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GEOTHERMAL TECHNOLOGIES PROGRAM

Exploration Technologies

Technology Needs Assessment

Prepared by: ENERGETICS A Subsidiary of VSE Corporation

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Executive Summary

To guide its strategy for leveraging resources to advance geothermal exploration tools, the Department of Energy's (DOE) Geothermal Technologies Program (GTP) sponsored a technology planning workshop on October 28, 2010, in Sacramento, California. The workshop brought together a diverse group of experts from industry, academia, and government. GTP solicited input from participants to identify technology needs and potential advances for the program to pursue over the coming years. The workshop specifically focused on technologies that have the greatest potential to contribute to the goal of lowering the risk associated with exploration and increasing capacity from new regions and resources.

The *Exploration Technologies Needs Assessment* is a critical component of ongoing technology roadmapping efforts, and will be used to guide the program's research and development. The assessment will be used as input for a technology roadmap that will present a pathway to develop and deploy economically viable, innovative, and scalable exploration technologies. By 2020, the U.S. geothermal industry could expand to new regions, discover new resources, reduce exploration risks and costs, and lower the levelized cost of geothermal energy. Figure ES-1 presents a graphical representation of the structure and logical flow of the technology needs assessment.

Mission and Vision

GTP and the larger geothermal community envision widespread deployment of exploration technologies that will help developers more efficiently locate viable geothermal resources. By lowering exploration risks and costs through research, development, and demonstration of geothermal exploration technologies, the program aims to spur the U.S. geothermal industry to seek greenfield (i.e., undeveloped) resources. These efforts are designed to support the GTP's mission and vision:

GTP Vision:
Geothermal is a major contributor to the nation's baseload energy supply.

GTP Mission:
To accelerate the development and use of geothermal energy by reducing the cost of identifying, extracting and converting geothermal resources.

GTP Hydrothermal Goal:
Research, develop and demonstrate new technologies and approaches to reduce exploration costs per site and lower the levelized cost of hydrothermal energy to 6 cents per kWh by 2020.

Key Challenges

This needs assessment document identifies key technology and non-technical challenges that must be faced while pursuing the GTP goal for hydrothermal energy described above. The technology challenges, for which this needs assessment proposes ten technology solutions, fall into five exploration technology areas: geophysics, geochemistry, remote sensing, geology, and cross-cutting. These are described in detail in this report. The non-technical challenges comprise four major themes: permitting, externalities, money/funding, and knowledge sharing/data. While these challenges are critical to the success of GTP goals, this assessment does not address non-technology-related issues.

Technology Needs

This assessment identifies ten technology needs that are deemed to represent the areas where technical advances would have the greatest potential impact on increasing exploration success rates and geothermal capacity. For each of these needs, this document provides a “technology needs map”, which outline the technology’s current and future states, key benefits, stakeholders, risks, and partnerships. These maps, organized by the five exploration technology areas (i.e., geophysics, geochemistry, remote sensing, geology, and cross-cutting) will be used to guide the program’s exploration technology roadmapping efforts for each technology need.

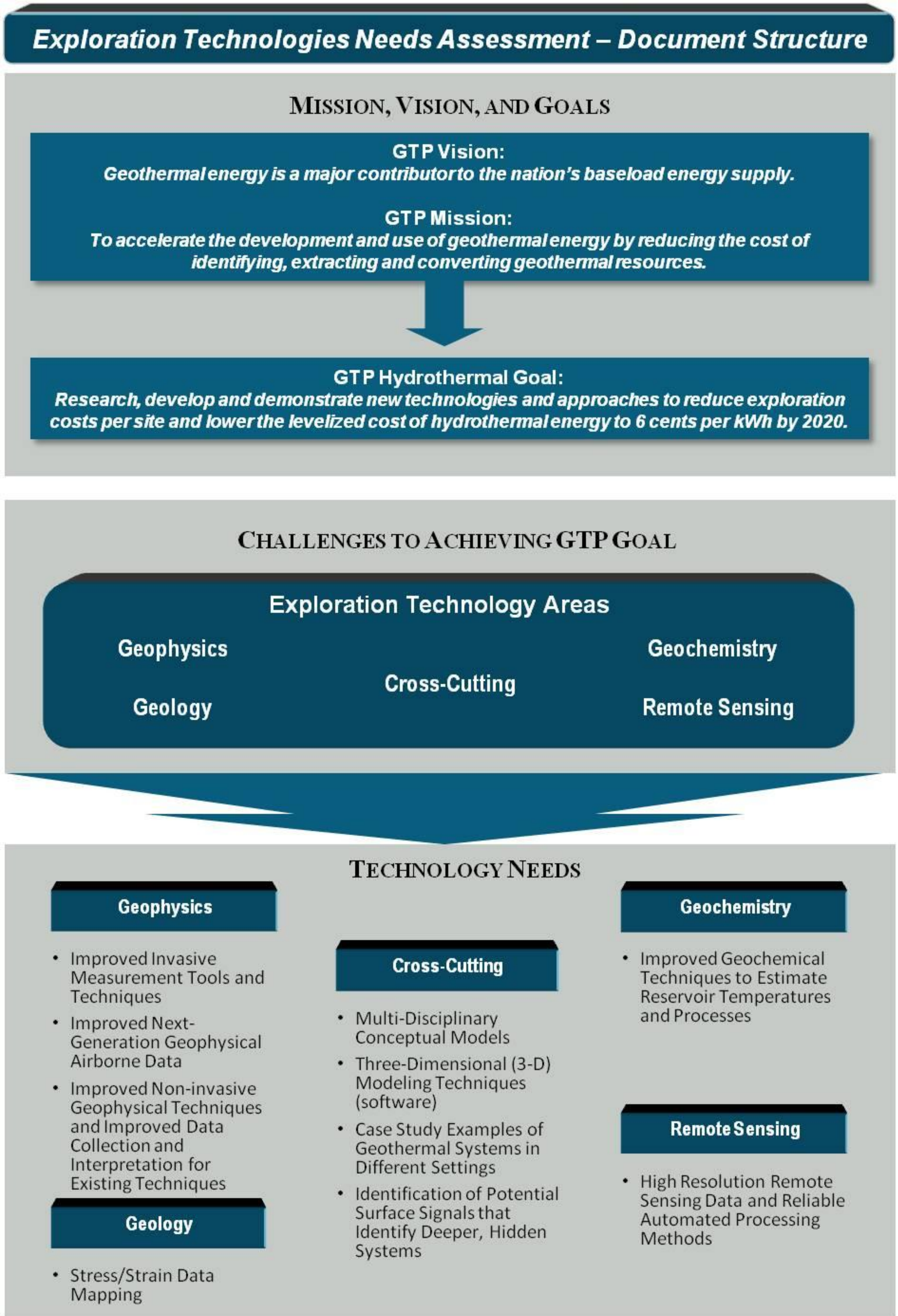


Figure ES-1. Exploration Technologies Needs Assessment overview

Path Forward

The results from this technology needs assessment will be used as critical inputs to ongoing technology roadmapping efforts for exploration technologies. In 2011, a second workshop will be conducted, during which experts from industry, academia, national laboratories, and government will develop pathways to advance the identified technology need areas.

As the program addresses the high-priority technology needs described in this assessment, it will evaluate and measure its own effectiveness, as well as the impact of its activities on industry. GTP will focus on whether and how much the technology solutions are contributing toward mitigating the key barriers to minimizing risk, improving exploration success rates, and increasing geothermal energy capacity.

It is important to note that, as performance is measured and evaluated, action items may be revised and resources reallocated. Evolving industry trends may cause program priorities to shift, resulting in new priorities and activities. Information from performance evaluations and changes in the industry landscape are likely to feed back into specific technology pathway plans and the overall needs assessment document.

I. Introduction

GTP assists in developing innovative technologies to find, access, and harness the nation's geothermal resources as a usable baseload source of renewable energy. In 2008, the United States Geological Survey (USGS) estimated that the 13 westernmost United States hold an average of 30,000 megawatts (MW) of undiscovered geothermal resources (see Figure I-1)[1], representing a substantial potential contribution to the U.S. energy portfolio. However, unlike other renewable energy sources such as wind and solar, a geothermal resource is not confirmed until a well is drilled into the reservoir, costing millions of dollars. Currently, the exploration success rate for identifying a hydrothermal resource is only around 35%[2], leaving upfront costs for early development and associated risk as the primary deterrent for rapid development.

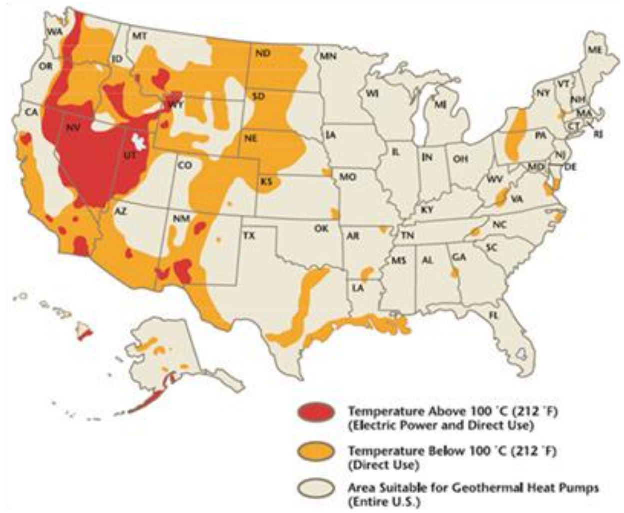


Figure I-1. Map of major potential geothermal locations across the United States[3]

The current low success rate for discovering geothermal resources is a major barrier to expanding the utilization, efficiency, and understanding of geothermal systems. The high upfront risk and cost deters investors and developers from exploring unknown areas, which hinders the industry's already limited knowledge of geothermal systems and why they occur. The consequences of this are immense, as the ability to accurately identify potential geothermal resources and increase utilization depends on the exploration of currently uninvestigated locations.

Exploration Technologies Research and Development

By investing in the research, development, and demonstration (RD&D) of geothermal exploration technologies, GTP seeks to encourage the exploration for and development of greenfield resources by the U.S. geothermal industry. The geothermal community agrees that gaining a more accurate understanding of the subsurface before drilling an exploration well will reduce upfront investment costs and result in a greater number of geothermal energy projects and installed geothermal capacity. In this way, exploration technologies RD&D is a critical component of GTP's strategy to achieve its goal of developing geothermal as a major source of renewable, domestic, and baseload energy for the United States.

The American Recovery and Reinvestment Act has designated $97.3 million in funding to support exploration projects that advance geothermal exploration technologies used for identifying undiscovered

[1] Colin F. Williams et al., "Assessment of Moderate- and High-Temperature Geothermal Resources of the United States," Fact Sheet 2008-3082 (Menlo Park, CA: USGS, 2008), http://pubs.usgs.gov/fs/2008/3082/pdf/fs2008-3082.pdf.

