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HYDROTHERMAL EXPLORATION BEST PRACTICES AND GEOTHERMAL KNOWLEDGE EXCHANGE ON OPENEI

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ABSTRACT

Though exploring for hydrothermal resources is not new, advances in exploration technologies and the pursuit of less visible resources have created a need to outline exploration best practices. This multi-year study outlines 21 geothermal exploration regions in the Western United States. These regions were developed based on the U.S. Geological Survey (USGS) physiographic regions, then adjusted to fit geothermal parameters such as differences in geologic regime, structure, heat source, surface effects (weather, vegetation patterns, groundwater flow), and other relevant factors. Literature searches were conducted in each of these 21 regions for the application of field reconnaissance, geochemical, geophysical and remote sensing techniques. At this time, data from more than 250 references have been cataloged in U.S. Department of Energy's (DOE) Open Energy Information (OpenEI, http://en.openei.org) website, which allows industry to access data information and run analyses on specific data attributes. The platform also allows updates, edits, and additions from the public so that the dataset can be expanded as industry's knowledge grows. In addition to the literature survey, interviews were conducted with exploration experts with both geothermal and oil-and-gas industry experience to identify the exploration challenges and best practices for the exploration regions. This paper defines and describes the geothermal regions developed for this study, describes how exploration techniques contribute to hydrothermal analyses (structural, petrologic, temperature, and hydrologic), and defines the exploration hurdles and best practices for each region. The results of the study and accompanying data sets on OpenEI will be available through the National Geothermal Data System.

INTRODUCTION

Exploration is often the most risky and one of the most difficult steps for which to obtain funding in geothermal development. One focus of the DOE Geothermal Technologies Program (GTP) is advancing exploration technologies to decrease this upfront risk for geothermal developers. Exploring for hydrothermal resources is not new; however, advances in technologies and the pursuit of less visible resources have created a need to outline exploration best practices that could help guide future exploration efforts and inform the development of innovative exploration technologies to identify undiscovered hydrothermal systems.

The GTP funded a study to survey available literature and industry experts to collect best practices in exploration techniques. The multi-year study, conducted by the National Renewable Energy Laboratory (NREL), outlines 21 geothermal exploration regions in the western United States. These regions were developed by NREL based on the USGS physiographic regions and adjusted to fit hydrothermal data and the 2008 USGS Resource assessment of undiscovered hydrothermal potential in the U.S. Data on exploration techniques were collected by conducting a literature survey and cataloging the application of field reconnaissance, geochemical, geophysical, and remote sensing techniques used by region from over 250 documents. In addition, interviews were conducted with exploration experts with both geothermal and oil-and-gas industry experience to identify the exploration challenges and best practices for each exploration region. The data collected in this study are not presumed to be complete—it is expected that many others in industry with experience in exploration can contribute additional data and insight on exploration best practices. The information collected in this study forms the basis for a knowledge database upon which industry can expand. A queryable, publicly accessible, and publicly updatable database was developed in OpenEI to catalog and share this information and help provide exploration guidance within specific geologic contexts.

This paper defines and describes the geothermal regions developed for this study, identifies and explains current exploration techniques, describes how each exploration technique contributes to hydrothermal analyses (structural, petrologic, temperature and hydrologic), and lists some of the exploration hurdles and best practices for each region. The results of the study and accompanying data sets on OpenEI will be available through the National Geothermal Data System. The data collected from this study forms the basis for the knowledge database upon which industry can expand.

OPENEI

The data and information collected in this study are provided to the public via OpenEI (http://en.openei.org). Open Energy Information (OpenEI) is a collaborative knowledge-sharing platform with free and open access to energy-related data, models, tools, and information, which is sponsored by the U.S. Department of Energy and has been developed by the National Renewable Energy Laboratory in support of the White House's Open Government Initiative. Here, we describe OpenEI and how the geothermal information and data are organized and accessed in it.

The OpenEI platform is a wiki and uses the same underlying technology as Wikipedia, which many users are already familiar with. The wiki enables users to view, edit, add and download, data – all for free. This allows the exploration dataset to be expanded as industry's knowledge grows. OpenEI has been developed as a semantic wiki, which allows the assignment of queriable properties to pages within the wiki so that relationships between pages are automatically created and data can be queried and exported, similar to a database, in universal formats such as RDF and CSV. Data that have been assigned as properties can also be used in semantic searches, for aggregation of pages or in-page analyses. Searchable data can be displayed in a variety of formats including maps, charts, graphs, and timelines. Structuring the data semantically in the wiki enables greater access to the data, often addressing questions that would otherwise be difficult to answer with a conventional database.

Data quality is key to the success of OpenEI, and every effort is made to ensure that only validated data with referenced sources are included in the platform. The user community can help expand the data and increase accuracy (OpenEI). All updates are tracked in the "History" portion of each page listing the contributor and contributor's notes. All previous versions of the page are saved and accessible, so that changes can be rolled back, if necessary. Wiki pages also allow for users to hold subject matter discussions and discuss improvements to page content. Discussions are saved and accessible by all users via the "Discussion" button located on each page. These features strengthen the wiki platform as a medium for data and information sharing. Users can also "watch" a page and receive notifications of any updates to that page.

Geothermal Location Information in OpenEI

During the literature search, the applications of exploration techniques are described in OpenEI as "activities," recording the location, technique, and reference or source of the information. This allows techniques to be queried by location (i.e., What techniques have been applied at a given location?) and locations to be queried by technique (i.e., At what locations has a given technique been applied?).

