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# Development of Genetic Occurrence Models for Geothermal Prospecting

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*Advected heat, occurrence models, geothermal, exploration*

## ABSTRACT

Exploration strategies based on an understanding of the geologic processes that transfer heat from the mantle to the upper crust, and foster the conditions for shallow hydrothermal circulation or enhanced geothermal systems (EGS) exploration, are required to search efficiently for “blind” geothermal resources. We propose a genetically based screening protocol to assess potentially prospective geothermal resources, beginning at the plate boundary scale and progressively focusing in on the scale of a producing electrical-grade field. We evaluated our approach by retrospectively applying the protocol to the characteristics of producing geothermal fields as documented in published studies. In all cases, the known resource areas fit the parameters identified from a genetic perspective. We conclude that this approach, grounded in basic geological data, is an effective way to delineate potential geothermal resource areas at all stages of exploration, from broad reconnaissance to detailed appraisal levels.

## Introduction

This paper presents a general model for the origin and occurrence of electrical-grade geothermal resources. Such *occurrence models* commonly are used in prospecting for minerals (Cox and Singer, 1986; Hodgson et al., 1995; Oreskes and Hitzman, 1993). They are especially useful in searching for “blind” deposits that lack obvious surface geothermal manifestations because, in these cases, the search for the deposit must be guided by an understanding of the processes and conditions that contribute to the occurrence of the resource. The approach outlined is illustrated and described below is based on our interpretation of the conductive and advective processes by which heat is transferred from the mantle to the upper crust, and is supported by a review of literature on the

geologic characteristics of electrical-grade resources around the world. We focus primarily on exploration strategies for the western United States, employing a genetic approach to explain the occurrence of known resources, and to guide exploration strategies for presently unidentified resources.

## Transfer of Heat from the Mantle to the Shallow Crust

Electrical grade geothermal resources are produced by a combination of conductive and advective processes that transfer heat from the asthenosphere into the middle and upper crust. This heat, in combination with fractures and fluids, leads to convective processes in hydrothermal systems and creates the conditions necessary for enhanced geothermal systems.

Volcanic arcs at convergent margins represent first-order advection of heat from the upper mantle and lower crust to the middle and upper crust by magmatic activity. High heat flow in these regions is due to conductive transfer of heat into the upper crust from mid-crustal magmatic intrusions (e.g., Kakkonda geothermal field, Japan: Muraoka et al., 1998). Enhanced permeability and shallow upper crustal hydrothermal circulation within volcanic arcs commonly is associated with young and/or active faults (e.g., Miravalles geothermal field, Costa Rica: Zuniga et al., 2005; Ogiri geothermal field, Japan: Shimada et al., 2000).

In regions of active crustal extension, transfer of heat from the asthenosphere to the crust is accommodated by both tectonic and magmatic processes. Major producing fields in extensional regions are associated with a thin lithosphere. Conductive transfer of heat from a relatively shallow asthenospheric mantle in these regions, as well as heat from lower crustal intrusion and underplating associated with lithospheric stretching, elevates the heat flow and increases temperatures at mid-crustal depths relative to stable continental regions. Heat flow in extensional regions may be further elevated, at least locally, by magmatic intrusions into the middle and upper crust (e.g., Wairakei and Ohaaki geothermal fields, North Island, New Zealand: Graham et al., 2000).

Our review of electrical-grade resources worldwide suggests that thin lithosphere and conduction of heat from the lower crust alone are not sufficient to produce significant electrical-grade geothermal resources. For example, the Rio Grande rift in the western United States is characterized by thin lithosphere and active extension, but this region has significantly fewer electrical-grade resources than the East African rift, which is comparable in terms of crustal structure, geophysical characteristics, and extensional strain rate (Keller et al., 1991; Abebe, 2000). The primary difference between the two continental rifts is relative magmatic activity: the volume of late Cenozoic extrusive rocks in the Rio Grande rift is estimated to be only 5-10% of that in the East African rift (Keller et al., 1991). Whereas elevated heat flow in the Rio Grande rift may be attributed to a broad “conductive” anomaly associated with lower crustal intrusion and underplating that occurred early in the development of the rift, very high heat flow in the East African rift is attributed to young intrusions that effectively advect heat to mid-crustal levels and conductively transfer heat to local areas of the upper crust (Keller et al., 1991). The major electrical-grade geothermal fields in the East African rift (e.g., the Olkaria geothermal field) are intimately associated with late Cenozoic silicic volcanic centers.

