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RIFT ZONES AS A CASE STUDY FOR ADVANCING GEOTHERMAL OCCURRENCE MODELS

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ABSTRACT

To search efficiently for blind geothermal systems, general geographic regions must first be identified based upon gross characteristics which together imply favorable heat flow, fluid flow, and permeability. Geothermal occurrence models seek to strategically identify those promising locations to focus exploration efforts and investment. In so doing, such models can increase the expected success rate of exploratory drilling, reduce risk, and attract investment. Among the most promising tectonic settings for blind geothermal systems are rift zones. Rift zones occur where lithospheric plates are thinned by tectonic extension and convection at zones of upwelling hot material. The continued supply of magma to this separation zone increases heat flow and thermal energy at shallower depths than in other tectonic settings. Given the inherent qualities of rift zones, the frequency of geothermal anomalies should be relatively high, making them attractive targets when searching for blind hydrothermal resources. Geothermal occurrence models specify characteristics (e.g., rock type, stress field, fault geometry, hydrology, local volcanism, etc.) that indicate where to find a blind resource within a rift zone. In this paper, we review literature contributions to the development of geothermal occurrence models and explore rift zones as a case study for their application. We identify the key data and analytical tools that are necessary to advance these models to effectively and efficiently inform regional-scale resource assessment.

INTRODUCTION

Most of the utility grade resources in the U.S. with obvious surface manifestations are either developed or fully characterized. If geothermal electricity generation is to increase significantly in the U.S., new blind hydrothermal resources must be identified and characterized. Unfortunately, geologic structure and formation data are often sparse or incomplete, introducing a high level of risk to a geothermal industry seeking blind systems. To increase the success rate of costly exploratory drilling, upfront investment in exploration and resource characterization is necessary. An essential component of early stage exploration is a geothermal occurrence model (e.g., Walker et al., 2005) to provide the framework for the set of characteristics to be sought during exploration. A broader overview of the technology pathways necessary to achieve cost reduction through improved exploration technologies is detailed in a strategic roadmap by the Geothermal Technologies Office, U.S. Department of Energy describes (Phillips et al., 2013).

A geothermal occurrence model describes a set of geophysical, geochemical, tectonic, structural, and geological features that are associated with a geothermal resource, or a "geothermal play". (A play is a repeating set of prospects with common characteristics, and a “play fairway” is the geographic area over which those prospects are thought to extend.) These occurrence models can provide a pathway toward integrating a variety of observations into a quantitative assessment of resource, or play, potential. Figure 1 is a conceptual flow chart of an occurrence model. The inputs are data regarding the geothermal potential; the model itself is a combination of descriptive conceptual models and quantitative spatial association analysis; and the outputs are exploration products that help quantify the resource potential and/or risk profile of geothermal development.

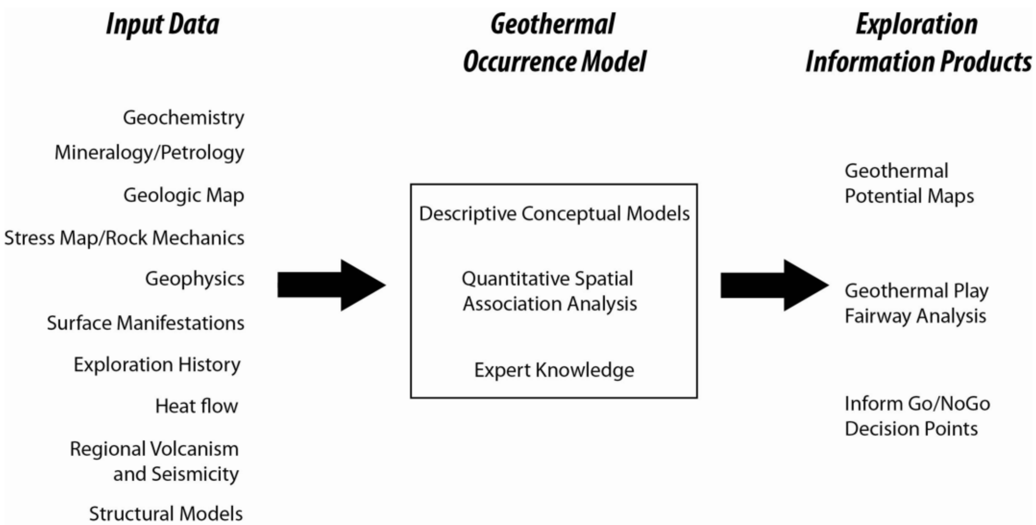

Figure 1: Conceptual flow chart of the implementation of a geothermal occurrence model.

Evaluating risk and uncertainty with incomplete and sparse data is a major challenge faced by the geothermal industry. Robust occurrence models, and their application to decision points and exploration products, can accurately assess the risk profile of a given play or prospect and rank the relative importance of missing data. Additionally, this approach is growing more relevant with the development and expansion of the National Geothermal Data System (http://geothermaldata.org/). Continued refinement of geothermal occurrence models will be essential for leveraging these data to discover new blind hydrothermal resources.

In this paper, we review the established characteristics of geothermal systems. We also review several strategies implemented in geothermal (and other resource) exploration scenarios to address the problem of imprecise or non-explicit parameters and values. We will focus on reviewing occurrence models for extensional rift systems with the goal of developing a framework for resource occurrence models that is adaptable to diverse settings and upcoming advances in exploration technology. Some characteristics are applicable in multiple tectonic settings, but each individual geothermal play has its own occurrence model that accounts for why heat, fluid, and permeability are present in that setting. Understanding existing and new models for geothermal reservoirs is key to unlocking additional resource potential.