[2] Katherine Young, Chad Augustine, and Arlene Anderson, *Report on the U.S. DOE Geothermal Technologies Program's 2009 Risk Analysis* (Oak Ridge, TN: U.S. Department of Energy, 2010), http://www.nrel.gov/docs/fy10osti/47388.pdf.

[3] Alexander Richter, *United States Geothermal Energy Market Report* (Reykjavík, Iceland: Glitnir International Bank, September 2007), http://www.zyen.info/joomla/londonaccord/images/reports/pdf/glitnir_report.pdf.

hydrothermal resources. Research and development is focused on overcoming technical barriers that most greatly hinder the development of geothermal systems at acceptable costs, risks, and time frames. To date, 24 projects funded by the Recovery Act are underway in nine states: Arkansas, California, Colorado, Hawaii, Idaho, Nevada, New Mexico, Oregon, and Texas.

Exploration Technologies Needs Assessment Scope

The exploration technologies addressed in this assessment span the four major tool areas—geophysics, geochemistry, remote sensing, and geology—that are used to assess hydrothermal potential and identify temperature and permeability before drilling an exploration well. Technologies covered in this document also include a fifth technology area, "cross-cutting," which includes tools that use a combination of the science and techniques in the four major areas. Tools used to confirm the geothermal resource, such as those used for drilling, are not included within the scope of this document. Below are brief overviews of the five exploration technology areas for which potential technology needs are proposed in Chapter 4.

- ***Geophysics:*** Geophysical exploration techniques are principally used to map subsurface structures that help identify and define geothermal systems, such as fracture networks, lithologic changes, heat flux, and the presence of fluids (or zones of high electrical conductivity). These subsurface features are mapped using the traverse and reflection of acoustic (seismic) and electro-magnetic waves, variations in the local gravity and magnetic fields, and thermal gradients.
- ***Geochemistry:*** Geochemical techniques provide information regarding fluid source, heat source, subsurface temperature and local and regional fluid flow paths and histories. The chemical and isotopic compositions of fluids collected at the surface provide subsurface temperatures using a variety of empirical and experimental water-rock geothermometers. Fluid and heat sources can often be identified through characteristic isotopic signatures, particularly water, helium, and carbon isotopes. Spatial changes in fluid chemistry and isotopic compositions reveal important information on the flow rates and paths of geothermal fluids through the system.
- ***Remote Sensing:*** Remote sensing techniques enable large scale mapping of surface features, such as mineral, vegetation, and thermal properties, as identifiers of geothermal resources. There are two main types of remote sensing: passive and active. Passive sensors detect natural emitted and reflected radiation. Active remote sensing uses the reflected, or backscattered, signal from energy emitted at pre-determined wavelengths. Satellite and airborne imagery can map zones of secondary mineral precipitation associated with emerging geothermal fluids and attributes such as heat flux. Aerial photography and terrain mapping with laser ranging also illuminate surface structural features associated with geologic settings.
- ***Geology:*** Geologic techniques provide the historical and structural framework within which geophysical, geochemical, and remote sensing data are interpreted. When combined with the other three technical areas, a geologic model for an exploration area can be developed and used as guidance for subsequent exploration strategies. Surveying and mapping the local and regional geologic structures, lithologies, and past and present strain rates are the most common geological methods for identifying potential geothermal sites.
- ***Cross-Cutting:*** Cross-cutting exploration technologies are those that involve some combination of science and exploration techniques described in the technology areas above. The goal of cross-cutting technologies is to improve data interpretation by combing techniques in a way that minimizes the ambiguity of acquired data when standing alone. The approach relies on the development of multi-disciplinary models, advanced visualization techniques, and case studies of known geothermal systems.

Purpose of this Document

This document presents a technology needs assessment for geothermal exploration technologies, which identifies areas of opportunity where technology advancements could increase geothermal exploratory success and reduce up-front development risks and costs. This document will help GTP prioritize and allocate its resources in each of the technology areas (geophysics, geochemistry, remote sensing, geology, and cross-cutting), and provides the groundwork for ongoing GTP exploration technologies roadmapping efforts.

Structure and Content

The remainder of this document is organized as follows:

- **Chapter II** presents the ***strategic framework*** from which the needs assessment has evolved.
- **Chapter III** discusses the ***technical (and non-technical) challenges*** faced by the geothermal exploration community.
- **Chapter IV** presents the high-priority ***technology needs.***
- **Chapter V** discusses the next steps and how the assessment will guide ***further roadmapping efforts***.

II. Strategic Framework

This chapter provides a framework for the program's investment strategy. Specifically, it outlines how the technology needs identified in this assessment feed into the program's mission, vision, and goals and ultimately support DOE strategies and national policies.

Exploration Technology Needs

The ten, high-priority technology needs identified and discussed in detail in this document (described further in Chapter 4) serve as a basis for the exploration technology roadmapping efforts. They will guide the program's investment strategy for allocating funds across the five technology areas in an effort to achieve the goal of reducing exploration costs per site and lowering the levelized cost of hydrothermal to 6 cents per kWh by 2020. These technology areas and the associated technology advancement needs are shown in Figure II-1 below.

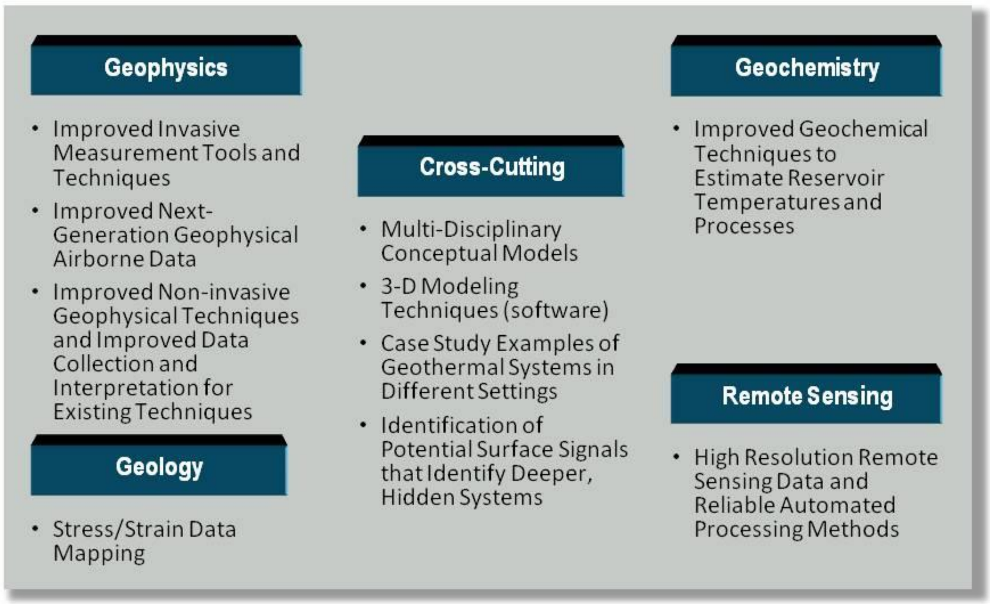


Figure II-1. Exploration technology areas and needs

Priorities

Each of the technology advancement needs can be viewed as an investment area for which the program should allocate funds. The ten technology needs that are discussed in this assessment are deemed by the geothermal community to provide the greatest opportunities for advancements that will help overcome the major challenges to achieving increased exploratory success rates. The advancements are aligned with the program's major goals and rank high with respect to the following exploration technology investment criteria, or "goal areas":

- Ability to reduce the high level of risk during the early stages of development
- Ability to increase the economic viability of exploration technologies
- Ability to improve the potential of technology to confirm new geothermal capacity
- Ability to foster useful data for the National Geothermal Data System

Hydrothermal Goal Alignment with the GTP Mission, Vision, and National Policies

A sound investment strategy will enable GTP to achieve its hydrothermal goal to research, develop and demonstrate new technology and approaches to reduce exploration costs per site and lower the levelized cost of hydrothermal energy. Improved, affordable, and widely available exploration technologies ultimately reduce the investment hurdle of resource risk faced by developers. As the risk is mitigated, financing costs will decrease and more projects will be initiated by private industry. Ultimately, this will contribute towards achieving GTP's higher-level vision of establishing geothermal energy as an economically competitive and more widely used energy source. Baseload geothermal electricity and heat is also part of the nation's strategy to bring more renewable energy sources online. A larger renewable energy portfolio will ultimately help address climate change and other environmental issues, and increase energy security through the availability of domestic energy sources.

