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A ROADMAP FOR STRATEGIC DEVELOPMENT OF GEOTHERMAL EXPLORATION TECHNOLOGIES

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ABSTRACT

Productive geothermal systems occur in diverse geologic settings, often without clear surface manifestations of the underlying resource. Characterizing these hidden systems is challenging and costly, with resource confirmation relying on the drilling of multimillion-dollar wells with varying success rates. Reducing this risk through improvements in exploration technologies is critical to the identification and ultimate development of an estimated (USGS, 2008) 30 gigawatts electric (GWe) of undiscovered hydrothermal resources in the western U.S. In July 2011 the Geothermal Technologies Office (GTO), U.S. Department of Energy (DOE), convened a workshop in Berkeley, California, to outline needs and opportunities for advancing exploration technologies on annual to decadal timescales. Geothermal community members identified critical technologies within traditional disciplinary foci categorized as geology, geophysics, geochemistry, and remote sensing. In this paper we summarize these needs through technical pathways that target the key geothermal signatures of temperature, permeability, and fluid content. We develop the time evolution of these pathways, tying the past and current status of each to the active GTO exploration Research and Development (R&D) portfolio. We discuss metrics that existing GTO exploration initiatives could help to realize on a five-year timescale. Technologies that could accelerate the confirmation of 30 GWe are further projected to 2030. The resulting structure forms the basis for a Geothermal Exploration Technologies Roadmap, a strategic development plan to help guide GTO R&D investments that will lower the risk and cost of geothermal prospect identification.

INTRODUCTION

Reducing risk through improving characterizations of the subsurface is critical to securing financing and ultimately lowering overall costs for developing geothermal power projects. Success here hinges on the understanding of temperature, permeability, and fluid signatures that indicate geothermal favorability. To this end, a primary goal of GTO is to foster improvements in exploration technologies critical to the identification and ultimate development of an estimated 30 GWe of undiscovered hydrothermal, 100+ GWe of enhanced geothermal systems (EGS) (USGS, 2008), and up to several GWe of low-temperature hydrothermal resources (Augustine and Falkenstern, 2012) across the U.S. Realizing these targets requires a decadal strategy for improving and validating geothermal exploration technologies.

The goals of strategic roadmapping within the Office of Energy Efficiency and Renewable Energy (EERE), DOE, are to guide investments and define target metrics for a given program. Since growing deployment through commercialization in a competitive energy market is an ultimate goal of EERE, these roadmaps are typically constructed around cost-reduction strategies and culminate in "waterfall" charts, which delineate development areas critical to meeting overall cost targets. In the case of GTO's hydrothermal strategy, resource characterization and well-field development account for more than one third of total 2020 cost-reduction targets (Figure 1). While the balance of these costs is in drilling, the potential to improve economics through strategic up-front investments in pre-drilling and preliminary borehole exploration technologies is the focus of this roadmap.

