Model (GETEM): Volume I - Technical Reference Manual", Washington DC, US Department of Energy, Office of Energy Efficiency and Renewable Energy.

Fairley, J. P., Ingebritsen, S. E. and Podgorney, R. K. (2010), "Challenges for Numerical Modeling of Enhanced Geothermal Systems," *Ground Water*, **48** (4), 482-483.

Garcia, J., Walters, M., Beall, J., Hartline, C., Pingol, A., Pistone, S., and Wright, M. (2012), "Overview of the Northwest Geysers EGS Demonstration Project," *Proceedings, Thirty-Seventh Workshop on Geothermal Reservoir Engineering Stanford University*, Stanford, California, January 30 -February 1, 2012, SGP-TR-194.

Hari, R. and Laun, L. (2010), "Improvements in Multistage Fracturing of Horizontal Wells Using a Newly Introduced Single Trip Coiled Tubing Conveyed Annual Perforating and Fracturing Tool – Benefits, Savings, and Case Histories," paper SPE 127738 presented at the IADC

Drilling Conference and Exhibition, New Orleans Louisiana, 2-4, February.

Harris, R. A. et al. (2009), "The SCEC/USGS Dynamic Earthquake Rupture Code Verification Exercise," *Seismological Research Letters,* **80** (1), 119-126.

Hickman, S. H. and Davatzes, N. C. (2010), "In-Situ Stress and Fracture Characterization for Planning of an EGS Stimulation in the Desert Peak Geothermal Field, NV," *Proceedings, Thirty-Fifth Workshop on Geothermal Reservoir Engineering Stanford University*, (2010) Stanford, California, February 1-3, 2010, SGP-TR-188.

Ingebritsen, S. E., Geiger, S., Hurwitz, S. and Driesner, T. (2010), "Numerical simulation of magmatic hydrothermal systems," *Reviews of Geophysics*, **48** (1), doi:10.1029/2009RG000287.

Itibrout, T., Blevins, J., Yates, M., Taboada, J.P., and Trummer, S. (2010), "Abrasive Jet Perforating and Fiber-Enhanced Proppant Plug Isolation Improve Efficiencies in Multistage Horizontal Completions," paper SPE 135413 presented at the SPE Annual Technical Conference and Exhibition, Florence, Italy, 19-22 September

King, G. E., (2010), "Thirty Years of Gas Shale Fracturing: What Have We Learned?", *SPE Annual Technical Conference and Exhibition*, Society of Petroleum Engineers, 19-22 September 2010, Florence, Italy.

King, G, E. (2012), "Hydraulic Fracturing 101: What Every Representative, Environmentalist, Regulator, Reporter, Investor, University Researcher, Neighbor and Engineer Should Know About Estimating Frac Risk and Improving Frac Performance in Unconventional Gas and Oil Wells," *SPE Hydraulic Fracturing Technology Conference*, 6-8 February 2012, The Woodlands, Texas, USA, doi: 10.2118/152596-MS.

Lohoefer, D., Athans, J., and Seale, R. (2006), "New Barnett Shale Horizontal Completion Lowers Cost and Improved Efficiency," paper SPE 103046 presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas, 24-17 September.

Lowry, T. S., V. C. Tidwell, et al. (2010), "A Multi-Tiered System Dynamics Approach for Geothermal Systems Analysis and Evaluation." GRC Transactions **34**: 85-90.

Lutz, S. J., Cline, E. J. and Martin, J. W. (2010), "Rock Mechanical Testing For the Desert Peak Enhanced Geothermal System (EGS) Project, Nevada," *44th U.S. Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium*, American Rock Mechanics Association, June 27 - 30, 2010 , Salt Lake City, Utah.

MacLeod, M., and Sammel, E. (1981), "Newberry Volcano, Oregon: IN: Guides to Some Volcanic Terranes in Washington, Idaho, Oregon, and Northern California:" *USGS Circular 838*

Maxwell, S. C., Rutledge, J., Jones, R. and Fehler, M. (2010), "Petroleum reservoir characterization using downhole microseismic monitoring," *Geophysics*, **75** (5), doi: 10.1190/1.3477966.

Mukhopadhyay, S. et al. (2013), "Model Comparison and Uncertainty Quantification for Geologic Carbon Storage: The Sim-SEQ Initiative," *Energy Procedia*, in press.