This paper focuses on hydrothermal system occurrence models, with the goal of synthesizing information that could be useful in prospecting for blind hydrothermal systems. However, exploration efforts for hydrothermal systems are closely coupled with exploration for potential sites for enhanced geothermal systems (EGS).

For EGS, heat is necessary, but the criteria related to fluid and permeability are somewhat relaxed. Permeability is created through reservoir stimulation, and the water or other working fluid does not necessarily need to be derived from the engineered reservoir. Ideal prospects for EGS may be a subset of sub-optimal hydrothermal sites that have a favorable stress state and rock mechanical properties that are well-suited for reservoir stimulation.

CHARACTERISTICS OF GEOTHERMAL RESOURCES

In the following sections, we review characteristics of a variety of geological settings with geothermal resources associated with active extensional tectonics. In Table 1, the general characteristics are summarized within the screening protocol framework presented by Walker et al. (2005). The broadest scale characteristics are at the regional scale, which includes traits that indicate geothermal potential without identify specific regions for detailed exploration. The prospect scale characteristics help to focus exploration to more specific targets. Finally, the project scale traits inform the decision of specifically where to drill exploration wells. This paper is not intended to be an exhaustive review of geothermal occurrence characteristics, but these sections should provide an overview of components of a generalized occurrence model and of key components that might constitute region-specific occurrence models. Our focus is on structural/geological controls for geothermal systems, which is reflective of the emphasis of much of the published work on geothermal occurrence models.

Rift Zones as Geothermal Targets

Basin and Range

The superposition of the regional effects of extension and volcanism/intrusion with complex localized structural settings make geothermal prospecting in the Basin and Range both promising and difficult. Though large scale structures such as grabens and their associated moderate to steeply-dipping normal faults may act as a primary structural control on upwelling geothermal fluids, not every extensional structure hosts an electricity-grade geothermal resource. Localized controls, those which must be identified at the prospect level include step-overs, relay ramps, fault intersections and normal terminations or tip-lines, which host most of the geothermal systems in the Great Basin (Faulds et al. 2012). Multiple overlapping fault strands and intersections between normal faults increase the fracture density and thus enhance permeability and concentrate geothermal fluids (Blackwell et al. 2012, Faulds et al. 2012, MacLachlan et al. 2011, Jolie et al. 2012). Further, any zone accommodating greater dilation than other segments, coupled with multiple fault strands near fault bends or jogs, may exhibit concentrated zones of stress and the reactivation of basement structures and deep intersections of multiple faults to promote the deep circulation of fluids (Hinz et al. 2011). Finding competent lithologies suitable for a geothermal reservoir coincident with these favorable structural setting is critical to locating an electricity-grade geothermal system (Hinz et al. 2011).

East African Rift Zone

The East African Rift is a system of classic grabens about 40-80 km wide, and is an example of an intracontinental divergence zone where rift tectonism is accompanied by intense volcanism from the late Tertiary to present. The central section of the East African Rift System corresponds to the Kenya Dome, an area of crustal uplift and thinning. As the dome formed, it stretched and fractured the outer brittle crust into horst and graben structures and associated normal faults typical of rift valleys. Volcanism in the rift system is consistent with a large magma chamber at relatively shallow depths (Alexander and Ussher 2011). Geothermal fields are numerous, and are characterized by high temperatures (~300 °C) and shallow heat sources (~6 km), and indicated by geothermal surface manifestations such as fumaroles, steam jets, steaming and solfatara (Alexander and Ussher 2011, Simiyu 2012). Geothermal manifestations are typically located along the margins of calderas, within summit craters, within trenches, and flank eruption centers (Alexander and Ussher 2011). Reservoirs are hosted by trachyes and other volcanic units (Njue 2012). Recharge of systems is controlled by the rift's deep-seated master faults along the rift scarps, rift axis and ring structures surrounding caldera collapse (Njue 2011, Ng'enoh and Ochieng 2011). The rift zone is characterized by numerous minor faults, tension cracks and fissures which are associated with the eruption of large volumes of

Table 1: Characteristics of geothermal resources. This table was derived from numerous sources; the identification of key papers is denoted by superscript ([1]Sabin et al. 2004, [2]Walker et al. 2005, [3]Hulen and Nielson 1990, [4]Faulds et al. 2011, [5]Blackwell et al. 2012)

	Regional	Prospect	Project
Heat	• Elevated heat flow signature[1,2]	• Association with young volcanism/magmatism[1,2,3] • Sufficiently high groundwater temperature gradients[1,2,3]	• Shallow fluids with high temperature[1,2,3] • Surficial hydrothermal manifestations[1,2,3]
Permeability	• Regional seismicity indicative of faulting and active deformation[1,2]	• High strain rates and/or localized deformation[1,2] • Active seismicity and faults with recent activity[1,2,3] • Association with intersections of complexities in faulting patterns[3,4,5]	• Intersection of regional and local faulting with high fracture density[3,4,5]
Fluid	• Hydrologic observations of regional groundwater circulation	• Groundwater chemistry suggesting input from a deep, hot geothermal reservoir[1,2,3]	• Localized geophysical anomalies including gravity, self-potential, and resistivity[1,2] • Surficial hydrothermal manifestations[1,2,3]