In the absence of young magmatism and volcanism, the primary difference between extensional areas in the western United States with and without electrical-grade resources is tectonic strain rate. For example, strain rates of  $10^{-15}$  /s and higher characterize productive areas of the Walker Lane belt and the western Basin and Range, whereas the considerably less productive areas of the Basin and Range and the Rio Grande rift are characterized by strain rates on the order of  $10^{-16}$  /s, an order of magnitude lower. Using GIS-based analysis of spatial data, Blewitt et al. (2002) and Coolbaugh et al. (2002) documented an empirical relationship between localized high strain rates and occurrence of electrical-grade resources in Nevada.

We propose that the correlation between high strain rate and production in the western United States is explained by tectonic advection of heat to the upper crust by rapid uplift of the footwall blocks in active normal fault systems. Extension rates (and hence fault slip rates) must be high enough so that heat in uplifted footwall blocks is not dissipated by conduction, thus producing a stable upward perturbation of isotherms over a geologically significant period of time. The producing areas of eastern California and Nevada are arguably part of the eastern boundary of the northwest-migrating Sierra Nevada microplate (Unruh et al., 2003), and regionally are characterized by strain rates typical of plate boundaries (i.e.,  $10^{-15}$  /s and higher). As noted by Blewitt et al. (2002) and Coolbaugh et al. (2002), electrical-grade resources in Nevada are correlated with normal fault systems that are oriented at a high angle to the regional direction of extension, which increases the slip rate on these structures and thus tectonic advection of heat from the middle crust.

Geothermal production in non-magmatic areas of high extensional strain rate may be due to increased permeability at greater depths. Coolbaugh et al. (2002) suggested that higher strain rates associated east-northeast-striking faults may effectively push the brittle-ductile transition lower in

the crust; i.e., to higher temperatures. Circulation of fluids along open faults to deeper and hotter depths may account for the high temperatures of fluids that ultimately are produced from these structures (Coolbaugh et al., 2002). Barton et al. (1995) previously recognized that active faults are likely to be important hydraulic conduits.

To summarize, electrical-grade geothermal resources are produced by a combination of magmatic and tectonic processes that transfer heat to the middle and upper crust and create permeability in the upper crust for hydrothermal convection. Based on these observations, we suggest that prospective electrical-grade geothermal resources are most likely to be found at plate boundaries where a combination of active volcanism and/or high extensional strain rates produce temperatures and permeability high enough to trigger development of shallow (i.e., exploitable) hydrothermal systems. This combination of heat and permeability also should produce the conditions characteristic of enhanced geothermal systems.

## Characteristics of Prospective Regions

Having identified above the first-order tectonic and magmatic processes required for the occurrence of high temperature fluids and permeability at economic depth, we are interested in identifying key geologic characteristics of these processes as seen in well-studied electrical-grade systems which are currently active. Areas considered for geothermal exploration should exhibit these characteristics to be prospective. Below, we summarize important geologic characteristics of high temperature systems, beginning at the plate boundary scale and proceeding to increasingly detailed scales of observation.

### Plate Boundary Setting

Most electrical-grade resources are associated with one of the following types of plate boundaries:

- Volcanic arcs at convergent margins (Japan, Central America)
- Oblique margins characterized by magmatism and transcurrent faulting (New Zealand, eastern California)
- Extensional back-arc settings, including areas above slab roll back (Turkey, Apennines)
- Volcanically productive continental rifts (Kenya)
- Hot spots (Iceland, Azores, Hawaii)•

### “Geothermal District” Scale Characteristics

Within the plate-boundary settings cited above, characteristics associated with geothermally prospective regions include elevated heat flow (typically greater than  $120 \text{ mW/m}^2$ ) relative to stable continental interiors and non-volcanic rifts, and high strain rates and/or localization of active deformation in discrete domains. The style of deformation in these regions commonly is extensional or transtensional, although contractional examples are known. Specific geologic characteristics of these regions include:

- Young/active volcanic centers or young intrusions
- Presence of neotectonic structures and active seismicity
- Surface manifestations of geothermal activity (steam, fumaroles, hot springs, mudpots)
- Evidence of youthful geothermal systems (hydrothermal mineral alteration, soil geochemistry anomalies, soil gas anomalies)
- Elevated groundwater temperature gradients
- Groundwater chemistry and geothermometry data suggesting geothermal reservoir input

Although all of these characteristics do not occur in every geothermal system, the identification of any of these features in the above plate boundary settings may be evidence of a geothermal system. It is important to note that the apparent absence of features such as elevated heat flow may also be the product of incomplete or inaccurate data sets in regions that have received limited investigations.

