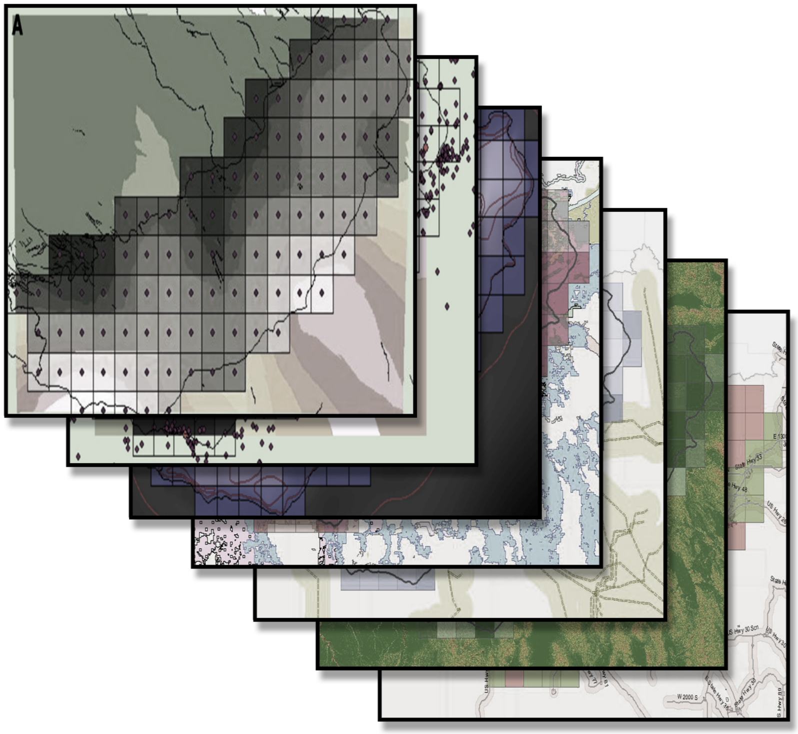
2012-13 DOE EERE
National Geothermal Student Competition

The University of Texas at Austin

team heatseekers

Reed Malin Katie Markovich Matt Uddenberg Daniel Noll



Final Report

August 31, 2012

Executive Summary

As part of the National Student Geothermal Competition, a student team from The University of Texas at Austin conducted an assessment of the geothermal potential of the Snake River Plain (SRP) in Southern Idaho. The team created a multi-attribute decision model to evaluate and score the development favorability for high temperature conventional geothermal resources in the eastern SRP. This model was built to be displayed on interactive, multi-touch platforms to promote education and stakeholder engagement. The model also allows users to dynamically update their preferences for individual decision attributes and generate new ranking scenarios. While favorability mapping of geothermal resources has been conducted in past studies, creation of a dynamic model available on a multi-touch interface offers a novel contribution.

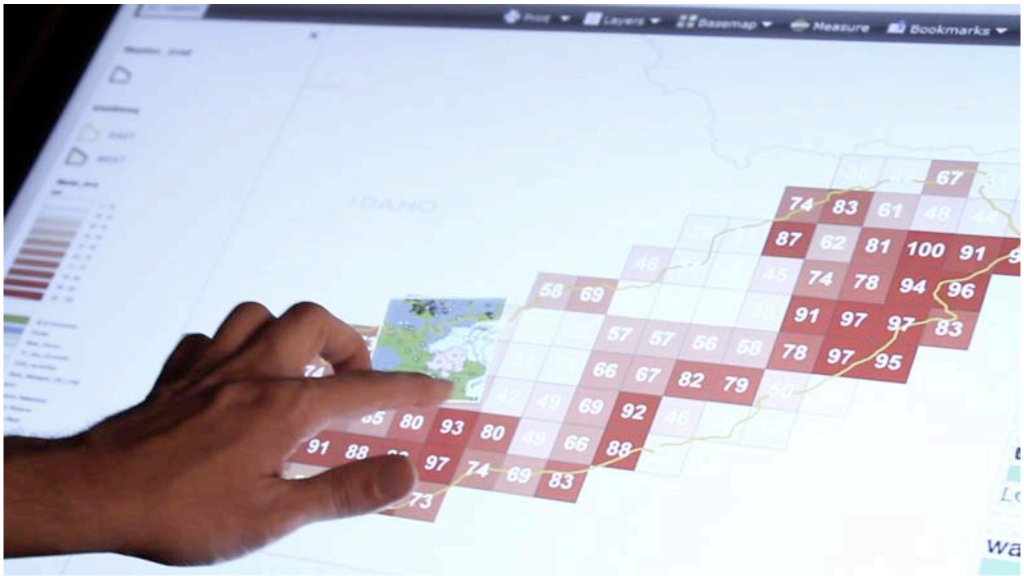


Figure 1: The UT Heatseekers multi-attribute interactive map. To watch a video demo go to: http://www.youtube.com/watch?v=SUhtSnl_ZRM

The team evaluated 104 equal-area land coverages in the eastern SRP and concluded that 22 cells—clustered in five high potential zones—represent the most favorable locations for further geothermal exploration. Secondary analysis of each zone identified one to ten development areas that satisfy additional criteria for geothermal project siting. The areas around Heise and Milford Sweat hotsprings were identified as having the highest potential for further exploration. These conclusions were supported by field mapping and new geochemical data, along with economic, social, and infrastructure analysis. The model, its results, and documentation of the team's work is available to the public online at: www.encompassproject.org/web/geothermal

By creating a flexible tool for evaluating geothermal development favorability, the team hopes to inspire future developers in the SRP to implement a new way of visualizing, prioritizing, and communicating exploration data.

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Student Team

Reed Malin

Reed Malin is a 3rd year dual degree Master's student in Energy and Earth Resources and Public Affairs at The University of Texas at Austin. His research focuses on how to integrate geoscientific data into public policy using decision support tools. He is currently writing his thesis on the geothermal development of the El Tatio geothermal field in northern Chile. Prior to coming to UT-Austin, Reed worked as a scientific project manager at the Institute of Earth Science and Engineering at the University of Auckland, New Zealand. He has been involved in geothermal explorations campaigns in the USA, Kenya, New Zealand, Australia, Iceland, and the Caribbean.

Matt Uddenberg

Matthew Uddenberg recently graduated from The University of Texas at Austin with a Master's degree in Earth and Energy Resources from the Jackson School of Geosciences. He has a Bachelors of Science degree in Earth Science from the University of California, Santa Cruz and has worked as mudlogger in Taft, California for Occidental Petroleum and at the Coso Geothermal Field in California for Terra-Gen Power. He has also completed an internship with Ormat exploring the Mt. Spurr prospect in Alaska. His current research explores the feasibility of developing geothermal resources in Texas.

Katie Markovich

Katie Markovich recently graduated from The University of Texas at Austin with a Bachelor of Science in Hydrogeology. She joined the UT Austin Geothermal Team to contribute to the understanding and field work associated with the Snake River Plain aquifer system. Her main interest in participating in the competition is to gain first hand experience in how water and energy research can inform each other. She will embark on her PhD in Hydrology this Fall at the University of California Davis.

Daniel Noll

Daniel Noll is a 3rd year dual degree Master's student in the Jackson School of Geosciences and LBJ School of Public Affairs at The University of Texas at Austin. His research interests include the economic and political evaluation of domestic and international energy resource utilization, in particular the relationship between new generation technologies and existing regulatory and infrastructure systems. His expertise includes econometric modeling and simulation, investment valuation and risk mitigation, data visualization, and geographic information system (GIS) mapping.

Faculty Advisor

Dr. Suzanne Pierce

Dr. Suzanne A. Pierce is a Research Assistant Professor with the Center for International Energy and Environmental Policy in the Jackson School of Geosciences. In addition, Dr. Pierce is the Assistant Director of the Digital Media Collaboratory in the Center for Agile Technology at The University of Texas at Austin and Fellow with the National Centre for Groundwater Research and Training in Australia. A trained hydrogeologist with a focus on deliberation, Dr. Pierce adopts a scholar-practitioner approach to integrate science-based information with human organizational systems for application to groundwater management and energy-water problems.

Introduction

From March to August of 2012 a team of four students and one faculty advisor from the Jackson School of Geosciences at The University of Texas at Austin (UT) participated in the annual Department of Energy (DOE) sponsored National Student Geothermal Competition. The 2012 competition focused on the Snake River Plain (SRP) in Southern Idaho. While there is a single commercially operational geothermal power plant on the southwestern periphery of the SRP, the central and eastern areas of the plain remain undeveloped. The stated goal of the competition is to investigate geothermal resources in the SRP and support the future development of these resources through creation of new knowledge and approaches to exploration.

For the purposes of this study, the team did not consider Enhanced Geothermal System (EGS) development and instead focused on conventional high-temperature geothermal development. While EGS has the potential to drastically change the outlook for geothermal development, it is still an emerging technology with a set of distinct technical and economic considerations. For this assessment a geothermal resource was defined as a resource with high temperatures (greater than 200 F) coincident with high permeability and the presence of fluids to conduct heat.

A traditional geothermal exploration campaign mitigates development risk by gathering geological, geochemical, and geophysical data about a potential site. In doing so, field surveys and technical geothermal system characterizations will ideally reduce the risk of costly drilling and maximize the chance of finding a useful geothermal resource through creation of more robust geological and geophysical models. However, this traditional model assumes that geologic information can be accurately assessed and does not consider other non-geologic factors that also have substantial impact on project siting decisions. Geographic suitability, land use restrictions, proximity to existing infrastructure, and other economic and physical characteristics have a significant impact on a project's viability. In the case of the SRP—due to its relatively unexplored nature and uncertain geologic characteristics—developers will need to begin evaluating a project from a broad, multi-attribute view to address these additional risk factors.

In order to incorporate these additional stages of development into its assessment of the SRP, the UT team developed a multi-attribute Geographic Information System (GIS) model that incorporates multi-disciplinary development variables to create a geothermal favorability map of the eastern SRP.

This multi-attribute model is useful for refining areas of interest and also addresses an often overlooked component of geothermal development: stakeholder engagement. Because geothermal energy continues to be a relatively boutique and less-understood form of renewable energy, developers often face upfront challenges in securing financing and explaining project constraints. The UT team's decision model is designed to be interactive and intuitive—equally useful for explaining to investors decisions about target areas for exploration and for presenting geoscientific data to geothermal experts.

The model uses an intuitive ranking system, whereby a set a predetermined variables can be dynamically weighted and reweighted to produce a final "favorability score" for grid cells on the map. This map is displayed on a large multi-touch interface, which allows users to interact with and iteratively update the map and save scenarios for exploration and development. GIS based favorability analysis for geothermal development has been conducted in geothermal areas worldwide (See Noorollahi et. al 2007, Yousefi et. al. 2007, and Einarsson and Hauksdóttir, 2010) and is an evolving field for geothermal exploration. The UT team seeks to update this model by allowing stakeholders to dynamically update their preferences and interact with data in a hands-on environment.

The primary advantage of a multi-attribute decision support tool comes from its ability to reflect and rapidly update user preferences. Certain variables are of greater importance to certain stakeholders—a multi-attribute decision model allows these users to update these preferences in an iterative sequence. For example, a government agency reviewing its land leasing policies may be primarily interested in land ownership status, whereas a developer may be more concerned with proximity to electric transmission infrastructure. Both stakeholders can use the model to analyze geological and geothermal potential and can also modify it to reflect their unique favorability preferences.

In this report, the UT team presents its interpretation of the data and indicators for geothermal development and provides a tool for developers to use in evaluating and communicating exploration information. By creating a flexible tool for evaluating geothermal development favorability, the team hopes that future developers in the SRP will have access to a new way of visualizing, prioritizing, and communicating exploration data.

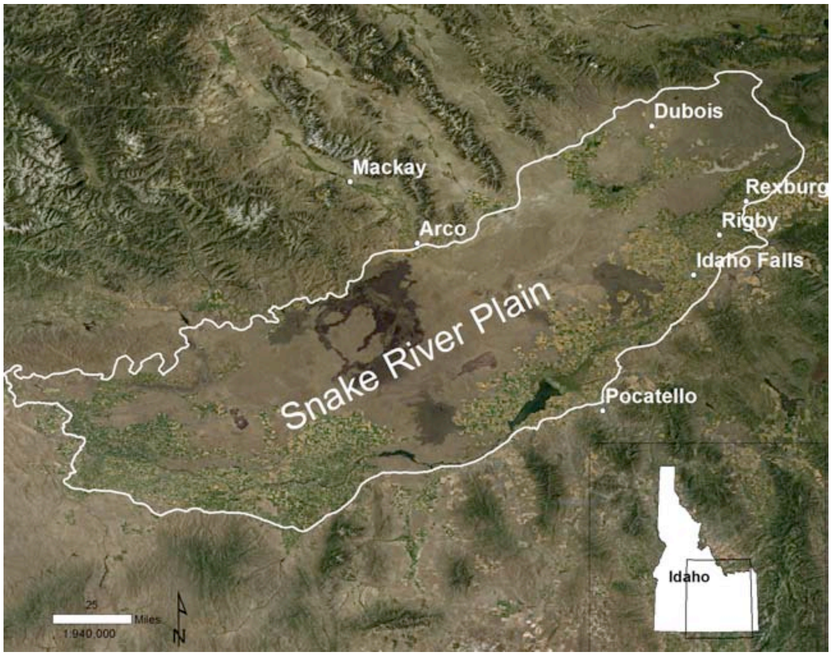


Figure 2: The eastern Snake River Plain, topographic map including boundaries of the SRP aquifer and major population centers.

Methodology and Scope of Work

The purpose of the DOE National Student Geothermal competition is to create new knowledge and value for potential developers in the SRP, shown in Figure 2. The UT team chose to focus on the eastern side of the SRP where there is currently the least amount of extant well data and no advanced geothermal energy projects. The eastern side of the plain is the youngest geologically and is proximate to the Yellowstone volcanic complex—the largest hotspot in the United States. The team's initial assessment of the plain was that the eastern area provided the best opportunity to conduct a study of areas for further exploration and contribute new knowledge about the SRP.