basalt lava (Ng'enoh and Ochieng 2011). Surface manifestations are concentrated at fault intersections (Simiyu 2012). Heat sources are field dependent, and may be deep dyke swarms along the faults or shallow magmatic bodies underlying the volcanoes (Simiyu 2012, Ng'enoh and Ochieng 2011, Njue 2011). Signatures of geothermal potential include young volcanism within and outside calderas, large caldera collapse and intense tectonics resulting in intense faults marking the area. Surface manifestations also indicate hydrothermal activity and possibility of geothermal reservoirs (Njue 2011). Oil and gas exploration is a ubiquitous presence in the East African Rift Valley. These efforts provide abundant exploration data that can be leveraged for geothermal exploration. Also promisingly, oil and gas exploration has revealed highly complex and localized structures and characteristics conducive to permeability, fluid flow, and heat (Karp et al. 2012, Lezzar et al., 2002, Lyons et al. 2011, Koehn et al. 2010).

Rio Grande rift

The Rio Grande Rift forms the eastern boundary of the Basin and Range. The region has many traits that suggest is a particularly promising candidate for geothermal exploration. The recent EarthScope Rio Grande GPS experiment has provided much more detailed data on the rates and patterns of deformation in the regions (Berglund et al. 2012). This experiment and the recent presence of the EarthScope transportable array could be leveraged to launch a detailed geothermal play fairway analysis of the Rio Grande rift.

The Rio Grande Rift consists of a series of asymmetric grabens bound by young, steeply dipping normal faults. The central rift valley widens significantly from north to south, averaging about ~50 km, and is about 1000 km long (Figure 2). Though presently at a low level, tectonism and volcanism in the Rio Grande rift has been active in the past. The region underwent a polyphase tectonic history, most recently two phases of extension: low angle faulting and shallow basin creation (30-18 Ma) followed by high-angle faulting and graben creation (10-5 Ma) (Keller et al. 1991, Wilson et al. 2005). Volcanic activity has been similarly phased. The most recent volcanism, beginning about 18 Ma, has occurred along and adjacent to the rift valley. The youngest volcanism of this recent phase occurs along the Jemez Lineament (~40 ka).

The Rio Grande Rift is still active and is associated with high heat flow, vertical movements , seismic activity and young faults scarps. Patterns of seismic activity correlate with rift structures, extension, and strike-slip faulting. Heat flow is high in the Rio Grande rift, and the circulation of groundwater is responsible for a large standard deviation in heat flow values along the rift. Recent volcanism, hot springs, and other geothermal features are obvious indicators of geothermal reservoirs. These geothermal anomalies within the rift system are associated with transfer and scissor faults, accommodation zones, and fault intersections (Easley et al 2011). There is a broad conductive heat anomaly underlying the Rio Grande rift possibly due to lower crustal intrusion and pre-rift volcanism, as well as highly localized heat flow maxima related to groundwater flow and younger upper crustal magmatism (Keller et al. 1991). Major structural intersections and concealed caldera ring-fracture zones, coupled with complex normal faulting and local young volcanism suggests a utility-grade geothermal resource in the Rio Grande rift area (Hulen and Nielson 1990).

The Rio Grande rift's relatively small volume of rift-related volcanism is likely due to the regionally elevated geotherm at the time of rift initiation indicated by ignimbrite volcanism ~30 Ma. The subducting Farallon plate may have created a zone of thermally weakened lithosphere beneath the region, which, when coupled with the low strain rate of the region, resulted in the laterally distributed lithospheric deformation approximately four times the width of the rift's surface expression. The low concentration of vertical mantle upwelling and less vigorous small-scale convection limited the amount of heat delivered to the shallow rift, resulting in a relatively small volume of volcanism compared to other rift systems (Wilson et al. 2005).

Despite the relative dearth of volcanism, the Rio Grande rift is an attractive candidate for geothermal exploration (Barse et al. 2012, Boyd et al. 2011, Easley et al. 2011).

Baikal Rift Zone

The Baikal Rift Zone, Siberia, is another example of an intracontinental rift zone with significant geothermal potential. The Baikal Rift forms the boundary between the Siberian craton to the north and northwest and the Sayan-Baikal fold belt to the south and southeast. The average heat flow within the Baikal Rift is relatively low, 40-75 mW/m^2, compared with 100-115 mW/m^2 in the Rio Grande, Rhine, and Kenya rifts (Lysak, 1992). The relatively low heat flow is consistent with a high effective elastic thickness of 30-50 km and suggests that Baikal is stronger and colder than other continental rift zones (Petit et al. 1997). Seismic analysis of the mantle structure beneath the Baikal Rift suggests that rifting is driven by mantle anomalies; however,