### “Geothermal Prospect” Scale Characteristics

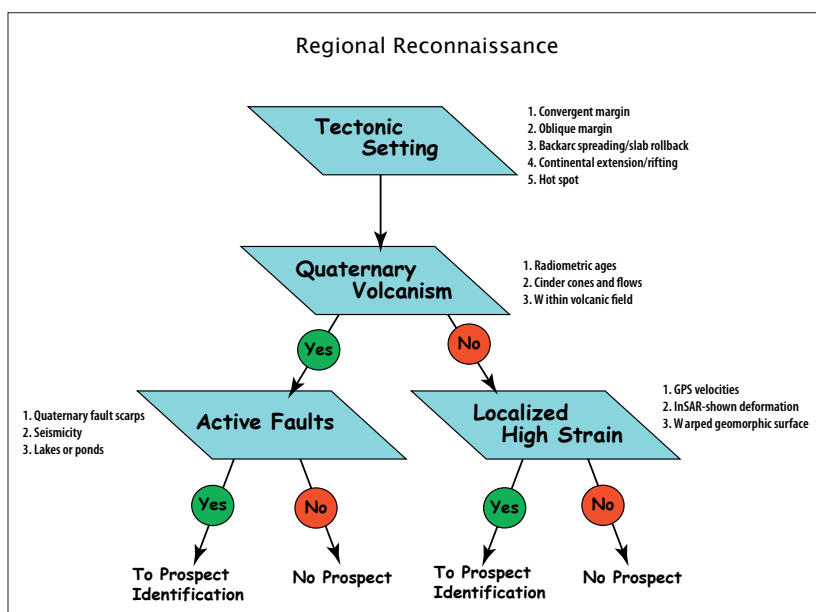
At the scale of a producing geothermal field, key geologic characteristics include:

- Presence of reservoir rocks with sufficient permeability for hydrothermal circulation
- Presence of active faults (late Pleistocene to Holocene activity) to localize permeability for production
- Presence of shallow fluids with utility-grade temperatures ( $\geq 85^{\circ}\text{C}$ )
- Localized potential field geophysical anomalies including gravity, self-potential, and resistivity
- Potential for enhanced geothermal system production

### Screening Protocol for Prospective Regions

A protocol for identifying and evaluating prospective regions that incorporates the genetic model and observations in the preceding sections is outlined in Figure 1. Starting at the plate-tectonic level, prospective regions occur in one of the five types of plate boundaries described above. Within these settings, electrical-grade geothermal resources are most likely associated with tectonically and volcanically active areas that demonstrate the presence of shallow heat sources and sufficient fault/fracture permeability to facilitate hydrothermal convection and production. Non-volcanic areas characterized by high extensional strain rates also may be productive, provided that there are sufficiently active faults to facilitate upward tectonic advection of hot crust and provide conduits for circulation of geothermal fluids. Drawing on mineral exploration and deposit characterization as analogs, regions that pass this level of screening (e.g., the Salton Sea, East African rift) represent “district-level” geothermal resources.

As is often the case in mineralized districts (e.g., the SE Missouri lead district; the Sudbury nickel-copper district,