In OpenEI, locations are semantically linked. For example, a city (Denver) is located in a state (Colorado) inside a country (USA), so that specifying in OpenEI that a certain restaurant is located in Denver automatically labels it as also being in Colorado and in the USA. This allows the restaurant to be listed when a query of all restaurants in Colorado is performed.

The same concept is applied for geothermal locations. In the geothermal scenario, "energy generation facilities" and "development projects" (e.g., Blundell I Power Plant) are located in "geothermal areas" (e.g., Roosevelt Hot Springs Geothermal Area), which are part of larger "geothermal regions" (Northern Basin and Range Region), so that location queries can be done at the area and region level. Explanations of these location breakdowns are given below.

Geothermal Regions

Geothermal regions were outlined for the western United States (including Alaska and Hawaii) to identify geothermal areas, projects, and exploration trends for each region. These regions were developed based on the USGS physiographic regions (U.S. Geological Survey), and then adjusted to fit geothermal exploration parameters such as differences in geologic regime, structure, heat source,

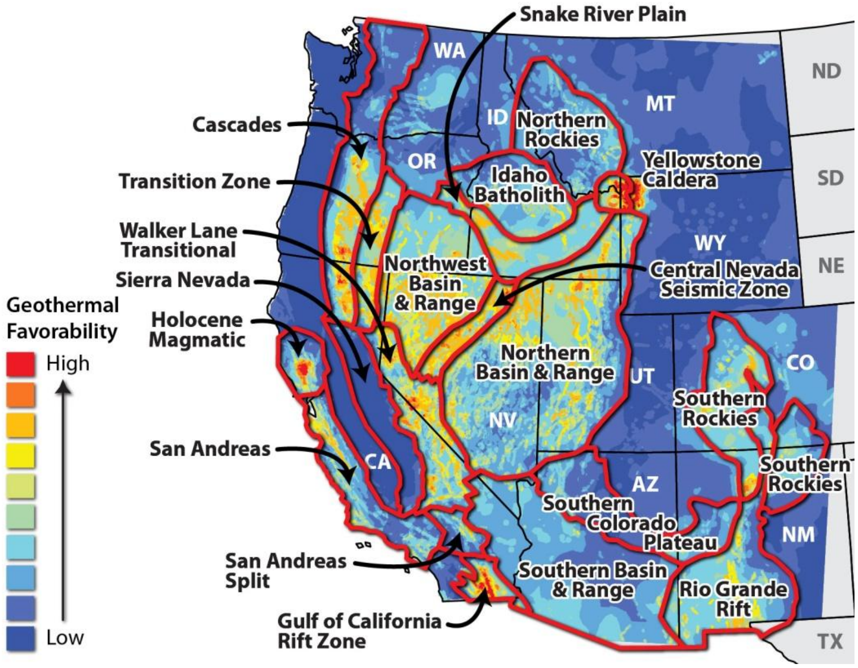

***Figure 1: Geothermal Regions** – The base map for this figure is the 2008 USGS Geothermal Favorability Map showing relative favorability for the presence of geothermal systenms in the western United States. It is an average of 12 models that correlates different geological and geophysical factors of moderate (90-150°C) to high (>150°C) temperature geothermal systems. Exploration regions outlined in red were derived for this study from USGS physiographic regions of the contiguous states. Data source: United States Geological Survey.*

***Table 1: Geothermal Region Properties –** Tabulated data for each of the 21 geothermal regions. Data sources for each column is listed in the table*

	Exploration Region	Region Size	Installed Capacity (GEA website)		Planned Capacity (GEA, 2011)			Resource Estimate (USGS, 2008)	
			Installed Capacity	# of Plants Installed	Planned Capacity	# of Planned Plants with capacity estimate	# of Planned Plants with Unknown Capacity Estimates	Identified Capacity	Un-discovered Capacity
		km²	*MWe*	---	*MWe*	---	---	*MWe*	*MWe*
1	BR: Central Nevada Seismic Zone	28,863	97	3	100	2	15	378	744
2	BR: Northern Basin & Range	327,187	68.8	5	134	6	18	358	3,741
3	BR: NW Basin & Range	137,091	214.36	9	161	6	9	1,044	2,238
4	BR: Southern Basin & Range	217,012	0	0	100	2	2	9	830
5	BR: Walker-Lane Transition Zone	81,265	431.1	16	244	7	9	763	1,130
6	Cascades	124,543	0.28	1	30	1	2	608	1,057
7	Gulf of California Rift Zone	20,044	658	21	388.6	8	0	3,147	8,790
8	Holocene Magmatic	25,977	1,587	19	26	1	3	1,128	316
9	Idaho Batholith	72,883	0	0	49	2	2	218	500
10	Northern Rockies	101,604	0	0	0	0	0	71	415
11	Rio Grande Rift	130,309	0.24	1	15	1	1	227	1,137
12	San Andreas	69,192	0	0	0	0	0	17	480
13	San Andreas Split	18,246	0	0	0	0	0	7	101
14	Sierra Nevada	58,554	0	0	0	0	0	0	26
15	Snake River Plain	61,320	0	0	0	0	1	130	778
16	Southern Colorado Plateau	92,142	0	0	0	0	0	0	274
17	Transition Zone	40,705	0	0	0	0	2	53	693
18	Yellowstone Caldera	11,842	0	0	0	0	0	44	210
19	Southern Rocky Mountains	128,454	0	0	0	0	0	0	1,010
20	Alaska	1,717,854	0.73	1	25	3	1	677	1,788
21	Hawaii	28,311	35	1	0	0	1	181	2,435
	Other (outside region boundaries)	---	0.25	1	---	---	---	0	1,341
	Table Totals	**3,493,398**	**3,093**	**78**	**1,273**	**39**	**66**	**9,060**	**30,033**

surface effects (weather, vegetation patterns, groundwater flow), and other relevant factors. The 21 regions can be seen outlined in red and overlain on the 2008 USGS Geothermal Favorability Map in Figure 1 (Williams *et al.*, 2008).Statistics for these regions are shown in *Table 1*, including the size of each region, installed and planned capacity estimates, and USGS estimates for mean identified and mean undiscovered potential capacity. These data, along with additional information about each region such as region descriptions, best practices, and linked data and references, can be found on the OpenEI website.