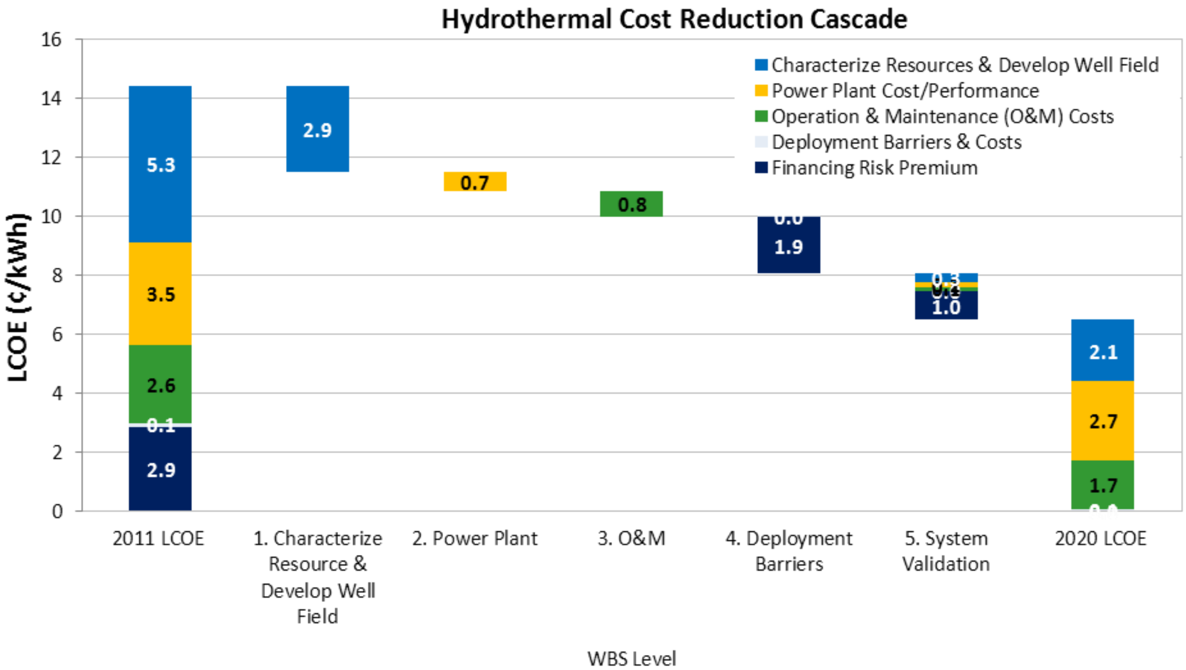

Figure 1: An example of GTO's cost-reduction cascade for a 30 MW binary hydrothermal plant with a 175 °C resource at 1.5 km depth, calculated using the Geothermal Electricity Technology Evaluation Model (GETEM) (Mines, 2008), beta version updated September 27, 2012. Resource characterization and well field development are the largest single component, contributing ~3 ¢/kWh to reductions from a 2011 levelized cost of electricity (LCOE) of ~14 ¢/kWh to a 2020 target of ~6 ¢/kWh.

Productive geothermal systems boast favorable combinations of high temperature, permeable pathways, and fluid content. On continental to regional scales, basic tectonic and hydrologic processes shape these zones of favorability and inform fundamental occurrence models for geothermal resources (e.g., Walker et al., 2005; King and Metcalfe, 2013). Exploration to characterize resource potential on regional to project scales hinges on interpreting the mostly indirect signatures of key properties prior to drilling. Given the fundamental nature of temperature, permeability, and fluids to realizing geothermal resource confirmation and development goals, we choose to denote these three characteristics as technology pathways (tech paths) to organize the exploration R&D strategy.

We begin with a brief overview of GTO hydrothermal and resource confirmation efforts and goals, and review the planning process that led to the development of this roadmap. Then, we describe the temperature, permeability, and fluids tech paths with their proposed time evolution targets. From this basis, we develop GTO priorities that couple the tech paths with spatial-operational phases of exploration and present an investment strategy. Finally, we discuss what GTO can do to implement and maintain relevance of this strategy.

HYDROTHERMAL PROGRAM PLANNING

GTO is comprised of the Hydrothermal, EGS, and Analysis Programs, with primary goals to:

Accelerate near term hydrothermal growth, by

- Lowering the risks and costs of exploration and development
- Lowering the LCOE to 6 ¢/kWh by 2020 (Figure 1)
- Accelerating the development of 30 GWe of undiscovered hydrothermal resources, and;

Secure the future with EGS, by

- Demonstrating 5 MW reservoir creation by 2020
- Lowering the LCOE to 6 ¢/kWh by 2030.

Towards reaching these goals, the Hydrothermal Program set a metric for its current R&D portfolio of confirming 400 megawatts electric (MWe) of new reserves by the end of fiscal year 2014. Meeting this near-term metric and realizing decadal goals for hydrothermal growth rely heavily on exploration

R&D. Additionally, subsurface characterization is critical for the discovery and efficient utilization of all types of geothermal resources including EGS, and low-temperature, co-produced, and permeable sedimentary systems. Advancing exploration technologies therefore carries the larger task of enabling the diversification of the nation's geothermal energy portfolio, including constraining the distribution and lowering the risk for development of an estimated 100+ GWe of EGS resources by 2050 (Tester et al., 2006; USGS, 2008).

In addition to a portfolio of exploration R&D projects further detailed below, the Hydrothermal Program supports a number of overarching analysis efforts aimed at helping to guide future investments in this space. These strategic initiatives include the National Renewable Energy Laboratory's (NREL) exploration best practices and case histories on DOE's Open Energy Information (OpenEI) website (Young et al., 2012), the data gap analysis (Esposito et al., 2013), and development of a baseline exploration suite (Jenne et al., 2013). The OpenEI resources provide public information on basic technology and field operations for permitting personnel and the surrounding community, and best practices for each technique facilitate knowledge exchange between experts. The data gap analysis is focused on surveying currently available exploration data and correlating with geothermal favorability maps to prioritize sites for future data collection. The creation of the baseline exploration suite is a first step in developing cost and time per project-site metrics. The suite outlines exploration technologies within the four operational phases of regional reconnaissance, prospect identification, project appraisal, and initial drilling, and assigns a baseline to which future costs can be compared based on surveys of industry experiences. These spatial-operational phases help to inform GTO priorities as described in following sections. GTO is also supporting the U.S. Geological Survey to improve geothermal resource assessments, develop new geothermal resource classification standards, and assist in resource data management (Williams and DeAngelo, 2011; Williams et al., 2011). These efforts are key to establishing and aiding in communication of regional exploration targets, and are used by Esposito et al. (2013) to spatially refine priority data gaps.