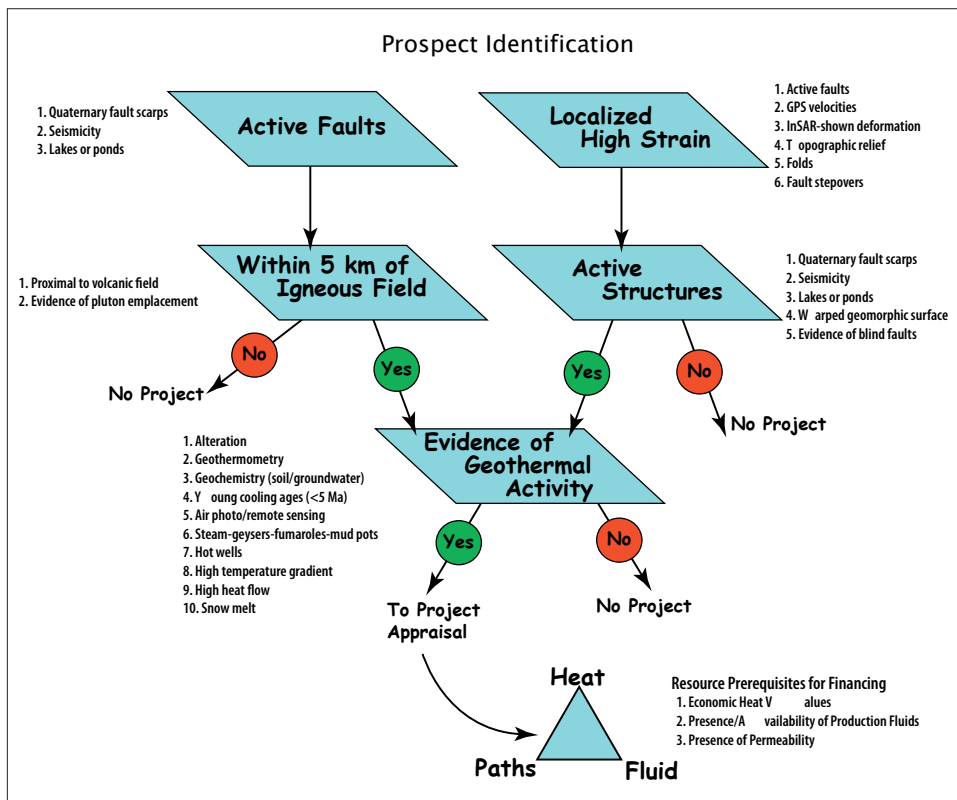


**Figure 1.** A regional reconnaissance decision path is part of the initial screening tool used to identify regional features potentially associated with geothermal occurrences. Significant geologic features that should be assessed or examined are listed next to each level.

Ontario; the Globe-Miami copper district, Arizona), a geothermal district may have multiple, discrete geothermal deposits or systems occurring in a distinct geographical area. Systems within a given district tend to be broadly related by one or more geological phenomena such as the spatial and temporal association of a young batholithic intrusion and one or more major, active structures.

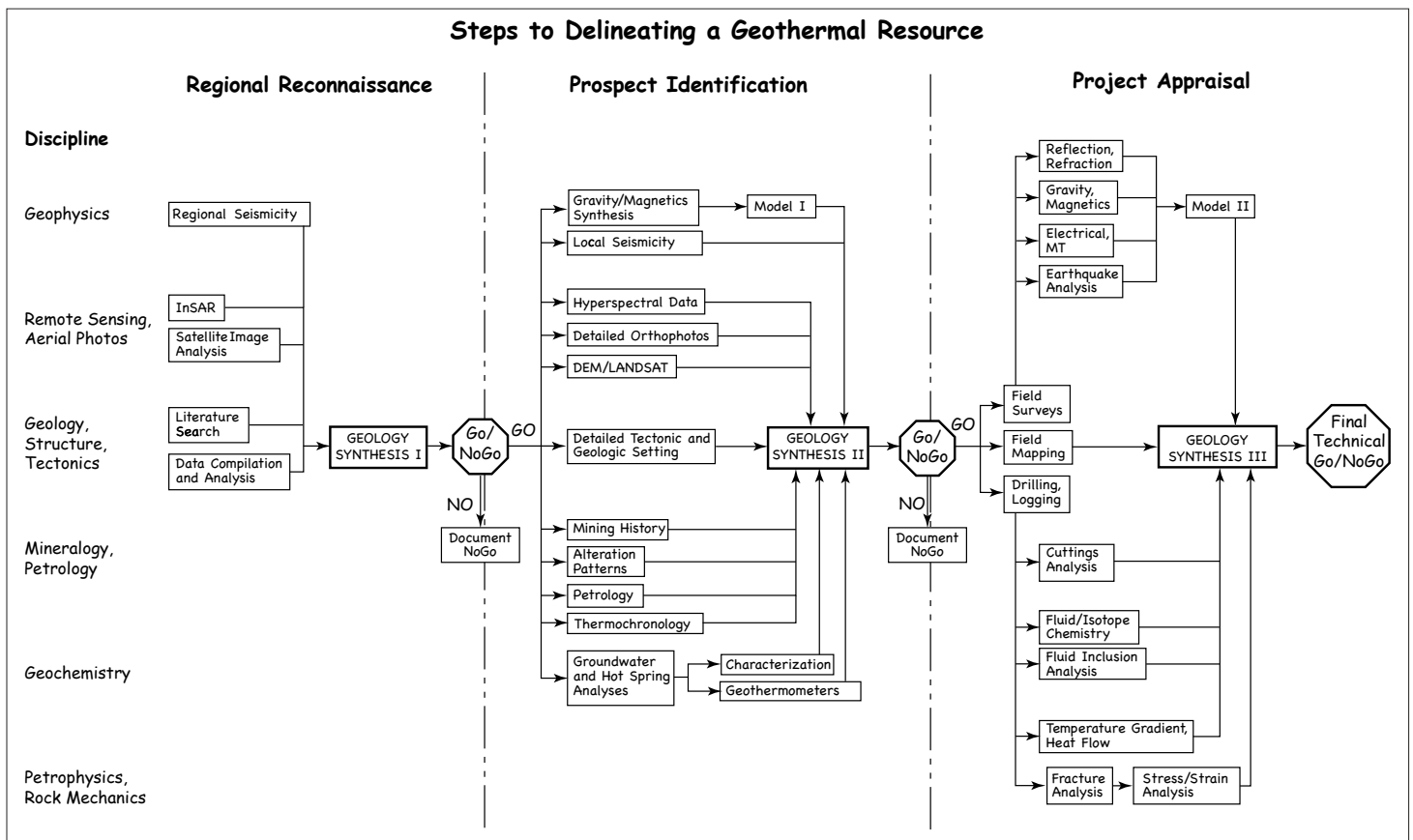
Identification of a specific prospect requires focusing in on an area within or directly adjacent to a young igneous field, or characterized by active normal or transtensional faulting at high slip rates in a non-volcanic area (Figure 2, overleaf). An example of the former is the Coso geothermal field in eastern California where Pleistocene rhyolitic magmatism and active normal faulting coexist. An example of the latter is the Dixie Valley field in Nevada, which is associated with a range-front normal fault in the tectonically active central Nevada seismic belt. Areas that pass this level of screening can be evaluated for evidence of local geothermal activity using a variety of methods, including geologic mapping of hydrothermal alteration; evaluation of temperature gradients and heat flow; local strain rates; geothermometry; soil and soil gas and groundwater, geochemistry; and surface manifestations of hydrothermal activity (Figure 2). Prospects that pass this level of screening may warrant more focused (and expensive) studies to determine the presence of economic heat values, production fluids, and permeability (i.e., “Project Appraisal”; Figure 3, overleaf).