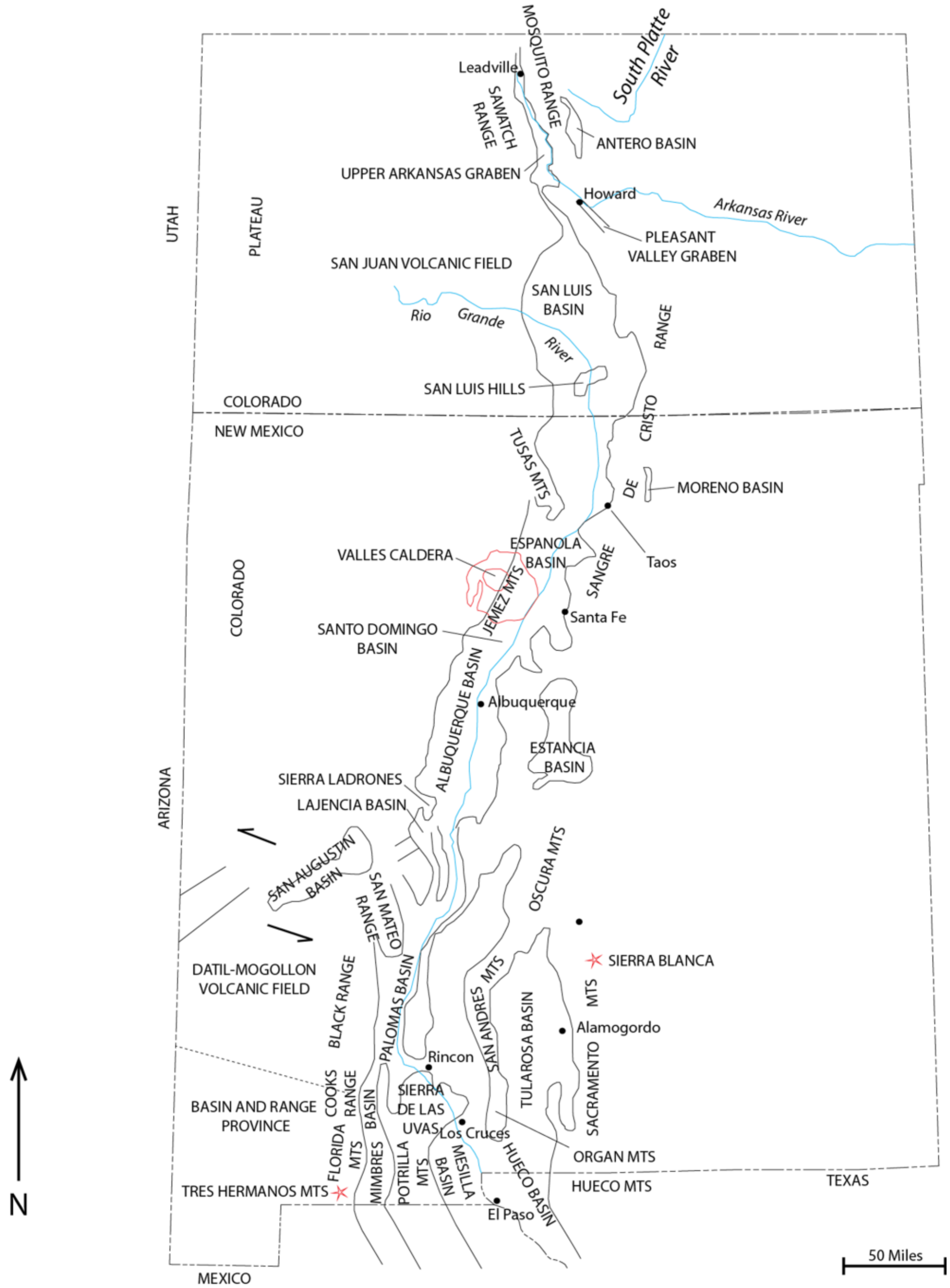

Figure 2: Generalized map of the Rio Grande rift (after Chapin and Seager, 1975).

similar to the Rio Grande Rift, the axes of the mantle anomalies are not directly aligned with the surface grabens (Gao et al. 1994). The asymmetry of mantle upwelling may be a major factor for why there is greater magmatism and higher heat flow in the Kenya rift. However, important variations in structure within the rift exist, and there are locations with clear surface expressions of geothermal activity. Cenozoic activity led to the formation of en echeloned rift basins within the rift zone form local thermal anomalies (Logachev, 1994).

Rhine Graben Rift - Soultz

The Soultz horst structure is located at the western boundary of the Upper Rhine Graben, the Upper Rhine Graben representing a typical example of synorogenic, intra-continental foreland rifting (Baillieux et al. 2011 & 2012). The formation of the Upper Rhine Graben is the result of a multiphased tectonic history: extension followed by transpressional and transtensional tectonics (Place et al. 2011 and Dezayes et al. 2010). The underlying granite is the target for geothermal development in this region, the Paleozoic granite basement containing the deep fault structures that control the major fluid flow paths and the hydraulic connections within the geothermal reservoir (Place et al. 2011, Dezayes et al. 2010). The geometry of the fracture zones in the underlying granite are different from the overlying sedimentary cover which corresponds to the extension and graben formation (Dezayes et al. 2010). Therefore the faulting related to the Oligocene extension does not seem to have an important role in the present day fluid circulations, and instead masks the controls on the existing geothermal reservoir.

DEVELOPING QUANTITATIVE SPATIAL RECOGNITION CRITERIA

Resource potential mapping draws upon both knowledge-driven methods in which expert knowledge is used to weight the importance of criteria, and data-driven methods in which quantitative analysis of spatial associations between evidence and known geothermal resources is applied (Carranza et al. 2008). Synthesis of the geological knowledge of regions and structural models of how permeability and fluid circulation are driven in a certain region, such as is reviewed in the preceding sections, forms a basis for knowledge-driven methods. Experts who can integrate geological data sets are essential to the exploration process.