Geothermal Areas

For this study, and in OpenEI, geothermal areas are specific locations of geothermal potential (e.g., Coso Geothermal Area). The base set of geothermal areas used in the database came from the 253 geothermal areas identified by the USGS in their 2008 Resource Assessment (Williams *et al.*, 2008). Additional geothermal areas were added, as needed, based on the literature search and on projects listed in the GTP's database of funded projects. Note that OpenEI users can easily add additional areas in the future, as needed.

For areas with operational geothermal energy generation facilities, background information on the area is provided in OpenEI including an area overview, details on the geology and hydrothermal system, and history and infrastructure. Additionally, technical problems and solutions, regulatory and environmental issues, and future plans are provided when the information was available. Detailed properties such as coordinates, geothermal region, development phase, USGS resource estimate data, power production profile data, and well field information data are provided for each area. Sources for each of the data are required input and displayed in each area's data table. Queries of power plants, development projects, and exploration techniques applied to the area are also provided.

Energy Generation Facilities

Energy Generation Facilities are listed on OpenEI for all renewable energy generation facilities in the United States. Specific geothermal properties were created for all geothermal energy generation facilities to allow for data input and queries (e.g. Geothermal Area in which the plant is located, average well depth, and average temperature of geofluid into the plant). Not all information and data in OpenEI have been populated; to expand this reference tool, additional data could be added either directly by the geothermal industry or through additional industry surveys.

Geothermal Projects

Geothermal Development Projects are listed in OpenEI, by geothermal area and region. The projects and associated data properties were adapted from the Geothermal Energy Association's (GEA) 2011 U.S. Geothermal Power Production and Development Update (Jennejohn, 2011). Properties include location (county, geothermal area, geothermal region), developer, project type, development phase, and capacity estimate.

Organization of Exploration Techniques and Activities in OpenEI

Exploration Techniques

Because the information in this study was destined for a database, a structure was needed to categorize exploration techniques. Therefore, exploration techniques and best practices were categorized into exploration groups, such as general exploration, field reconnaissance, geochemistry, geophysics, and remote sensing.

In addition, four different types of exploration analyses were identified: lithology, stratigraphic/ structural, hydrological, and thermal. Each technique can be described in terms of the data it could provides for each type of analysis. A few examples are given in Table 2. See the data on OpenEI for a full listing of exploration techniques and the data that could be provided for each analysis.

In OpenEI, each listed exploration technique is assigned a set of properties, including the exploration group to which it belongs, the analysis information it could provide, and technique cost data. Queries are also provided for each technique indicating the activities, areas and regions in which the technique was applied. As with all OpenEI data, these properties are populated with known available data.

Table 2: *Example descriptions of exploration techniques and their application to exploration analyses.*

Technique	Exploration Analysis			
	Lithology	Stratigraphic /structural	Hydrological	Thermal
Field Mapping	Map surface geology	Map fault and fracture patterns, kinematic information	Map surface manifestations of geothermal systems	Map surface temperature
Trace Element Sampling			Map permeable structures connected to geothermal reservoir	
Geo-thermo-metry				Estimate temperature of hydrothermal reservoir

Additional exploration techniques and associated data can be added in the future, either directly by the geothermal industry, or from additional industry surveys.

Exploration Activities

In OpenEI, a unique exploration activity is defined by describing the use of an exploration technique at a geothermal area as described by a specific reference. For example: "2-M Probe at Alum Geothermal Area (Kratt *et al*., 2010)." Additional properties for exploration activities for which users can provide data include details about DOE-funding for the activity (if applicable), usefulness of the activity, and any additional notes. Over 1,300 activities are currently cataloged in the database from the literature survey. It is noted, however, that exploration activities are rarely documented in conference or journal articles, so this is a small sampling of exploration activities that have occurred in the United States. This is an area where it is hoped that industry might provide additional information to populate this dataset.

EXPLORATION BEST PRACTICE INSIGHTS FROM INDUSTRY

Exploration interviews were conducted with industry experts including developers, consultants, national laboratory and university personnel. About 75% of experts initially contacted provided feedback. Still, this represents less than a dozen independent inputs. Interviews were conducted via phone and in person from a prepared list of interview questions and with follow up questions in subsequent phone calls. Additional information, beyond the questions asked, was often provided by the interviewee.

In conducting these interviews and synthesizing information, we encountered different perspectives and approaches to applying exploration techniques. Comments presented here are sometimes internally inconsistent. We realize that many others in industry have valuable exploration experience and may have much to contribute to these discussions. These efforts are a first effort to open the dialog on exploration best practices; these interviews helped to develop the framework in OpenEI for all to contribute to the body of knowledge.

The recommended best practices received from these interviews are too numerous to report in full in this paper. Selected information from industry interviews is presented here, for five of the exploration groups. For additional information on best practices and for detailed best practices for specific techniques, see the OpenEI website (http://en.openei.org).

Information from published documents was used to supplement interview information. Unless otherwise noted, the source of all information presented in this section is aggregated industry interviews.