Due to the large expanse of the eastern SRP, the team chose to break the project into two general categories: a macro-level analysis of the eastern SRP's geothermal exploration potential and a micro-scale analysis of key sites within the SRP through a literature review and GIS analysis. The micro-scale field studies and mapping were used to calibrate and validate the macro-scale multi-attribute GIS decision model and are described in detail in conclusions of this report. The field studies were also used to reweight and select the final input variables for the decision model. This included collecting new geochemical data from four hot springs in the SRP.

In order to complete these tasks, the team divided its approach into four phases:

- Literature and data review
- Geological and geochemical mapping
- Policy and economic analysis
- Model integration and multi-touch tool

In its initial scope of work submitted to the DOE the team had planned to analyze the SRP using three variables: geologic structure, socioeconomics, and infrastructure. The team collapsed socioeconomic and infrastructure into a single variable category and also chose to omit more detailed analysis of satellite imagery and localized geophysical studies for the geologic structure variable.

Project Phases

Phase 1: Literature and Data Review

The team began macro-level analysis by conducting a literature review on geothermal resources and regional geology in the SRP. The team reviewed geologic maps, academic papers, and governmental reports on geothermal resources in Idaho. Starting with this broad review, structural and hydrological aspects of the SRP were identified as areas for additional focus and investigation. The geology team members prepared an initial summary of the SRP's geological structure and primary geothermal characteristics with a focus on high level descriptions of the SRP's geologic history and the aquifer's flow regime.

Parallel to this initial geological and structural analysis, the team began compiling a database of publically available GIS data for the SRP. This data drew from multiple sources including Idaho state agencies, federal agencies, and universities. The team relied on foundational work by the Idaho Bureau of Water Resources, the USGS, and SMU's National Geothermal Well Database. The datasets used in this study are listed in Appendix A. By analyzing and comparing these datasets, initial areas of interest and patterns of higher temperature flow began to emerge. Sites for the team's field visit and field sampling were selected from this initial GIS work.

The team also conducted basic background research into geothermal favorability mapping and looked for previous projects to use as benchmarks. The favorability map methodology presented in this report differs from previous studies primarily in its geographical scope. Earlier studies have either focused on extreme macro-level assessment (See Coolbaugh, et. al 2005 favorability map of the Great Basin)--or small scale assessment of a specific geothermal field --(See Noorollahi & Itoi, 2008). The model presented here occupies the middle ground—a sectional analysis of a large aquifer system which is home to multiple geothermal systems—and expands the utility of geothermal favorability models through a dynamic multi-touch interface.

Phase 2: Geological and Geochemical Mapping

Geological Setting

The Snake River Plain is characterized by two main regional geological characteristics, Basin and Range faulting, and magmatism resulting from the Yellowstone hotspot track. Given the lack of subsurface data available for the Snake River Plain, the strategy for identifying geothermal reservoirs should be focused on areas with presently active faulting and fracturing. Using GPS measurements on a regional scale the rate of extension for different geographic regions surrounding and encompassing the Snake River Plain have been determined. Strain rates for the normally faulted zones on the periphery of the Snake River Plain have been found to be in the range of 5.6 ± 1.3*10-9 yr-1 and 12.2 ± 4.7*10-9 yr-1. For the volcanically active region of the Snake River Plain strain rates are 1.6 ± 4.8*10-9 yr-1, (Payne et al., 2008). Furthermore, Figure 3 shows that most active faulting occurs along the periphery of the Snake River Plain as well.

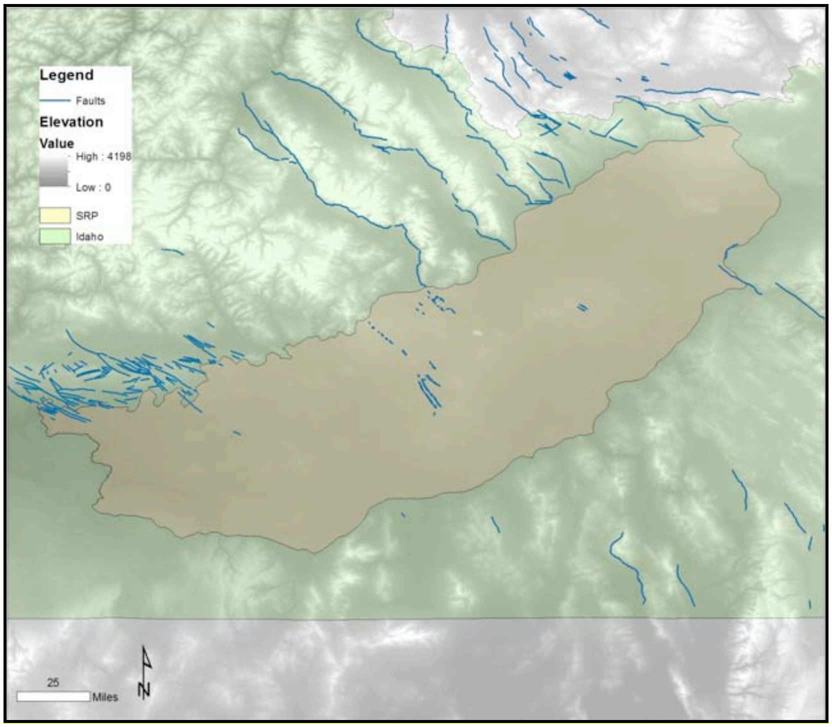


Figure 3: Diagram of Holocene faults from the Idaho Geological Survey database.

One of the key constraints of determining a viable geothermal resource is whether a defined resource has an existing reservoir. In a general sense, it is well known that permeability tends to decrease with greater depth, a relationship that has been discovered through the analysis of global data. This is because of a host of factors including, mineral precipitation, compaction, and hydrothermal alteration (Ingebritsen and Manning, 2010).

This poses a significant problem for geothermal resources because within crustal rock heat is generally a function of depth as well. Therefore, to obtain heat from the subsurface one must balance the need for temperature, which will allow a geothermal plant to operate efficiently, and the need to pull significant volumes of water efficiently from the reservoir. However, there are exceptions to this general rule. The most significant exception is an insight made by oil and gas operators as well as geothermal developers. They have discovered that low permeability matrix reservoirs can be efficiently produced if there are critically stressed fractures present. This idea is known as the *critically-stressed-fault hypothesis*, which states that faults and fractures that are hydraulically conductive today are those that are critically stressed in the current stress field (Zoback, 2007).

Given the evidence presented above it is clear that a search for conventional geothermal resources should be focused on the presently active faults on the periphery of the volcanically active region. Therefore our decision tool assigns higher ranks to grid cells which contain active faulting in areas with high shearing rates. Exploration in these areas will have a higher probability of containing fractured permeable reservoirs at depth.

Hydrogeological Setting

The Eastern Snake River Basin is associated with a regional aquifer system that is hosted in the Pliocene-aged fractured basalt flows. Several losing streams which are fed by snowmelt and runoff from the surrounding mountains act to naturally recharge the aquifer (Roback, 2001). However the majority of recharge comes from irrigation return flow on the plain. Storage values for the aquifer are estimated to be 200 million acre feet, and studies have found the average groundwater residence time to be 50 years (Smith, 2004 and Mcling, 2000). The upper unconfined aquifer occurs in a Pliocene-aged fractured basalt layer averaging about 400 feet in thickness, which overlies a Miocene basaltic flow, and yet deeper are older silicic volcanic rocks.

Groundwater flow is generally towards the west-southwest, and the main discharge points are Thousand Springs and American Falls near Twin Falls, Idaho. Thousand Springs discharges about 5,200 cfs, comprising a majority of the total annual discharge. At a less regional scale, storage and flow is highly dependent on the presence of sedimentary interbeds and fractures, respectively (Welhan and Reed, 1997). A conceptual model of the system is shown in Figure 4. The Snake River is the major surface water expression of this groundwater system, as there is a strong connection from spring contribution in certain stream lengths (Whitehead, 1994).

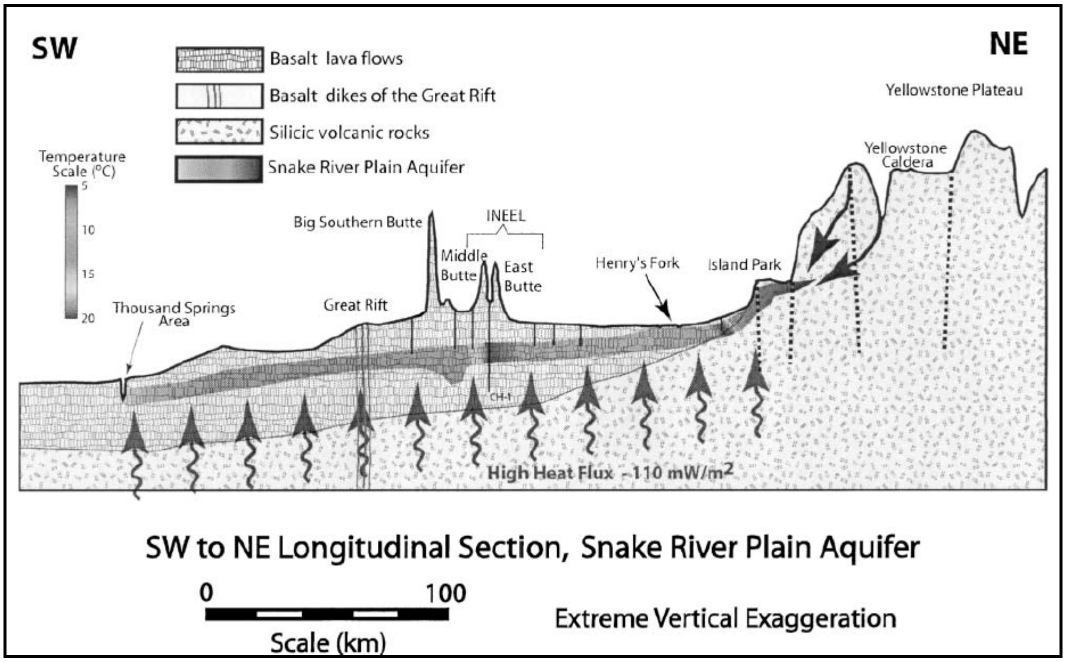


Figure 4. Conceptual model of the ESRP Aquifer showing the thermal gradients along the central axis of the plain (Smith, 2004).

Field Work and Groundwater Analysis

From June 27 to July 6 two members of the UT team—a geologist and a hydrogeologist—conducted site visits to the eastern SRP to sample and map key areas of interest. Their route and target areas, which were determined from the initial GIS analysis, are listed in Figure 5. The primary purpose of this visit was to validate initial conclusions from analysis of publicly available data and collect new geochemical data. Surface mapping and additional geochemical measurements were targeted at identifying the boundaries and flow direction of these aquifers. Ultimately, the data gathered from these sites was used to verify our multi-attribute models and construct a conceptual hydrogeological model of the flow, heating, and convection mechanisms of geothermal resources in the SRP.

The first half of the field visits was dedicated to characterizing the fault and fracture behavior on the eastern SRP. The site selection was based on our knowledge of three major NW-SE trending faults on the northern part of the eastern SRP. These active normal faults are associated with Basin and Range tectonics, and they are exposed at the surface in the valleys leading into the plain, making them ideal for understanding fracture behavior at depth (Holmes et al., 2008 and Payne et al., 2008). Due to time and location constraints, we selected one of these major faults, the Lost River Fault (highlighted in Figure 5), and visited four sites starting near the fault-plain intersection at Arco and ending up near Mackay. At each of the sites we noted the rock type, general strike and dip of bedding, fracture orientations, and mineral alteration patterns. From this we interpreted multiple generations of faulting and their associated fractures, as well as confirmed the dominant fault zone for the region.

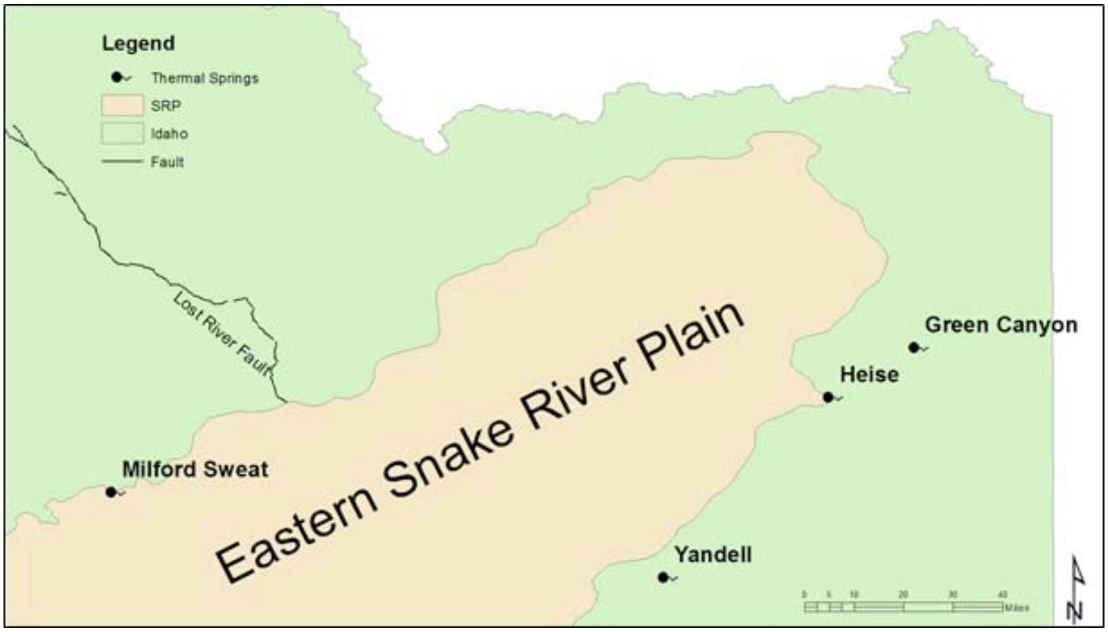


Figure 5: Map showing the four spring sites as well as the Lost River Fault which were the focus of the SRP field visit.