Spatial distribution analysis is another important method for analysis of data to identify which geological features indicate the presence of a resource. In evaluating the geothermal potential of West Java, Indonesia, Carranza et al. (2008) compared several methods of spatial distribution analysis. Fry analysis (Fry, 1979) is a geometrical method of spatial autocorrelation that enhances subtle patterns in spatial distribution based on distance and orientation. This analysis can be particularly useful in geothermal exploration to identify if a specific orientation or trend of structures is associated with geothermal resources. Another method, spatial frequency analysis, clearly highlights if there is a specific distance interval from a type of geological feature at which a geothermal resource is likely to occur. A curve of the distribution of geothermal occurrences at cumulative distances from a category of geological features (such as northeast trending faults) is compared to a curve of the distribution of random points (Bonham-Carter, 1994). If the curves are similar, then geothermal resources are randomly distributed relative to the geological feature, but deviations from a random distribution can highlight relationships that should be incorporated into occurrence models for the region. These and other methods of spatial analysis are relatively cheap to conduct and can be performed with standard GIS software. Their implementation can leverage the rapidly accumulating amount of data relevant to geothermal exploration in order to inform geothermal exploration.

USING OCCURRENCE MODELS FOR DECISION-MAKING

The ultimate purpose of establishing spatial recognition criteria and geothermal occurrence models is to inform decision-making in the exploration and development process. Occurrence models are an essential component of a geothermal play fairway analysis and can be applied in several different ways depending upon the situation and the desired exploration information product (Figure 1). For example, occurrence models might be used to create a resource potential map, to inform go/no-go decision points in regional reconnaissance, or to inform the specific location of the next exploration well in a geothermal field. In this section we review methods that have been used in geothermal exploration as well as methods used to characterize other resources.

Screening Protocols

The general workflow of a geothermal developer flows from large scale to small scale, with increasingly dense and diverse data coverage at smaller scales. Nonetheless, exploration decisions must always be made within a framework of uncertainty. Walker et al. (2005) presented a screening protocol that captures the steps to delineating a geothermal resource. The protocol consists of three stages: regional reconnaissance, prospect identification, and project appraisal with a go/no-go decision point between each phase (Table 1). However, the approach is adaptable to different numbers of decision points.

The emphasis in the screening protocol, as formulated by Walker et al. (2005) is on the types of data collected, rather than the specific characteristics that should be observed in order to merit a 'go' at the decision point. At the broadest geographical level, the data are generally of the type that is publicly available, and the costs associated with this phase are primarily in processing the data. These data types include regional seismicity, various remote sensing imagery, and published papers and maps detailing the regional geology and structures. The next phase in the screening protocol, prospect identification, includes both a broader review of existing data and additional geophysical, geochemical, and petrological data that are either purchased or collected. The final phase, project appraisal, involves detailed field surveys, field mapping, and exploratory drilling.

The final phase is by far the most expensive phase due to the high cost of drilling. It represents a significant investment and is the phase at which a developer assumes the greatest risk. The goals of exploration are to 1) minimize the number of viable resources that are eliminated early in the screening process (false negatives) and 2) minimize the number of non-economic projects that incur the costs of exploratory drilling (false positives). Developing more sophisticated and adaptable occurrence models for discovering blind hydrothermal resources is central to this effort.

The screening protocol is a practical method that fits well with the workflow of a geothermal developer. This method is an effective way to assess the potential of a prospect or project at several well-defined decision points to prevent unnecessary expenditure on data collection and analysis and to focus financial resources on the most promising prospects. However, this approach does not lend itself directly to creating exploration products that could be a part of a geothermal play fairway analysis. To produce generalized resource assessment products, it is valuable to include a component of spatial statistical analysis of the data used to determine resource potential.

Probabilistic Approaches

Whether explicitly stated or not, the screening protocol outlined above involves synthesizing a large and complicated set of conditional probabilities. That is, the decision making framework involves asking "what is the probability of discovering a profitable geothermal resource given the occurrence of the known set of characteristics at this time?" Through methods of quantifying uncertainty, risk can be better evaluated and managed during exploration and development.

Many probabilistic approaches that have been presented in the literature for oil and gas resource exploration, and some have been adapted to geothermal exploration. There is significant overlap among many of the approaches, and the distinction between methods may be subtle and mainly philosophical in nature, but the references from which they draw upon provide rigorous instruction for applying many different statistical methods to sparse or incomplete data sets to inform decision making, which is a key challenge in geothermal exploration. The intention here is not to give a rigorous description of each of these methods, but to provide examples of novel uses of spatial statistics for resource exploration.

Evidential Belief Functions (EBFs)

The concept of evidential belief functions (EBFs), based upon the Dempster-Shafer theory of evidence (Dempster, 1966; Shafer, 1976), has the potential to be a powerful tool for exploration. EBFs provide an explicit representation of evidential uncertainty and missing evidence (Carranza et al., 2008). In this way they mitigate the problem that sites appear favorable due only to the fact that data is present in that location. The defining element of EBFs is that the function defines an interval bounded by the degree of belief, which is a 'pessimistic' measure or lower bound, and degree of plausibility, which is an 'optimistic' measure or upper bound (in other words, belief is always less than or equal to plausibility). Uncertainty is the difference between belief and plausibility, and it represents the "doubt" that the evidence supports a given proposition.

Carranza et al. (2008) utilize EBFs for regional-scale geothermal potential mapping in Indonesia. Spatial recognition criteria are developed through a combination of expert knowledge of the region and the spatial analysis methods described in an earlier section. These quantitative methods provide a data-driven approach to determining which geological information should be weighed most heavily in geothermal exploration.

Bayesian Networks

Bayesian networks are closely related to EBFs, and Bayesian statistics can be applied in a wide variety of ways to evaluate conditional dependence. In particular, for resource exploration, Bayesian networks offer a method for evaluating prospect dependencies. Introducing prospect interdependency has the potential to significantly improve a sequential drilling program. At a small enough scale at which there is significant density of data and knowledge of the factors that determine a resource occurrence, probabilities can be determined for the success at a drilling location given the results of an adjacent drilling location.