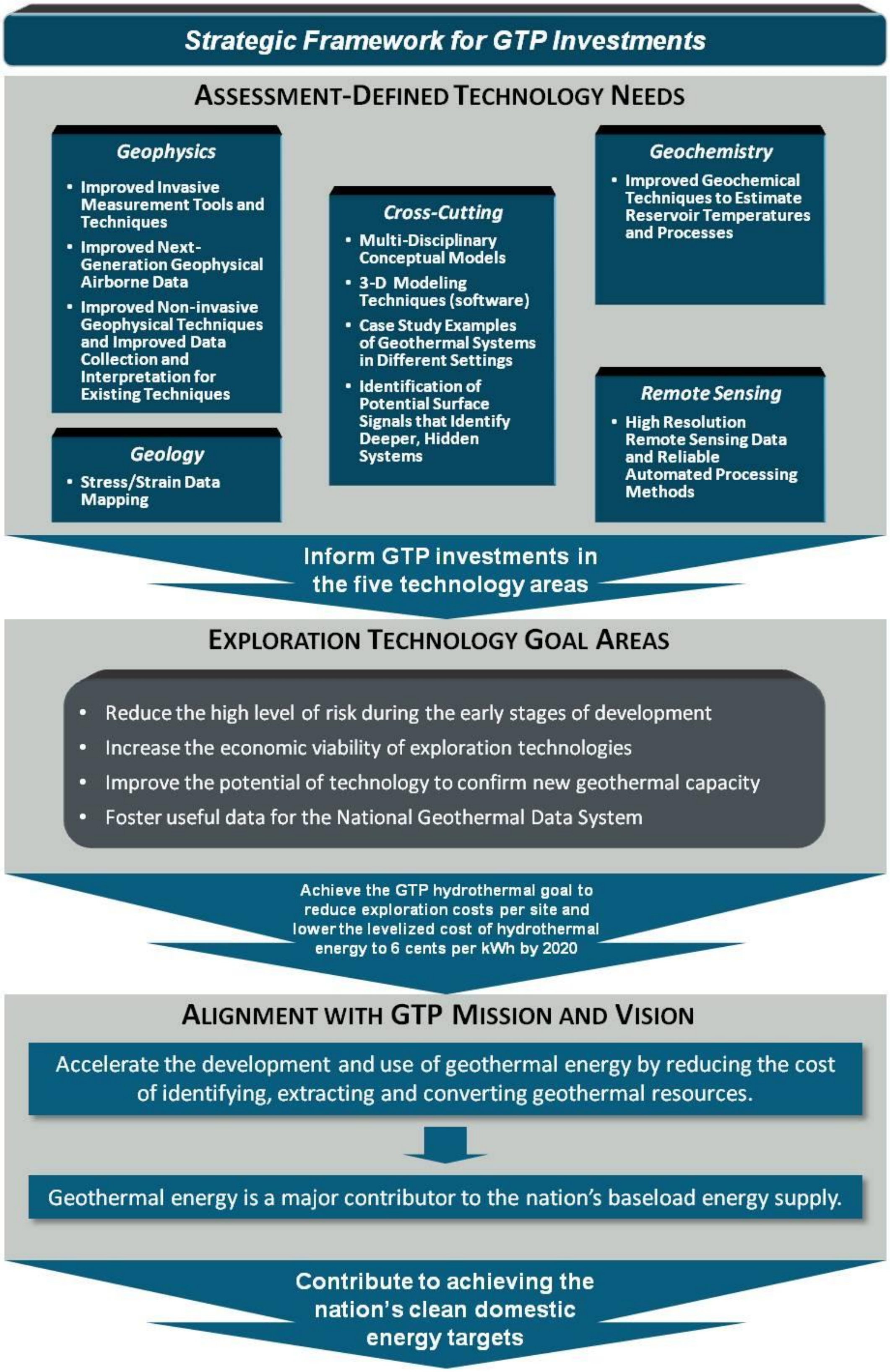


Figure II-2. Strategic framework for exploration technology investments

III. Key Challenges

Geothermal has immense potential as a renewable, zero-emission energy source providing stable, cost-competitive, and reliable base-load-capable power that is valued by the public and well-integrated with other resources and infrastructure. It is the goal of the U.S. geothermal community to increase capacity from new regions and resources and overcome the current barriers preventing geothermal energy's advancement. As mentioned previously, decreasing exploration risks and costs through exploration research and development will play a major role in achieving the nation's potential for adopting geothermal energy. The following sections describe the technical and non-technical challenges faced by the exploration community in its efforts to contribute towards a successful geothermal energy future in the United States.

Technology Challenges

The key technical challenges that currently restrict the large-scale deployment of exploration technologies or prevent these technologies from being used effectively to detect hydrothermal resources are grouped into the five exploration technology areas.

Geophysics

Geophysical tools currently lack the ability to sufficiently image fluids and flows and have difficulty remotely predicting temperature at depth. There is a lack of detailed heat-flow maps and limitations to predicting open fracture locations. Geophysical barriers to the successful use of exploration techniques include limitations on the depth at which the tools can detect parameters such as resistivity variations, and the inadequate coupling of geophysics techniques with other technologies (such as geothermometers) to get more reliable indicators of geological resources from the surface or the air. Translating resistivity data into meaningful inferences about reservoir permeability is currently a complex, time-consuming process. Presently it is challenging to use data acquired by geophysics tools to determine the system size and whether a resistivity anomaly is related to current geothermal activity. The issue of the "non-uniqueness" of inversions is another issue that has not been addressed. There is also a need for logging tools that are small in diameter but can perform at high temperatures, and a particular lack of inexpensive wide-area reconnaissance tools for areas where data is sparse.

Geochemistry

Geochemical and isotopic technologies for identifying fluid and heat sources in geothermal systems are well established. However, the geothermal industry lacks reliable tools for estimating subsurface temperatures, fluid flow paths, and rates; and for identifying surface manifestations of hidden systems. Chemical and isotopic geothermometers are based largely on empirical data, and interpretations of calculated temperatures for natural systems rely largely on experience. Next-generation geothermometers that incorporate chemical and isotopic thermodynamics of the water-mineral systems need to be developed. These new tools will also provide a basis for evaluating fluid flow histories, such as dilution, phase separation, flow rates, and flow paths.

Remote Sensing

Remote sensing's feasibility has yet to be demonstrated at a large scale. Challenges remain in utilizing regional light detection and ranging (LIDAR), hyperspectral, forward-looking infrared, and thermal imaging data, and there is an ongoing need for high-resolution, low-cost strain maps to enable remote sensing. The area to be surveyed is often vast and the data sets can be large, hence current automated regional reconnaissance data analysis and processing are inadequate. Especially for data-sparse areas, there is insufficient experience in the use of wide-area reconnaissance tools.

Geology

Many geologic features of a potential geothermal exploration site are currently challenging to understand. These include the site's tectonic context, structure setting and detail, strain-stress inversion, and permeability at depth and at fracture scale. Regional active structures, such as the structural settings of hydrothermally active systems, tend to be insufficiently understood. It is challenging to age-date hot spring deposits, and no good methods currently exist for determining if a hot feed lies below thermal anomalies. In addition, the limited availability of sufficient geologic maps for exploration hinders the ability of using other exploration technologies for effectively detecting geothermal resources.

Cross-Cutting

Beyond the specific challenges in the geophysics, geochemistry, remote sensing, and geology domains, various cross-cutting issues currently affect all geothermal exploration technologies. In general, there is insufficient understanding of what geologic environment is necessary for hydrothermal systems. Therefore, many productive geothermal reservoirs have been found by accident or trial and error. If there was more insight into why high-temperature systems exist, this knowledge could be applied toward more efficiently finding hidden systems and new sites. Defining such occurrence models will require input from all technical disciplines involved in geothermal exploration. With respect to data management, there is currently no world atlas of geothermal occurrences and no classification scheme that systematically links characteristics of the subsurface reservoir to measurements made at the surface across each geothermal setting. The key parameters that indicate the presence of geothermal resources vary across different environments, which create another level of complexity as each type of setting requires different exploration tools. Case studies, information on the habitats and meso-scale tectonic settings of geothermal systems, and occurrence trends are also insufficiently described; there is a need to explore new areas and to delineate anomalous areas (including via surveys).

Cross-cutting barriers also exist in data synthesis, including the lack of multi-disciplinary conceptual models that integrate geophysical, geochemical, remote sensing, and geological data; the high cost of 3-D integrative data software; and the lack of geothermal-specific software. Even where data and tools exist, they may not be sufficiently leveraged by geothermal developers. For example, the extensive body of oil, gas, and mining industry knowledge, as well as federal agency tools such as the National Science Foundation's Earth Scope, NASA's airborne science surveys (e.g., InSar, Hyperspec, and LIDAR), and USGS surveys and maps, could be used more effectively.

According to the USGS resource assessment, many of the undiscovered geothermal systems are expected to be hidden in the sense that they lack conventional surface manifestations such as hot springs. Since these hidden systems may account for a significant fraction of the resource base, particularly in the western United States, there is a distinct need to determine, using combinations of geological, geophysical and geochemical techniques, if hidden systems do or do not have chemical or isotopic signals at or near the surface that have gone undetected to date.

Non-Technical Challenges

The geothermal industry faces various challenges in successfully deploying exploration tools that are not related to specific technical limitations. The challenges lie in four main areas. The first three challenges—permitting, externalities, and money/funding—relate to economics and policy issues, and are recurring themes faced by the entire geothermal community. The fourth challenge, knowledge sharing/data, pertains more specifically to exploration.

- ***Permitting.*** Permitting and leasing agencies often lack knowledge of geothermal energy technologies and procedures. Not only is geothermal poorly understood, its permitting must conform to different standards than oil and gas permitting. Conflicts also occur between the regulatory constraints of different agencies surrounding the use of public land.

- ***Externalities*****.** The geothermal industry faces challenges regarding the state of the current energy environment. These externalities include the current price of electricity, which is still relatively inexpensively provided by traditional fuels; public perception, which is not always on the side of those developing exploration technologies since drilling funds may be seen as "corporate welfare"; and the dearth of available qualified scientists in geothermal exploration.
- ***Money/Funding.*** The cost of exploration drilling for geothermal sources is persistently high. There is a lack of capital and cooperative mechanisms to conduct high-risk reconnaissance as the geothermal community does not adequately utilize cost-sharing opportunities with the oil and gas industry to conduct, for example, stratigraphic tests used in hydrocarbon exploration. Rather than enrolling in such partnerships, the geothermal industry currently competes with the oil, gas, and mining industries for services. Additionally, the cost of cutting-edge technology is high, limiting the breadth of its utilization. In particular, the companies interested in innovations may be under funded, since major geothermal companies do not participate in funding exploration. There is no debt financing available for exploration, and risk-tolerant equity funding has proven difficult to attract. All these factors impair interested parties in their ability to adopt such technologies.
- ***Knowledge Sharing/Data*****.** Insufficient documentation exists on past successes and failures in geothermal exploration. Challenges also surround intellectual property and data sharing; e.g., developers may hold data for leasing purposes. Regional data collection is a challenge, especially in areas outside those that have been proven, as is identification of new geothermal provinces or trends in data-sparse areas.

While these challenges are critical to the success of the GTP hydrothermal goal, this assessment does not identify potential solutions to these issues which are not directly related to technology.

IV. Technology Needs

This chapter presents an overview of the technology advancement opportunities associated with each of the five exploration technology areas by highlighting the high-priority technology needs in each area. Detailed worksheets for the ten highest-priority technology needs, listed below in Table IV-1, are presented in Appendix A.

• Improved Invasive Measurement Tools and Techniques • Improved Next-Generation Geophysical Airborne Data • Improved Non-invasive Geophysical Techniques and Improved Data Collection and Interpretation for Existing Techniques	GEOPHYSICS
• Improved Geochemical Techniques to Estimate Reservoir Temperatures and Processes	GEOCHEMISTRY
• High Resolution Remote Sensing Data and Reliable Automated Processing Methods	REMOTE SENSING
• Stress/Strain Data Mapping	GEOLOGY
• Multi-Disciplinary Conceptual Models • 3-D Modeling Techniques (software) • Case Study Examples of Geothermal Systems in Different Settings • Identification of Potential Surface Signals that Identify Deeper, Hidden Systems	CROSS-CUTTING

Table IV-1. Ten high-priority technology needs in five exploration technology areas

Technology Areas

Geophysics

Both geophysical models and geophysical data are needed to advance geothermal technologies. Research programs should be developed to define geothermal signatures in different tectonic settings and to identify geophysically-detectable features in geothermal reservoirs.

There is a need for advancements in temperature gradient and heat-flow measurement tools and processing methods. Improved techniques for measuring thermal conductivity in high temperature environments are needed, as well as broader understanding of existing heat-flow measurement tools and their impacts on improving the accuracy of geothermal system characterizations. Beyond temperature gradient and heat flow measurement technology, there is a need to improve the next generation of geophysical airborne data. This need could be met by testing advanced airborne tools, including magnetotelluric and time-domain electromagnetic tools over known geothermal systems, by leveraging other agencies' satellites and airborne data and combining multiple airborne sensors on a single platform. In general, better and potentially new borehole tools are needed, including smaller diameter tools capable of higher-temperature operation. Advancements are also needed to better interpret ambiguous geophysical signals, such as seismic reflection data in crystalline environments.