The strategy described here was informed by planning efforts that engaged the geothermal community for input. In October 2010 GTO sponsored a technology-planning workshop in Sacramento, California. The workshop brought together a diverse group of experts from industry, academia, and government who identified technology needs and potential advances for the Office to pursue. The resulting Exploration Technologies Needs Assessment (DOE, 2011) catalogues the current state and future needs of high-priority geophysics, geochemistry, remote sensing, geology, and crosscutting technologies. GTO followed up with a Metrics and Milestones Roadmapping Information Exchange in July 2011 in Berkeley, California, to further detail proposed technology targets within the priority areas. These results were distributed at the February 2012 Stanford Geothermal Workshop and May 2012 GTO Peer Review Meeting in Westminster, Colorado, for a period of public comment. The above input was then considered in developing the programmatic strategy presented in this roadmap.

EXPLORATION TECHNOLOGY PATHWAYS

Exploration for resource characterization is one of the key cost levers for geothermal development (Figure 1). To chart a roadmap for reducing these costs we categorize the possible R&D space by key physical resource properties.

Temperature, Permeability, and Fluids

Geothermal targets are elucidated pre-drilling through measurements and methods that indirectly infer favorable temperature, permeability, and fluid content at depth. Many regional- to prospect-scale temperature constraints are strongly dependent on geochemical signatures. Chemical geothermometers interpret concentrations of temperature-dependent constituents from groundwater or gas discharges, but suffer from complications of mixing and re-equilibration during fluid transport from depth (e.g., Ferguson, 2009). Constraining correlations between mineral alteration and resistivity may help bound the distribution of high-temperature alteration products through electromagnetic (EM) imaging methods such as magnetotellurics (MT) (e.g., Ussher et al., 2000; Newman et al., 2008; Spichak and Manzella, 2009). Beyond geochemistry, seismic methods may also aide in constraining temperatures through thermal effects on fluids and hence attenuation (Jaya et al., 2010). Multispectral imaging methods such as thermal infrared (TIR) remote sensing can yield empirically calibrated surface temperatures efficiently on regional scales. While TIR is not new (Hodder, 1970), significant room still exists for interpreting relevance to resource conditions through modeling of diurnal effects, albedo, and other surface characteristics (e.g., Coolbaugh et al., 2007; Haselwimmer and Prakash, in preparation).

Estimating porosity and permeability is especially difficult because of volume dependence and anisotropy, and fracture and bulk matrix permeability are both important. Permeability can be inferred by translating surface expressions of strain at depth, with remote methods such as light detection and ranging (LiDAR) leading to improved detection of faults and facilitating increased coverage (e.g., Silver et al., 2011). The potential for mapping strain rates on regional to prospect scales has also grown with the proliferation of the global positioning system (GPS) (e.g., Blewitt et al., 2003; Payne et al., 2012), and interferometric synthetic aperture radar (InSAR) capabilities that have demonstrated efficacy in operational fields may also hold promise for exploration (e.g., Oppliger et al., 2004). Understanding the effects of hydrothermal alteration on permeability of reservoir rocks from laboratory studies of core samples (e.g., Dobson et al., 2003) opens up the potential for inferring these conditions in the reservoir. For example, seismic signatures validated on samples with known porosities, states of stress, and fluid pressures in the laboratory can ground truth field measurements of attenuation and scattering of these properties at depth (e.g., King, 2009). Such efforts point to the need for organized rock-property datasets, built in concert with instrumentation and processing developments.

The above hydraulic properties are directly coupled to fluid saturation and flow at depth in faulted, fractured, and porous media. Fluid content can be interrogated with seismic methods via velocity and attenuation effects (e.g. O'Connell and Budiansky, 1974; Knight et al., 2010). EM methods connect back to temperature through fluid content (Spichak and Manzella, 2009), and the potential to couple these with seismic approaches could provide further robust constraints (e.g., Muñoz, 2010). Geothermal gradients may be used to constrain hydrogeologic properties such as flow rate and permeability (Saar, 2011). Again, building databases to validate indirect observations through laboratory experiments is critical (e.g., Violay, 2012). Constraining the chemistry of geothermal fluids and their effects through reactive transport, both within natural reservoirs on geologic time scales (e.g., Dempsey et al., 2012) and through well fields and surface power plants on operational time scales (e.g., Frick et al., 2011), is also important for inferring potential resource viability and sustainability.

Temperature, permeability, and fluid processes are brought together along with many of the above constraints on the project scale through numerical modeling, including coupled thermal-hydrological-mechanical-chemical (THMC) models. Numerical models are critical for predicting the multi-decadal sustainability of candidate reservoirs in production, including fluid deposition and phase issues, and pressure and temperature decline. See Ingebritsen et al. (2010) for a recent review of methodologies and challenges in the modeling of hydrothermal systems.

Advancing and adding to the types of methods described above to optimally improve resource identification and characterization is the goal of GTO exploration efforts.