General Exploration

Most experts interviewed commented that the most effective exploration tools are a well-trained geologist and a well-constrained conceptual model that explains not only what a hydrothermal resource looks like or where it occurs, but *why* it occurs. For example, resistivity and temperature gradient information are isolated datasets and provide little project insight without understanding the geological context of those data in that geothermal setting.

Conceptual Models

A conceptual model is a diagram which shows of a set of logical and quantitative relationships between factors that are believed to impact or lead to a target condition.

Insights from industry:
A well-constrained conceptual model can help guide decisions when designing an exploration plan and aid in interpreting the results of the collected data. To develop an effective geothermal conceptual model, it is important to integrate all gathered information (e.g., geochemistry, geophysics, hydrological, structural, and petrological) into a consistent model to answer questions like: Does a reservoir exist? If it exists, how big is it? Is the reservoir sufficiently permeable? What are the controls on permeability? What is the probability of development and expected value? What is the lowest cost drilling strategy to discover, prove, and develop the resource? A fully developed conceptual model will illustrate reservoir fluid and rock properties that affect production performance, such as temperature, permeability, volume, pressure, porosity, and chemistry (Cumming, 2011).

When only one conceptual model is developed, there is sometimes a tendency to interpret data to fit that model. Therefore, it is important to develop multiple possible conceptual models that are consistent with all data, so that, as additional data are collected, the model(s) can be adjusted based on the new information. The exploration plan may still target the elements of the most likely model, but probabilities should be estimated for all models to consider the risks being taken for each.

Value of Information Analysis

A value-of-information analysis (VOIA) is a probabilistic decision analysis that provides a measure of the expected cost, benefit and net value of proposed exploration techniques, which can then be used to set priorities in exploration plans.

Insights from industry:
VOIAs, which have commonly been used by the oil and gas industry, have seldom been applied to geothermal exploration methods due to constraints of time, budget and supporting information. An ideal VOIA considers not only the immediate financial cost of techniques, but also the potential value lost by diverting staff attention and delaying a project. A simple decision matrix can illustrate the relative risk-weighted value that would be added by alternative surveys in a realistic context. The analysis can also help a project decide between two techniques when budgets are limited by estimating the incremental cost and benefit of the alternative data. Such an approach will be better informed if it is also applied to project look-back studies. An effective VOIA does not just assess the value of a method given its uncertainty in a particular decision context, it indicates how the method can be made more effective, for example, by investing more in the method earlier in the decision process (Cumming, 2011).

Blind Systems

The term "blind system" has been used in the geothermal industry to discuss areas with geothermal potential that have little to no obvious surface expression. In an effort to guide exploration to identify some of the USGS-estimated 30 GW of undiscovered potential in the western United States, experts were asked their thoughts on exploring for blind systems, though other best practices in this report may apply to blind systems, as well.

Insights from industry:
Because hot water is buoyant, permeable hot reservoirs are very likely to have surface or near-surface (at least as shallow as the water table) manifestations. Even in areas with a perfect cap rock that prevents convection of hot water to the surface, geothermal systems will still be an anomalous thermal disturbance because of higher conducive heat loss. The conceptual model for a blind system must have geology consistent with being hidden, such as a more effective clay cap than is found at most developed reservoirs together with a deeper water table. Exploration techniques would then be chosen that are best suited to identify and delineate such a system.

Resistivity surveys can be used to image the geometry and hydrothermal alteration content of a clay cap. It can also indirectly image the depth to the water table and, if the aquifer is hot, the reservoir. The magnetotelluric (MT) method is the most common resistivity imaging technique used for exploring geothermal reservoirs deeper than 500 m, which likely includes most hidden systems. Although MT can detect resistivity to great depth, the resolution of all resistivity methods degrades with depth more rapidly than reflection seismic methods. Therefore, reflection is often chosen over resistivity methods, but there have been relatively few successful case histories validated by rock physics measurements. Pattern drilling is another alternative. Mining and oil and gas companies such as Phillips, Amax, Oxy, and Unocal have applied this technique in the Basin and Range and Salton Trough regions. Depending on the hydrology and cap geometry, a pattern of wells are drilled from 100 to 2000 ft, with a 500 ft depth probably the most common because of the the regulatory limit on drilling without a blow-out preventer on the rig (at 150 m, 300°F maximum temperature). This method can be effective in defining resources in the Basin and Range Region, even where they are much deeper than 500 ft, providing that the results are interpreted in the context of a realistic range of thermodynamically consistent conceptual models.

Reporting Failure

Reports of failed applications of exploration techniques and lessons learned in geothermal exploration are not common in the geothermal industry.

Insights from industry:
Companies have little incentive to report exploration difficulties and researchers tend to take a positive view of almost all outcomes, so surveys that are failures in the application of an exploration technique are seldom reported within that context. Why a technique failed is equally important; why other exploration programs have been mislead in applying effective techniques is important both in developing better interpretations of data and in developing reasonable conceptual models.

This tendency to under-report failure can be misleading when assessing strategies for applying or improving technologies. Accurately reported outcomes significantly decreases the uncertainty of a resource decision analysis, which greatly benefits from supplemental knowledge of correct and false positive, and correct and false negative results. Reporting this information can help develop more effective, less expensive exploration methods and projects.

An example of a published negative case history is a 2010 report on seismic reflection data collected at the

Blue Mountain Geothermal Area and the Pumpernickel Prospect in Nevada (Melosh *et al.*, 2010). The paper was not strictly negative since it included lessons learned in one problematic survey and more promising results from a different survey. When the paper was presented, however, questions were directed at the relevance of the failure to any other case. The paper had been motivated by knowledge of similar failures at unrelated projects but, because only one case was made available for publication, a wider application to improvements in seismic reflection surveys could not be demonstrated.

