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GEOTHERMAL RESOURCE CONCEPTUAL MODELS USING SURFACE EXPLORATION DATA

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ABSTRACT

The most important element of an analysis to target a geothermal well or assess resource capacity is a resource conceptual model consistent with the available information. A common alternative approach to both targeting and assessment is to focus on a data anomaly or, in some cases, several stacked anomalies. However, even stacked anomalies are commonly misleading without support from a conceptual model. The most important element of a geothermal conceptual model is a predicted natural state isotherm pattern, especially in section view. Although inferring such an isotherm pattern at an exploration stage can be challenging, many case histories show how this can be done based on surface geochemistry, resistivity, hydrothermal alteration, geology, hydrology and structure. This highlights a few basic rules of thumb for building and characterizing the uncertainty of geothermal resource conceptual models based on information from typical geothermal exploration data sets. A conceptual model approach is particularly effective when exploring blind prospects because it makes fuller use of more limited data and helps identify strategies to address the lack of information, as well as identifying targets.

INTRODUCTION

A widely noted incidental effect of the boom-and-bust energy economy is the demographic gap in the geothermal industry. Professionals now entering the industry bring valuable new skills but face the challenge of learning best practices with few mentors. This has inspired a resurgence in training, including a renewed Auckland Geothermal Institute program in 2008, short courses sponsored by the Geothermal Resources Council and many in-house courses by geothermal developers.

During courses on geophysics and geothermal exploration and development, participants commonly request publications that more fully explain a few slides that I include in the introductions to geothermal case histories and to exercises on building resource conceptual models. Related questions include; what approach works best for targeting geothermal wells, how should resource capacity be assessed at different project stages, what are the basic elements of a geothermal conceptual model, and how are geothermal conceptual models built from surface information.

This paper briefly outlines three approaches commonly used to use data to target wells and assess resource capacity in conventional permeable geothermal reservoirs from 120 to 350°C at the exploration stage of a prospect. It promotes a conceptual model approach as a plausible best practice, recognizing that no practice is best in every context. After a cursory review of the importance and properties of natural state isotherms in defining a geothermal conceptual model, a synthetic example illustrates how a typical data set could be used to derive a realistic model. A few details are included to illustrate the types of considerations involved, but these are not comprehensive. An additional synthetic example is reviewed in more detail to illustrate how the same approach can be particularly effective in targeting blind resources.

Given its intended audience, this paper would ideally support its claims by referring to recently published elementary papers that are freely available on the internet. However, such papers are not available on fluid geochemistry and the thermodynamics of geothermal systems. Therefore, I reference a book that covers these topics (Nicolson, 1993).

EXPLORATION APPROACHES

The approaches that developers use to target wells include anomaly hunting, anomaly stacking and conceptual model targeting. The same categories can be applied to resource capacity assessment.

Anomaly hunting

Anomaly hunting is usually based on either an analogy or an assumed correlation. An example of an analogy would be to use the 10 ohm-m contour that encloses a mapped low resistivity zone as a reservoir boundary because that contour roughly matches the boundary of a developed reservoir. Ussher (2007) provided a classic example of the drawbacks of such a resistivity boundary approach at the Ohaaki geothermal field. Other examples of anomaly hunting would include targeting a well on an unusual local reflection in a seismic survey that was assumed to correlate with a fault without a physical justification. Anomaly hunting usually has a conceptual basis but, because it focuses on targeting the data rather than a fully integrated physical interpretation of the data, the relevance of the underlying analogy or the assumed correlation is not checked for physical consistency.

One unfortunate aspect of an anomaly hunting approach is that it is not characteristic of a learning organization. If a well targets a 10 ohm-m anomaly and the well is bad, the anomaly is still 10 ohm-m. If it tests an interpreted isotherm, that isotherm is directly tested by the well. The reasons for any mismatch must be reviewed and addressed for the next well.

Anomaly stacking

Anomaly stacking might seem to be a slight variant of anomaly hunting where a number of roughly coincident anomalies are considered together. However, anomaly stacking requires more care because coincident patterns often have a disproportionate psychological effect on perceptions of uncertainty, even for experts who suspect the anomalies may be irrelevant or redundant when considered in context. For example, low resistivity is consistently found over geothermal reservoirs but also in inter-volcanic valleys full of sediments. Low magnetic intensity is also found over geothermal fields. The coincidence of a magnetic low with a resistivity low has sometimes greatly increased well targeting confidence. However, magnetic lows are also characteristic of inter-volcanic valleys. Moreover, there are many more valleys than there are geothermal fields. If coincident features are interpreted in the context of the physical properties of a conceptual model consistent with all the available information, misinterpretations attributable to coincidence are less likely to occur.