Technology Evolution Timelines

The overall proposed progression for the GTO Exploration Program through 2030 along with evolution timelines within each of the three tech paths are shown in Figure 2. The beginning and terminus of arrows reflect the time period over which Program investments focus on the stated technology space. These spaces often overlap, with investment in one area phasing out as new technologies are pioneered. The geothermal community may continue to use techniques supported by DOE at earlier times, but the investment focus transitions to an emerging space near the end of a given arrow. The vertical dotted line is for 2014, coincident with the metric of 400 MWe of new reserves. At the highest level, GTO is transitioning from an emphasis on application of multiple, qualitatively-integrated techniques to quantitative coupling through joint inversions, integrated THMC models, and uncertainty analyses linked to real success rates, for example.

In the past, temperature was constrained largely through shallow, but invasive and site-specific temperature gradient and heat-flow measurements augmented by empirical geothermometers. All of these techniques are conducted on the project scale, making broader regional resource characterization difficult. The accuracy of geothermometers has also been limiting. Improving geochemical techniques along with development of geophysical methods as described above has been GTO's emphasis over the past decade. Remote-sensing methods are becoming more promising for probing temperature, and near-term improvements here are seen as a priority for growing and improving regional prospect databases. As more such methods are developed and demonstrated, integrating the resulting data streams through joint inversions and other quantitative means will maximize their utility. Discoveries of new chemical or physical signatures (i.e., a new isotopic biogeochemical thermometer) that improve the accuracy of temperature estimates are also of great interest. The ultimate goal of the temperature tech path is to grow and improve the performance of a suite of thermometers for measuring temperature at depth from regional to project scales.

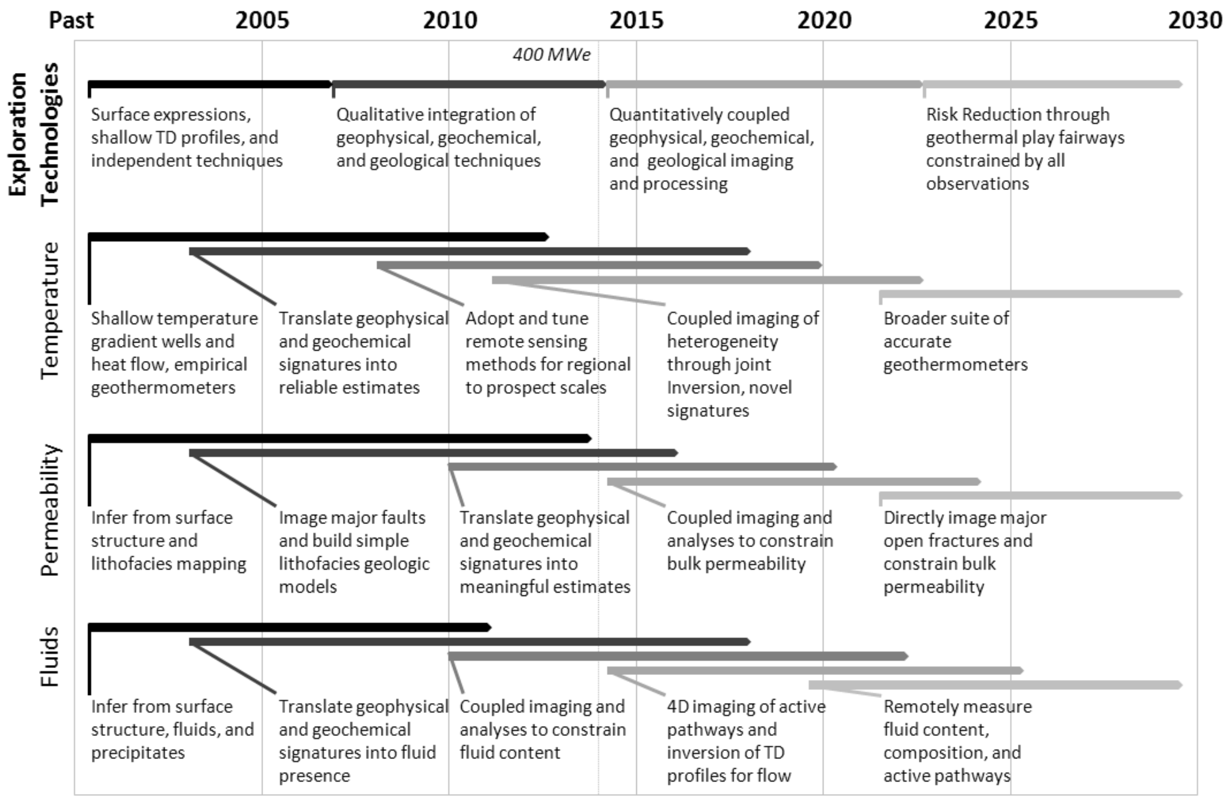

Figure 2: Exploration technology evolution timelines for temperature, permeability, and fluids through 2030. The top-level arrows summarize the proposed progression of GTO investments. Specific timelines for the three pathways are shown below in more detail. The beginning and terminus of arrows reflect the time period over which GTO investments focus on the stated technology space. The vertical dotted line is for 2014, coincident with the targeted metric of 400 MWe of new reserves confirmed.