When confronted with obvious surface manifestations of hydrothermal activity—such as fumaroles and boiling mud pots—it is of course possible to skip all of the steps outlined in Figures 1 and 2 and move straight to project appraisal. Although understanding the geologic context of surface manifestations is necessary for efficient exploration and development, the features themselves provide evidence of upper crustal hydrothermal convection, and thus imply magmatic and



**Figure 2.** A district level decision path follows regional reconnaissance with a goal of identifying potential prospects. In parts of the Basin and Range where no apparent surface geothermal manifestations exist, localized high strain rates and subtle, active structures may be the only guides to geothermal targets.

tectonic activity. In the jargon of the oil industry, developing such resources would be equivalent to “drilling the seeps”. We are interested here, however, in developing approaches for finding the blind geothermal resource that lacks obvious surface manifestations. It is likely that most of the electrical-grade resources in the western United States associated with surface manifestations have been developed—or at least explored—at the prospect identification level. Identification and development of presently blind resources will be necessary if the potential capacity for and the production of geothermal electricity in the western United States are to be increased significantly.



**Figure 3.** This flow chart graphically lists the tools, data, and geologic features that can be assessed during geothermal exploration as it progresses from regional reconnaissance to a project level-appraisal. Once a prospect has been identified via the screening protocols described above or any other methods, a project appraisal typically includes many or all of the disciplines listed in this chart.



## Conclusions

We present a refined approach for exploration rooted in the genetic factors associated with geothermal occurrences. A fundamental prerequisite for exploitable geothermal resources is the presence of heat in the near surface; we thus have focused on geological processes that facilitate advection and conduction of heat from the mantle to the middle and upper crust. Our occurrence model approach is developed from a wide variety of mostly hydrothermal systems, but attempts to capture the primary conditions necessary for heat to be present in the upper crust. We evaluate primarily the conditions for shallow crustal heat, and secondarily we explore the mechanisms necessary for the presence of fluid pathways; we do not address, at the occurrence model level, whether sufficient fluids are present to make a hydrothermal system. Our approach thus identifies areas suitable for hydrothermal systems as well as enhanced geothermal systems.

We also argue that genetically based exploration approaches for high-temperature geothermal systems are necessary for the efficient identification and development of blind resources that lack surface geothermal manifestations. We believe that the geothermal industry should adopt occurrence model exploration concepts and use them to increase proven reserves and capacity in the western United States, analogous to the ways the hydrocarbon and mineral industries successfully employed similar genetic approaches.

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