Field Reconnaissance

Field reconnaissance includes exploration activities such as mapping and field sampling of rock types, hydrothermal alteration features, faults, fractures, and any other observable geologic feature. Many best practices in field reconnaissance have been documented in sample collection standards (e.g., http://www.astm.org/Standard/index.shtml)

Insights from industry:
Suggestions were made by experts interviewed to spend more time in the field developing detailed geologic maps. Oil and gas companies typically spend more time than geothermal companies mapping prospective locations, and it has helped to explain why individual projects have succeeded and failed. Even for currently operating geothermal systems, often there is not a solid understanding of the underlying geology.

Reiterating a previous point, a well-trained geologist is important to developing geologic maps. Although modern computer processing and mapping software have promoted the ubiquitous generation of maps, the can also result in the erroneous use of automated contouring of non-uniform data point distributions (Klein, 2007).

Geochemistry Techniques

Insights from industry:
Some experts stated that the factor that changes the risk assessment of a prospect the fastest is obtaining attractive chemical confirmation (geothermometry, gas analyses) that a prospect exists in that location. In the United States, geochemical analyses have been performed and cataloged for most places that have accessible surface waters (e.g. USGS GEOTHERM geochemistry database, UNR's geochemistry database for the Great Basin). As the resource areas with the most easily interpreted chemistry are developed, the uncertainty in the interpretation of the data from the surface manifestations of the remaining prospects becomes a greater challenge. For hidden systems, a strategy is needed to get a suitable water sample at low enough cost from a slim hole, a water well or a core hole drilled for mineral exploration. As in all geothermal exploration methods for both hidden and conventional systems, geochemistry interpretations are more reliable when integrated in a conceptual model consistent with other data.

In some areas, such as the Cascades Region, it has been suggested that high rainfall masks shallow expression of geothermal features. However, many areas in Indonesia and the Philippines have much higher rainfall with no such "rain curtain." The most common cause of the lack of surface expressions at known systems like Glass Mountain and Newberry is the unusually thick and permeable meteoric zone (related to rock type, eruption history, and deep water table). To obtain a representative geochemical sample, it is typically necessary to drill below the zone mainly influenced by meteoric water, and penetrate an aquifer more closely connected to the reservoir below the clay cap.

Geothermometry

Geothermometers are used to estimate temperatures of the geothermal reservoir based on rock-water equilibration at depth, and are therefore equilibrium specific. Dozens of geothermometers have been developed and many papers have been written describing the systems, calculations and assumptions (e.g. Giggenbach, 1988; Powell and Cumming, 2010).

Insights from industry:
Geothermometers are very useful tools – perhaps the best tool for remotely estimating subsurface conditions.

Some commonly used geothermometers (e.g. silica, Na-K) were developed in high-temperature (>200°F) magmatic-volcanic geothermal systems, so trying to apply them to other regions—like the Basin and Range—can give misleading and discordant results (Shevenell and DeRocher, 2005). Cation geothermometers are still incorrectly applied to low-pH fumarole condensates where the cation equilibration is dominated by leaching under acid conditions yielding anomalously and unreasonably high geothermometer estimates. To accurately use geothermometry data, it is important to consider the reaction kinetics, thermodynamics, mineral suites, and reaction or fluid paths that are involved and to keep in mind that the components of the liquid geothermometers are not sufficiently soluble in steam, and are, therefore, applicable only to water systems. (White, 1973). Gas geothermometers may be more applicable to boiling systems, although they are sometimes more difficult to interpret.

For example, in many low-temperature Great Basin geothermal prospects, the silica geothermometer has been considered the most applicable geothermometer, because its thermodynamics have been studied in greater detail than other geothermometers. The fact that there are multiple phases of silica, however, impacts the ability to interpret geothermometry data. Silica geothermometry data can give erroneous results due to the:

- Presence of high salinity fluids, which alter quartz solubility
- Effects of steam separation, which can concentrate the fluid causing early precipitation of silica
- Effects of precipitation after sampling, since the rate of quartz precipitation increases drastically as temperature drops
- Effect of pH on quartz solubility
- Effects of dilution due to cold water mixing (Fournier, 1981).

Other geothermometer systems (e.g. K-Mg), have been developed through the collection, cataloging and mapping of these data in known geothermal systems. For example, the fundamental assumption of the Na-K-Ca geothermometer is that these cations are in equilibrium with feldspars at depth. In the Basin and Range Region, geothermal fluids often flow through Na-K-Ca rich rocks and alluvium on its way to the surface, which can alter the fluid chemistry and complicate the interpretation. Without additional information about a hydrothermal system (e.g., pH, TDS, and dissolved gases), it is unclear how widespread these geothermometers can be applied, though they appear to be less affected by mixing and boiling than silica geothermometers (Reed *et al.*, 2007).

The best practice in using geothermometers is to apply them with caution. Understand what is being asked. Understand the system in which they are being applied. Understand the assumptions. Use correction factors, if available, or develop new correction factors, if possible. Use geothermometers that are not solute dependent, if available.

Volatiles

Volatile analysis involves the collection of volatiles that may be indicative of deep geothermal fields from soil gas samples and has been applied both in geothermal and oil and gas exploration. Anomalously high levels of carbon dioxide, mercury, and methane can be indicators of the presence of a geothermal system. Helium isotopes have also been used to indicate deep permeability from surface measurements locally and used to locate potential resources in large, regional-scale trend analyses (Kennedy and van Soest, 2007).