Inferring permeability started similarly on the ground with mapping of outcrops and fault traces. Improved seismic techniques led to direct imaging of faults at depth and the construction of geologic models of lithofacies. Devising and improving signature detection methods for permeability as described above has been GTO's emphasis in recent years. Moving forward, emphasis will be placed on advancing subsurface interrogation methods coupled with laboratory and field validation. A long-term goal is to advance detection thresholds to resolve primary reservoir fractures below the scale of tectonic faults.

Surface features, lithology, and deposits are also the early indicators of fluid content and properties at depth. For fluids as for permeability, integrating non-invasive methods with sample interrogation in the laboratory and case studies in the field is essential moving forward. The long-term goal of real-time imaging of active fluid pathways will be facilitated by adoption of existing, and development of new, four-dimensional (4D) methods and inversion schemes.

GTO EXPLORATION R&D PRIORITIES

The overall goal of GTO exploration R&D investments is to shift the balance in project development costs towards validated risk reduction through up-front pre-drilling exploration, significantly reducing initial- and production-drilling costs. An initial survey of industry exploration practices suggests that ~90% of total exploration costs currently reside in the initial drilling phase (Jenne et al., 2013), and this phase is perceived to have low rates of success. The Hydrothermal Program contends that improvements in early-phase technologies could provide for major cost and risk reduction if properly validated and adopted by industry. In other words, greater preliminary investment in relatively inexpensive methods could yield significant overall reductions in cost.

To focus future GTO investment priorities, below we consider the tech paths as they relate to operational and scale-dependent exploration phases. As defined in the NREL baseline suite, these phases are regional reconnaissance, prospect evaluation, project appraisal, and initial drilling (Jenne et al., 2013).

Community-Identified Technology Needs

A group of experts met in July 2011 in Berkeley, CA, to discuss and refine exploration technology advancement needs as a follow up to the Technology Needs Assessment (DOE, 2011). The specific technology advancements discussed at this workshop are listed in Table 1.

Figure 3 shows a condensed version of the technology solutions shown in Table 1, refined for ease of communication with DOE management and updated to reflect GTO interests. Technologies are grouped based on the primary physical properties that are targeted, and the scale of interrogation after Jenne et al. (2013). Color corresponds to the associated tech path. Black bars represent technologies that are primarily geared towards inferring temperature, while dark gray bars are relevant to both temperature and permeability. Medium gray bars show technologies focused on porosity and permeability, transitioning to include relevance also for fluid detection and characterization in light gray. Broadly crosscutting technologies and methods are shown by dotted boxes that schematically cover the most relevant physical-property to operational space.

Table 1: Technology solutions and metrics identified at the Metrics and Milestones Roadmapping Information Exchange, July 7, 2011, Berkeley, California.

Proposed Technology Solution	**Proposed Metric**	**Target Date**
Basic Geologic Setting and Permeability	Complete 5 studies	2017
Conceptual Geospatial Models	Improved geospatial source images	2016 – 2020
Core Log Analysis	Systematic logs on 10% of core 2 new techniques applied Automated logging on 1% of chip samples	2016 2020
Database of Case Histories and Analysis Tools	Compile 5 case databases per year	2015
Gravity Tools	Improve airborne resolution from 100s to 10s of km Reduce non-uniqueness from ~10^6 to 100s of solutions	2014 2020
Inverse Techniques	Improve processing speed by a factor of 3-4	2020
Isotopic Exchange/Permeability Distribution	Validate 1 new signature for a 1-10 km scale heterogeneity	2017
MT/EM Tools/AFMAG	Build and test an airborne system sensitive to 2 km depth	2020
New Signal Detection Tools	Identify 1 new geochemical/isotopic signal for a previously considered “hidden” system	2015
Reactive Transport Models	Improve project-scale resolution from 100 to 10 m Improve processing speed by a factor of ~10 4 new reactive stable and radiogenic isotopes used in models Add ~8 relevant minerals/phases to thermodynamic/kinetic databases	2014 2015
Regional Remote Sensing	Complete, multi-instrument prospect coverage with centralized data management	2020
Seismics (reflection, passive, source)	Expand active methods to volcanic terrains Prove success of passive and source methods at 1 site	2016
Stress/Strain Data Mapping	Develop assessment protocol Implement in 8-12 settings	2013 2017
Structural Evaluation	100% data collection for a case study site	2016
Synthesize Multiple Datasets	Analysis methodology for each geothermal system type Increase software data-handling capabilities from ~2-5 datasets Improve processing speed by a factor of ~10	2014 2016 2017
Well Logging Tools	Slimhole tools ≤3” diameter Increase temperature hardiness from 150-200 to 300 °C	2016 2020
3D Visualization and Modeling Software	Development of a new software tool	2016