In a paper exploring prospect analysis for oil and gas exploration in the North Sea, Martinelli et al. (2011) implement a network of segments linking nodes that are past or proposed drilling locations. The network can be used to rapidly explore which proposed drilling site yields the greatest amount of information for the network as a whole. The authors demonstrate that this method is an effective way to prioritize exploratory drilling locations to improve the success rate.

The example from Martinelli et al. (2011) applies to the later stages of the exploration process and would be most relevant to strategically developing a high-potential geothermal resource. However, the method can be adapted to a broader scale analysis. For example, in a play fairway analysis for a tectonic setting that has an occurrence model dominated by the intersection of faults, a probability network could be constructed. Fault intersections would be nodes, and the faults themselves would be segments. Hydrological data and expert knowledge would inform the determination of probabilities for the presence of hot fluids at these favorable locations for fracture permeability. Locations of proven resources provide anchor points and the network could be used to explore which fault intersections should be subjected to more detailed data collection and exploration in order to best inform the entire network.

Fuzzy Logic

Fuzzy logic is another closely related tool that can be employed when data are imprecise or scarce. Rather than dividing variables into binary sets of true and false, fuzzy logic allows for probabilistic treatment of variables, perhaps assigning a 'truth value' that ranges between 0 and 1. Fuzzy logic can be applied to decision trees for investment analysis in a way that is well suited to risky ventures, such as drilling (Kahraman, 2008).

In an example from oil and gas exploration, Fuzzy logic was combined with an expert system in an innovative way into a resource exploration tool (Balch et al., 2003; Balch & Broadhead, 2005). An expert system is a form of artificial intelligence that implements expert analysis methods and knowledge to process large data sets and emulate human decision making.

Geostatistics in Geothermal Exploration

An approach to geothermal exploration that involves integrating multiple data sets in quantifying a level of "trust" of the data has been implemented at Dixie Valley (Iovenitti et al., 2011 & 2012). The methodology uses qualitative correlation of geo-science data sets as well as a variety of geostatistical methods to seek correlations among a variety of lithological parameters. Preliminary results suggest that quantitative cross-correlation reveals valuable information. For example, seismic data, magneto-telluric data, and the combined gravity-magnetic geophysical model together may be able to predict temperature and vertical stress (Iovenitti et al., 2011). The products resulting from this geostatistical analysis include EGS favorability maps and associated trust maps. The trust values allow those implementing the exploration protocol to quickly determine if the favorability is based upon a broad set of supporting data sets or only a few observations that indicate favorability.

<u>TOWARD A RIFT ZONE OCCURRENCE MODEL</u>

In reviewing the characteristics of geothermal resources in extensional continental rift zone settings, we find that the structural setting is of primary importance. Stress concentrations associated with fault bends, interactions among multiple faults, fault zone dilation, and other complicated structures not only signal enhanced permeability, but they also indicate mechanisms that promote enhanced fluid circulation. The various rift zones we reviewed have different regional scale tectonic structure controlled largely by the symmetry of rifting, which can inform likely areas of enhanced heat flow. At scales spanning across prospect and region, the quantitative methods described in the prior sections provide a method to screen for favorably trending faults, steeply dipping faults, fault intersections, proximity to shallow magmatism and other signals associated with geothermal resources. A detailed occurrence model detailing the common set of characteristics for geothermal prospects is an essential component of a geothermal play fairway analysis for a region such as the Rio Grande rift.

<u>CONCLUSIONS</u>

Exploration for new geothermal resources hinges upon discovering settings with sufficient heat, permeability, and fluid. The crustal thinning associated with rift zones and extensional tectonic settings creates a favorable setting for high heat flow. The active deformation in these regions also creates structures that have the potential to enhance permeability. Pinpointing specific locations with all necessary conditions to develop an economical geothermal resource, however, remains difficult and risky.

Our review of occurrence models for geothermal resources in a variety of extensional settings suggests that promising drilling targets can be identified through establishing proxies for geothermal resources specific to the geothermal play. Mapping and analysis of the regional structures associated with active deformation is an essential component of developing a coupled geological-hydrological model with predictive power. Universal criteria exist for identifying geothermal targets. However identification of the subtle, yet important, identifying characteristics depends upon combining expert knowledge of regional geology with quantitative analysis of spatial recognition criteria. We have reviewed a variety of approaches for applying probabilistic methods to geothermal data sets to identify region-specific occurrence models, and see promise in the application of these models for geothermal exploration.

REFERENCES

Alexander, K.B., Ussher, G. (2011) "Geothermal Resource Assessment for Mt. Longonot, Central Rift Valley, Kenya," *Geothermal Resources Council Transactions*, **35**, 1147-1154.

Baillieux, P., Schill, E., Dezayes, C. (2011) "3D Structural Regional Model of the EGS Soultz Site (Northern Upper Rhine Graben, France): Insights and Perspectives," *Proceedings, 36th Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, California, January 31 - February 2, 2011*. SGP-TR-191.

Baillieux, P., Schill, E., Moresi, L., Abdelfettah, Y., Dezayes, C. (2012) "Investigation of Natural Permeability in Graben Systems: Soultz EGS Site (France)," *Proceedings, 37th Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, California, January 30 - February 1, 2012*. SGP-TR-194.