Conceptual models

A conceptual model approach to geothermal resource assessment addresses the weaknesses of anomaly hunting and anomaly stacking by integrating data sets across all disciplines in the context of a physical model. It avoids the artificial perception of reliability characteristic of anomaly stacking by explicitly illustrating how data sets constrain geothermal target parameters, like those in Figures 1 and 2.

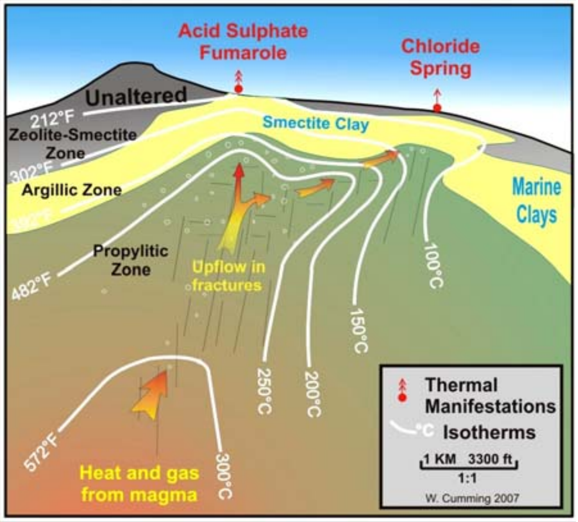

Figure 1: Conceptual model cross-section of a 250 to 300°C geothermal reservoir with isotherms, alteration zones, and structures

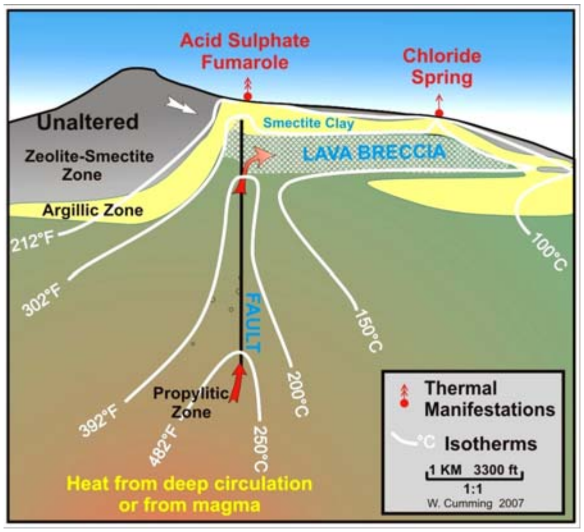

Figure 2: Conceptual model cross-section of a 150 to 200°C geothermal reservoir with isotherms, alteration zones, and structures

A conceptual model approach requires a far greater range of expertise than anomaly hunting. However, the basics of building conceptual models can be learned by many geoscientists in a few months using exercises based on synthetic and real case histories. When building conceptual models to address real decisions, an expert mentor is helpful, although a conceptual model approach also provides a basis for an effective self-education as wells are drilled and resource assessments tested.

GEOTHERMAL CONCEPTUAL MODELS

Geothermal conceptual models like the generic >200°C and <200° geothermal reservoirs in Figures 1 and 2 bring together the observed and inferred information that best illustrates the reservoir fluid and rock properties. In terms of reservoir performance, temperature, pressure and permeability are always important parameters and porosity and water chemistry are usually important. Over the last decade, the surface data sets that have probably been most influential in constraining reservoir properties at the exploration stage have been cation and gas geochemistry from thermal manifestations and MT resistivity interpreted in the context of basic geology and hydrology. Mapping active surface alteration is also important. As systems with more modest surface manifestations in structural settings like the US Basin and Range have been given greater attention, temperature gradient wells and structure mapping methods have had greater prominence. The integration of these data sets into a conceptual model is primarily done in cross-sections and maps.

Interpreting isotherms on cross-sections

Cross-sections provide a more intuitively appealing format than maps for interpreting how buoyant flow of higher temperature water will interact with the permeability distribution of a geothermal reservoir. The pattern of the isotherms in Figures 1 and 2 are closely correlated with the permeable and impermeable elements of the conceptual models.

Upflow and outflow

In geothermal systems, thermal buoyancy causes the water to flow upward, against gravity, in permeable rocks, metaphorically dragging the isotherms with it. Therefore, the pattern of the isotherms illustrates the pattern of flow in permeable rocks. For the purposes of this paper, the upflow zone is the reservoir zone in which flow is predominantly vertical and temperature generally increases with depth. In the outflow, flow is predominantly horizontal and temperature declines with depth below the main outflow zone, like on the right side of the upflow in Figure 2. At temperatures over 100°C, the outflow is still driven by buoyancy and so it has a small upward component of movement.. The temperature decrease with depth below the outflow is commonly called a temperature reversal.