The following three geophysics technology advancements were identified as having the greatest potential to support the achievement of the GTP hydrothermal goal:

- ***Improved Invasive Measurement Tools and Techniques.*** Widespread understanding and use of advanced and commercially available heat-flow tools will significantly improve the accuracy of geothermal system characterizations. Efforts to educate the exploration community on existing heat-flow measurement technology through demonstrations could be started in the near future and completed within a 1–2 year time frame. Achieving significant improvements in techniques for measuring thermal conductivity will be more difficult to attain and could take up to 5 or more years.
- ***Improved Next-Generation Geophysical Airborne Data.*** Advancement in this technology area will help identify hidden resources. Technical challenges include issues with flying surveys and interception in areas of high relief. Significant advancement in this area can be achieved in 2 years.
- ***Improved Non-invasive Geophysical Techniques and Improved Data Collection and Interpretation for Existing Techniques.*** This advancement focuses on improving and validating data collection tools (e.g. control source electromagnetic), and improving data processing techniques through advanced coupling processing techniques to better interpret geophysical signals, such as seismic reflection data in crystalline geological environments.

Geochemistry

One of the most needed advancements in geochemistry is improved geochemical and isotopic geothermometers based on the thermodynamics and kinetics of fluid–mineral systems. Specifically, there is a need for geothermometers that clearly identify geochemical temperatures and new geothermometers, if they exist. Advancements are needed to insure applicability to variable fluid and lithologic environments.

The following geochemistry technology advancement was identified as having the most potential to support the achievement of the GTP hydrothermal goal:

- ***Improved Geochemical Techniques to Estimate Reservoir Temperatures and Processes.*** Technologies that address this need will improve the ability to quickly assess the thermal conditions of a subsurface geothermal system. No technical risks to success were identified during the workshop for development of improved geothermometers, and it was estimated that success could be achieved in 5–10 years. Better data is needed. Data is inexpensive and will improve the ranking of potential resources, evaluation and management of reservoirs, prediction of temperature at reservoir depth, and understanding of fluid rock structure in reservoirs and during transport/flow. Difficulties in scaling lab determined data to field data can present challenges to advancement in this area. Improvements in thermodynamic and kinetic data can be accomplished in 1–2 years, but full success with validation of improved reaction transport models will take 5−7 years.

Remote Sensing

Remote sensing advancements are needed to enable the acquisition of high-resolution remote sensing data sets via multiple methods over large areas in new regions. Specifically, there is a need to establish reliable automated processing tools and techniques and develop affordable software for subsurface data-set model integration.

The following remote sensing technology advancements were identified as having the most potential to support the achievement of the GTP hydrothermal goal:

- ***High Resolution Remote Sensing Data and Reliable Automated Processing Methods.*** Improved data and methods will create multiple modern regional data sets and defray the cost of cutting-edge exploration tools. In order to accomplish this, links between data and resource potential need to be defined. This technology can be achieved in 1–3 years.

Geology

In the geology arena, advancements are needed in stress and strain data mapping and in correlating improved tectonic stress and strain data with thermal data. Stress and strain maps would predict fractures and assist in solving the question of permeability. Advancement could be made through acquiring additional data to fill in gaps of borehole, local structural, and regional geodetic data, and developing detailed district maps and 3-D models of strain and stress. A confirmed model connecting geophysics, hydro-geochemical, and geologic data to map permeable paths in the subsurface would also improve the technical community's understanding of permeability. Overall, there is a need for an improved conceptual model to understand the subsurface, so as to require fewer slim holes and thereby reduce costs. There is a need to adapt projects to model fluid flow in the fractured crust, and for a reliable "crack finder." Lastly, a decisional tree or matrix describing the effectiveness of various techniques in various geological settings could help meet explorers' needs for detailed geological information.

The following geology technology advancements were identified as having the most potential to support the achievement of the GTP hydrothermal goal:

- ***Stress/Strain Data Mapping.*** This technology will apply to case studies, reduce risks of drilling, and assist the understanding of induced seismicity. Challenges in this area include abnormal stress regimes and lack of borehole data. Development objectives in stress/strain mapping can be achieved in 1–3 years.

Cross-Cutting

Opportunities exist for technical advancements that will provide "cross-cutting" support for all geothermal exploration technologies. Improved, multi-disciplinary conceptual models hold promise for increasing the understanding of the subsurface, thereby requiring fewer slim holes and avoiding the associated costs. Development and confirmation of a model that connects geophysics, hydro-geochemical data, and geologic data and maps permeable paths in the subsurface would enhance understanding of subsurface permeability.

Opportunities also exist to develop projects to model fluid flow in the fractured crust. 3-D modeling techniques and software are needed, as are improved and more user-friendly data integration tools and software for model development. Improvements in 2- and 3-D data inversion codes, especially of multiple data sets, have promise. The application of stochastic or Monte Carlo inversions to match cross-disciplinary datasets is able to generate a range of possible models.

Case study examples of geothermal systems in different settings could serve to identify key attributes to use in exploration, and also to establish occurrence models. To provide these case studies, DOE could support multi-company, multi-disciplinary projects; these "group shoots" could test combinations of technologies and publish all of the resulting data. Case studies would support the important work of identifying the key attributes and parameters required for a productive (commercial) geothermal system. These parameters, and the needed exploration tools and technologies, will vary across geothermal settings. Such a classification system will aid in the development of conceptual models across different geological settings.

Likewise, district mapping programs show promise for increasing the knowledge base regarding existing resources. There is a need for combined studies of the correlation between geochemistry and thermal studies at specific locations. Such studies would couple diverse data sets through common and overlapping physical and chemical laws, providing combined data. In addition, there may be opportunities for a program to define geothermal signatures in different tectonic settings.

Exploration strategies would greatly benefit from the identification and evaluation of new surface geochemical signals from deep hydrothermal systems and the development and validation of new tool(s) to analyze and interpret the new signals. Combined geology, geomorphology, and geophysics (e.g., high resolution MT, gravity) approaches, including the coupling of surface signals to surface structural features, should guide the search for new geochemical surface signals. The development of improved geothermometry techniques may help to pick up hidden thermal attributes, and shallow thermal gradient holes should be investigated as potential sample collections points for identifying subsurface systems. As mentioned elsewhere, greater understanding of why high-temperature systems exist will provide more insight into potential new surface signals.

The following four cross cutting technology advancements were identified as having the most potential to support the achievement of GTP goals:

- ***Multi-Disciplinary Conceptual Models.*** Improved conceptual models will lead to increased drilling and exploration success. The limited availability of non-proprietary data could be a barrier to success in creating these models. Success can be achieved in 1–3 years.
- ***3-D Modeling Techniques (software).*** Enhanced software will lead to improved understanding of conceptual models, which leads to reduced drilling costs. This drives industry to provide more and more functionality, and benefits developers by providing better and more affordable tools. Success can be achieved in 1 year.
- ***Case Study Examples of Geothermal Systems in Different Settings.*** Better case studies will streamline explorations by highlighting key attributes and data that are required in each geological setting. This improvement can be achieved in 3–5 years, but a classification scheme for geothermal systems is a critical initial step.
- ***Identification of Potential Surface Signals that Identify Deeper, Hidden Systems.*** If surface signals exist, it would greatly improve the industry's ability to explore for and identify anticipated vast hidden resources. A systematic study coupling the different technical areas, particularly geochemistry and geology, could fulfill this need in 2–3 years, with full success in 4–5 years, as measured by implementation at the industry level.

V. Path Forward

The technology needs identified in this assessment provide the groundwork for further technology roadmapping within GTP. Using the ten identified high-impact research areas, GTP and stakeholders will collaborate to develop technology pathways with milestones and metrics to advance geothermal exploration technologies.

Measuring Success Towards the GTP Hydrothermal Goal

The ultimate goal for exploration technology advancements is to lower exploration costs and risks, thereby encouraging the discovery of the significant unidentified geothermal resources in the United States. In order to measure progress towards achieving this goal, the geothermal exploration community needs to define metrics with which to measure the impact of program technology advancement activities and to measure advancement of specific technologies. These metrics should be able to be tied to the overall GTP mission and vision, in which geothermal becomes a major contributor to the nation's baseload energy supply.

To establish program goals for exploration, there is a need for a clear MW goal towards which the program should strive, and for clear understanding of the assumptions behind the USGS projection of an average 30 GW of undiscovered U.S. hydrothermal potential. Appendix D lists preliminary metrics identified by GTP for assessing its performance towards achieving the overall goals with respect to new geothermal deployment. These preliminary metrics will serve as a guide for the program in developing metrics specific to its technology advancement activities.

Beyond Roadmapping

It is important to note that as performance is measured and evaluated, action items may be revised and resources reallocated. Evolving industry trends may cause program priorities to shift, subsequently resulting in new priorities and activities. Figure V-1, below, depicts the overall pathway from the current technology assessment and roadmap development through activity implementation, increased deployment of exploration technologies, and achievement of the program goals. Figure V-1 also shows that information from performance evaluation and changes in the industry landscape are likely to feed back into specific pathway plans and the overall assessment and strategic roadmap.

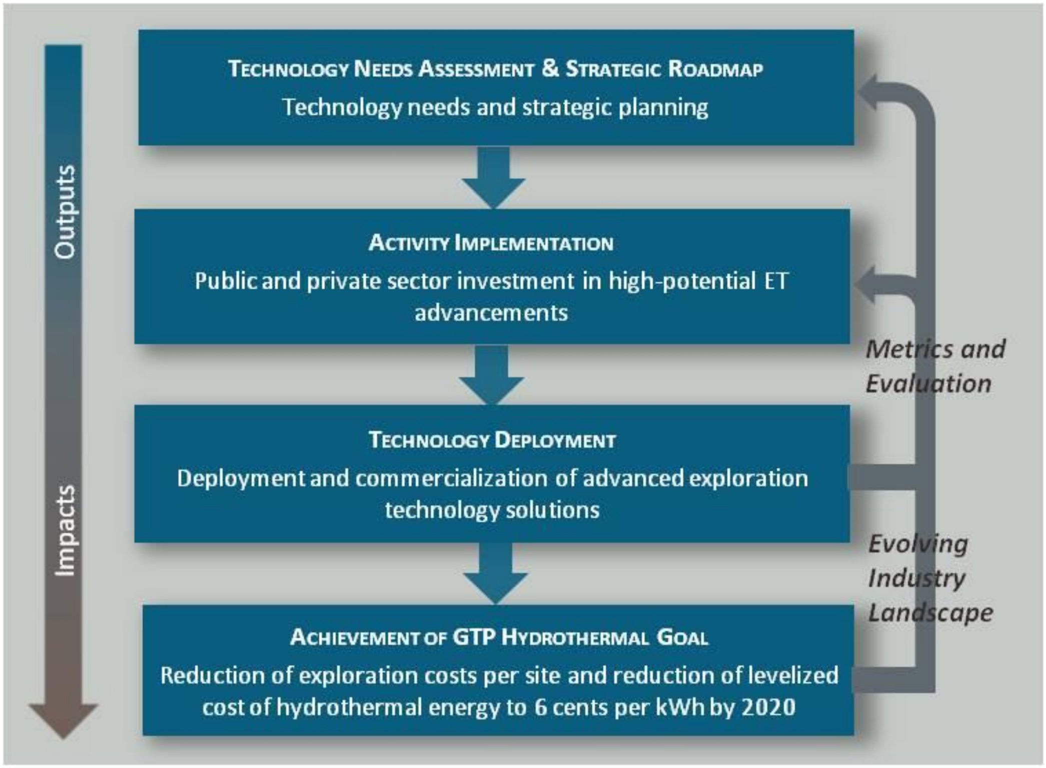


Figure V-1. Technology assessment and roadmap implementation and evaluation

Appendix A: Technology Needs Maps

Each of the ten technology needs described in the following pathway maps represents an area of investment for GTP to consider. Each map describes the current state of the technology; the desired future state; the benefits of achieving the advancement; and the associated risks, key stakeholders, and projected time frames. The maps also include an approximation of where the technologies currently reside along the technology development pathway—from fundamental research and development to commercial deployment.