Balch, R.S., Ruan, T., Weiss, W.W., and Schrader, S.M. (2003) "Simulated Expert Interpretation of Regional Data to Predict Drilling Risk," *paper SPE 84067, presented at the SPE Annual Technical Conference and Exhibit, Denver, CO, October 4-8.*

Balch, R.S., Broadhead, R. (2005) "Risk Reduction with a Fuzzy Expert Exploration Tool," *Final Report prepared for U.S. Department of Energy*. DE-AC-26-99BC15218.

Barse, K.A., McDonald, M.R., Crowell, A.M. (2012) "Evaluation of the Geothermal Potential in the Rio Grande Rift: Truth or Consequences, New Mexico," *Geothermal Resources Council Transactions*, **36**, 1315-1320.

Berglund, H.T., Sheehan, A.F., Murray, M.H. Roy, M., Lowry, A., Nerem, R.S., Blume, F. (2012) "Distributed deformation across the Rio Grande Rift, Great Plains, and Colorado Plateu" *Geology*, **40**, no. 1 p. 23-26.

Blackwell, D.D., Waibel, A.F., Richards, M. (2012) "Why Basin and Range Systems are Hard to Find: The Moral of the Story is they Get Smaller with Depth!" *Geothermal Resources Council Transactions*, **36**, 1321-1326.

Bonham-Carter, G.F., 1994. Geographic Information Systems for Geoscientists: Modeling with GIS. Pergamon Press, Ontario, Canada, 398 pp.

Boyd, T., Hall, J., Boyle, R., Cole, S., McBride, K., Hass, C., Anderson, A., Miranda, J., Benedict, M., Maddi, P., Evans, J., Coulson, C. (2011) "The Feasibility of Geothermal Potential in the Rio Grande Rift Area of New Mexico and Texas," *Geothermal Resources Council Transactions*, **35**, 1551-1556.

Carranza, E.J.M, Wibowo, H., Barritt, S.D., Sumintadireja, P. (2008) "Spatial data analysis and integration for regional-scale geothermal potential mapping, West Java, Indonesia," *Geothermics*, **37**, 267-299.

Chapin, C.E., Seager, W.R. (1975) "Evolution of the Rio Grande rift in the Socorro and Las Cruces Areas," *New Mexico Geol. Soc. Guidebook, 26th Field Conf., Las Cruces Country, 1975.* 297-321.

Dempster, A.P., (1966) "New methods for reasoning towards posterior distributions based on sample data," *Ann. Math. Statist.* **37** 355-374.

Dezayes, C., Genter, A., Valley, B. (2010) "Overview of the Fracture Network at Different Scales Within the Granite Reservoir of the EGS Soultz Site (Alsace, France)," *Proceedings of the World Geothermal Congress, Bali, Indonesia, 25-29 April 2010.*

Easley, E., Garchar, L., Bennett, M., Beasley, B., Woolf, R., Hoopes, J. (2011) "Investigation of Geothermal Resource Potential in the Northern Rio Grande Rift, Colorado and New Mexico," *Geothermal Resources Council Transactions*, **35**, 761-768.

Faulds, J.E., Hinz, N.H., Coolbaugh, M.F., Cashman, P.H., Kratt, C., Dering, G., Edwards, J., Mayhew, B., McLachlan, H. (2011) "Assessment of Favorable Structural Settings of Geothermal Systems in the Great Basin, Western USA," *Geothermal Resources Council Transactions*, **35**, 777-783.

Faulds, J.E., Hinz, N, Kreemer, C., Coolbaugh, M. (2012) "Regional Patterns of Geothermal Activity in the Great Basin Region, Western USA: Correlation with Strain Rates," *Geothermal Resources Council Transactions*, **36**, 897-902.

Fry, N. (1979) "Random point distributions and strain measurement in rocks," *Tectonophysics*, **60**, 89–105.

Gao S., Davis, P.M., Liu, H., Slack, P.D., Zorin, Y.A., Logatchev, N.A., Kogan, M., Burkholder, P.D., Meyer, R.P. (1994) "Asymmetric upwarp of the asthenosphere beneath the Baikal rift zone, Siberia," *Journal of Geophysical Research*, **99, B8**, 15,319-15,330.

Hinz, N.H., Faulds, J.E., Stroup, C. (2011) "Stratigraphic and Structural Framework of the Reese River Geothermal Area, Lander County, Nevada: A New Conceptual Structural Model," *Geothermal Resources Council Transactions*, **35**, 827-832.

Hulen, J.B., Nielson, D.L. (1990) "Possible Volcanotectonic Controls on High-Temperature Thermal Fluid Upflow in the Valles Caldera, New Mexico," *Geothermal Resources Council Transactions*, **14**, 1457-1464.

Iovenitti, J., Blackwell., D., Sainsbury, J, Tibuleac, I, Waibel, A., Cladouhos, T., Karlin, R., Kennedy, B.M., Isaaks, E., Wannamaker, P., Clyne, M., Callahan, O. (2011) "EGS Exploration Methodology Development using the Dixie Valley Geothermal District as a Calibration Site: A Progress Report" *Geothermal Resources Council Transactions*, **35**, 389-395.

Iovenitti, J., Blackwell., D., Sainsbury, J, Tibuleac, I, Waibel, A., Cladouhos, T., Karlin, R., Isaaks, E., Clyne, M., Ibser, F.H., Callahan, O. Kennedy, B.M., Wannamaker, P., (2012) "Towards Developing a Calibrated EGS Exploration Methodology Using the Dixie Valley Geothermal System, Nevada" *Proceedings, 37th Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, California, January 30 - February 1, 2012*. SGP-TR-194.