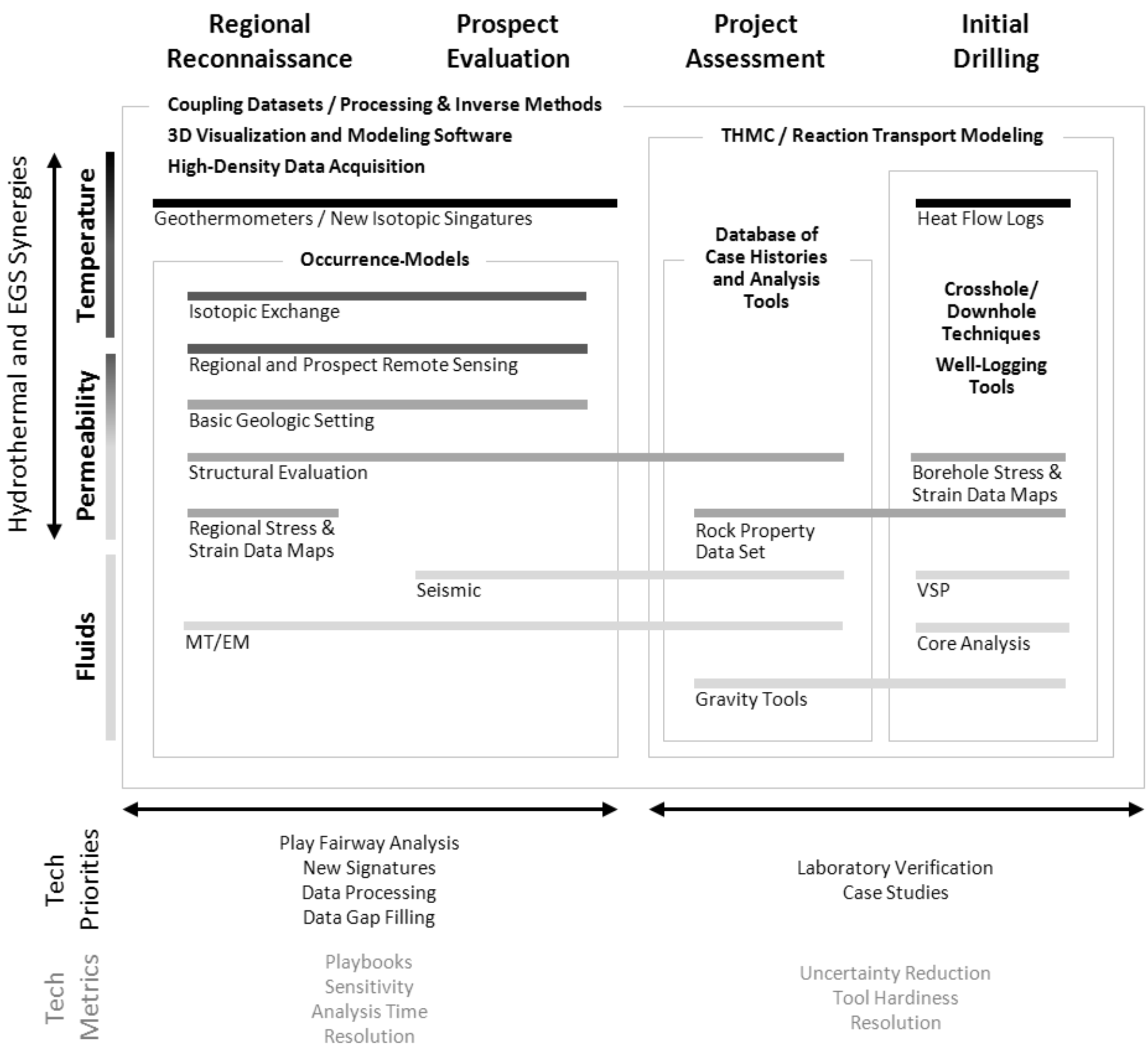

Figure 3: Technologies identified through the Exploration Technologies Needs Assessment (DOE, 2011) and refined during the GTO Metrics and Milestones Roadmapping Information Exchange in July 2011 in Berkeley, California. Technologies are grouped with respect to primary physical properties targeted on the vertical axis, and by operational- and scale-dependent phases on the horizontal axis. Boxes labeled in bold fonts represent highly crosscutting technologies. There is overlap along both variable spaces as indicated by bar color (tech path) and length (operational phase). Key tech priorities are listed at the bottom along with proposed metrics, further detailed in Table 2. Also indicated is the priority for improving measurements of temperature, and in situ state-of-stress and fracture distribution, to maximize crosscutting benefits between hydrothermal and EGS settings.

Geothermal Play Fairway Analysis

Figure 3 illustrates how one component of GTO's strategy is scale dependent. While DOE's mandate does not include ubiquitous support of site-specific R&D to reach nationwide deployment goals, risk for individual industry projects can be reduced by supporting the development of geothermal play fairways on regional to prospect-scales. Play fairway analysis is an approach borrowed from the oil and gas sector (e.g., Luheshi et al., 2011) that details the set of characteristics associated with a particular province that is inferred to contain viable prospects. In the geothermal case, this involves highlighting a geographic area over which the most favorable combinations of heat, permeability, and fluid are thought to extend. See King and Metcalfe (2013) for a more detailed discussion of geothermal occurrence models and associated play fairway development. A key priority for the Hydrothermal Program is to support development within all of the tech paths at regional- to prospect-scales. This includes development of new signature detection tools and techniques; advanced data processing methods; and data gathering that employs innovative technologies that have not yet been implemented by industry, or have never been applied in a geothermal context, focused within priority regions informed by the data gap analysis (Esposito et al., 2013).