Realistic isotherm patterns

The upper limit on isotherm values at any particular depth is the boiling point of water versus depth, assuming a hydrostatic pressure gradient defined by the water table (Nicolson, 1993).

The laws of thermodynamics and fluid flow imply that isolated high and low temperature zones are either transients or represent flow in or out of the plane of a cross-section. For exploration models, an arrow head or tail should show the interpreted direction of flow.

Because the isotherms are related to heat flow by both conduction and fluid flow, where fluid flow is particularly important, it is helpful to include arrows indicating the direction of fluid movement, as in Figures 1 and 2.

Permeable zones

Permeable zones will have lower temperature gradients, as illustrated by the 250 to 300C contour spacing in Figure 1 and the 150 to 200C contour spacing in Figure 2. The two models illustrate two common types of permeability distribution. In both, the ultimate source of the heat is a fluid upflow in fractures.

Figure 1 is characteristic of many relatively high temperature volcanic systems where almost all permeability that is relevant to well deliverability is related to fractures. However, permeability at intermediate depths of about 500 to 1500 m commonly reflects the interaction of faults with formation properties, such as the jointing that tends to occur where faults intersect weak formations.

Figure 2 shows a system that has an upflow in a very narrow fault zone, like many Basin and Range systems. The upflow intersects a formation with significant primary permeability and becomes an outflow. Such outflows are hosted in a variety rocks including sandstones, lava breccias and granite rubble zones. In some cases, wells must still intersect a structure to have adequate deliverability in the outflow but there are probably as many cases where this is not required.

Impermeable zones

Where isotherms are regularly and more closely spaced, implying a relatively high linear gradient, permeability is relatively low. This does not imply that there is no fluid movement but that it is probably lower than in areas where isotherms are more widely spaced. The effect of permeability variations on temperature patterns in fractured geothermal reservoirs is so large that variations in the thermal conductivity of the rock is usually ignored when interpreting temperature by visual inspection within and immediately adjacent to the reservoir.

Juxtaposed permeable and impermeable zones

Where isotherms are very closely spaced, implying a very high temperature gradient, permeability is also very low, as in the clay cap shaded yellow in Figures 1 and 2. Such a high gradient also implies that permeable zones exist on either side of the impermeable zone. At the impermeable clay cap in Figure 1, a cool meteoric aquifer cools the top while the permeable reservoir upflow and outflow heats the bottom.

Cooler water entering an upflow

Cooler water can flow into a geothermal upflow zone but, for the geothermal system to be stable, most cold inflows are small leaks or are in permeable channels with limited connections to the upflow. Cooler water can enter either from the side where it may be at higher pressure due to the greater density of the cooler water column outside the reservoir. It may also enter from an overlying aquifer at higher elevation than the water level that controls the geothermal reservoir pressure. The isotherm patterns in Figures 1 and 2 suggest some deep convective return flow towards the reservoir upflow but conductive heat loss could account for much of the pattern and so no arrows are included.

BUILDING A CONCEPTUAL MODEL

Although constructing the isotherms for conceptual models like those in Figure 1 and 2 based only on surface geoscience data might seem to be a very uncertain exercise, many case histories have demonstrated its reliability, providing that a range of models is considered. Interpreters must estimate a reservoir temperature and rough temperature geometry and begin to sketch isotherms following the expected buoyant flow through a pattern of permeability inferred from geophysics.

Well data

At many exploration prospects, there may be unproductive wells already drilled and their temperature, alteration, geology, fluid or gas chemistry and like data are high priority data. The correlation of the smectite-illitite clay alteration transition (Cumming and Mackie, 2009) with resistivity data is a standard check on the reliability of the geophysical interpretation. However, the temperature data are the highest priority at an exploration stage, and possibly geochemistry data if it hints at higher temperatures in a nearby permeable reservoir.

Even temperatures measured in wells require interpretation. For example, a borehole immediately after completion is cooled by drilling. Therefore, the time after drilling and the recent status of the well must be considered in interpretations of natural state temperature from a well log. Regardless of their complications, such inferences are likely to be more reliable than geothermometry from a hot spring.

Geochemistry

When no wells are drilled but reliable cation or gas geothermometry data are available, it can be decisive. Besides providing geothermometry, the geochemistry of thermal features can characterize the distribution of fluid types around the reservoir, identify boiling zones, mark the water table and hint whether the system might be acidic or high in gas. However, the main issue is temperature and a scenario based on the example in Figure 1 illustrates how decisive the geothermometry can be for developing a conceptual model.