GEOPHYSICS 1: IMPROVED INVASIVE MEASUREMENT TOOLS AND TECHNIQUES

FROM WHAT? – Current State

What is the state of knowledge or technology that needs to advance?

- In general, there is a lack of widespread understanding of temperature behavior in geothermal systems. Industry is not consistently aware of how to best use the heat flow/temperature data for characterizing geothermal systems, (other than simply making temperature gradient measurements). As a result, temperature measurement and analysis techniques as well as heat flow modeling tools are underutilized. In addition, there are many new/inexperienced people getting involved in geothermal and the challenging economics often drive exploration/development work to rely on bare-bones budgets.
- ***Technology availability and capabilities***
  - Many high-temperature tools that acquire precise, high-frequency temperature measurements are available but not widely used. These technologies were built ~20 years ago and the tools and applications are well understood by a community of experts. Primarily specialized groups have developed and maintained the technologies over the past few decades.
  - Modeling tools used to understand the thermal regime are commercially available, but there is lack of widespread knowledge of how to use them.
  - Some temperature measurement technologies are not used because they are not easily accessible or commercially available, and/or the techniques to analyze the data are too expensive, requiring the outsourcing of the task to expensive consultancies/labs (e.g., measurement of thermal conductivity using drill cutting)
  - There are issues with the stability of fiber optic cables (a distributed temperature sensing tool) under high temperatures. Some progress has been made, but currently the technology still does not cover the temperature range that the geothermal industry needs.
- ***Data availability and gaps***
  - Thousands of geothermal temperature gradient boreholes and some deeper wells exist, but they are mostly clustered around areas with known resources. There are significant gaps in data.

TO WHAT? – Definition of a Successful Advancement

Where does the knowledge or technology need to go? What achievements or outcomes would a funded project need to produce to be a worthwhile investment (i.e., what should the criteria be for the advancement/project)? What is a good measure of success?

Demonstrate existing heat flow measurement technology

- Educate industry on the availability and value of geophysical temperature measurements through demonstrations of existing temperature measurement tools.
- Disseminate information on: the importance of heat flow measurements to characterizing geothermal systems; the techniques used to interpret data; and the software tools available for modeling the thermal regime.

Improve commercial availability of existing heat flow measurement technology

- Conduct applied research to improve the stability of fiber optic cables under high-temperature environments.
- Conduct long-term research on understanding thermal properties and thermal conductivity.
- Research and develop easier and cheaper ways to measure thermal conductivity from well cuttings so that the technique is more accessible to the geothermal community. This could involve longer-term technology improvements and development of new logging tools for thermal conductivity, or simply reducing the costs of and commercializing existing technology.
- Develop techniques for measuring temperature changes over time.

Address data gaps to complete heat flow maps

- Acquire temperature data on a larger scale and beyond areas of known resources.

HOW DO WE GET TO DEPLOYMENT END-STATE?

What are the benefits?

Widespread understanding and use of commercially available heat flow tools will significantly improve the accuracy of geothermal system characterizations and ultimately improve drilling success rates and reduce exploration costs.

What are the risks to success?

Significant improvements in techniques for measuring thermal conductivity may prove difficult to attain.

Who benefits?

Geothermal developers/owners, geophysical service companies, and drillers

Who are the participants/partners?

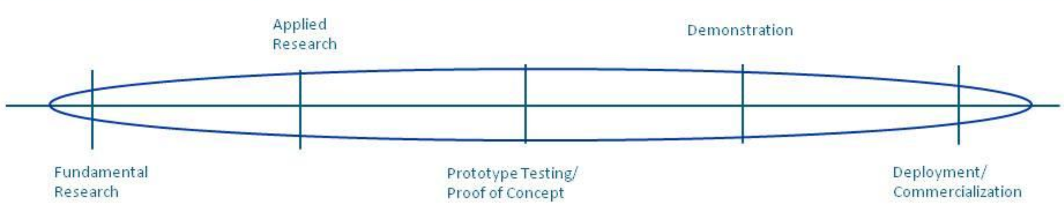
Universities, geophysical service companies, geothermal consultancies, developers, national laboratories, government agencies (e.g., USGS)

How soon can success be achieved

- Education programs carried out in the near-term could begin having impacts in a 1–2 year time frame
- Technology advancements and addressing data gaps: 2–5 years

Comments?

TECHNOLOGY READINESS LEVEL/MATURITY



FROM WHAT? – Current State

What is the state of knowledge or technology that needs to advance?

- Technology currently used a lot in other industries (e.g., mining, oil and gas); airborne data is expensive to obtain
- Penetration of airborne data (e.g., magnetotellurics [MT]/electromagnetics [EM]) has reached depths of interest to geothermal and is being applied in minerals exploration; MT maps out resistivity variation down to approximately 500 meters over geothermal targets
- Mining industry's use of airborne MT still relies on ground-based data to increase reliability of airborne data
- Airborne gravity is well understand in mining but not in geothermal applications
- Aeromagnetics (high resolution) and Airborne MT show alteration destruction of magnetite in young volcanics where there is sulfite
- Few companies use airborne MT inversion to correct for topography, as it is expensive; however, inversions are becoming cheaper with LIDAR, which provides extremely accurate topography enabling inversions. LIDAR and topography data sets are becoming cheaper
- Hundreds of airborne magnetics surveys have been done but neither successful nor negative case histories (failures) have been published

TO WHAT? – Definition of a Successful Advancement

Where does the knowledge or technology need to go? What achievements or outcomes would a funded project need to produce to be a worthwhile investment (i.e., what should the criteria be for the advancement/project)? What is a good measure of success?

Detailed records

- Failed cases in addition to successes
- Provide access to these records

Development of processing methods to adapt the airborne MT/EM tools to geothermal applications, particularly with respect to handling topography:

- Robust 3-D MT inversion code capable of handling topography that runs on standard workstations
- Benchmark data set (possibly forward modeled synthetic data set) to test code accuracy and performance
- Reduction of time and cost of performing airborne MT 3-D inversions
- Potential to combine with other airborne sensors, such as chemistry or remote sensing, on the same platform to establish useful sensor combinations (e.g., spectral gamma, radiometry, hyperspectral imaging, and LIDAR)
- Indicators of success include reduced time and cost of performing MT inversions; ability to handle topography

HOW DO WE GET TO DEPLOYMENT END-STATE?

What are the benefits?

Greater resolution of MT and EM data and reduced time and cost for data processing—performing multiple tests from a single airborne platform reduces permitting costs and ensures consistency of results across time and space

What are the risks to success?

Problems in flying and interception in areas of high relief; for platform combining airborne sensors there is a risk of interference by different instruments in such close proximity. Mining and even geothermal companies do not publish results, particularly when something works

Who benefits?

Bureau of Land Management (revenues from new prospects), companies (profits), and mankind (expand capacity)

Who are the participants/partners?

Geotech (most recent and extensive experience in this area), Fugro, Geosystems (now owned by Schlumberger), U.S. Geological Survey, other industries like coal mining, Chevron, international collaborations (New Zealand, Australia, Canada)

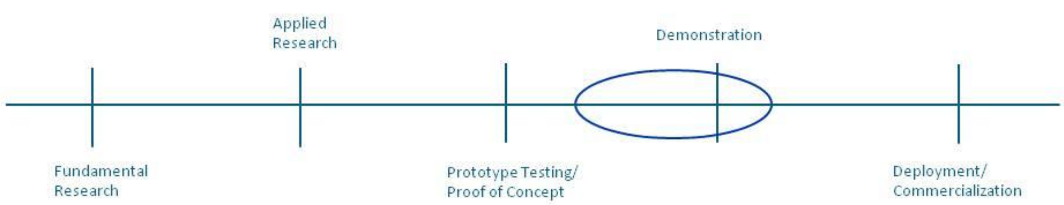
How soon can success be achieved

2 years

Comments?

The International Partnership for Geothermal Technology could facilitate collaborations so DOE could study Australian data from mineral deposits; the technology needs to be proved for geothermal applications

TECHNOLOGY READINESS LEVEL/MATURITY



Geophysics 3: Improved Non-invasive Geophysical Techniques and Improved Data Collection and Interpretation for Existing Techniques

From What? – Current State

What is the state of knowledge or technology that needs to advance?

- Currently, most geophysical technologies (e.g., MEQ, MT) pick up reservoir signals that are a not directly related to fluids/fractures, but rather are secondary signals from other formations such as clay minerology that comes from hydrothermal fluids. Drilling is required to further characterize the resource.
- Resolution of resistivity data, such as MEQ arrays (50m – 0.5km pixel size) is insufficient to give definitive information about the presence of fractures and fluids at drilling level. MT data has better resolution. Resolution is ultimately limited by the wavelength of the signal – e.g., gravity data is lowest resolution.
- Seismic data is difficult to read due to sensitivity of geophysical tools to movement when the reservoir is stimulated, which is required to collect the seismic signals. In complex crystalline environments such as volcanic terrain, there is too much noise to make any sense of the seismic images., even when using active source seismic methods.
- Oil and gas industry has extensive coverage over sea bed to pin point where reservoirs are – this has cost a considerable amount of time and money in acquiring and processing data.
- New techniques are being experimented with to address the complexity of seismic data (e.g., by low path filtering/smoothing); however, industry lacks the data sets needed to develop and validate new technologies
- Controlled source MT newly developed in oil and gas industry but has not been applied in geothermal industry. Electrical measurements using controlled source helps to reduce noise, but it is more expensive
- Temperature gradient information is often the most useful information, since it is a direct measurements, but much of the existing thermal gradient data is proprietary.