A component of play fairway analysis does include site-specific validation to ensure that the playbook is robust. A parallel priority is therefore to support project-scale case studies and laboratory experiments and analyses. Such efforts should work towards quantification of value added from applying particular innovative exploration technologies to specific sites, and demonstrate the applicability of the site or sample to a broad number of reciprocal sites. Combining this approach with improved data coverage and quality at larger scales will enable the development of a robust set of geothermal play fairways and reduce industry development risk.

Continuum of Resource Targets

Accelerating the development of 30 GWe of undiscovered hydrothermal resources is a critical metric for the Hydrothermal Program, but this goal is also closely coupled to the greater geothermal aspiration of characterization and ultimate development of 100+ GWe of EGS resources. In prospecting for blind hydrothermal systems, discoveries that lack traditional hydrothermal favorability may contain characteristics suitable for EGS or other forms of geothermal development. Identifying and documenting the potential value in such currently marginal reserves is a critical part of ensuring success in future resource growth.

Exploring for favorable temperatures and understanding natural permeability are synergies between hydrothermal and EGS (Figure 3). In particular, techniques that help constrain in situ state-of-stress and fracture distribution are critical for both systems, even if the characteristics that hold promise for one may differ from that of the other. Efforts that develop classifications that value and delineate the characteristics of traditional and blind hydrothermal, EGS, and low-temperature resources are therefore of particular interest moving forward. Coupling observations with modeling to better understand the distribution of key properties is a critical component of this effort (Cloetingh et al., 2010).

Current Investments

The Hydrothermal Program R&D portfolio currently includes 42 projects with a specific focus on exploration technologies. Projects were funded over several years through different funding instruments including Financial Assistance through the American Recovery and Reinvestment Act (ARRA) and other annual appropriations, and U.S. National Laboratory Annual Operating Plans, combining various strategic approaches, drivers, and goals.

Cataloguing projects by their primary objectives with respect to the three tech paths, we find that 33% of projects specifically address the development of temperature-seeking technologies, 55% address permeability, and 36% emphasize fluid identification or characterization. Nearly half of projects consider more than one tech path, with a common trend of combined permeability-fluid investigations representing the close ties between these properties. This balance shows that all tech paths are being addressed under GTO’s current investments.

If we look at the portfolio with respect to spatial-operational phases, we find that 24% projects are relevant to regional reconnaissance, 50% to prospect evaluation, 31% to project assessment, and 12% to initial drilling. The small number of projects with a drilling component is reflective of the high costs associated with drilling R&D. Furthermore, drilling technologies are important across GTO’s interests, and significant investments supported by the EGS Program that are relevant to exploration are not captured here. See Ziagos et al. (2013) for further details about GTO’s drilling R&D strategy. Currently, GTO investments focus on prospect to project scales. A relatively small number of projects with a regional focus reflects in part the existence of baseline data at this scale, leveraged in part from collection and analysis efforts that span multiple Earth sciences research communities (e.g., Blewitt et al., 2003; USGS, 2008; Esposito et al., 2013). However, Esposito et al. (2013) highlight in particular a shortage of regional geophysical data in high favorability zones, suggesting a need for additional attention at this scale. Following this assessment and GTO’s strategy for supporting play fairway analysis, it is a priority to explore future opportunities to improve regional data quality and quantity for geothermal-specific signatures.

Adapting Opportunities from Related Sectors

Geothermal energy is not the only subsurface exploit that requires detailed knowledge of temperature, structure, and other properties at depth. Coupling this with the small size of the geothermal sector, a great opportunity exists to leverage investments and insights garnered in related fields such as oil and gas, water resources, mining, carbon sequestration, and environmental management. Some midterm geothermal technology development targets have already seen significant development in parallel settings and applications. For example, mapping permeability through time-lapse seismic imaging is at the cutting edge in the oil and gas sector (e.g., Vasco et al., 2008; Feng and Mannseth, 2010). Identifying natural, active fluid pathways may also be feasible through combinations of EM imaging and modeling, as demonstrated for groundwater targets (Van Dam et al., 2009; Xie et al., 2012). Looking for relevant technology space across disciplines and developing mechanisms for adapting advanced methodologies to geothermal settings can have far-reaching impacts to complement GTO-sponsored R&D.