In Figure 1, an initial isotherm segment could be estimated if the fumarole has geothermometry of 250°C using a relatively reliable gas ratio geothermometer (Powell, 2000) and the chloride spring to the right plots on a Na-K-Mg cation geothermometry ternary diagram along a trend consistent with that temperature (Nicolson, 1993). A boiling point for depth curve for pure water would provide an estimate of the minimum depth at which that temperature would be found below the water table, in this case about 500 m or maybe 600 m allowing for some gas content. Assuming that the chloride hot spring elevation is close to the water table, the top of the 250°C isotherm might reasonably be plotted below the fumarole, just as shown in Figure 1. A similar process can be applied to geothermometry from the hot springs in Figure 2, to characterize the outflow at about 150°C.

As described here, the geochemistry provides a temperature at a location and depth on a cross-section. Several thermal features might indicate the likely extent of an outflow at a particular temperature. The types of geothermometry have different strengths, cation geothermometry from chloride hot springs has a reputation for greater reliability but, because gas more commonly goes straight up from reservoirs (Powell, 2000), it is often more relevant to the construction of a conceptual model. Both are uncertain but this uncertainty can be addressed by assessing how it fits with the other elements of the conceptual model.

Geophysics

Resistivity methods have dominated geophysical exploration for geothermal resources because, over a wide range of resource temperature from 70 to 350°C, low resistivity is closely correlated with the low permeability smectite clay cap shaded in yellow in Figures 1 and 2 (Cumming and Mackie, 2008; Ussher et al, 2000). Because it is the lowest cost portable resistivity method that can resolve the base of a clay cap to depths greater than 1000 m, MT is often preferred. However, for the model shown in Figure 2, the clay cap is thin enough to be resolved by a lower cost method like AMT or CSMT. Because the low resistivity zone imaged by these methods closely matches the smectite clay cap, it also indirectly images the high thermal gradient corresponding to the low permeability of the cap. Therefore, starting at the short segment of the 250°C isotherm inferred from geochemistry in the Figure 2 scenario discussed above, isotherms consistent with a steep thermal gradient can be sketched within the clay cap to outline the reservoir.

BLIND GEOTHERMAL SYSTEMS

As exploration progresses in a region and top rank prospects are developed, the remaining prospects are less likely to have the type of manifestations used to constrain the isotherms of the conceptual models in Figures 1 and 2. Conventional geothermal geoscience data sets can effectively constrain the conceptual elements of blind geothermal systems. The process of building a conceptual model often highlights another advantage of this approach; it both characterizes uncertainty and identifies strategies to effectively address the higher risk of exploring such prospects.

The synthetic scenario below is a compromise between the usually circuitous reasoning of the real world and the results oriented focus of real case histories. This particular scenario is for a blind prospect where sediments overlie fractured Paleozoic metamorphic rocks, a prospect type commonly encountered around the world, for example, in the US Basin and Range and in Turkey.

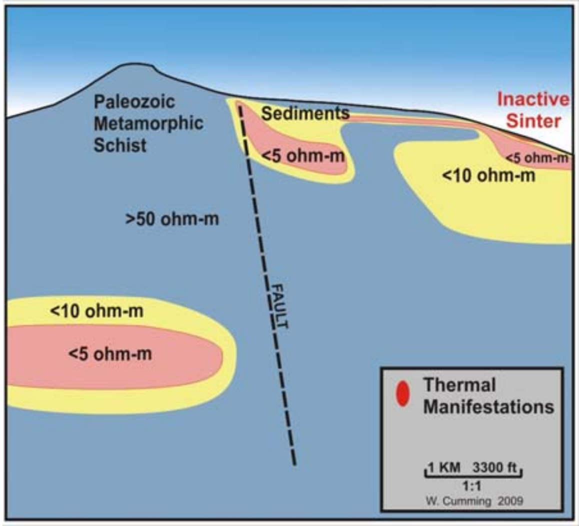

Figure 3: Annotated MT resistivity cross-section of a blind geothermal prospect with sediments exposed to the right of the fault and schist to the left.