The latter part of the field visits involved the collection of data and water samples at four hot springs on the plain, also shown in Figure 5. Thermal springs associated with the regional groundwater system are important for SRP geothermal exploration in that they are surficial expressions of the hot spot generated heat, which is otherwise insulated by the aquifer. The basic geochemical parameters of these springs are described in Table 1.

Additionally, several exploration wells that bypass the aquifer into the deeper volcanic rock reveal higher Bottom Hole Temperature (BHT) values of up to 150 degrees Celsius, and so combining these two hydrogeologic parameters will provide insight into sites for potential geothermal production (Blackwell, 1989 and Shervais et al., 2011). Sites were taken from the Idaho geothermal database and then selected based on spring discharge temperature and bottom hole temperature from nearby groundwater wells when available. The four samples for geothermometry analysis were collected at Heise Hot Springs, Milford Sweat Hot Springs, Green Canyon Hot Springs, and Yandell Warm Springs.

In situ parameters such as pH, Total Dissolved Solids (TDS), and water temperature were recorded at each site, and the water samples were sent to Thermochem Laboratory and Consulting Services in Santa Rosa, California for the lab analysis. These samples were analyzed for major anions and cations (Na, Ca, K, Mg, Cl, SO4, HCO_3/CO_3) and a few relevant trace elements (Li, Rb, Cs, B, F) which serve as inputs into Geothermometry spreadsheets for graphical analysis and ultimately to constrain reservoir temperatures (Powell and Cumming, 2011). Lab results and the accompanying geothermometry interpretation are discussed in the technical findings section of this report.

NAME	COUNTY	TEMP (°C)	PH	ALK. (mg/kg)	TDS (mg/kg)
Yandell Warm Springs	Bingham	32	7.1	197	714
Green Canyon Hot Springs	Madison	44	6.8	137	621
Milford Sweat Hot Springs	Blaine	44	7.3	241	371
Heise Hot Springs	Jefferson	49	6.7	902	5940

Table 1: List of the four thermal springs sampled for this project with selected physical and chemical attributes.

Phase 3: Policy and Economic Analysis

This section provides a basic overview as to the economic, regulatory, and social dimensions to geothermal development in Idaho and how these factors were incorporated into the team's analysis of the SRP. In preparing an assessment of the regulatory, economic, and environment constraints on geothermal development the UT team conducted a short literature review. The economic risks associated with geothermal production have been studied in several comprehensive reports (Delloitte, 2008 and Tester et. al, 2006). Industry group papers have also already outlined the primary political and regulatory barriers to development (Fleischmann, 2006). From these reports and interviews with experts, the UT team developed a conceptual understanding of the relative importance of economic and regulatory factors.

The Regulatory Environment

A 2006 study by the Western Governors Association Geothermal Task Force concluded that Idaho ranked 3rd behind California and Nevada in near-term geothermal power capacity. Yet despite its relatively active and hot geological setting, Idaho has not seen major development of geothermal power (WGA Task Force, 2006). The 10MW Raft River power plant, located on the very southern periphery of the eastern SRP, is the sole operational geothermal power project in Idaho.

Electricity production in Idaho has historically been dominated by hydropower. In 2011, more than 80% of Idaho's net electricity production came from hydropower and an additional 8% from wind power. However, as Idaho's electric demand continues to grow it has needed to rely on imported electricity from outside of the state (EIA, 2012). Currently this does not present a major reliability problem, as this imported power comes primarily from coal fired generation in bordering states and the low cost of coal and hydropower have combined to make Idaho residential and commercial electric rates among the lowest in the nation.

Perhaps as a result of historically abundant resources Idaho does not currently have any state-level incentives or major restrictions with regard to development of geothermal energy. The state government has only recently moved to make changes to its state geothermal leasing policies (Streater, 2011). Unlike many western states, Idaho has not yet established Renewable Portfolio Standards (RPS) for its electric utilities. While utilities that operate in neighboring states have become subject to those states RPS, the Idaho state government has not actively promoted renewables through regulatory incentives.

Such incentives are generally badly needed by developers to offset the high upfront infrastructure costs associated with developing a geothermal project. Like other renewable resources, such as wind and hydro, geothermal energy is inherently geographically constrained. Its fuel source—geothermal steam—cannot be transported any distance. As a result, proximity to existing electric transmission infrastructure and road access are both critical factors in siting a successful project. With the cost of road construction ranging in the millions of dollars and new 138kv transmission lines costing approximately $400,000/mile developers immediately face major financial constraints before even beginning geological investigations.

Adding to the increased cost is the risk of extended development timeframes due to environmental and federal land use permitting. The Bureau of Land Management (BLM) owns nearly 12 million acres of land in Idaho, much of it within the eastern SRP. The process of winning a concession, leasing, and permitting on BLM land is well defined, but can often take multiple years and extended negotiation with the BLM and the National Forest Service. If at all possible, developers strongly prefer siting projects on private land where the timeframe and costs for permitting and negotiation are much smaller.

From a permitting perspective, surface and groundwater regulation are critical policy issues for Idaho. Idaho is an arid state and relies heavily on withdrawals of surface and ground water to fuel its agriculture based economy. In 2005, Idaho ranked 3rd behind California and Texas in total water withdrawals per day (Barber, 2009). The Idaho Bureau of Water Resources has in the past issued moratoriums on geothermal development near sensitive areas in the south eastern portion of the SRP. While these moratoriums do not preclude geothermal development in the majority of favorable areas, they constitute the primary environmental impact risk for geothermal developers in Idaho.

The UT team concluded that while there are considerable regulatory and environmental concerns for developers of geothermal in the eastern SRP, the variables are typically difficult to quantify. While developers must be cognizant of other potential growing regulatory risks, the two factors of land use and infrastructure proximity are dominant and were selected as the team’s primary economic and regulatory variables. Land use and infrastructure proximity are well defined risk variables that can greatly decrease project feasibility for a developer.

Phase 4: Model Integration and Multi-Touch Tool

Modeling Approach

There is no one universally accepted methodology for assessing geothermal exploration prospects. As described in the technical findings, we chose a straightforward prioritization of high temperature and active faulting to determine favorable areas. In creating a decision support model for geothermal exploration, our primary concern was to build in flexibility and clearly document all assumptions. In doing so, we intended to present our approach and show how preferences—utility functions, base assumptions, cost calculations, etc.—can be modified in future versions of the model. The team's interpretation and assignation of relative weights is supported by our research and fieldwork, but is by no means intended to be definitive.

ArcGIS was selected as the primary modeling tool due to its large analysis toolkit and its status as the de facto GIS software package. While open source considerations were important, the team felt it was most practical and time efficient to use the established industry tool. The multi-touch interface and application were developed in Javascript and pull ArcGIS shapefile data from the ESRI ArcGIS online hosting tool. The decision support software suite Logical Decisions v7.1 was used to weight and assign utility functions for input variables. Multi-touch display and interaction with GIS layers was accomplished using the Open Exhibits open source suite.

This web application was also built to be delivered and manipulated via a multi-touch interface. The team leveraged matching funds from the Jackson School of Geosciences to purchase a 32 inch multi-touch display to conduct application development. The multi-touch display was used to experiment with modes of data display and interaction for potential end-users. The final configuration, which has reached a proof-of-concept stage, is built to emphasize flexibility in scenario building. This report presents one set of conclusions based on the UT team's assessment of geothermal favorability. This tool allows for multiple scenarios and rapid reweighting of input variable utility.

Final Display - Why Multi-Touch?

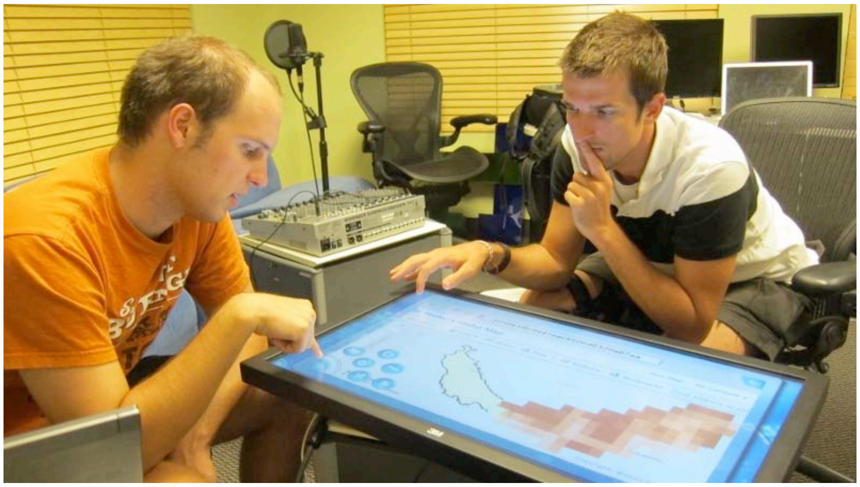


Figure 6: Team members using the multi-touch display

In development of this multi-attribute model, the team followed the principles of participatory modeling and collaborative decision making. See Figure 6. The final model can be understood as a basic Decision Support System (DSS) for stakeholders engaged in geothermal development in the eastern SRP. These principles and ideas have been widely applied to decision making in business management but have not yet been formally applied to geothermal energy development. Many geothermal energy developers develop their own decision support tools in the form of spreadsheet models, temperature gradient maps, and drilling cost estimates but may not think of these as a DSS. This project proposes a formalized DSS in the form of the team's interactive GIS favorability model.

The concept of a 'shared space' was introduced by Schrage in 1995 and it describes the concept of adding symbolic aspects to a dialogue or deliberation in ways that augment shared understanding, interactivity, and memory (Schrage, 1995). Recently, multi-touch technology is emerging as a powerful and disruptive tool for enabling interactive 'shared space' by creating a mechanism for collaborative display of information and knowledge for groups (Conklin, 2006).

Collaborative displays act as a boundary object, which is the concept that technology can act as a translator between different understandings of the problem, or sets of information, and contexts (Bowker and Star, 1999). For example, using the decision analysis application developed by the UT team on a multi-touch surface can support conversations among groups with vastly different understanding of information such as a geothermal exploration team composed of geophysicists, drillers, managers, engineers, and business consultants.

The touchscreen serves as an interactive medium for delivering information so that a group can evaluate the combined information and knowledge about a field site simultaneously and the format will support substantive interactions among a team. An alternative example for possible uses of the technology and application may be in the context of stakeholder and public engagement. Technical teams from the geothermal industry can communicate the intricacies of a planned development site with community members in an interactive manner that develops shared understanding.

Geotechnical Findings

Geochemical Findings

Quantitative geothermometry is a useful method for geothermal exploration in that it relies on the concentrations of indicator elements to determine reservoir temperatures. This method assumes that temperature-dependent reactions govern the concentration of the indicators, and also that the sampled water was in equilibrium with the reservoir rock and did not undergo any reequilibration upon reaching the surface (Fournier, 1977). The geothermometers used for this report are commonly used in geothermal exploration and can estimate a large range of temperatures (<100°C up to 225°C).

The silica geothermometer uses the dissolved concentration of either quartz or chalcedony in the spring water via conductive cooling to provide a maximum reservoir temperature. An additional analysis was run for maximum steam loss, which is more appropriate for boiling hot springs, but not relevant for the four thermal springs sampled as part of this report (Powell and Cumming, 2010). The resulting values from graphical analysis are listed in Table 2, and both quartz derived values show good agreement while the chalcedony temperature is much lower for each spring. Ultimately, since it is not well known whether quartz or chalcedony is the dominant silica species at depth, this geothermometer cannot be used to independently predict the reservoir temperature (Mariner, 2005).

	Reservoir Temperature (deg C)		
Source	Chalcedony Cond	Quartz Cond	Quartz max steam loss
Milford Sweat Hot Springs	41.3	73.5	77.4
Green Canyon Hot Springs	40.9	73	77
Heise Hot Springs	52.4	84	86.6
Yandell Warm Springs	28.4	60.6	66.4

Table 2: Lab and graphical analysis derived results for various silica geothermometers.

The next reservoir indicator utilized is the Na-Ca-K or cation geothermometer, and it relies on the temperature dependency of equilibrium exchange constants for ascending waters (Fournier, 1977). Based on assessment studies, it has been suggested that this geothermometer is more accurate for low temperature reservoirs, however dilution does affect the end result. This has implications for this study, as dilution is likely occurring as the thermal water interacts with the Snake River Plain Aquifer. Upon graphical analysis of the cation concentrations, the corrected Na-K-Ca geothermometer values showed very good agreement with the quartz temperatures.

The final set of geothermometers are known as the Giggenbach geoindicators, and they also use ratios of cations and temperature dependent exchange reactions to determine a maximum temperature of the water. Na/K and K/Mg are commonly used high and low temperature geothermometers, respectively because they avoid the uncertainty of silica and concentrations for these species and are readily available for many springs and wells (Mariner, 2005). Table 3 shows the resultant estimated reservoir temperatures, and while the K/Mg values continue to show agreement with the other geothermometers, the Na/K values are noticeably higher than any other temperatures. Previous studies have noted similar anomalously high values for waters that are below 100 degrees Celsius using this geothermometer (Fournier, 1977).

	Reservoir Temperature (deg C)	
Source	Na/K	K/Mg
Milford Sweat Hot Springs	285.1	63.3
Green Canyon Hot Springs	520.8	35.6
Heise Hot Springs	252.4	117
Yandell Warm Springs	337.7	38.8

Table 3: Lab and graphical analysis derived results for various Giggenbach geothermometers.