IMPLEMENTATION

To maximize value from the above strategy, targets for technology development and quality control are needed. Community members outlined a number of near- to mid-term metrics for the technologies listed in Table 1 that could help guide their development. It is important to note that the target dates for meeting individual metrics were defined independently, and so do not take into account potential variations due to investment prioritizations. In the next 1-2 years (2013-2014) community priorities point towards development of key protocols and methodologies, and improvements in resolution for a number of imaging and modeling techniques. On a 5-year timescale (through 2017) proposed metrics include data collection, compilation, and processing advancements, and completion of case studies and validation across numerous technologies. Metrics targeted on a decadal (2020) timescale focus on specialized tool development and application, and some regional data advancements.

Figure 3 lists high-level mid- to long-term technology development metrics, and these are further detailed with respect to tech path in Table 2. These concepts generalize and extend the ~1-10 year metrics described above, and provide targets for development through the next ~10–20 years. The overall metric for Hydrothermal Program exploration technologies is viable play risk (Figure 4). All other metrics point to increasing the number of viable geothermal plays and reducing the risk of their exploitation. Key goals for temperature-sensing technologies include reducing uncertainty in temperature measurements along with improving sensitivity, or increasing the number of viable indicators for temperature. This should include both geochemical tools and new physical signatures. Spatial resolution is a key metric for imaging discrete

Table 2: Tech path performance metrics.

Tech Path	Tech Metric	Description
Exploration Technologies Overall	Viable Play Risk	Improve signature recognition and resolution, reduce costs, and grow reserves
Temperature	1. Sensitivity 2. Reservoir Temperature Uncertainty	Identify new signatures and improve accuracy of techniques (geochemical to geophysical, sample analysis to remote)
Permeability	1. Spatial Resolution 2. Matrix Permeability Uncertainty	Accurate direct imaging of major open fractures and precise measurement of scale-dependent matrix permeability
Fluids	1. Sensitivity 2. Spatial Resolution	Develop ability to remotely measure fluid content, composition, and active pathways
Crosscutting	1. Playbooks 2. Tool Hardiness 3. Analysis Time	Improved acquisition tools and processing techniques, and a growing portfolio of validated play fairways

faults and fractures, as well as constraining the signatures of variations in matrix permeability. This carries over to identification of fluid content, with added sensitivity for constraining composition and time-varying properties as another key metric. There are three metrics that crosscut all tech paths. A primary goal is to develop the first playbooks of validated play fairway analyses, and steadily increase their number and the diversity of characterized geologic settings over time. At the initial drilling phase, durability of tools under high temperatures and pressures is a critical hurdle. Across methodologies, the time to analyze data is also important, especially as the size of datasets and the complexity of joint inversions and other advanced analyses grow. Some such tools still need to perform in the field and ultimately in real time on portable computing platforms to have the greatest positive impact on project development.

The Hydrothermal Program will set specific target values for each of these metrics as appropriate to focus the award and execution of key exploration technology developments, drawing for example from the goals listed in Table 1. A key component of roadmapping within EERE is re-evaluation. The priorities and metrics discussed here and progress in reaching goals need to be discussed within GTO, with DOE management, and with the geothermal community on a regular basis to ensure proper alignment and execution.

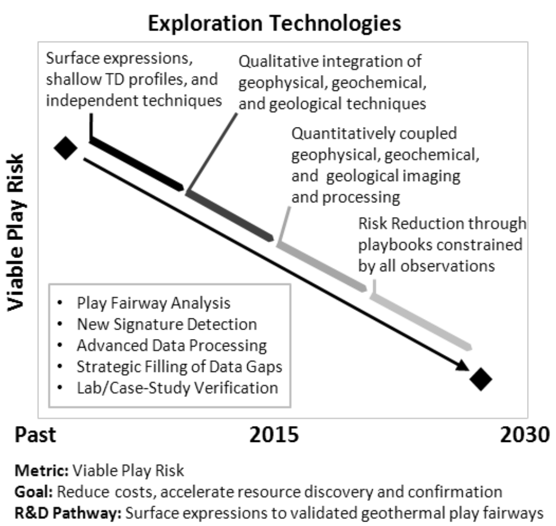

Figure 4: Schematic summary of GTO's exploration R&D strategic plan, with overall technology evolution timeline, metric, and goal. The box lists general tech priorities.

CONCLUSIONS

This Geothermal Exploration Technologies Roadmap is a living document that characterizes the current state and short- to long-term goals of the Hydrothermal Program. A key goal is to develop validated playbooks for multiple types of geologic provinces and associated geothermal prospects. To enable this, GTO is interested in filling data gaps at the regional- to prospect-scales using technologies that are newly developed or improved for geothermal signatures, or at least newly adapted to geothermal settings from other related sectors. Validation will require continued, focused laboratory and numerical analyses; and case studies at the project scale that seek to quantify risk reduction attributable to specific technologies, while demonstrating applicability to a wide array of reciprocal sites. Considering the full array of geothermal resource types during these developments, from low-temperature, to traditional and blind hydrothermal, to EGS, will further accelerate geothermal deployment. Revisiting these objectives regularly is important to gauge progress and realign approaches with the needs of the geothermal community and DOE renewable-energy targets.

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