NETL (2007), "DOE's Unconventional Gas Research Programs, 1976-1995: An Archive of Important Results," National Energy Technology Laboratory Report, Strategic Center for Natural Gas and Oil, U.S. Department of Energy, January, 2007, online: http://www.netl.doe.gov/kmd/cds/disk7/disk2/Final Report.pdf

Nottenbohm, M., Licha, T. and Sauter, M. (2012), "Tracer design for tracking thermal fronts in geothermal reservoirs," *Geothermics*, **43**, 37-44.

Phillips, B. R., Ziagos, J., Thorsteinsson, H. and Hass, E. (2013), "A Roadmap for Strategic Development of Geothermal Exploration Technologies," *Proceedings, Thirty-Eighth Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, February 11-13, 2013, SGP-TR-198.

PNNL (2013), "Geothermal Technologies Program Code Comparison Study," Pacific Northwest National Laboratory, online: https://gtp.velo.pnnl.gov.

Petty, S., Bour, D., Nordin, Y., and Nofziger, L. (2011), "Fluid diversion in an open-hole sloted liner- a first step in multiple zone EGS stimulation," *Proceedings, Thirty-Sixth Workshop on Geothermal Reservoir Engineering Stanford University*, Stanford, California, January 31 -February 2, 2011, SGP-TR-191

Polsky, Y., Capuano, L., Finger, J., Huh, M., Knudsen, S., Mansure, C., Raymond, D., Swanson. R. (2008), "Enhanced Geothermal Systems (EGS) Well Construction Technology Evaluation Report," *Sandia Report*.

Portier, S., Vuataz, F. D., Nami, P., Sanjuan, B. and Gérard, A. (2009), "Chemical stimulation techniques for geothermal wells: experiments on the three-well EGS system at Soultz-sous-Forêts, France," *Geothermics*, **38** (4), 349-359.

Potter, R. M., Robinson, E. S. and Smith, M. C. (1974), "Method of Extracting Heat from Dry Geothermal Reservoirs," U.S. Patent 3,786,858, Jan. 22, 1974.

Raymond, D., Knudsen, S., Blankenship, D., Bjornstad, S., Barbour, J. Schen A.. (2012), "PDC Bits Outperform Conventional Bit in Production Geothermal Drilling Project, " *Geothermal Resources Council Transactions*, **36,** 307-315.

Robertson-Tait, A. and Lovekin, J. (2000), "Potential Sites and Experiments for Enhanced Geothermal Systems in the Western United States," *Proceedings World Geothermal Congress*, Kyushu - Tohoku, Japan, May 28 - June 10, 2000.

Rogala, A., Krzysiek, J., Bernaciak, M. and Hupka, J. (2013), "Non-Aqueous Fracturing Technologies for Shale Gas Recovery," *Physicochemical Problems of Mineral Processing*, **49** (1), 313-321.

Soliman, M., Pongratz, R., Rylance, M., and Prather D. (2006), "Fracture Treatment Optimization for Horizontal Well Completion," paper SPE 102616 presented at the SPE Russian Oil and Gas Technical Conference and Exhibition, Moscow, Russia, 3-6 October.

Snyder, D., and Seale, R. (2011), "Optimization of Completions in Unconventional Reservoirs for Ultimate Recovery- Case Studies," paper SPE 143066 presented at the SPE EUROPEC/EAGE Annual Conference and Exhibition, Moscow, Russia, 3-6 October.

Tester, J. W. et al. (2006), "The Future of Geothermal Energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st century," *Massachusetts Institute of Technology and U.S. Department of Energy Report*, Idaho National Laboratory, INL/EXT-06-11746.

Tolman, R.C., Simons, J.W., Petrie, D.H., Nygaard, K.J., Clingman, S.R. and Farah, A.M. (2009), "Method and Apparatus for Simultaneous Stimulation of Multi-Well Pads," paper SPE 119757presented at the SPE Hydraulic Fracturing Technology Conference, The Woodlands, Texas, 19-21 January.

USGS (2008), "Assessment of Moderate- and High-Temperature Geothermal Resources of the United States," *USGS Fact Sheet*, 2008-3082, U.S. Geological Survey.

Wassermann, I., Hahn, D., Reckmann, H., Nguyen, D.H., and Macpherson, J. (2008), "Mud-pulse Telemetry Sees Step-change Improvement with Oscillating Shear Valves." *Oil & Gas Journal*, **106** (24), 39-40, 42-44, 46-47

Wyborn D. (2011), "Enhanced Geothermal Systems (EGS)- Where Are We Now," *American Geophysical Union*, Fall Meeting, 2011.