The motivation for utilizing geothermometry in this study stemmed from the lack of deep wells in the eastern portion of the Snake River Plain. Not only does this method give the potential of quantifying reservoir temperatures, but it serves as a validation step for the model-recommended sites for geothermal exploration. The geothermometry data is too sparse to merit its own layer in the mult-attribute model, and so instead it can be used as an added metric in the final assessment of potential regions for geothermal development on the SRP. By using multiple geothermometers, this study minimized the potential for any one indicator to overestimate a reservoir temperature, and also provided insight into the behavior of the ascending water. The two consistently highest reservoir temperatures were found to be that of Milford Sweat and Heise Hot Springs. The full laboratory report and geothermometry graphs are attached in Appendices B and C.

Final Model Integration

After a full review of the available data and new geochemical and geological data, the team undertook a deliberative process to determine the final input variables into the multi-attribute model. After careful consideration a final set of seven decision variables were finalized and loaded into the GIS model. This section describes in detail the rationale for the selection of each variable and how these GIS layers were constructed. The UT team's proposed utility curves for these variables and relative weighting are also clearly documented for each variable.

The final set of variables is displayed in Figure 7. These variables were grouped into two parent categories: Physical/Socio-Economic and Geological/Geochemical

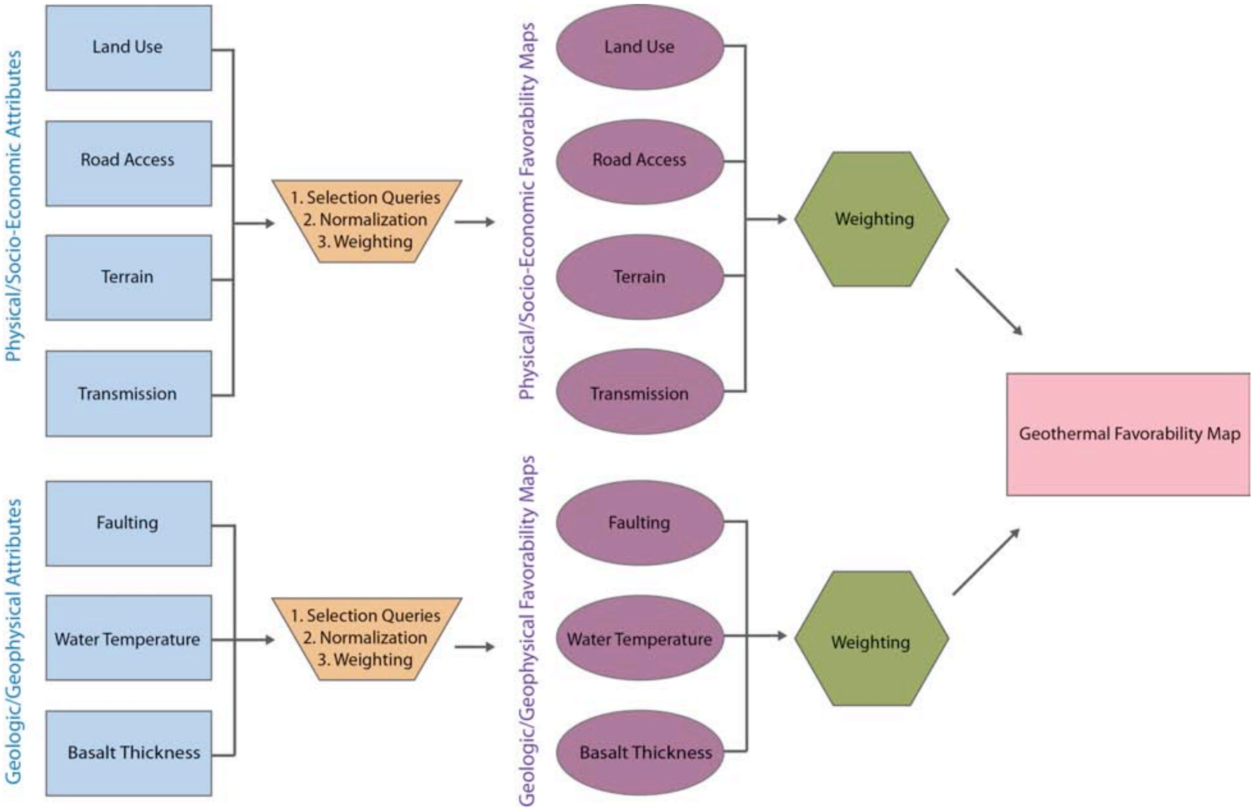


Figure 7: Diagram of the favorability modeling process

Defining Areas

For modeling purposes a grid consisting of 104 unique cells was superimposed upon the area of study. Each grid cell measures 16.2 km by 22.2 km, which roughly corresponds to a standard USGS quadrangle map. Because many of the areas are somewhat geographically, geologically, and infrastructurally homogenous, the team decided that additional granularity would not add value to the final analysis. Each of these grids cells was assigned a unique ID to be used for assessing input variable utility score and the final favorability ranking which were both calculated on a scale of 0-100.

Assessing Utility

After creating a final GIS layer containing georeferenced input variable data a selection query was performed to determine a cell's individual attribute score. This selection query is used to convert raw data—such as the number of square kilometers of usable land in a cell—to a utility score. This utility score was calculated using utility curves created and manipulated using Logical Decisions. Rationale for these utility curves are described below.

The Scoring Methodology

The final step in building the favorability map was applying a final weight to the input variable scores. The final objective function of the ranking is as follows:

$$u(x) = \left(\sum_{n=1}^{4} w_n \times a_n\right) + \left(\sum_{n=1}^{3} v_n \times b_n\right)$$

Subject to:

$$\left(\sum_{n=1}^{4} w_n = 50\right); \left(\sum_{n=1}^{3} v_n = 50\right)$$

u(x) = Utility of a given cell
a = Physical/Socio-economic variables
b = Geological/Geophysical variables
w = Weight of Physical/Socio-economic variables
v = Weight of Geological/Geophysical variables

Assigning Weights

In order to assess a final favorability score, each of the seven independent variables was assigned a relative weight. The team chose to weight the variables equally against each other within their categories. That is, from a geological perspective, faulting, water temperature, and basalt thickness were considered of equal importance. Similarly, the socio-economic variables were weighted as equal to each other. This flat ranking methodology was used in order to ensure internal consistency and provide a basepoint for reweighting using the multi-touch tool. Future versions of this ranking tool should consider using an Analytical Hierarchy Process (AHP) to ensure consistency in relative rankings.

Assessing Input Variables

The seven selected input variables are: Water temperature at depth, basalt thickness, faults, land use, road access, terrain, and transmission.

Water Temperature

Antecedent water data was acquired from three independent archives: Mariner, USGS NAWQWA, and the SMU Geothermal Database. Ultimately, this layer integrated our understanding of groundwater occurrence and flow, as well as thermal gradients in the SRP. One of the main challenges for this layer was to tease out the thermal gradient from a bimodal temperature distribution Figure 8. The anomalously high temperatures in shallower wells are likely a function of highly fractured and thus permeable rocks near the surface, and wells that bypass this zone show a more typical thermal gradient.

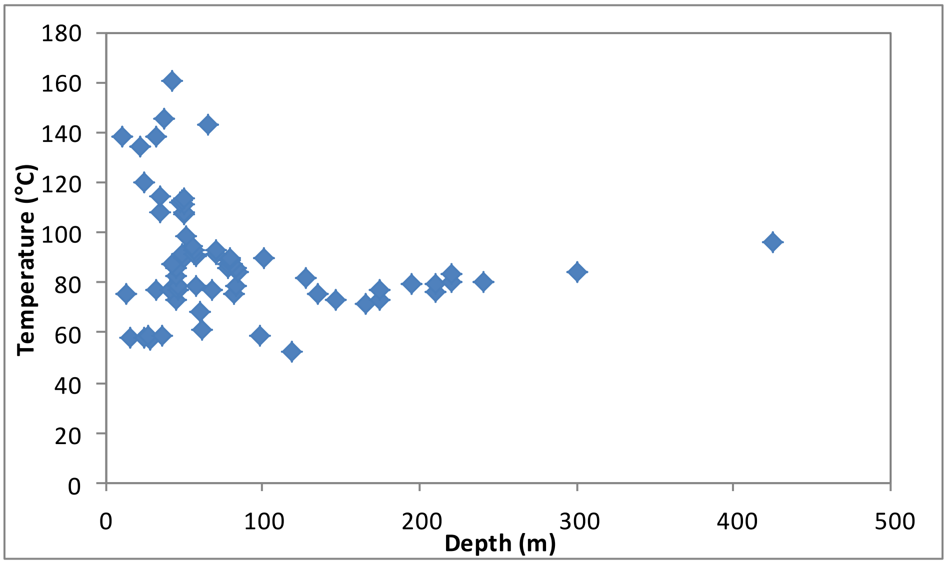


Figure 8: Graph of the bimodal temperature depth relationships for a selected cluster of SRP wells.

In total 922 well data points were used in the GIS water analysis, which consisted of creating pilot points across the plain and selecting the nearest wells. Using the bottom hole temperature to depth plots, a linear regression established depth to the 200 degree Fahrenheit (93 degree Celsius) isotherm for each of the clusters. The isotherm was chosen based on the minimum values for binary cycle power generation. A mean depth to isotherm value was calculated for each cell, and the values were assigned a utility value between 0 and 100 based on a normalization curve generated using a Logical Decisions program, see Figure 9.

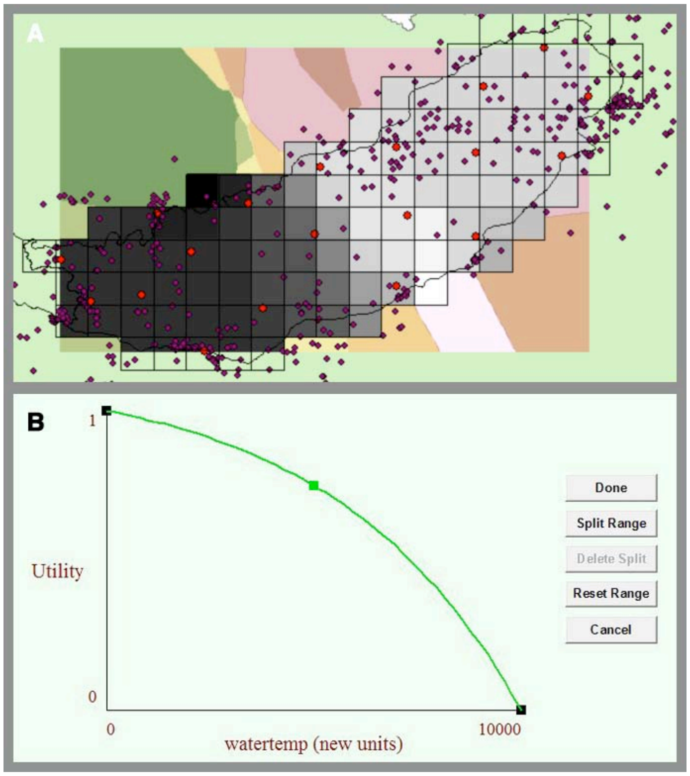


Figure 9: **A.** Screen capture showing a schematic of the well locations (purple), pilot points (red), and relative weighting of depth to the isotherm for each grid cell. **B.** Utility curve

Basalt Thickness

The quaternary basalts underlying the SRP have implications for heat flux as well as drilling costs, and so the multi-attribute model incorporates this with a layer ranking the spatially varying thickness. The basalt thickness was determined by georeferencing mapped contours from a digital map acquired from the USGS online repository. These contours were then interpolated across the plain and a zonal mean was assigned to each model grid cell shown in part A of Figure 10. The average thickness values were then normalized using a basic utility curve and assigned utility values ranging from 0 to 100 shown in part B of Figure 10.

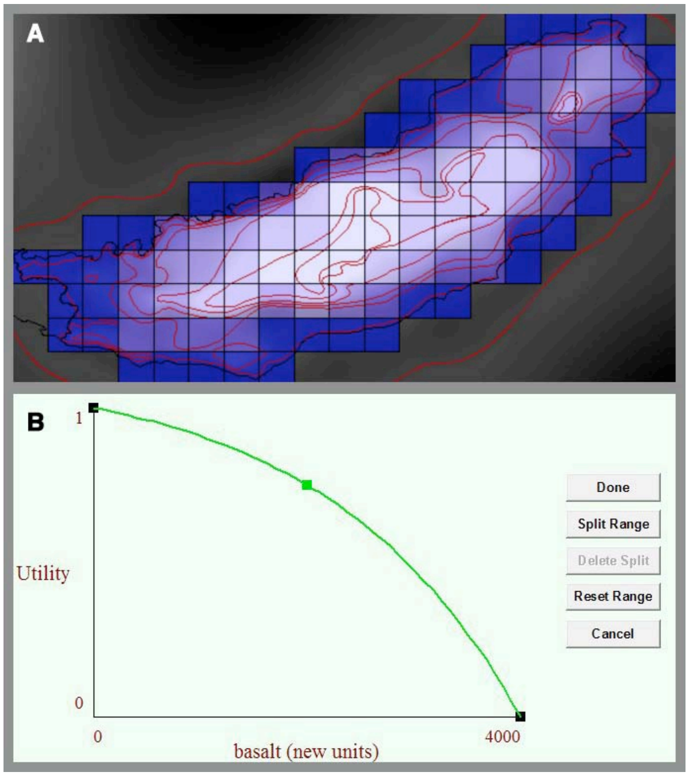
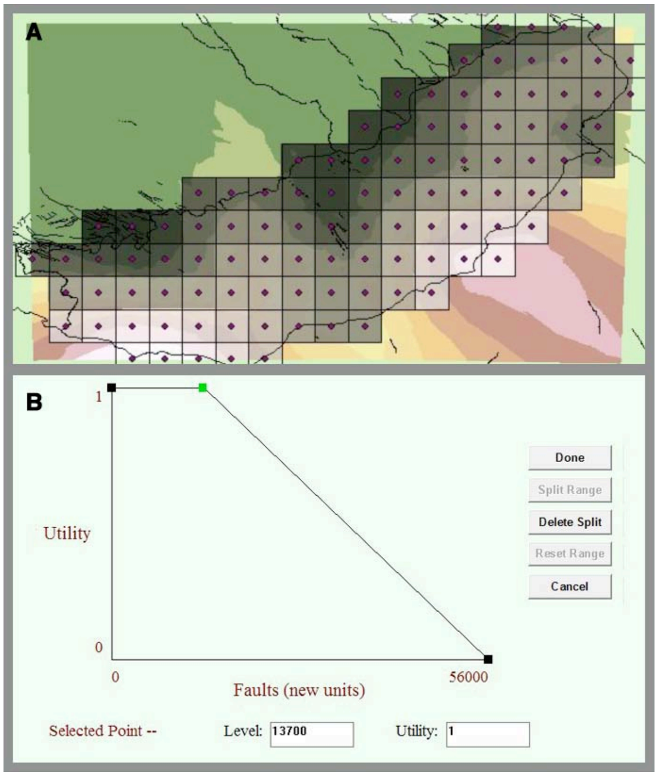


Figure 10: A. Screen capture showing a schematic of the basalt thickness contours as well as the relative weighting of thickness for each grid cell. **B.** Utility curve

Faults

For the fault layer in the geological portion of the multi-attribute model, a GIS shapefile of mapped faults in the eastern SRP region was acquired from the Idaho Geological Survey's online database. With this information, an average value for proximity to fault zones was established for the centroid of each of the grid cells Figure 11. The values were then normalized using Logical Decisions, where a utility function was generated to assign a value of 100 for any absolute distance value less than the distance from a centroid to the corner of a cell plot. Higher values were then assigned utility values using a linear utility function shown by Figure 11.