Insights from industry:
There are other, non-geothermal explanations for the presence of these gases, however, so additional analyses (typically isotopic analyses) are needed to identify the source. For example, the sugar cane grown in Hawaii contributes so much CO_2 to the soil that it masks potential hydrothermal CO_2 signals. In Nevada, however, where vegetation is at a minimum, anomalous CO_2 concentrations in the soil are likely indicative of upflow of deep CO_2. Isotope studies are still recommended to confirm the CO_2 source.

Additional Geochemical Methods

There are a number of additional geochemical analyses that are typically conducted in the geothermal industry. Many are used in reservoir characterization (e.g., to trace flow patterns and get age determinations of the geothermal source) and not in the initial exploration phase of a project, so these were not discussed in detail in this report.

Geophysical Techniques

The goal of geophysical surveys is to image rock units below the shallow subsurface and determine deeper structure that might represent permeability in a geothermal system. There are two kinds of geophysical surveys.

Electrical surveys (e.g. direct-current resistivity, magnetotellurics) measure the conductivity or resistivity of the rocks. These surveys were developed for geothermal in volcanic systems looking for a clay-rich cap over the geothermal system. .

Potential field methods (e.g. gravity, magnetics) look at differences in density and magnetic contents of rocks, and have been used in the geothermal industry to help identify faults at depth.

Insights from industry:
Electrical methods have been applied in low temperature systems with varying results. If the system temperature is less than 200°C, there may be a broader distribution of clays at depth without a well-defined clay cap. Resistivity methods (e.g. direct-current, MT) are given more emphasis than other geophysical methods because the goal is to detect not just the geometry and the aerial extent of the reservoir's clay cap, but also the intensity of clay alteration associated with the permeability of the underlying reservoir.

Geophysical techniques developed for oil and gas and mining industries are often also applicable to geothermal exploration. However, the value of geothermal fluid available in a cubic meter of rock is much lower than if it was oil or massive sulfide ore extracted from that same volume of rock. To make an exploration technique economically feasible, the value to a geothermal project of geophysical data must be greater per cubic meter of imaged rock volume than for oil and gas (Cumming, 2011).

An important step in obtaining useful geophysical data is to have a conceptual understanding of the area before applying the technique. For example, if you are looking to characterize a north-south trending dike swarm, it is more useful to fly an aeromagnetic survey in east-west swaths instead of north-south swaths.

It is also important to understand the expected results of a geophysical survey. For example, galvanic resistivity (for shallow systems) and magnetotelluric surveys have been routinely used to delineate the extent of the clay cap of most geothermal systems from 70 to 350°C in volcanic and sedimentary settings, including the Cascades, the Salton Trough, and the Basin and Range. However, a misapplication of interpretation concepts used for oil and gas reservoirs in sandstones has led to a widespread mistaken expectation that geothermal reservoirs themselves, in the Basin and Range, should be relatively low in resistivity. When considered in the context of imaging the base of the clay aquiclude that corresponds to the top of the reservoir, then resistivity methods are successful.

A more serious problem for some Basin and Range prospects is noise from nearby regional power lines like the 3100 MW Pacific Intertie.

Magnetotellurics

Magnetotellurics (MT) is a natural-source (i.e., passive), electromagnetic method that measures the ratio of earth's naturally varying electric and magnetic fields over a wide range of frequencies to determine the resistivity structure of the subsurface (Reynolds, 1997).

Insights from industry:
MT is currently the resistivity method of choice for many geothermal exploration companies due in large part to its superior range of depth of penetration (several tens of meters to several tens of kilometers) over other resistivity methods.

In geothermal applications MT can be used to delineate the resource by indirectly mapping the smectite clay ring (where low temperature clay alteration transits to more resistive higher temperature alteration) that typically exists around a geothermal resource. MT is commonly used in the volcanic settings (such as the Cascades Region), because most projects are relatively deep, and most successful conventional resources will have a thick clay cap.

MT methods can be impacted by noise caused by natural or man-made phenomena, such as nearby power lines. MT is also affected by "static shift," a type of distortion that affects all methods of imaging resistivity that measure an electric field. Severe noise or static distortion can make more advanced 3D inversion and resistivity model generation less effective.

Audio-frequency magnetotellurics (AMT) is a higher-frequency MT technique for shallower investigations. Though it shares many of MT's complications, the primary advertised advantages include shorter measurement times (approximately one hour – compared to 24 hours), smaller, lighter sensors and lower cost. Unfortunately, it tends to be too shallow and measurement times are closer to a day for most geothermal targets.

Controlled Source Audio-Frequency Magnetotellurics (CSAMT) technique uses an artificial electromagnetic source, providing a stable signal that decreases noise and measurement time for soundings shallower than 400 m, though, like MT, it is still affected by static shift. Because of this, CSAMT is typically more effective where electromagnetic cultural noise (e.g., power lines, electric fences) creates problems for MT. In geothermal settings, the transmitter geometry and frequency limitations typical make the maximum depth of resolution about 700 m. CSAMT is often used to constrain shallow MT (~1 km) measurements for interpretation of deeper sections. Time-domain electromagnetic (TDEM) methods also have been effectively used in the past to more effectively constrain shallow MT interpretations.

Gravity

Gravity surveys measure density differences in rocks and are a relatively inexpensive way to map gross structural features not visible at the surface.

Insights from industry:
Gravity surveys can provide useful data in many different types of systems. The difference in gravity measurements caused by density contrasts among rocks is usually quite small, so highly sensitive equipment is needed. Gravity surveys are often

conducted in the Basin and Range Region and in sedimentary basins to map structures beneath the surficial alluvium deposits because of the marked density contrast between each geologic unit. The information is often used to select locations for a gradient drilling program or potential fault targets for deeper production tests.