To What? – Definition of a Successful Advancement

Where does the knowledge or technology need to go? What achievements or outcomes would a funded project need to produce to be a worthwhile investment (i.e., what should the criteria be for the advancement/project)? What is a good measure of success?

Applied research of geophysical measurement technology with greater resolution to more accurately identify where fractures in the system are:

- Technology targets
  - Deeper probing resolution, greater resolution, reduced noise in crystalline environments
  - Can be used in isotropic systems
- Potential advancements:
  - Detect fluid and fracture systems directly
  - Use of overlapping systems of different wavelengths
  - Integrated geophysical imaging and acquisition techniques
  - Active source seismic data collection technology
  - Control source MT/electrical – technology transfer from oil & gas industry

Applied research of more sophisticated geophysical data processing techniques:

- Smoothes out the noise in data and makes sense of crystalline environments
- Incorporates multiple geophysical signals (e.g., MT, MEQ, seismic, control source EM, heat flow) – advanced coupling
- Imaging volumes down to a level where better predicts fluid baring fractures

Validation of measurement and processing tools using data from known geothermal reservoirs and surface structures

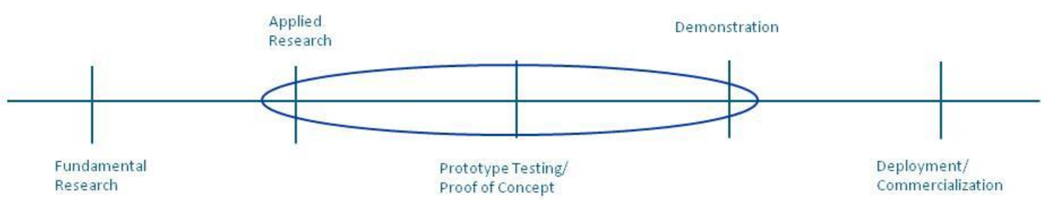
- Finer samplings points and extensive coverage to improve precision
- Test for metrics where there is subsurface turf, where fractures are highly vertical and there is a lot of reflectivity/noise
- Technology transfer of electrical data from oil and gas industry

Demonstration of rigorous ways to integrate geophysics attributes on data sets

How Do We Get to Deployment End-state?

What are the benefits? More accuracy in targeting wells	*What are the risks to success?* Failure in early development; cost to improve technology (e.g., to collect data for validation) may be prohibitive; may not be able to improve resolution enough to reduce number of wells and ultimately lower LCOE.
Who benefits? Geothermal developers/owners, geophysical service companies, and drillers	*Who are the participants/partners?* Universities, geophysical service companies, geothermal consultancies, developers, national laboratories, government agencies (e.g., USGS)
How soon can success be achieved 3 – 5 years	*Comments?*

Technology Readiness Level/Maturity



Geochemistry 1: Improved Geochemical Techniques to Estimate Reservoir Temperatures and Processes

From What? – Current State

What is the state of knowledge or technology that needs to advance?

Geothermometers

- Geothermometers largely reflect empirical correlations developed in 1980–1990 and are not specifically related to the range of lithologic and tectonic regimes and electrolyte compositions in which geothermal systems are found. The range of uncertainty is too large.
- Geothermometers are not specifically adapted to the conceptual targets (e.g., the NaKMg geoindicator plot)—limitations in detecting the level of permeability
- Need new plots that are more effective in differentiating permeability and characterizing permeability from associated water samples.
- Looking for less dramatic permeability through much more diffusive rock, which requires more sophisticated technology
- Transport to reservoir; re-equilibration overprints deep-water rock equilibration temperature

Thermodynamics data

- Determination of thermodynamics and kinetic-rate parameters relies primarily on applied technologies and feeds off of ongoing fundamental research funded by DOE. Reaction transport models are presently being applied, but need better constraints

To What? – Definition of a Successful Advancement

Where does the knowledge or technology need to go? What achievements or outcomes would a funded project need to produce to be a worthwhile investment (i.e., what should the criteria be for the advancement/project)? What is a good measure of success?

Next-generation geothermometers

- Capabilities of next-generation geothermometers:
  - Reliable application to wider range of fluids types and lithologies
  - Have longer memory and capability to see through lower temperature re-equilibration
  - Reliable corrections for processes occurring along flow paths, such as dilution and phase separation
- Laboratory work needed to examine the behavior of liquid and gaseous chemical component in variable lithologic, hydrologic flow, and temperature conditions
- Need development of predictable and reliable correlations of the geothermometers with data from real geothermal metamorphic terrains/systems
- Success can be measured by comparing drilling/sampling results to geothermometer predictions

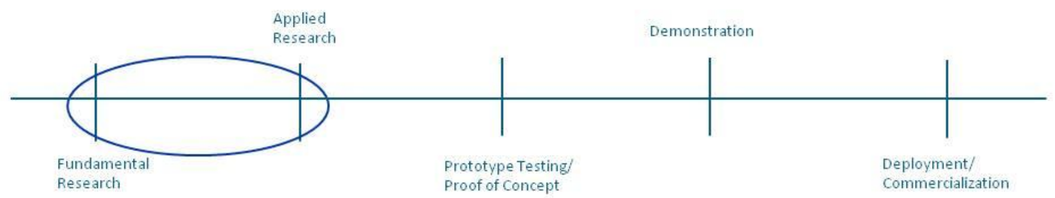
Thermodynamics Data

- Determination of improved thermodynamic and kinetic data for fluid-mineral systems that are needed to develop the next generation of geothermometers—done in context, targeting correct species of rock
- Incorporation of improved thermodynamics and kinetic rate data into robust reaction transport models
- Greater empirical validation for low-temperature/low-permeability systems, enabling determination of longer history of water

How Do We Get to Deployment End-state?

What are the benefits? Ability to quickly assess the thermal conditions of a subsurface geothermal system	*What are the risks to success?* Discontinuous funding and low priority of the activity within the organizations involved (including industry, academia, and national labs)
Who benefits? Geothermal developers, academic researchers, and national laboratories	*Who are the participants/partners?* Academia, national laboratories, geothermal tool vendors and geothermal developers
How soon can success be achieved 5–10 years	*Comments?*

Technology Readiness Level/Maturity



Remote Sensing 1: High Resolution Remote Sensing Data and Reliable Automated Processing Methods

From What? – Current State

What is the state of knowledge or technology that needs to advance?

High-Resolution Remote Sensing Data

- Free satellite data is already available, which helps to narrow down zones for collecting airborne data
- Airborne systems are in place and being used by other industries (e.g., hyperspectral used for mineral exploration), but they are not fully exploited or used as routine parts of geothermal exploration
- Low-resolution magnetic, resistivity, and gravity data are available for large parts of United States. There is a paucity of high-resolution data over geothermal targets
- Published literature in geothermal remote sensing is still limited compared to other application areas

Reliable Processing Methods

- Commercial off-the-shelf tools exist for processing data, but remote sensing data and tools have not been fully exploited for geothermal exploration
- Processing of airborne remote sensing data (especially automating the process of data georectification and mosaicing) is still a challenge—a lot of manual time is invested in making data usable

To What? – Definition of a Successful Advancement

Where does the knowledge or technology need to go? What achievements or outcomes would a funded project need to produce to be a worthwhile investment (i.e., what should the criteria be for the advancement/project)? What is a good measure of success?

High-Resolution Remote Sensing Data

- Acquire airborne gravity magnetics, hyperspectral, light detection and ranging, resistivity, thermal infrared, and similar data over target areas; target surveying 25%–50% of the known geothermal resource areas (KGRAs)
- Links between data and resource potential need to be defined
- Monitoring an area with remote sensing (temporal) after the area is developed to collect multi-temporal data
- Resource assessment should be based on analysis of multiple data sets
- Make data publically available as a baseline for geothermal prospects, including documentation of:
    - The accuracy and reliability of results through systematic sensitivity analysis
    - How data is converted to quantitative information (temperature, heat capacity) and translated into production capacity

Reliable Processing Methods

- Prove automated data processing for large area surveys

How Do We Get to Deployment End-State?

What are the benefits?

Multiple modern regional data sets over a data location; reduction of time to process data; greater usage of airborne data; defray costs of cutting edge exploration tools

What are the risks to success?

Low risk—could spend money acquiring airborne data over area that is not a potential site; however, the information would still be useful

Who benefits?

Companies, universities, and the National Geothermal Data System (NGDS)

Who are the participants/partners?

Service providers, universities, and non-governmental organizations

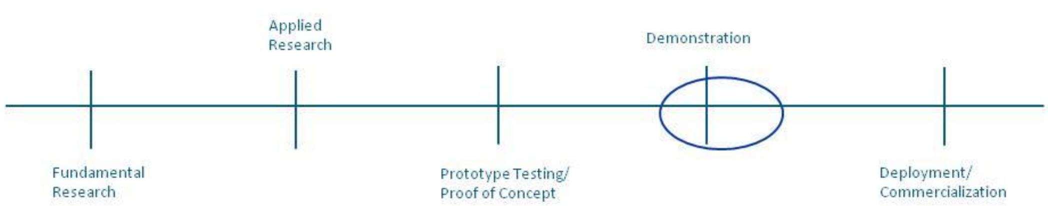
How soon can success be achieved

1–3 years

Comments?

The technology is developed, the challenges are implementing technology to geothermal exploration, automating the data processing, and bringing the technique from regional to local scale

Technology Readiness Level/Maturity



Geology 1: Stress/Strain Data Mapping

From What? – Current State

What is the state of knowledge or technology that needs to advance?

- Data is sparse in most areas
- Some areas lack well-exposed strain indicators
- Lack of detailed geologic mapping
- Lack of borehole data
- Need comparison of borehole data and local fault kinematics data
- Need quaternary fault studies

To What? – Definition of a Successful Advancement

Where does the knowledge or technology need to go? What achievements or outcomes would a funded project need to produce to be a worthwhile investment (i.e., what should the criteria be for the advancement/project)? What is a good measure of success?

Fill data gaps

- Identification of places in the United States that have data sets/logs large enough where subsurface stress regime can be determined
- Determination of the predictive value of the data for each location (What geological environments does surface data best predict subsurface attributes?)
- Integration of regional geodetic, local structural, and any borehole data; availability as part of national geothermal database
- Determination of changes in stress with depth
- Case studies of specific geothermal areas with known induced seismicity, borehole data, structure, and Quaternary fault study

Detailed district maps – maps should include:

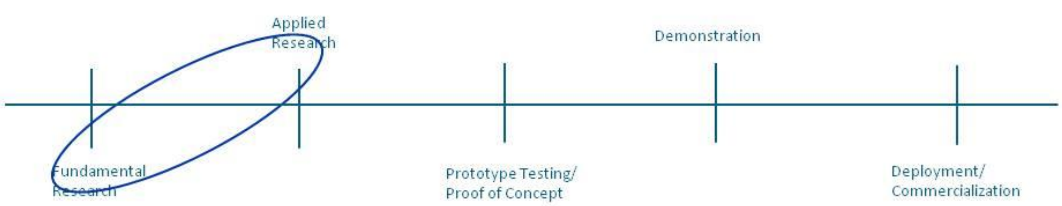
- Stress inversions and modeling
- Slip tendency analyses
- Induced seismicity estimates

Publication of district maps and slip tendency maps

How Do We Get to Deployment End-State?