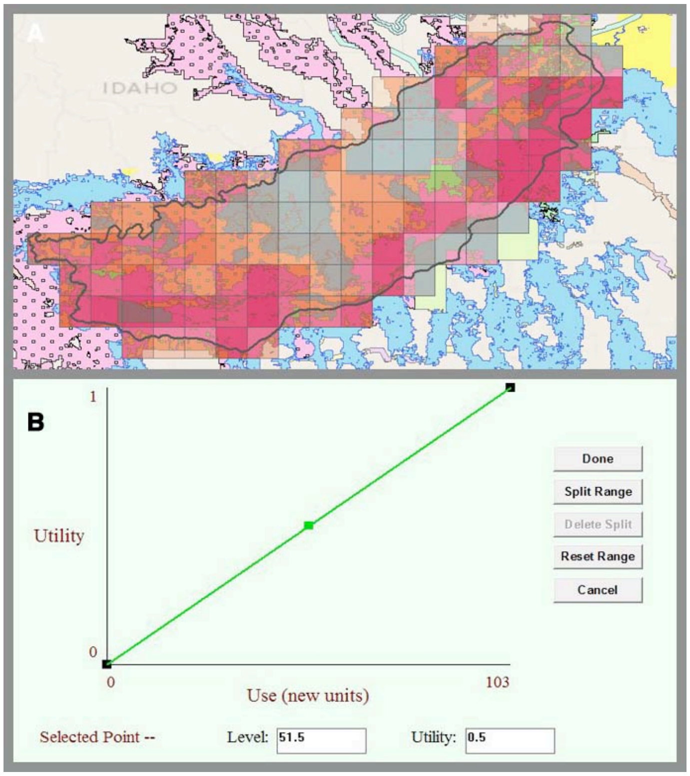


Selected Point -- Level: 13700 Utility: 1

Figure 11. A. Screen capture showing a schematic of the relative weighting of each grid cell for proximity to mapped faults. **B.** Utility curve

Land Use

Geothermal resources are subject to various jurisdictions, permitting requirements, and prohibitions according to a land parcel's ownership and relevant state and federal regulations governing the use of the land. Both ownership type and restrictions on land use impact the value of a land parcel's value by increasing transaction costs and reducing the area available for development. In the eastern SRP, land ownership is divided between Indian Country, federal, state, and private ownership. Using public geospatial data, a coverage map was created with an associated utility curve which are illustrated Figure 12.



Selected Point -- Level: 51.5 Utility: 0.5

Figure 12. A. Screen capture showing a schematic of the relative weighting of each grid cell for land use. **B.** Utility curve

Road Access

Access to and use of existing road infrastructure is critical to the economic viability of a new power development project. Generic estimates for road construction predict a per mile cost of between 1 and 5 million dollars, making the need to construct new road infrastructure over large geographic areas a prohibitively expensive barrier to project siting. Using CENSUS MAF/TIGER data on existing Idaho road infrastructure, a binary determination is made to assign values of 1 and 0 to cells with and without intersecting road infrastructure. These are converted into utility values of 100 and 0, this binary map is displayed in Figure 13.

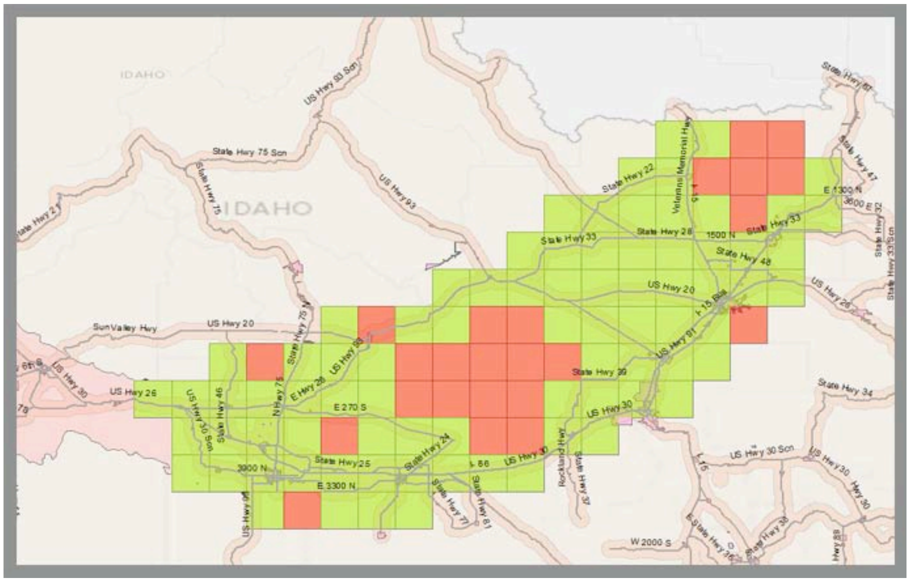
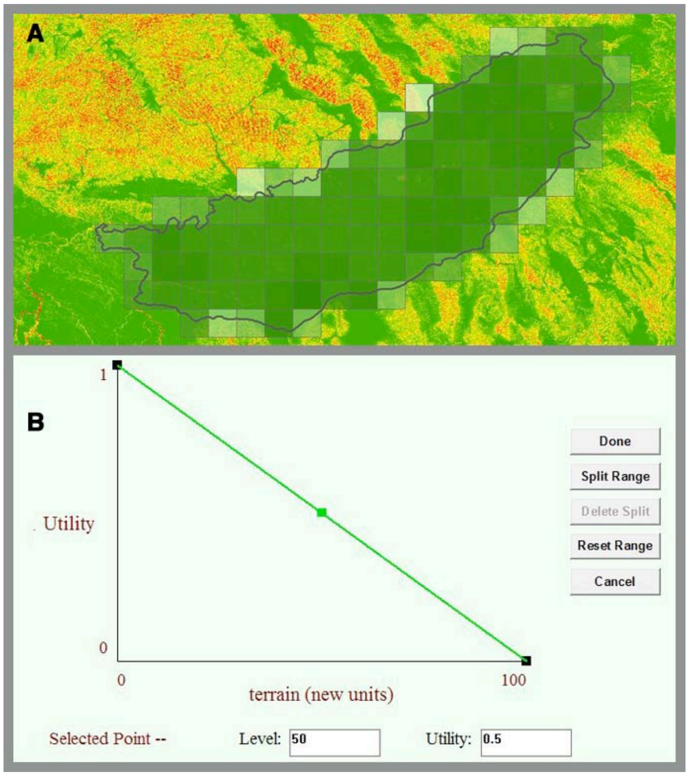


Figure 13. Screen capture showing a schematic of the binary weighting of grid cells containing roads

Terrain

Terrain refers to the steepness of the land surface. Higher slope values limit the viability of geothermal siting because it increases the cost of construction, transportation, as well as obstructing subsurface water pathways. Using geospatial data from the USGS National Elevation Dataset, a mean terrain (slope) value is calculated for each cell Figure 14. These values are then normalized by assigning a utility score on a scale for theoretical slope values between 0 and 100 Figure 14. Given that the majority of the SRP contains terrain with little or zero grade, it is not expected that this variable will have a large impact on the model. Nevertheless, consideration of terrain is an important factor for future use of the model.



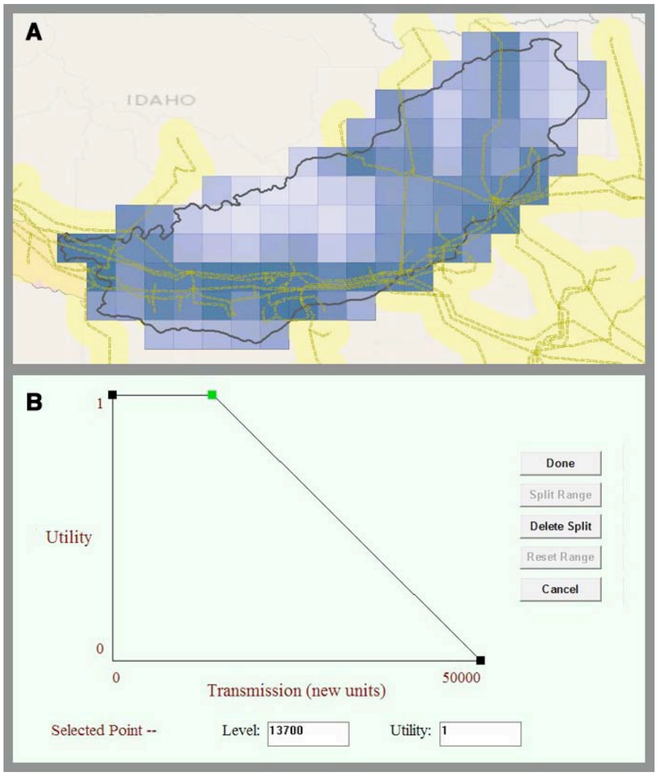
Selected Point -- Level: 50 Utility: 0.5

Figure 14: A. Screen capture showing a schematic of the relative weighting of each grid cell for terrain. **B.** Utility curve

Transmission

Resources best-situated for siting new geothermal developments are located adjacent to existing transmission lines since the need to build new transmission capacity adds substantially to the overall cost of a power project (Hurlbut, 2012). While the cost for a new transmission line depends on many factors, the cost increases in proporation to the distance over which new transmission must be built. One estimate for the construction of a 138 kV overhead line in Idaho suggests a cost of approximately $350,000 to $400,000 per mile.

Data from the Federal Emergency Management Agency (FEMA) is used to create a schematic representation of existing transmission routing. A distance between the centroid of each cell and the nearest line is calculated to provide an absolute value in meters. The values are then normalized using a utility function to assign a value of 100 for any absolute distance value less than the distance from a centroid to the corner of a cell plot (e.g. the line crosses the cell boundary). Higher values are then assigned utility values using a linear utility function. Both the schematic and the utility function are displayed in Figure 15



Selected Point -- Level: 13700 Utility: 1

Figure 15: A. Screen capture showing a schematic of the relative weighting of each grid cell for transmission infrastructure. **B.** Utility curve

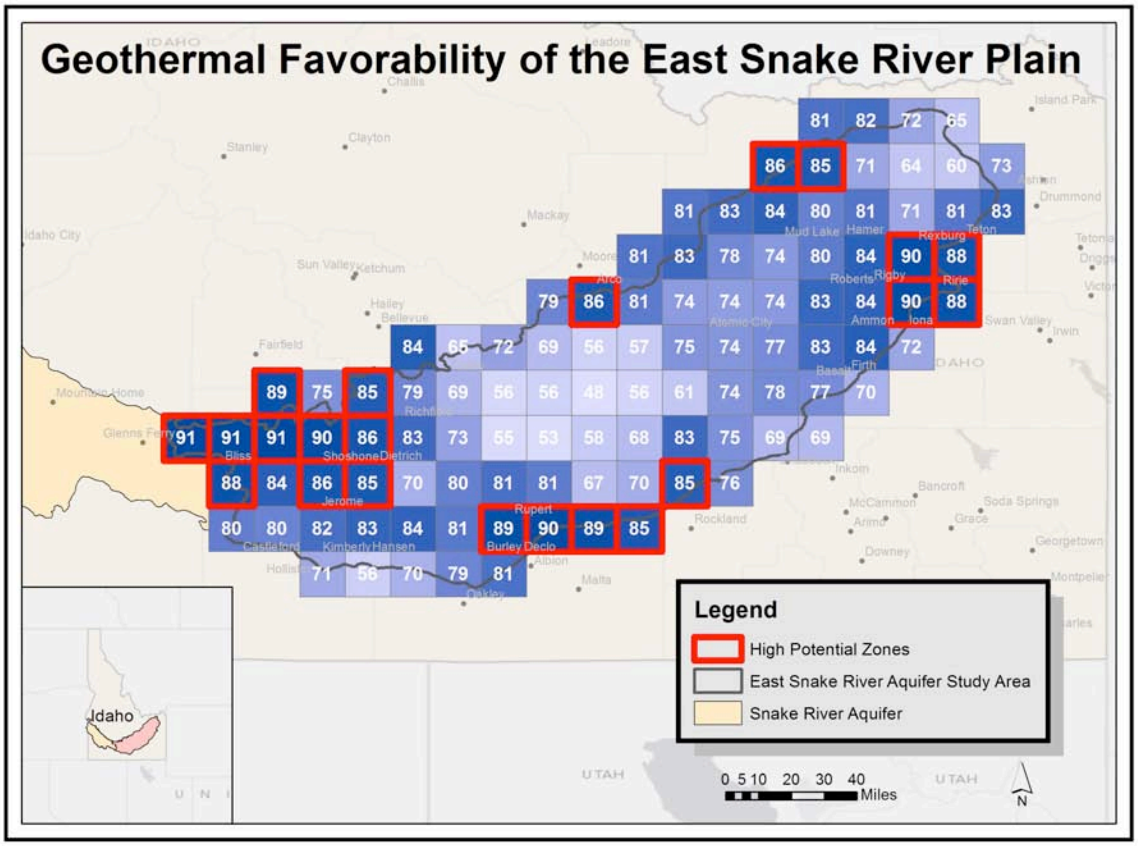


Figure 16: Geothermal development favorability map of the eastern SRP

Conclusions

The UT team's final assessment of geothermal favorability in the SRP is displayed in Figure 16. After construction of the final model, the team elected to highlight the 22 highest ranking grid cells as there was natural break and clustering in the data. The data displayed a natural break between the 22 highest rated cells which were clustered in 5 regional zones as shown in Figures 18-22.