It has been suggested that gravity surveys are not often useful is in the Cascades region. The argument is that volcanic rocks in this region include very low density ash and pumice (some of which floats) next to very dense lava. However, near a geothermal system, the ash and tuff consolidate rapidly with depth and by reservoir depth have density only slightly lower than the lava. Therefore, the large differences in gravity measurements created by rock contacts close to the surface makes it difficult to identify the smaller contrasts of interest at depth. Currently, there are no operating plants in the Cascades region, so some experts suggest gravity's usefulness may not yet be known.

There are examples in the Cascades Region, however, where a gravity survey appears to have been useful. For example, gravity can have utility in delineating the general dimensions and geometry of a buried caldera. In most areas, however, cinder cones and lava can be mapped via aerial photography (e.g., Glass Mountain). It is also frequently used to map faults.

Reflection Seismic

Seismic velocities through a rock body are controlled by rigidity, density, degree of fracturing, temperature, and the presence and degree of fluid saturation. Data collected from reflection seismic surveys are used to map subsurface structures and are often considered the workhorse of the sedimentary-structure-dominated oil and gas industry.

Insights from industry:
Reflection seismic surveys are not always as useful in hard-rock geothermal settings. As with all geophysical techniques, it is important to understand the target and the anticipated results of the survey before applying the technique. For example, reflection seismic targets below range front faults in Paleozoic-Mesozoic metamorphic rocks often act as a scattering medium without coherent reflections that can be interpreted in terms of conventional structure. For a wide variety of reasons, including the increasing homogeneity noted in the discussion of gravity surveys, reflection seismic data in volcanically hosted systems (e.g., Cascades Region, basalts in the Snake River Plain Region) may also be of low value.

Good reflection seismic surveys are relatively expensive. For a geothermal prospect at a depth of 1 km, a 5-6 km long line is needed to get 3-4 km of data in the middle. If a less expensive survey is designed, the edges of the area will not be imaged.

Remote Sensing Techniques

Remote sensing utilizes satellite and/or airborne based sensors to collect information about a given object or area. Remote sensing data collection methods can be passive or active. Passive sensors (e.g., spectral imagers) detect natural radiation that is emitted or reflected by the object or area being observed. In active remote sensing (e.g., radar) energy is emitted and the resultant signal that is reflected back is measured.

Data Acquisition

Insights from industry:
The best time to acquire the majority of remote sensing data is in the summer (specifically, those months with the highest sun angles and longest days). Exceptions to summer data acquisition is the collection of both long-wave thermal data and active sensor data (eg. Radar, LiDAR). In thermal imaging where detectors are measuring heat, it is best to fly when the ground vs. air temperature gradient or contrast is highest. Cooler months are thus better for this type of imaging as are the several hours before dawn any time of year.

There are additional considerations to keep in mind. Radar, for example, cannot image the bare-ground surface in thick snow cover; ditto with LiDAR. However, these active images are insensitive to light (or lack thereof) making them excellent choices for high latitude environments (as one example). Furthermore, both Radar and LiDAR are capable (depending on wavelengths used) of imaging beneath tree canopy making them useful in highly vegetated regions. In contrast, spectral data collection (both hyperspectral and multi-spectral) requires mostly sunny days; data collected in low-light conditions are typically low signal-to-noise making processing and interpretation more difficult And while hyperspectral data is capable of mapping and identifying vegetation ecosystems, it (and multi-spectral) are not capable of penetrating the tree canopy to measure the surface below.

Spectral Imaging

Spectral imaging is a large umbrella that covers two major subsets of sensors: Hyperspectral and Multi-spectral Imagers. The distinction between the two is both technical and thematic.

Technically, hyperspectral sensors (or imaging spectrometers as they are also known) image the earth in many hundreds of narrow bands (typically over a hundred) while multi-spectral sensors image in an average of only ten, wide bands. The most common hyperspectral sensors image in the Visible, Near-Infrared, and Shortwave Infrared wavelength range (~0.35 – 2.5 microns). Hyperspectral sensors measure the electromagnetic spectrum continuously, rather than piecemeal like their multi-spectral cousins.

Thematically, hyperspectral sensors are capable of absolute surface material identification while multi-spectral sensors are only capable of relative material delineation. As an example, historical, multi-spectral images from NASA's LANDSAT satellite (collecting 7-bands of data over the visible, near IR and shortwave IR spectrum) can be used to create maps of the surface, delineating clay from iron-oxides. With today's hyperspectral imagers, hundreds of bands allow unique identification of minerals such as kaolinite vs. alunite or hematite vs. goethite.

Insights from industry:
Spectral fidelity comes at a price; hyperspectral datasets are large and computationally intensive to work with (imagine 224 pieces of information—one for each band—stored for each pixel in an image). However recent processing advances and the ever-increasing speed of computers in the last five years, means that data is interpreted into usable mineral or other material maps in very short time periods (weeks vs. months). Though many in the industry still appreciate the 7-band LANDSAT images or the 14-band ASTER images (public-sector multi-spectral imagers producing data at low, government-subsidized prices), the four common thematic remote sensing-based maps created from hyperspectral data for use in geothermal exploration, (including mineral maps, cultural maps, vegetation maps, and high-resolution digital photographs), are categorically more accurate, more precise and richer in information than multi-spectral datasets .