Zhou, X. X., Ghassemi, A. and Cheng, A. H.-D. (2009), "A three-dimensional integral equation model for calculating poro- and thermoelastic stresses induced by cold water injection into a geothermal reservoir," *International Journal for Numerical and Analytical Methods in Geomechanics*, **33** (14), 1613–1640.

APPENDIX: EGS TECHNOLOGIES

As part of the EGS Technical Roadmap Workshop held in San Francisco, industry EGS experts and practitioners developed a list of EGS-advancement ideas, technologies and concepts that benefit from additional research. This list was not meant to be all encompassing or complete but rather was the product of that workshop with those participants. This collection was organized by topic and then tech path and is presented below. Some ideas are currently under research, some are emerging and either under evaluation or newly funded and some are new. Further explanation of items on this list is available. Adding and/or editing this list are welcomed and encouraged by the program. These items may inform GTO in its investment choices and may be useful to the community.

Characterize

Identify Natural Fractures and Flow Paths

- Reflection Seismology
- Electrical Methods
- Ambient Noise Tomography
- Electro-Seismics
- In situ elastic/deformation moduli and other elastic rock properties

Drilling

- Rock Reduction Technologies
- Directional steering and mud motors for highly deviated wells
- LWD/MWD
- Geothermal drilling best practices/data sharing
- Well Completions
- Microholes/Slim Hole/Sidetracks

Modeling

- Geomechanical/Fracture Models
- Geochemical Models (equations of state)
- Geomechanical/MEQ (T-H-M)
- Integration of Models into T-H-M-Q-C) Model
- MEQ focal mechanism inversion

Tools

- Mass "Fluxometer"
- Integrated PTF
- Field deployable reservoir pressure and microseismic volume tool
- High-performance logging tools
- Improve Mini-frac technology
- Improve borehole televiewer technology

Create

Create New Fractures and Flow Paths

- Alternative fracturing methods
- Advanced Hydraulic Stimulation
- Viscosifiers
- Diverters
- Packers

Monitor Flow Paths

- Fracture-Specific Tracers
- Induced seismicity as energy source to determine location of fractures
- Tiltmeter
- Microseismic
- Microseismic While Drilling
- Relate microseismic data to size/volume of reservoir
- Advanced Downhole Sensing and Observation
- Induced seismicity to determine location of fractures

Zonal Isolation

- HT Super packers
- HT Chemical diverters
- HT Chemical diverters for drilling
- Cased-hole applications
- Packers
- Smart Well Technology
- Diverters

Drilling

- Directional steering and mud motors for highly deviated wells
- LWD/MWD
- Geothermal drilling best practices/data sharing
- Continue to Develop Conventional Wireline Tools
- Improve Downhole-Logging Tools

Modeling

- Induced Seismicity Models
- Geomechanical/Fracture Models
- Geochemical Models (equations of state)
- Geomechanical/MEQ (T-H-M)

Tools

- Mass Fluxometer
- Integrated PTF
- Field deployable reservoir pressure and microseismic volume tool

Operate

Manage Fractures and Flow Paths

- Fracture Permeability Evolution
- Chemical Injection
- Zonal Isolation
- Field Expansion/Wellbore Modification
- Maintain Enthalpy or Expand Reservoir

Drilling

- Nano-sensors and/or smart tracers
- Develop Fiber Optic Sensors
- Continue to Develop Conventional Wireline Tools
- Improve Downhole-Logging Tools
- Improve Ultra-slimhole Costs
- Geothermal drilling best practices/data sharing
- Well Completions
- Control Scaling

Modeling

- Improve Zonal Isolation Tools
- Improve Pumping Technology
- Control Scaling
- Improve MEQ Analysis
- High-performance modeling tools
- Model Comparison and Validation
- Sensitivity analysis to a priori knowledge
- High-performance modeling tools

Tools

- Field deployable reservoir pressure and microseismic volume tool
- Sensitivity analysis to a priori knowledge
- Improve Fracture Fluid Flow Imaging tools and techniques
- Permanent Instrumentation and Monitoring of Production and Injection Wells
- Improve Broadband Seismic Sensors
- Improve Zonal Isolation Tools
- Improve Pumping Technology