What are the benefits?	*What are the risks to success?*
Application to case studies, improved targeting of permeability (statistically), and understanding of induced seismicity	Abnormal stress regimes and lack of borehole data
Who benefits? Regulators, operators, developers	*Who are the participants/partners?* Academia—need expert for surface work (e.g., UNR—surface stress and remote sensing); and USGS, DOE, industry—Chapel Hill and Terragen for large imaging data sets; also Cal Energy
How soon can success be achieved 1–3 years	*Comments?*

Technology Readiness Level/Maturity



Cross-Cutting 1: Multi-Disciplinary Conceptual Models

From What? – Current State

What is the state of knowledge or technology that needs to advance?

- Variable knowledge base across disciplines and explored locations
- Relatively complete data sets can be tested against production to understand the value of the data sets; however, there are few such data sets, including some that are very old and not up to professional standards, in which case software to process them has become outdated
- Lack of case studies and lack of synthesis, existing studies are of varying quality; no one has compiled all the data sets
- Paucity of publically available data, including failure case histories (data sets that did not work); some newer developments have little or limited public knowledge
- Chevron is the only large U.S. developer with a large technical base, but no longer has domestic fields
- Various methods are not being combined: seismic (active and MEA), electrical (airborne, surface, downhole), stress-strain (structural geological, geodesy, LIDAR), geology, (distributed temperature measurement [fiber optic]) borehole breakouts, borehole flow), and geochemical
- Knowledge needs to advance in all disciplines
- Educators are generally not familiar with conceptual geothermal reservoir properties that are objectives of the data integration
- Education curriculum does not include integration

To What? – Definition of a Successful Advancement

Where does the knowledge or technology need to go? What achievements or outcomes would a funded project need to produce to be a worthwhile investment (i.e., what should the criteria be for the advancement/project)? What is a good measure of success?

A unified model utilizing physical, chemical, and hydrological data with characteristics including:

- Development of more complete and comprehensive data sets and better integration across multiple disciplines/locations. Data sets should include subsurface temperature and permeability data, surface/airborne geophysical data acquired for 3-D subsurface imaging (e.g., seismic reflection, MT), geochemical data (e.g., isotope geochemistry) and geological data (e.g., surface geology, borehole temperature gradients, and well-logs)
- Survey 25%–50% of the known geothermal resource areas (KGRAs) with high resolution/multiple instrument techniques

Technical improvements should include:

- Better characterization of known systems and extrapolation to undeveloped areas to identify favorable settings with more certainty; use of geophysics for determining permeability
- Better definition of geothermal fingerprints using case studies

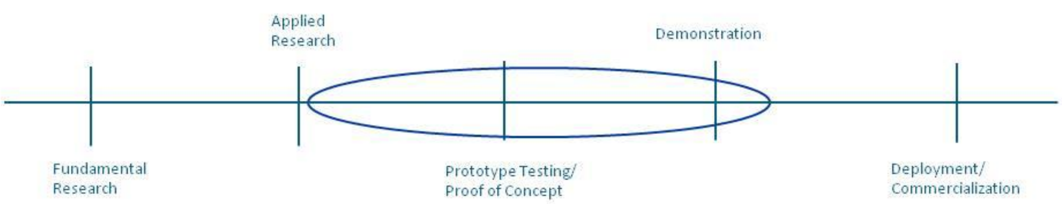
Some indicators of success/milestones

- Models, trials, and case studies, including greenfields, are published in open literature as well as failure case histories documented thoroughly
- Graduation of experienced multi-physics modelers educated in integration techniques

How Do We Get to Deployment End-state?

What are the benefits? Improved conceptual models leading to better exploration strategies, increased drilling, and exploration success	*What are the risks to success?* Uncooperative producers and a need to collect some additional data
Who benefits? Operators of participating projects, competitors, and industry	*Who are the participants/partners?* Geothermal developers need in-house experts, consultants or service companies with geothermal conceptual credentials; exploration companies; assistance from other researchers such as reservoir geologists
How soon can success be achieved 1–3 years	*Comments?* The focus here is on developing new understandings, not on new techniques or tools

Technology Readiness Level/Maturity



CROSS-CUTTING 2: 3-D MODELING TECHNIQUES (SOFTWARE)

FROM WHAT? – Current State

What is the state of knowledge or technology that needs to advance?

- 3-D software exists for imaging/mapping magnetotellurics (MT) data
- Multiple programs from a variety of vendors—each software has its pros and cons
- Academic 3D MT inversion algorithms exist but the code is not shared; many academic groups share a few 3-D MEQ inversion packages that are open source
- Typically vendors offer the 3-D surveys, modeling, and interpretation as a combined service; customized software for in-house use by developers is done mostly for the oil and gas industry where there is more funding
- Academic 3-D MT inversion algorithms exist (e.g., Newman at LBL, Sasaki, Siripunvarapom) but the code is not shared
- One very widely tested commercial (proprietary) 3-D MT inversion is available and widely used in geothermal settings (WesternGeco-Schlumberger)
- Chevron has licensed the Newman code for in-house use in geothermal
- MT has numerous success cases and well understood failures
- Ranging in cost from $3,000 (hiring another company to do the inversion)–$500,000 (acquiring in-house capabilities)
  - High cost reduces use of "proven" technology
  - Complex or "buggy" software limits easy adoption

TO WHAT? – Definition of a Successful Advancement

Where does the knowledge or technology need to go? What achievements or outcomes would a funded project need to produce to be a worthwhile investment (i.e., what should the criteria be for the advancement/project)? What is a good measure of success?

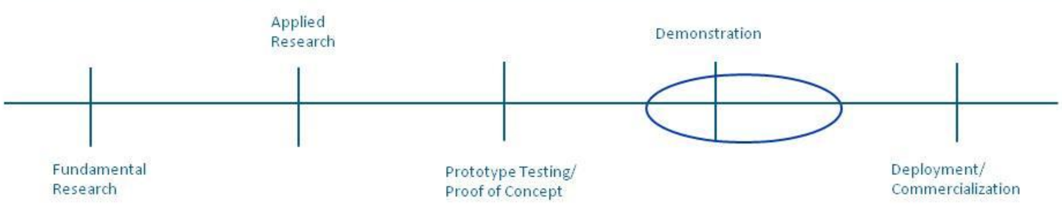
Open source 3-D MT code:

- Software advancements include:
  - Greater ability to integrate complete data sets, resulting in improved resolution
  - Use of a common platform, allowing for greater interoperability and easier exchange of information sharing
  - Simplification of data input with built-in quality checks
  - Improved graphics
- Indicator(s) of Success:
  - Reduced software costs
  - Increased availability (to gain wider use and competition)

HOW DO WE GET TO DEPLOYMENT END-STATE?

What are the benefits? Software that interprets integrated data sets leads to increased 3-D mapping resolution and an improved understanding of conceptual models (ultimately resulting in reduced drilling costs)	*What are the risks to success?* Few, including a lack of widespread adoption
Who benefits? Drives industry to provide more functionality, and developers and explorations have better and more affordable tools	*Who are the participants/partners?* Software development/sales working with industry to develop geothermal-specific 3-D modeling packages.
How soon can success be achieved In one year the technology will exist, but it will be expensive for individual companies	*Comments?* Could work with Google Earth and SketchUp to expand to geological/geophysical display

TECHNOLOGY READINESS LEVEL/MATURITY



FROM WHAT? – Current State

What is the state of knowledge or technology that needs to advance?

- Currently there is no world atlas of geothermal occurrences
- There is no classification scheme that systematically links characteristics of the subsurface reservoir to measurements made at the surface across each geothermal setting.
- Case studies, information on the habitats, and meso-scale tectonic settings of geothermal systems and occurrence trends are insufficient
- Need better data and imaging paradigms for geothermal fluids
- The extensive body of oil, gas, and mining industry knowledge as well as federal agency tools such as the National Science Foundations' Earth Scope, NASA's airborne science surveys (e.g., InSar, Hyperspec, and LIDAR), and USGS surveys and maps, could be used more effectively

TO WHAT? – Definition of a Successful Advancement

Where does the knowledge or technology need to go? What achievements or outcomes would a funded project need to produce to be a worthwhile investment (i.e., what should the criteria be for the advancement/project)? What is a good measure of success?

Major components of case study analysis include:

- Identification and documentation of well-characterized geothermal systems for each setting that can be used as case studies
- Use of multidisciplinary data sets leads to "group shoot," testing/verification of conceptual models of case studies
- Development of conceptual models (using integrated data) for case studies
- Development of classification scheme using identified key attributes/parameters required for a productive (commercial) geothermal system at a given setting. For settings, use the USGS classification system (not yet published) or other appropriate methods (volcanic or extensional mixed)
- Development of a conceptual model for each setting

HOW DO WE GET TO DEPLOYMENT END-STATE?

What are the benefits?
Streamlines explorations by highlighting key attributes and data needed in each setting

What are the risks to success?
Insufficient data; systems not readily classified by an existing work-flow process do not characterize into geothermal reservoir systems well enough to be exploiting commercially

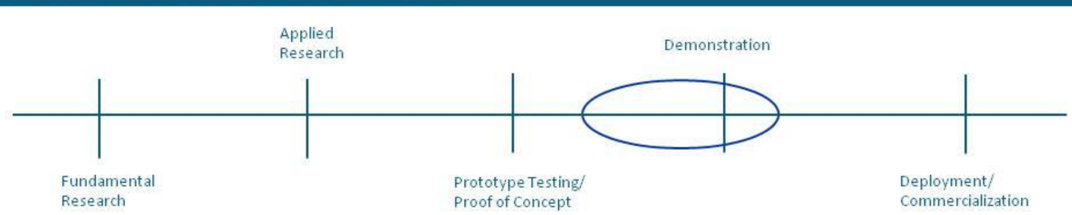
Who benefits?
Companies, data to/from the NGDS, researchers (university and national laboratories)

Who are the participants/partners?
NGDS, companies, universities, laboratories, service providers, and international partners

How soon can success be achieved
3–5 years

Comments?
The classification scheme is a critical initial step

TECHNOLOGY READINESS LEVEL/MATURITY



Cross-Cutting 4: Identification of Potential Surface Signals that Identify Deeper, Hidden Systems

From What? – Current State

What is the state of knowledge or technology that needs to advance?