The team conducted a micro-level secondary analysis of each zone and identified between one and ten development areas that met additional criteria for geothermal project siting. These criteria joined buffer zones in geologic and infrastructure requirements (tranmsissions, roads, and fault zones) and removed exclusionary zones (land use limitations, municipal boundaries, terrain suitability, and lakes and rivers). The remaining coverages represent the development areas with the highest potential for lowest cost project development which are shown in the figures for the 5 zones. This process is represented in the following categorical equation and described in Figure 17:

$$DA = (a_1 \cap a_2 \cap a_3) \cap (b_4 \cap b_5 \cap b_6 \cap b_7)$$

DA = Development Area , a_n = Required criteria, b_n=Exclusionary criteria

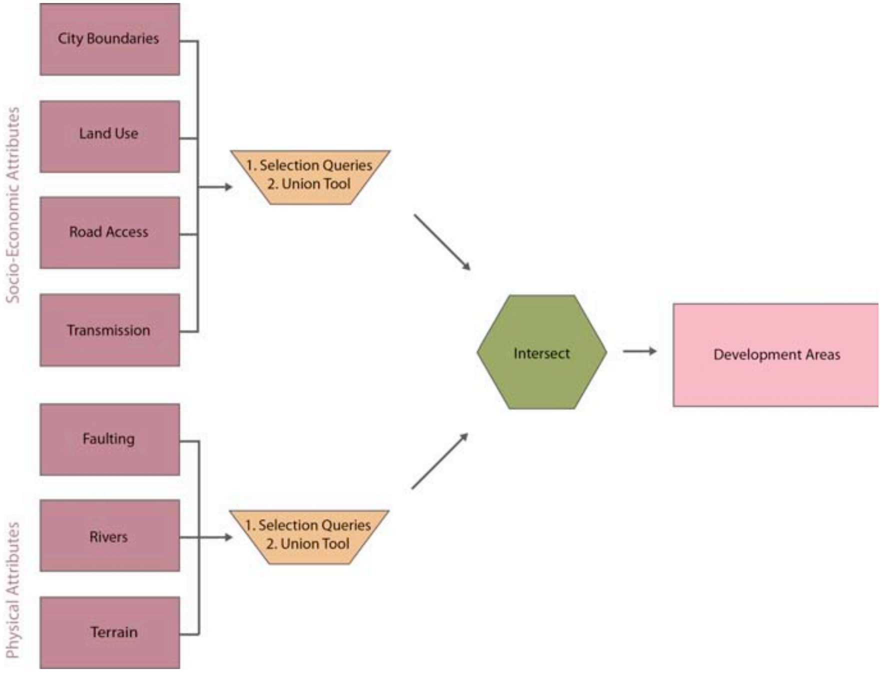


Figure 17: Diagram of the geospatial union process

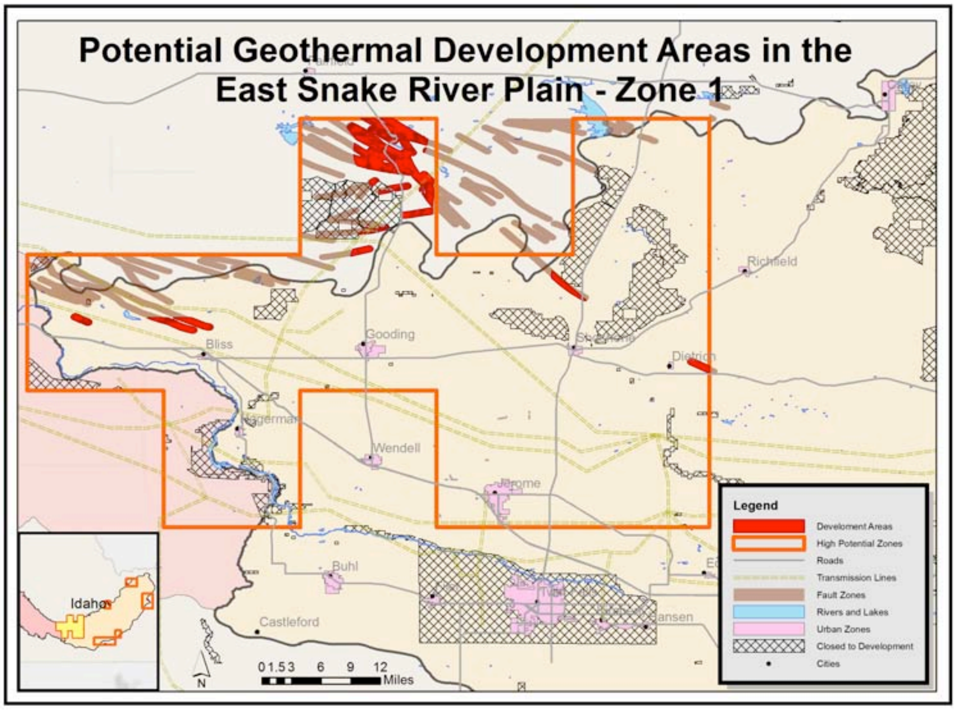


Figure 18: Zone 1 in the eastern SRP depicted potential areas for development based on modeled results.

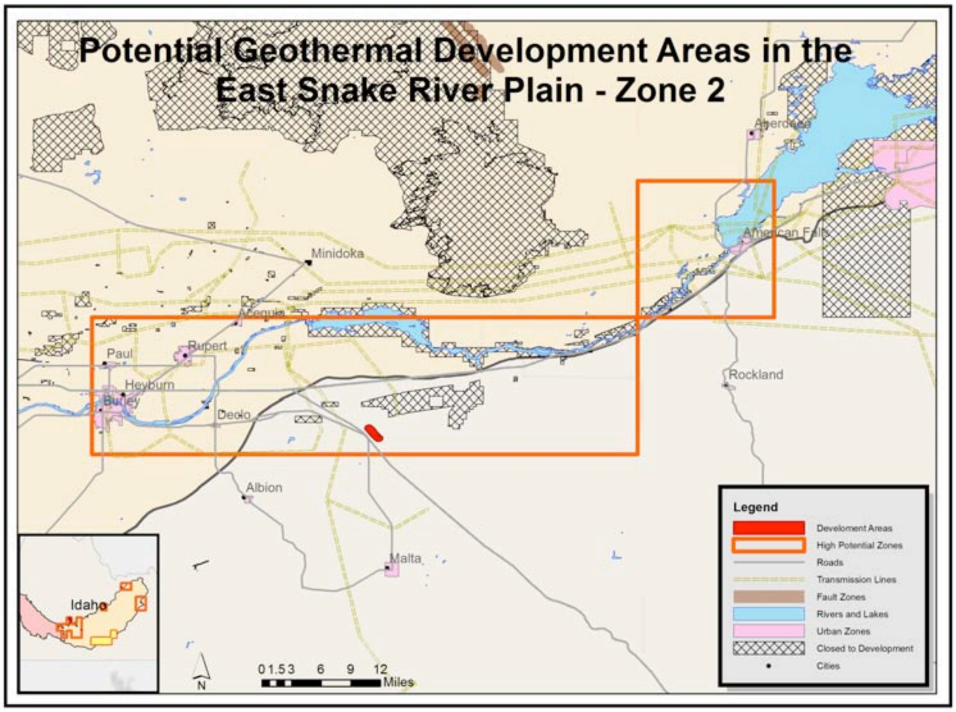


Figure 19: Zone 2 in the eastern SRP depicted potential areas for development based on modeled results.

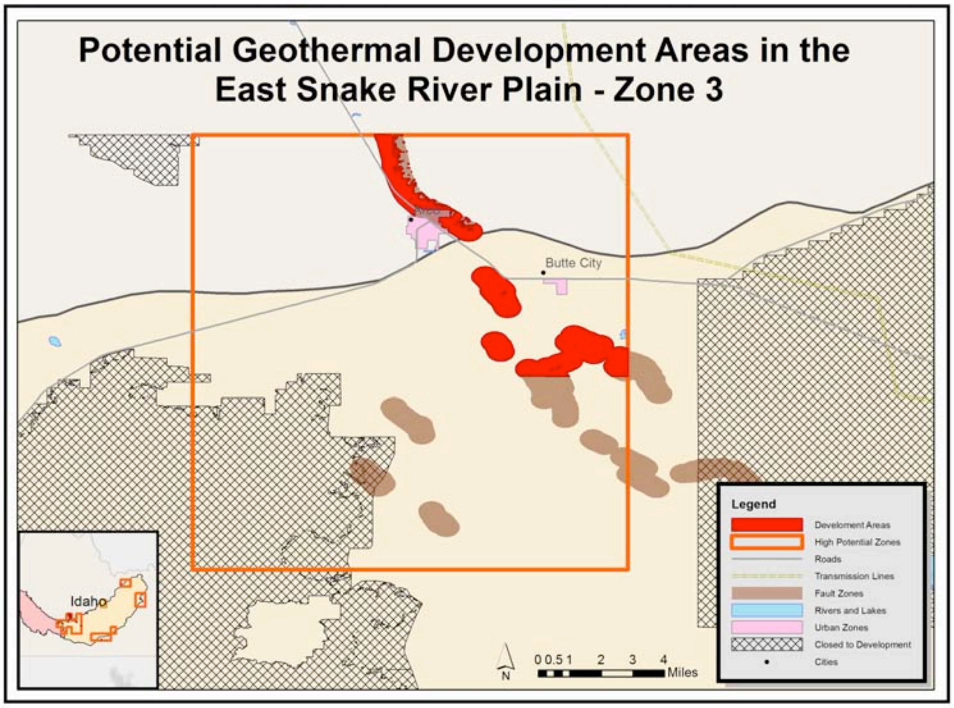


Figure 20: Zone 3 in the eastern SRP depicted potential areas for development based on modeled results.

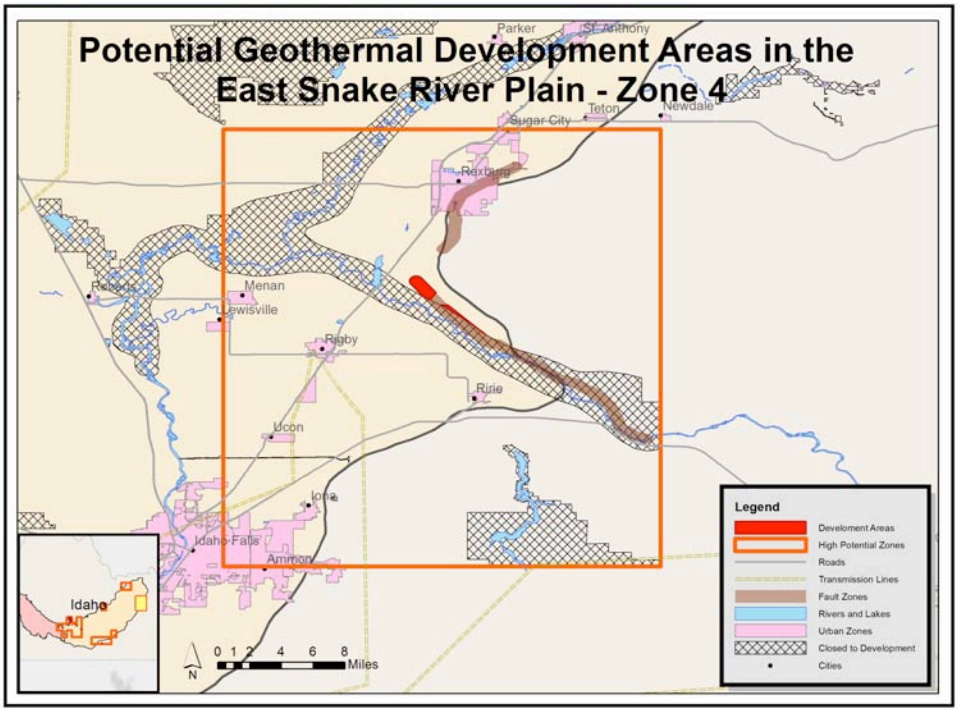


Figure 21: Zone 4 in the eastern SRP depicted potential areas for development based on modeled results.