Exploration data

Figure 3 shows the results of a conventional exploration program including thermal manifestation, MT resistivity, geology, and structure analyses. Paleozoic schist is mapped to the left and Recent sediments to the right of a steeply dipping normal fault. The sediments are low resistivity, as expected if they contained a lot of clay, although a higher resistivity zone appears to intrude from below into the sediments. An isolated, large low resistivity zone appears at over 2000 m depth on the left (upthrown) side of the fault. No thermal manifestations exist at the surface except for an inactive sinter deposit

Exploration scenario

Although an estimate of temperature from the geochemistry of a hot spring or fumarole is not available in a blink system, a range of likely reservoir temperatures can be estimated while a plausible conceptual model is assembled.

A reliable starting assumption is that, where the sediments are particularly low in resistivity, they have a high clay content and are impermeable. The high resistivity zones have the potential to be permeable but, where it is not fractured, the schist is like to be high resistivity and impermeable.

The local low resistivity zone below 2000 m on the left side of the fault is a detail that illustrates a pitfall if exploration reverts to anomaly hunting in this setting. This type of feature is often promoted as a drilling target because it is such an attractive anomaly. However, it has the appearance of a graphitic body characteristic of Paleozoic schist. In this case, it is more reasonable to assume that it is not relevant to the geothermal resource conceptual model, except to the extent that it can illustrate structure.

Since no thermal manifestations are observed at the surface trace of the imaged fault, if there is a viable reservoir, it is reasonably likely that the upflow extends along subsidiary structures to the right of the fault. The base of the sediments is likely to have particularly low resistivity where hot water is rising. Therefore, the upflow is interpreted to occur between the fault and the area about 800 to the right of it, beneath the area where the <5 ohm-m part of the clay cap (red) extends to about 500 m depth. It is reasonable to expect further upflow where the resistive (blue) zone extends into the sediments. It looks like a structure that hosts an upflow that, in turn, intersects an almost flat aquifer (blue) that extends almost 1000 m to the right at about 250 m depth and terminates near the sinter. That geometry is suggestive.

Although the sinter is not active, it implies that temperatures were, at some time, about 180°C very close by. The flat-lying resistive (blue) zone is about 200 m below the water table, suitable for hosting a 180°C aquifer without boiling (and creating gas that is not observed). The inactivity of the sinter might be attributed to a minor drop in the water table. Because temperature is still the highest risk, a cost-effective test of this model could be a 250 m slim hole sited just to the right of the final “s” in the label

"Sediments." It would be engineered to produce a clean water sample from the high resistivity aquifer.

To continue this scenario, after drilling Well A, the aquifer turns out to be a silicified sandstone with a temperature of 100°C at 250 m depth. The temperature declined under the minor production possible with a slim hole. However, the cation geothermometry is 200°C.

Based on this data from the first Well A, the conceptual model in Figure 4 could be assembled and a Well B could be targeted directionally across as many structures as possible between Well A and the main fault.

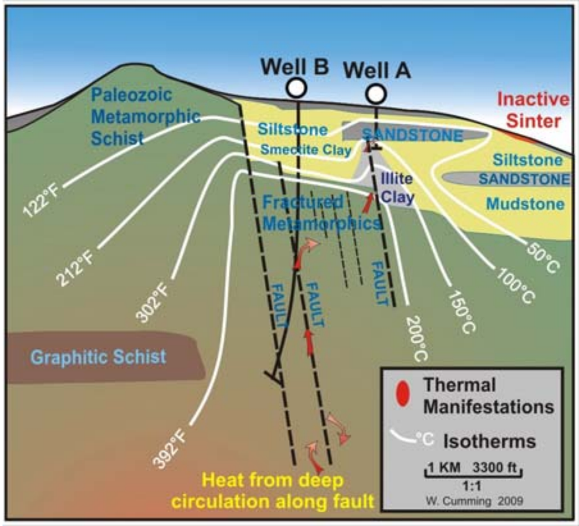

Figure 4: Conceptual model cross-section of a 200°C blind geothermal reservoir with isotherms, alteration zones, structures

A conceptual model for a blind system that lacks surface manifestations must include a mechanism to prevent fluid and gas leakage to the surface. In this case, it is the very thick clay cap.

CONCLUSIONS

At the exploration stage, the conceptual model is usually embodied in a few annotated temperature cross-sections tied together with maps of conceptual elements and illustrative data sets. Even without wells, isotherms can be constrained using geothermometry from surface manifestations, boiling point considerations and characterizations of permeability using resistivity and other methods. Even if a prospect is blind and so lacks conventional geothermometry, at least the shape of the isotherms can be characterized based on resistivity and structure interpretations, supporting the design of a more cost-effective temperature gradient well or shallow water sampling well.

One advantage of using a conceptual model approach in well targeting is that the well will directly test the properties of the model, especially the temperatures, and any needed revision based on the well results can be directly included in the resource assessment or follow-up targeting.

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