- USGS estimates 30,000 MW of deep hidden geothermal resources in United States
- Hidden systems are defined as either hydrothermal systems with no conventional characteristic surface manifestations (e.g., thermal springs, fumaroles, secondary mineralization, volcanic activity, etc.) or hydrothermal systems for which information regarding deep high temperature water-rock equilibration in surface features has been masked by near surface processes (e.g., re-equilibration at lower temperatures in secondary reservoirs, mixing with cooler water, degassing and phase separation, etc.)
- Industry does not know what other surface attributes signify hydrothermal resources at depth and does not know how to identify these other signals, or if they exist
- Conventional application of traditional exploration techniques inadequate

To What? – Definition of a Successful Advancement

Where does the knowledge or technology need to go? What achievements or outcomes would a funded project need to produce to be a worthwhile investment (i.e., what should the criteria be for the advancement/project)? What is a good measure of success?

Identification and evaluation of new surface signal(s) of deep hydrothermal systems

- Coupling of surface signals to surface structural features
- Combine geology, geomorphology and geophysics (e.g., high resolution MT, gravity) to guide the search for new surface geochemical signals
- Investigate the use of shallow thermal gradient holes as potential sample collection points for identifying sub-surface systems
- Improved geothermometry techniques that can pick up hidden thermal attributes

Development and validation of new tool(s) to analyze and interpret new surface signal(s)

How Do We Get to Deployment End-State?

What are the benefits?
New ways to identify hidden systems

What are the risks to success?
Inability to identify new system or new ways of identifying systems because they are truly hidden, e.g., due to no permeability from system all the way to the surface. Hidden systems may be prohibitive to look for.

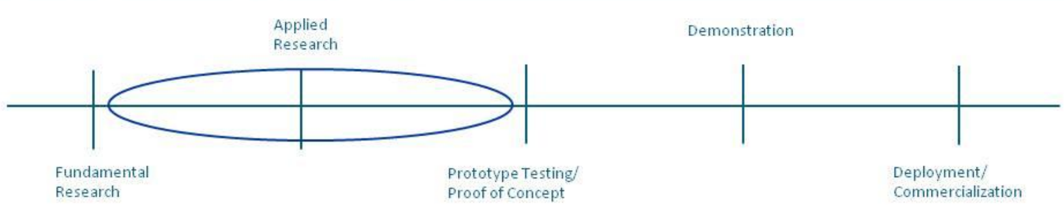
Who benefits?
Geothermal developers/owners, geophysical service companies, and drillers

Who are the participants/partners?
Geochemistry, geological and geophysical service companies; geothermal consultancies; developers; national laboratories; government agencies (e.g., USGS)

How soon can success be achieved
New ways to identify hidden systems: 3 – 5 years
New technology development: >5 years

Comments?

Technology Readiness Level/Maturity



Appendix B: Workshop Participants

Name	Organization/Company
Chad Augustine	NREL
Dick Benoit	Magma
Steve Bjornstad	U.S. Navy
Wendy Calvin	UNR/GBCGE
John Casteel	NGP
Pat Dobson	LBL
Jim Faulds	UNR/GBCGE
Catherine Fahey	DOE
Ted Fisla	GPO
Sarah Francis	DOE/New West Technologies
Mike Hillesheim	NREL
Joe Iovenitti	Alta Rock
Mack Kennedy	LBL
Kerry Klein	DOE/New West Technologies
Brian Koenig	NGP
John Louie	UNR/NSL
Brigette Martini	Ormat
Rob Mellors	LLNL
Kim Niggemann	NGP
Tim Reinhardt	DOE
Joel Renner	Consultant
Andy Sabin	Navy
Gene Suemnicht	Environmental Geothermal Services
Hidda Thorsteinsson	DOE
Charles Visser	NREL
Albert Waibel	Newberry Geothermal Holdings, LLC
Ken Williamson	Consultant
Chris Clark	Energetics Incorporated
Chris Kelley	Energetics Incorporated
Amanda I Greene	Energetics Incorporated
Samantha Solomon	Energetics Incorporated

Appendix C: Workshop Results

Key Technical Challenges

Geochemistry

- Refine and test geothermometers, gases, liquids, isotopes, trace elements, and inconsistent lab results ●●●●● (5)
- Better tools–lower cost, higher temperature, smaller for slim holes (0)

Remote Sensing

- Demonstrate the feasibility at large scale ●●● (3)
- High, low-cost resolution strain maps ●(1)
- Area to be surveyed is vast and data sets can be large—need new tools for automated regional reconnaissance data analysis and processing; lack of experience in wide-area reconnaissance tools for sparse-data areas ●(1)

Geology

- Tectonic context; structure setting and detail strain and stress inversion; define permeability at depth at fracture scale ●●●●●(5)
- Availability of sufficient geologic maps for exploration ●●● (3)
- Lack of understanding of regional active structures ●(1)
- Age dating hot spring deposits (0)
- No way to tell if hot feed is below thermal anomalies (0)

Geophysics

- Permeability at depth without drilling with geophysics, geochemistry, and geology ●●●●●●●●●●● (11)
- Lack of ability to image fluids and flows ●●● (3)
- Non-uniqueness of geophysical inversions ●● (2)
- Lack physics-based anomalies that can be targeted by geophysics (in the reservoir) ●● (2)
- Remotely predicting temperature at depth ● (1)
- “Detailed” (to be defined) heat flow map (0)
- Couple magnetotelluric/resistivity anomalies with other technologies (isotope to get reliable indicator of geological resource from surface to air (0)

Cross-cutting

- Big picture—evaluating combinations of technologies in addition to each individually ●●●●●●●(7)
- Lack of occurrence models ●●●●●(5)
- Lack of affordable tools to integrate 3-D and multiple data sets ●●●● (4)
- Need to link subsurface reservoir to surface measurements ●●● (3)
- Need to explore new locations ●● (2)
- Availability of existing data ●● (2)
- Use other federal agency tools—collaborative partner, NSF Earth Scope, NASA airborne science surveys (InSar, Hyperspec, LIDAR, etc.), USGS survey and map (0)

● Each orange dot represents one vote as a high priority/critical technical barrier

Non-Technical Barriers

Permitting	Externalities
• Lack of geothermal knowledge on permitting/leasing side • Double standards for oil and gas versus geothermal permitting	• Electricity rates • Public perception of drilling funds as potential "corporate welfare" • Growing the scientist base • Sufficient quantity of quality investigators available in a reasonable time frame

Money/Funding	Knowledge Sharing/Data	Policy
• Under-funded companies interested in innovations • Costs of cutting edge technology is high—limits broad utilization • Exploration drilling costs • Lack of capital and mechanisms to conduct high-risk reconnaissance (e.g., cooperative strategraphic test costs) • Competition with oil, gas, and mining for services (more industry partnerships—we need a champion)	• Lack of documentation of success and failure • Shared database of resources • Lack of a comprehensive database available to all companies • Intellectual property/data sharing issues (i.e., balancing between data sharing and developers potentially wanting to hold data for leasing purposes) • No participation from major geothermal companies—need to attract risk-tolerant equity funded • Context conceptual models • Identifying new geothermal provinces or trends in sparse data areas • Data integration (affordable tools are needed) • Regional data collection, especially in areas outside those proven	• ARRA funds—the strings attached are so onerous it may not be worthwhile for National Environmental Policy Act, Davis Bacon Act, and permitting • Need a long-term phased program and science-based effort • Sustained effort from DOE • Get the supporting government entities on same page • Lack of focus in DOE program • Lack of geothermal experience in DOE • Unrealistic time frames in TSX • DOE money supporting the small companies • Federal lands, regulatory constraints, and conflicting interests on public land use

Technology Needs

Geophysics

- Better multi-physics models to improve/extend use of geophysical data to identify subsurface permeability ●●●●●●●●●●●●●● (14) *
  - Program: define geothermal signatures in different tectonic settings
  - Develop a research program to identify geophysical detectable features in geothermal reservoirs
  - Subsurface imaging: look outside of geothermal to physics arena, issue technical challenge/contest
- Improve next-generation geophysical airborne data ● (1) *
- Technology advancement: seismic reflection data in volcanic strata ● (1)
- Higher temperature and/or [new] bore-hole tools (0)

Geochemistry

- Improved thermodynamic and kinetic data for fluids and minerals needed to develop the next generation of geothermometers ●●●●●● (6) *
- Accurately defining geothermometery as it applies to variable lithologic regimes using lab and field experiments ●● (2) *
  - Geothermometers that clearly identify geochemical temperature and new geothermometers, if they exist
- Basic research on fluid chemistry from known geothermal systems using modeling packages and to find new geothermometers (0)

Remote Sensing

- Acquire high-resolution remote sensing data sets (multiple methods) in new regions over large areas ●●● (3) *
  - Establish reliable automated processing ● (1)
  - Create affordable software for subsurface data set model integration (0)

Geology

- Stress/strain data mapping—improve tectonic stress/strain data then correlate to thermal data ●●● (3) *
  - Stress/strain maps to predict fractures (solve permeability)
- Develop a reliable "crack finder" (0)
- "Geothermal Wikipedia," tree based on effectiveness of various techniques in various geological settings (0)

Cross-cutting

- Create case study examples of geothermal systems in different settings to identify key attributes that can be used in exploration ●●●●●●●●●●●●●● (14) *
  - DOE supports a few "group shoots"—multi-company, multi-disciplinary, all data published → combinations of technologies
  - Case studies to establish occurrence models
- Multi-disciplinary conceptual models—improved conceptual model to understand the subsurface so fewer slim holes are needed, reducing cost ●●●●●●●●●●● (11) *
  - Projects—model fluid flow in fractured crust
  - Permeability—continuous model that connects geophysical hydro-geological and geological data that maps permeable paths to subsurface
- 3-D modeling techniques—software ●● (2)*
  - Improve and create easier to use data integration tools/software for model development
- Combined studies of the correlation between geochemistry and thermal studies at specific locations ●● (2)
  - Coupled data—coupling diverse data sets through common physical and chemical overlapping laws
- Lack of adequate workforce ●● (2)
- District mapping programs ● (1)
- Improved data inversion codes especially of multiple data sets ● (1)
  - Apply stochastic/Monte Carlo inversion to match cross-disciplinary datasets—range of possible models
- Develop regional geothermal centers ● (1)
- Projects—publish syntheses of results from previous DOE USGS programs, regional versus small scale (0)
  - Aggregated database of proprETary data
- Program to define geothermal signatures in different tectonic settings (0)

● Each orange dot represents one vote as a high priority technology solution

*Green star means that the advancement was developed into a worksheet

Appendix D: Geothermal Technologies Program Performance Metrics

Preliminary Targets for Hydrothermal Performance Metrics

Metric	Unit of Measurement	2011 Status	2020 Target
Exploration cost per Site	Dollars ($)	Developing baseline	TBD
New sites discovered	Number of sites	Developing baseline	TBD
Levelized costs of hydrothermal electricity	cents/kWh	9-12 cents	6 cents

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