As an example, hyperspectral data is capable of mapping current and fossil hydrothermal systems. Specifically the presence of a mineral in conjunction with other minerals may indicate the presence of a hydrothermal system in what might be called a hydrothermal mineral assemblage. For example, the presence of kaolinite might not indicate the presence of a hydrothermal system (since kaolinite can form from weathering, not only hydrothermal alteration). However, the co-location of kaolinite, alunite, and opal (amorphous silica) could indicate hydrothermal alteration. The hyperspectral mapping of these hydrothermal minerals has been complicated in the past by the difficulty in displaying millions of categorized pixels in a way that is meaningful to geologists and fits with geophysical and geological mapping norms. Such issues have been resolved in the last five years with the advent of 'targeting' maps that plot mineral assemblages of interest in a myriad of ways including as density maps (that look similar to geophysical gradient maps) and as small, but easily accessible digital files compatible with not only standard software, but also web-based portals such as Google Earth.

Mineral assemblage maps are a useful way for presenting and understanding both airborne and satellite spectral images. They ultimately provide a way to rapidly map vast areas of land (tens of thousands of acres), targeting areas with prospective hydrothermal mineral assemblages for more in-depth geothermal prospecting (i.e. high resolution geophysics and field mapping).

Thermal Imaging

Insights from industry:
Two types of remote sensing images are collected for use in geothermal exploration that are commonly referred to as "thermal" images, and they can sometimes be confused.

One type of long-wave heat sensor collects information in the infrared portion of the spectrum (typically considered to be between 3.0 and 5.0 microns). Imagers collecting data in this wavelength region include Forward-Looking Infrared or FLIR cameras. Data is typically collected only from one or two bands and is used to look for relatively warm or hot materials (e.g., hot springs, pools, hot rock/lava and snow melt).

The second type of long-wave heat sensors collect information in much higher wavelengths in the long-wave infrared (LWIR) portion of the spectrum (typically considered to stretch from ~8.0 to 14.0 microns). These systems can identify minerals associated with hot springs/mineral deposits that have characteristic signatures in this portion of the spectrum. In particular, framework silicates (such as quartz) are identifiable in the LWIR (but not in the shortwave infrared exploited by the hyperspectral imagers discussed previously). There are several airborne hyperspectral thermal sensors in existence, though none considered commercial.

LiDAR

Light detection and ranging (LiDAR) is an active, airborne remote sensing technique used to derive highly accurate digital elevation models (DEMs) and to delineate both subtle and obvious surface features such as faults. They do this via high energy, pulsed lasers typically in the visible and near-infrared wavelength regions). In addition, data from LiDAR surveys can be used to correct geophysical data (compensating for changes in surface elevation).

Insights from industry:
Similar to hyperspectral imaging, LiDAR datasets are large and computationally intensive. However, processing and computer speed are now quite advanced and usable datasets are deliverable in weeks, not months.

Unlike spectral imaging, very little, non-military, federal government LiDAR data is collected for general use by the public, so it must be obtained commercially. Some states agencies (e.g., Oregon Department of Geology and Mineral Industries) have contracts with LiDAR collection companies to collect and provide LiDAR data to the public for the entire state.

Although DEMs themselves are useful, looking on the horizon, we see the development of products that could make LiDAR even more immediately useful. For example, the creation of automated lineament mapping algorithms for LiDAR data (collected for the DOE-Ormat project at Glass Buttes in central Oregon), are under development. Automation of lineament mapping (i.e. fault, fracture, unit boundary mapping) will significantly increase rates of mapping in green-field environments.

Synthetic-Aperture Radar

Synthetic-Aperture Radar (SAR) and Interferometric SAR (InSAR) are active satellite and airborne remote sensing techniques used to develop, among other things, highly accurate digital elevation models (DEMs) with similar resolution to LiDAR (depending on the wavelengths employed).

Insights from industry:
Two major advantages to SAR are that, as previously mentioned, the signal can penetrate tree canopies (making it useful in places like the Cascades, Alaska, and Hawaii) and that the platforms (particularly the satellite platforms) can collect repeat surveys, allowing tracking of very small fault and ground movements. Radar collection is also insensitive to time-of-day and atmospheric conditions.

SAR data, similar to spectral and LiDAR, can be difficult to process. It requires trained personnel who understand both the complex theory behind radar data collection and the data processing software packages (often stand-alone from other remote sensing software packages).

Unlike the LANDSAT sensor (and other spectral satellites), which continuously collected data as it flew, the radar sensors only collect data when tasked to do so. Therefore, there are certainly areas in the world which lack coverage, though geologically active areas (in which geothermal prospects tend to reside) have historically have more coverage.

In addition to use in the initial exploration phases at a geothermal prospect, InSAR data can be used to compare pre-geothermal development images with images obtained during and after production and after injection. Information on ground and fault movement in the area may help in refining the area's reservoir models or in guiding the location of the next production or injection well. Though this application of SAR data to geothermal fields is relatively new and under development, it is commonly applied in oil and gas to characterize reservoirs.

SUMMARY

This research activity represents only a first effort to communicate the exploration experience of a subset of industry experts. The data collected have been compiled and shared in this paper, and in more detail on the OpenEI platform. The authors do not claim that either source comprises a complete listing of exploration best practices for the geothermal industry.

What we have learned in this effort is that industry experiences with the application of these techniques are varied, ever-changing, and not often reported in detail. The geothermal knowledge exchange developed on OpenEI represents a new forum where industry will have more opportunity to share information and personal experiences to increase industry's collective knowledge. The "discussion" feature allows for conversations on the nuances of exploration and the different expert experiences in the application of these techniques.

The OpenEI platform allows this initial best practices research effort to be a growing body of industry knowledge, both for data collected and shared in specific geothermal areas and regions, as well as for specific exploration techniques.

Input and population of this database by industry can make this platform a more powerful tool for reducing cost and risk in geothermal exploration, and make it possible to more quickly identify additional hydrothermal resources.

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