Jolie, E., Faulds, J., Moeck, I. (2012) "The Development of a 3D Structural-Geological Model as Part of the geothermal Exploration Strategy – A Case Study From the Brady's Geothermal System, Nevada, USA," *Proceedings, 37th Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, California, January 30 - February 1, 2012*. SGP-TR-194.

Kahraman, C. (2008) "Investment Analysis Using Fuzzy Decision Trees", *Fuzzy Engineering Economics with Appl.* STUDFUZZ **233**, 231-242.

Karp, T., Scholz, C.A., McGlue, M.M. (2012) "Structure and Stratigraphy of the Lake Albetr Rift, East Africa: Observations from Seismic Reflection and Gravity Data," *in* O.W. Baganz, Y. Bartov, K. Bohacs and D. Nummedal, eds., Lacustrine Sandstone Reservoirs and Hydrocarbon Systems: AAPG Memoir **95**, 299-318.

Keller, G.R., Khan, M. A., Morgan, P., Wendlandt, R.F., Baldridge, W. S., Olsen, K.H., Prodehl, C., Braile, L.W. (1991) "A Comparative Study of the Rio Grande and Kenya Rifts," *Tectonophysics*, **197**, 355–371.

Koehn, D., Lindenfeld, M., Rumpker, G., Aanyu, K., Haines, S., Passchier, C.W., Sachau, T. (2010) "Active transection faults in rift transfer zones: evidence for complex stress fields and implications for crustal fragmentation processes in the western branch of the East African Rift," *Int. J. Earth Sci.*, **99**, 1633. 1642.

Lezzar, K.E., Tiercelin, J., Le Turdu, C., Cohen, A.S., Reynolds, D.J., Le Gall, B., Scholz, C.A. (2002) "Control of Normal Fault Interaction on the Distribution of Major Neogene Sedimentary Depocenters, Lake Tanganyika, East African Rift," *AAPG Bulletin*, **86**, 1027-1059.

Logachev, N. (1994) "The Baikal Region of Siberia," *Geothermal Resources Council Bulletin*, June 1994, 218-220.

Lyons, R.P., Scholz, C.A., Buoniconti, M.R., Martin, M.R. (2011) "Late Quaternary stratigraphic analysis of the Lake Malawi Rift, East Africa: An integration of drill-core and seismic-reflection data," *Paleogeography, Paleoclimatology, Paleoecology*, **303**, 20-37.

Lysak, S.V. (1992) "Heat flow variations in continental rifts," *Tectonophysics*, **208**, 309-323.

Martinelli, G., Eidsvik, J. Hauge, R., Forland, M.D. (2012) "Bayesian networks for prospect analysis in the North Sea," *AAPG Bulletin*, **95**, 1423-1442.

McLachlan, H.S., Benoit, W.R., Faulds, J.E. (2011) "Structural Framework of the Soda Lake Geothermal Area, Churchill County, Nevada. *Geothermal Resources Council Transactions*, **35**, 925-930.

Njue, L.M. (2011)"The Menengai Caldera Structure and its Relevance to Geothermal Potential," *Geothermal Resources Council Transactions*, **35**, 1201-1208.

Ng'enoh, D., Ochieng, L. (2011) "Geothermal Exploration in the Kenya Rift: A Case Study of Silali Geothermal Prospect," *Geothermal Resources Council Transactions*, **35**, 955-960.

Petit, C., Burox, E., Deverchere, J. (1997) "On the structure and mechanical behavior of the extending lithosphere in the Baikal Rift from gravity modeling," Earth and Planetary Science Letters, 149, 29-42.

Phillips, B.R., Ziagos, J., Thorsteinsson, H., Hass, E., (2013) "A Roadmap for Strategic Development of Geothermal Exploration Technologies" *Proceedings, 38th Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, California, February11-13, 2013.* SGP-TR-198

Place, J., Le Garzic, E., Geraud, Y., Diraison, M., Sausse, J. (2011) "Characterisation of the Structural Control on Fluid Flow Paths in Fractured Granites," Proceedings, 36th Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, California, January 31 - February 2, 2011. SGP-TR-191.

Sabin, A.E., Walker, J.D., Unruh, J., Monastero, F.C. (2004), "Toward the Development of Occurrence Models for Geothermal Resources in the Western United States," Geothermal Resources Council Transactions, 28, 41- 46.

Shafer, G. (1976) "A Mathematical Theory of Evidence." Princeton University Press (Princeton, New Jeresy).

Shako, L. (2011) "Determination of Reservoir Extent and Priority Drilling Zones in a Geothermal Prospect Using GIS (A Case Study for Paka Geothermal Project)," *Geothermal Resources Council Transactions*, **35, 991-994.

Simiyu, S.M. (2012) "Status of Exploration in Kenya and Future Plans for Its Development," *Proceedings of the World Geothermal Congress, 2010. Bali, Indonesia, 25 – 29 April 2010*, 1-11.

Walker, J.D., Sabin, A.E., Unruh, J.R., Combs, J., Monastero, F.C. (2005), "Development of Genetic Occurrence Models for Geothermal Prospecting," *Geothermal Resources Council Transactions*, **29**, 309-313.

Wilson, D., Aster, R., West, M., Ni, J., Grand, S., Gao, W., Baldridge, W.S., Senken, S., Patel, P. (2005) "Lithospheric Structure of the Rio Grande Rift," *Nature*, **433**, 851-855.