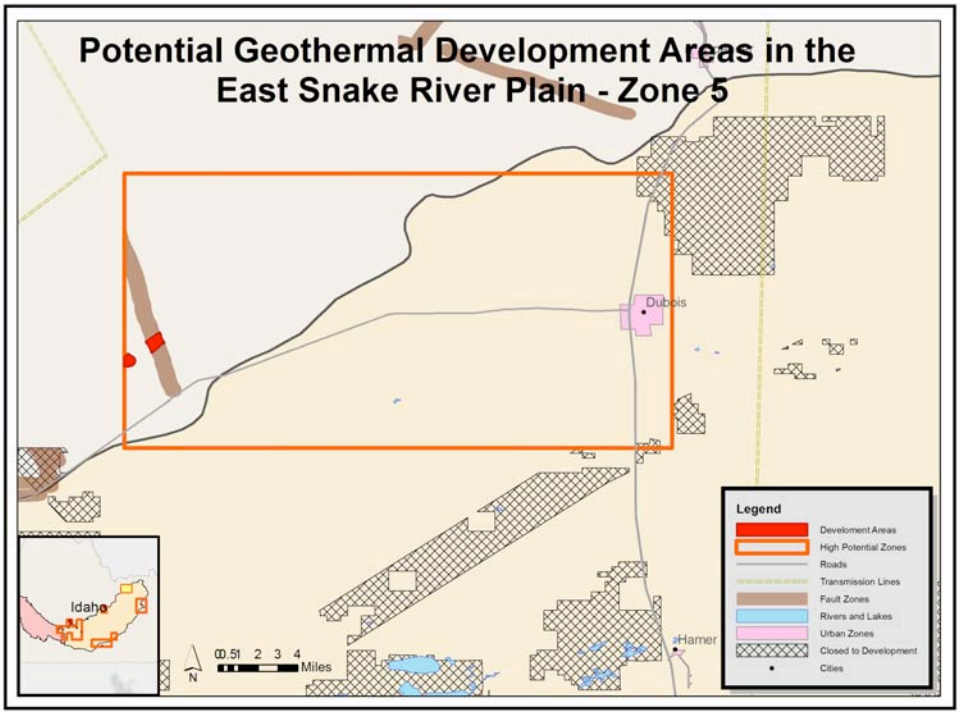


Figure 22: Zone 5 in the eastern SRP depicted potential areas for development based on modeled results.

The above results are based on our specified weighting, however future iterations of the model can be modified based on the user-defined weighting. Ultimately, the model worked as a proof of concept, which we will continue to develop by improve functionality and further exploring the integration of open source software.

Our geothermometry results proved to correlate with the initial strictly geological assessment of the high potential zones, in that the two highest reservoir temperature estimates—Heise and Milford Sweat—are located in the high potential zones. This validates the use of geothermometry as a final calibration step of the multi-attribute model, where the initial geological and economic assessment can delineate zones of feasible exploration and geothermometry can quantify the associated resource.

Future Work

The emerging field of Decision Support Systems engages groups to explore collaborative decision making with the use of multi-attribute models. These collaborative processes meld the use of scientific information with stakeholder participation and technical decision support systems (Pahl-Wostl, 2008). As collaborative approaches become more common, the need to educate decision makers with the capacity to explore complex scientific topics and participate in substantive dialogue will continue to be increasingly important.

The results of this project will be used in the Fall 2012 graduate course offering of Decision Pathways: Integrated and Adaptive Modeling for Energy and Earth Resources at The University of Texas at Austin. The application and development process will be presented and discussed in the course as an example of team design for collaborative and participatory modeling initiatives. Additionally, the application and touchscreen will be used to engage with the Serious Gaming High School course at a local Austin high school.

The application will also be presented at the Geothermal Center for Excellence in Chile as part of an on campus workshop at the Universidad de Chile in October and again at a follow-on event with indigenous community members at the El Tatio geothermal basin. Finally, the application will be presented at an informal outreach event in March 2013 called Explore UT, which is an on campus event open to the public that engages more than 50,000 students and families from around Texas.

Beyond this case-study of the SRP, the UT team believes new stakeholder outreach and decision support tools will be critical in the future development of geothermal technologies. The public attention to induced seismicity related to EGS projects provides a cogent example of where additional stakeholder education and engagement is needed to support development of new innovative technologies. To support and growth the geothermal community should embrace new disruptive technologies—like multi-touch—and actively apply them to exploration and development activities.

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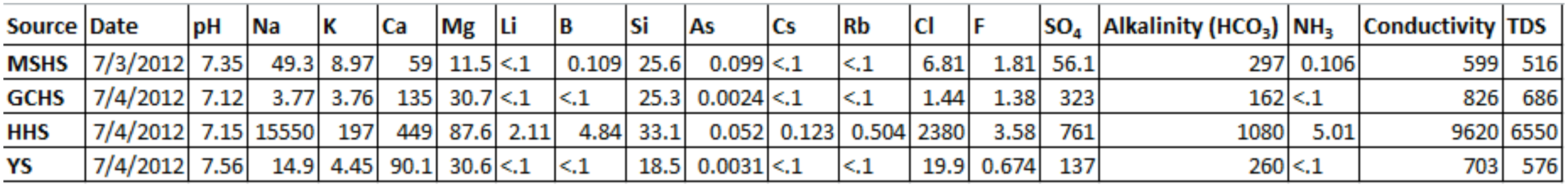
Appendix A: GIS Data Sources

Model Layers	Data Type	Data Sources	URL
Water Temperature	Spreadsheet	Mariner Database	http://hotspringchem.wr.usgs.gov/
		USGS NAWQA	http://infotrek.er.usgs.gov/apex/f?p=NAWQA:HOME:0
		SMU Geothermal Database	http://smu.edu/geothermal/georesou/resource.htm
Faults	Shapefile	USGS	http//earthquake.usgs.gov/regional/qfaults/
Basalt Thickness	Digital Map	USGS	http://imnh.isu.edu/digitalatlas/geo/snkrvpln/basalt/srpbslt.htm
Land Use	Shapefile	BLM	http://www.blm.gov/
		NPS	https://irma.nps.gov/App/Portal/Home
		IDWR	http://maps.idwr.idaho.gov/PLSLookup/Map
Transmission	Shapefile	FEMA	http://www.pasda.psu.edu/uci/FullMetadataDisplay.aspx?file=NREL_FEMATransmission.xml
Roads	Shapefile	Census MAF/TIGER	http://www.census.gov/geo/www/tiger/tgrshp2012/tgrshp2012.html
Terrain	Digital Elevation Model	USGS National Elevation Dataset	http://cloud.insideidaho.org/data/anonymous/elevation/ned/1999_30m_idaho/metadata.xml

Appendix B: Geochemical Analysis Results

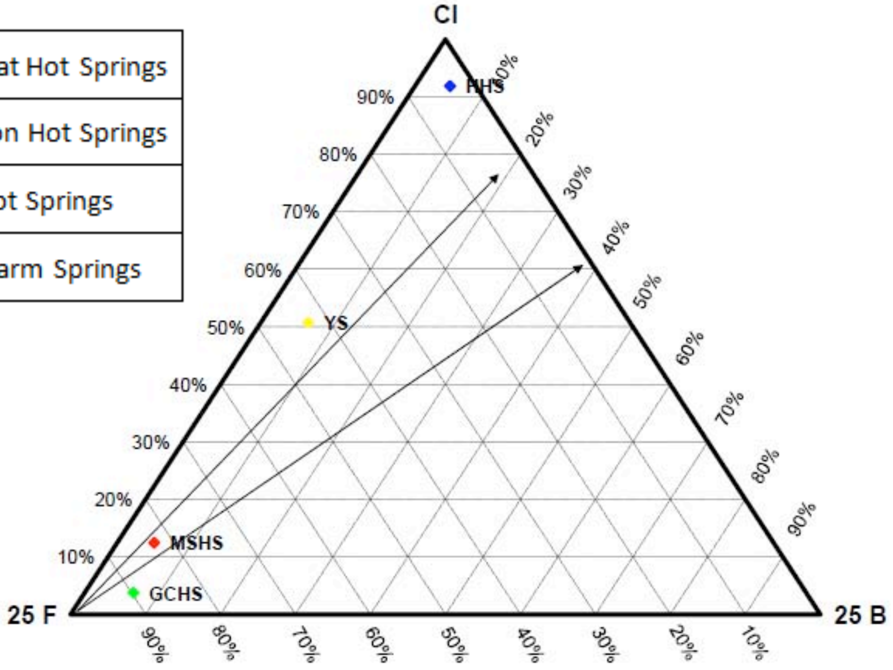
MSHS	Milford Sweat Hot Springs
GCHS	Green Canyon Hot Springs
HHS	Heise Hot Springs
YS	Yandell Warm Springs



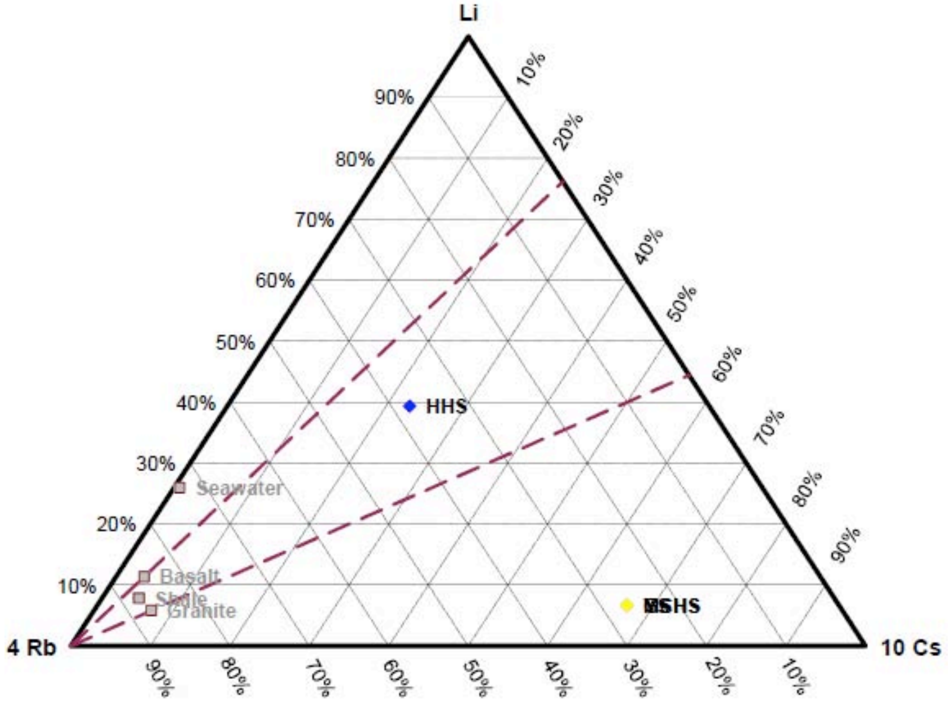
Source	Date	pH	Na	K	Ca	Mg	Li	B	Si	As	Cs	Rb	Cl	F	SO_4	Alkalinity (HCO_3)	NH_3	Conductivity	TDS
MSHS	7/3/2012	7.35	49.3	8.97	59	11.5	<.1	0.109	25.6	0.099	<.1	<.1	6.81	1.81	56.1	297	0.106	599	516
GCHS	7/4/2012	7.12	3.77	3.76	135	30.7	<.1	<.1	25.3	0.0024	<.1	<.1	1.44	1.38	323	162	<.1	826	686
HHS	7/4/2012	7.15	15550	197	449	87.6	2.11	4.84	33.1	0.052	0.123	0.504	2380	3.58	761	1080	5.01	9620	6550
YS	7/4/2012	7.56	14.9	4.45	90.1	30.6	<.1	<.1	18.5	0.0031	<.1	<.1	19.9	0.674	137	260	<.1	703	576

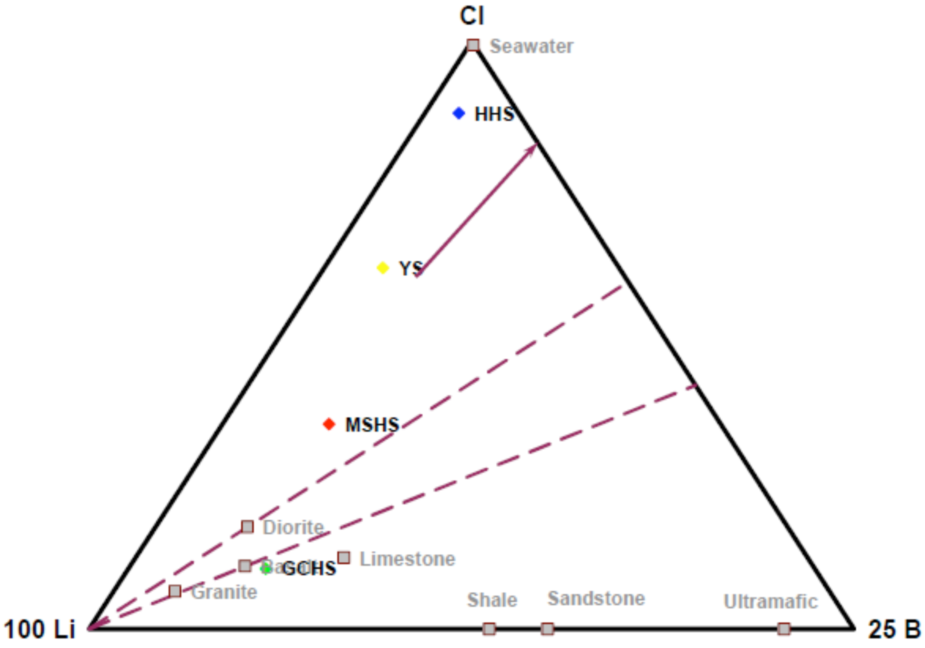
Appendix C. Geothermometry plots used in the determination of reservoir temperature estimates.

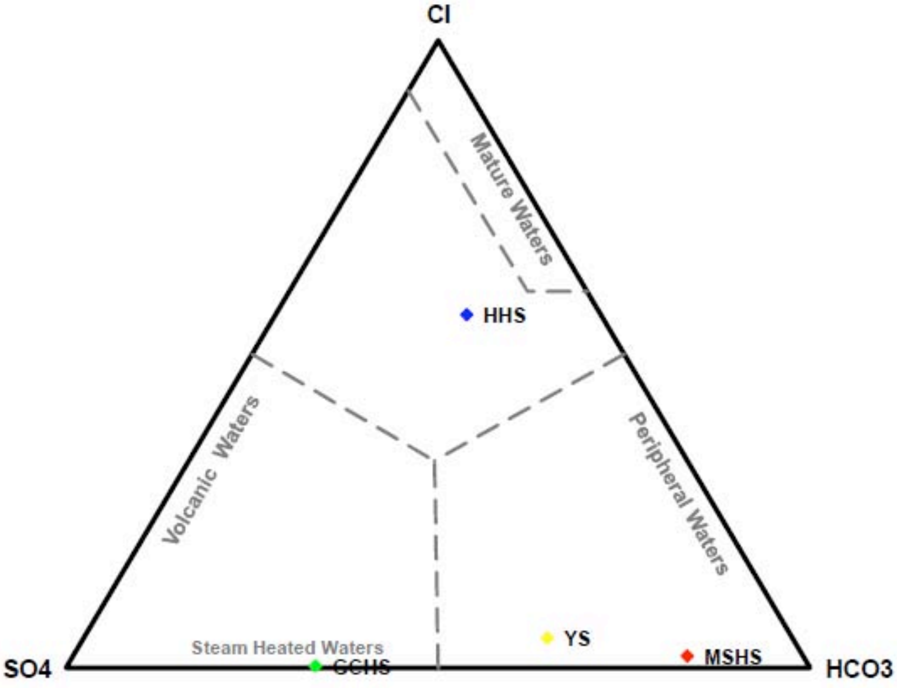
MSHS	Milford Sweat Hot Springs
GCHS	Green Canyon Hot Springs
HHS	Heise Hot Springs
YS	Yandell Warm Springs

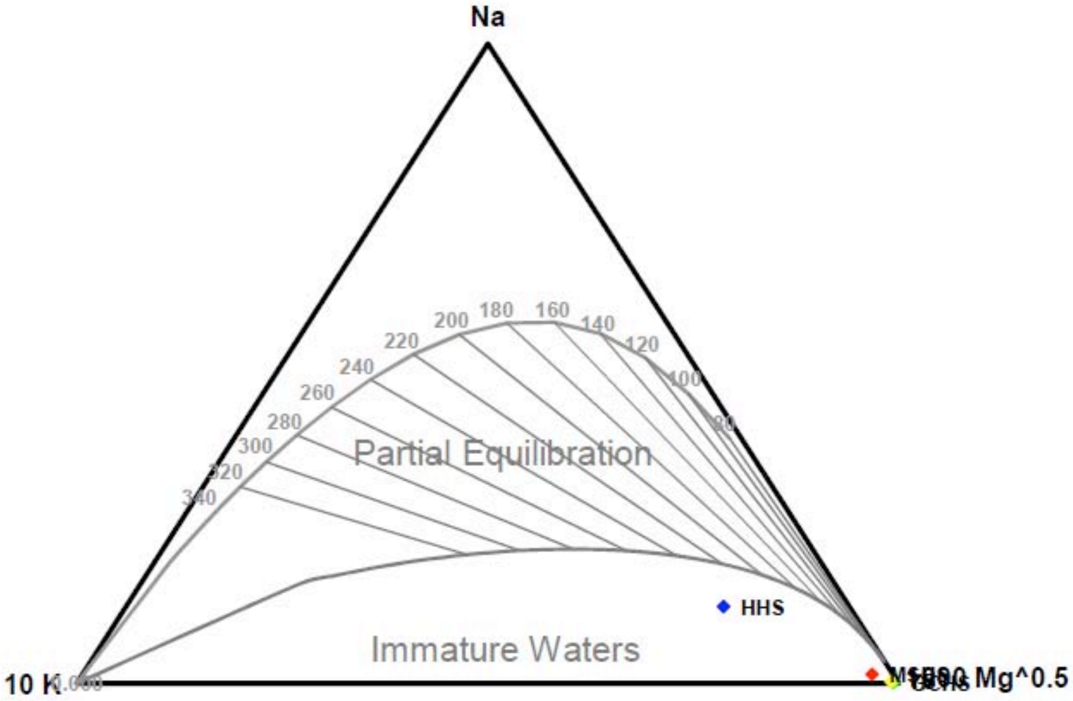


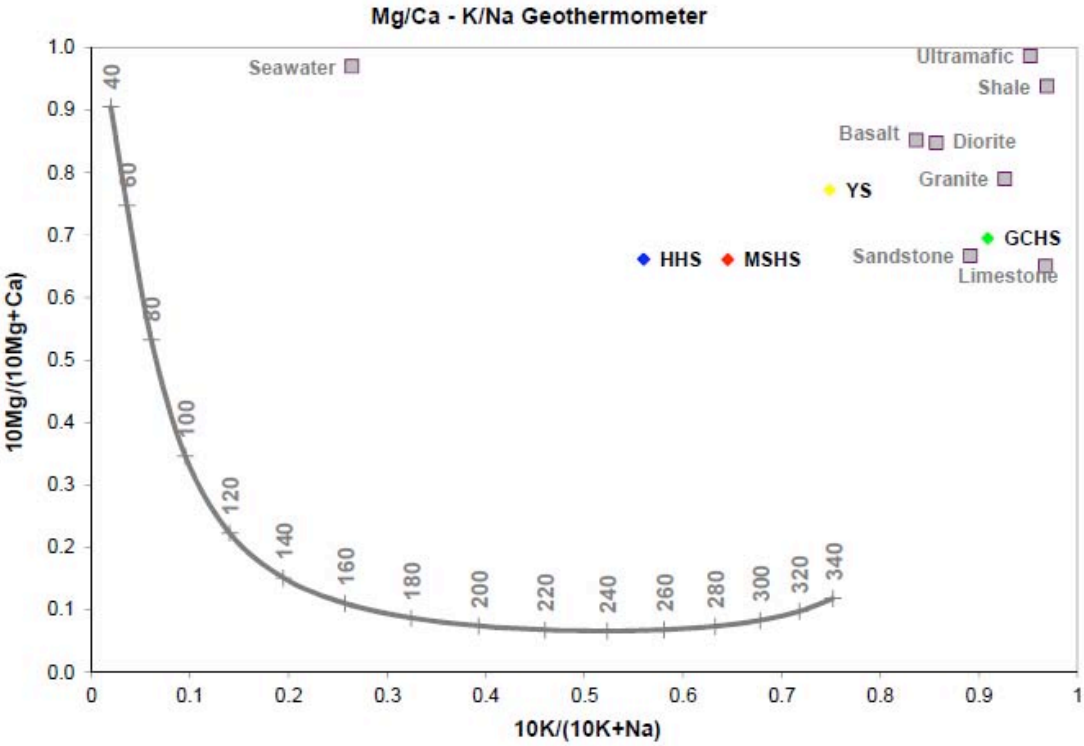
Li - Rb - Cs Ternary

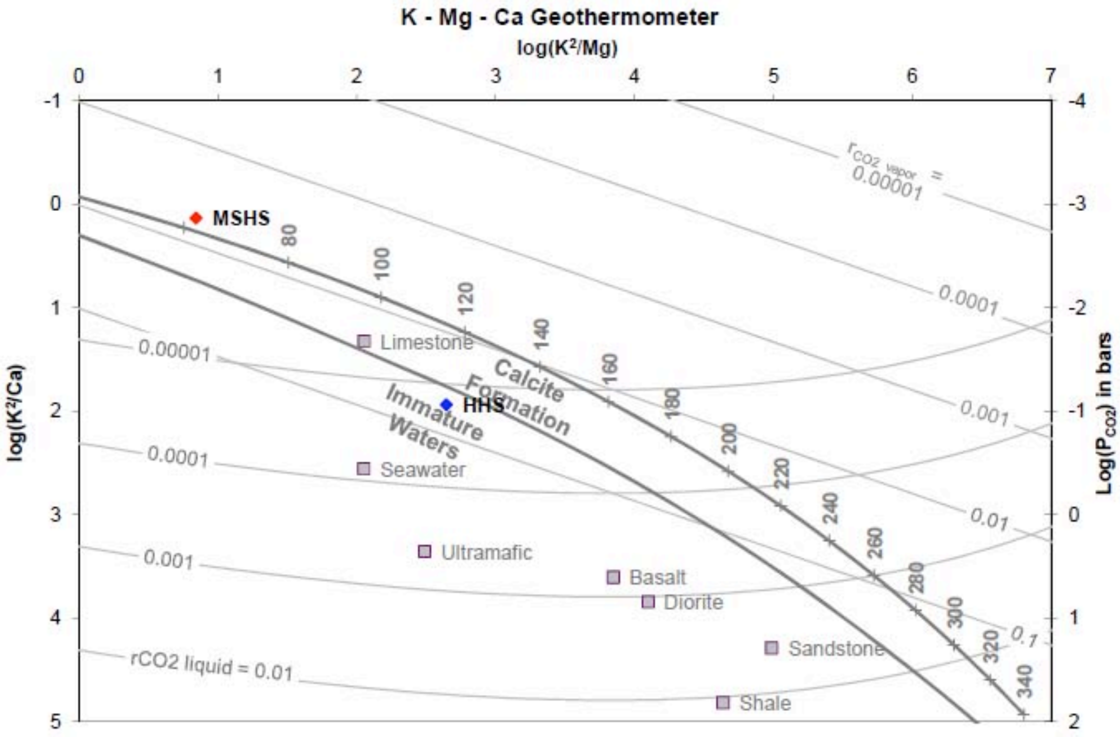


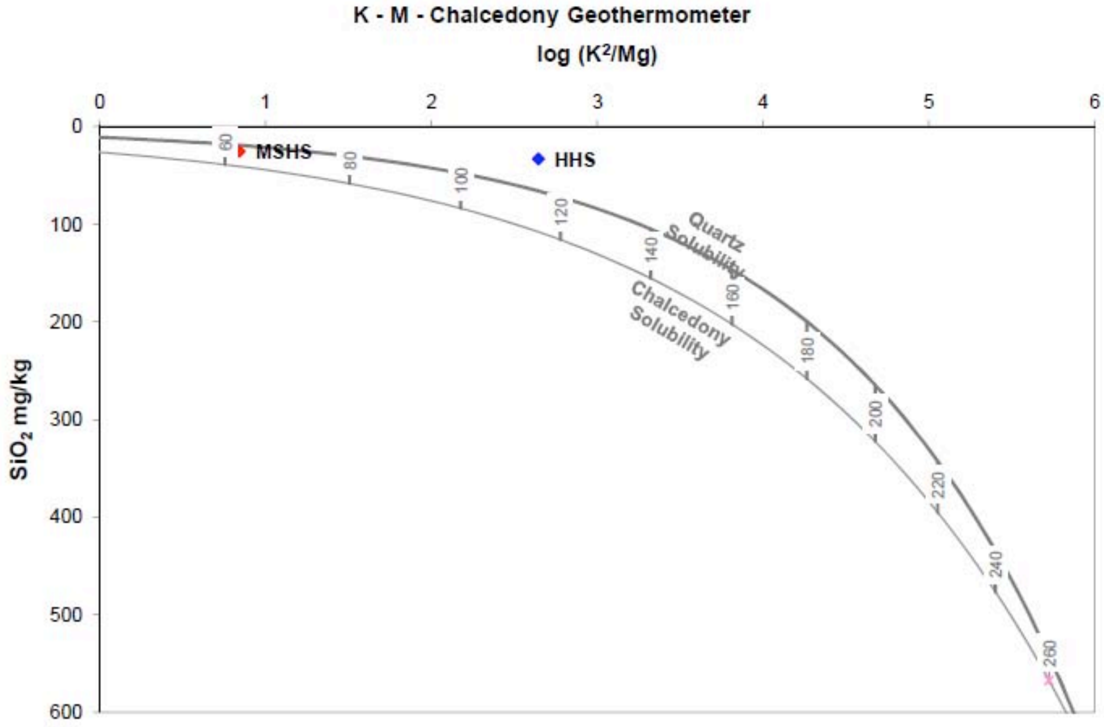

Cl
Seawater
HHS
YS
MSHS
Diorite
Basalt
GCHS
Limestone
Granite
Shale
Sandstone
Ultramafic
100 Li
25 B


Cl
Mature Waters
HHS
Volcanic Waters
Peripheral Waters
YS
MSHS
Steam Heated Waters
GCHS
SO4
HCO3


Na
200
180
160
140
120
100
80
220
240
260
280
300
320
340
Partial Equilibration
Immature Waters
HHS
MSHS
YS
GCHS
10 K
Mg^0.5


Mg/Ca - K/Na Geothermometer
10Mg/(10Mg+Ca)
10K/(10K+Na)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
Seawater
Ultramafic
Shale
Basalt
Diorite
Granite
YS
GCHS
HHS
MSHS
Sandstone
Limestone


K - Mg - Ca Geothermometer
log(K²/Mg)
0
1
2
3
4
5
6
7
log(K²/Ca)
-1
0
1
2
3
4
5
Log(P_CO2) in bars
-4
-3
-2
-1
0
1
2
rCO2 vapor = 0.00001
0.0001
0.001
0.01
0.1
0.00001
0.0001
0.001
rCO2 liquid = 0.01
MSHS
HHS
80
100
120
140
160
180
200
220
240
260
280
300
320
340
Calcite Formation
Immature Waters
Limestone
Seawater
Ultramafic
Basalt
Diorite
Sandstone
Shale


K - M - Chalcedony Geothermometer
log (K²/Mg)
0
1
2
3
4
5
6
SiO2 mg/kg
0
100
200
300
400
500
600
MSHS
HHS
60
80
100
120
140
160
180
200
220
240
260
Quartz Solubility
Chalcedony Solubility