Why Basin and Range Systems Are Hard to Find: The Moral of the Story is They Get Smaller With Depth!

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ABSTRACT

A four-dimensional model of the most common geothermal systems in the Basin and Range is presented and discussed. A model founded on empirical data from the known characteristics of active systems at 0 to 2+ km depths expanded by comparison to epithermal mineral deposits to the 0.5 to 4 km depth range. In general the systems have a relatively broad shallow fluid dispersal zone fed by a narrow high-flow-rate stem much smaller than the near surface areas (they are mushroom shaped) The structurally controlled stems are small in area but highly permeable and occur in very localized tensional sites. The subtle configurations of fault, fracture and statigraphic relationships complicate exploration and development efforts. The stems connect (represent a short circuit to) a large, diffuse volume of variably permeable upper crust and harvest fluid in a continuously evolving manner. Consequently, the volume of rock sampled by the flow system (the" reservoir") cannot be determined by examining shallow/intermediate depth structural settings and use of idealized geological models. These observations explain why the system production capacity estimates in the initial stages of exploration and development are so unreliable and why many of the common geophysical techniques used for exploration and development have often proved to be so ineffective. The most appropriate analogues for active geothermal systems are epithermal mineral systems and the **only** unique signature of an active geothermal system is its temperature which, by definition, is higher than the surrounding rock. Therefore temperature directed drilling is the most appropriate technique for locating the "stem" and maximizing the production capacity of the geothermal system.

Introduction

There are several impediments to the exploration for and development of geothermal systems The most perplexing is the absence of a clear model identifying the geometry of a geothermal system and a structural understanding of how geothermal systems occur. Fault zones bounding the ranges and valleys are very complicated fracture systems that are not easily characterized from the surface expression. Intersecting active faults, reactivation of older structures, and slump blocks are just some of the features masking the surface expression of deeper structures along these boundaries. There have been three other papers in this series discussing the subject (Richards and Blackwell, 2002, Blackwell et al., 2009, and Waibel, 2011); this contribution addresses the overall system model as an uncertainty affecting the success of the exploration and development process. The general model of the Basin and Range system has been flow upward along a planar feature, i.e., a normal fault. While this model is strongly held, normal faults cannot, in and of themselves, be the controlling factor. The Basin and Range is replete with normal faults, most of which do not host geothermal resources. So while normal faults may be associated with most Basin and Range systems, the association may be as much a complicating factor as a useful exploration feature. Fault zones bounding the ranges and valleys are very complicated fracture systems that are not easily characterized from the surface expression. Intersecting active faults, reactivation of older structures and slump blocks are just some of the mechanisms masking surface expressions of deeper structures along these boundaries.

It has traditionally been felt that the surface thermal and/or structural expression of a geothermal system is the indicator of reservoir size at depths where the system will be developed for power production. In fact most Basin and Range systems are smaller at depth than the thermal expression at the surface and the surface fault structure may not have a simple relevance to the deeper structural behavior controlling fluid flow! The near-surface geometry of these geothermal systems is commonly an artifact of shallow structural splaying of the faults and of the dispersing of geothermal fluid into the regional groundwater system. Most of the developed Basin and Range systems are examples of the actual complexity rather than the assumed simplicity of the structural setting. This fact has been emphasized by the preceding papers and by Faulds (1998) among others, but is still not generally recognized by the geothermal exploration community.

The two primary models used to evaluate production capacity and longevity are the volumetric method of the USGS and numerical modeling of the "reservoir" (Sanyal and Sariemento, 2005). The volumetric model is based on a Monte Carlo simulation of the production capacity based in an assumed range in "reservoir" sizes and temperature. Yet there is no empirical evidence as to the real volume of any Basin and Range geothermal system! The numerical modeling approach is based on oil and gas modeling concepts and programs. In the numerical modeling approach the volume of the "reservoir," the heat recovery (fraction of in-place heat that can be extracted), and the "rate of recharge" are the three main parameters. However, there has never been a quantification of either of the first two parameters for geothermal systems in the Basin and Range based on empirical evidence!

Thus initial system evaluation is based on statistics and/or on parameters to be matched by production behavior (not available for that specific system). So in the initial stages of system development empirical data for size evaluation are not available and therefore are not a constraining factor in modeling! Assessed "areas" are rarely shown on maps. One limited example of the volume method is the assessment of the Dixie Valley producing field (Williams, 2004). There are two producing clusters of wells, in section 33 and in section 7. The surface area of the reservoir proposed for the two areas differs by a factor of 10 but the production over 30 years has been similar. Drilling 10 years after production started has shown that the structure and size of the system in section 33 is much different (Allis et al., 1999)

The curve matching of measured flow and temperature (two known) parameters using "estimates" of the first two unknown parameters based on a "model" of the volume of the "reservoir" is used to predict future behavior in the numerical modeling approach. However, recognizing that geothermal systems in the Basin and Range cannot be passive "in place" volumes but dynamic crustal scale systems, the third parameter, whose basic characteristics are also largely unknown, the rate of "recharge." For this parameter there can be only limited knowledge until well into the production phase. A result of the use of these parameters, all of which lack empirical measurements in early stages of exploration and development, is that the electrical power output of Basin and Range systems has not proved to be very predictable, with major consequences, both positive and negative, for developers of geothermal power.

The Model

Epithermal Mineral Deposits

A model is suggested based on the experience of exploration for epithermal ore deposits as this information gives a three dimensional time integrated model of many present Basin and Range geothermal systems. It uses Basin and Range epithermal mineral deposits as examples of the deep structure and evolutionary behavior to be expected. Partial evidence of this association is the fact that several Basin and Range systems have been discovered as an unexpected consequence of mineral exploration (Blue Mountain, Dixie Valley, Humboldt House, etc.) and the thermal system is clearly associated with the mineral system. Thus in the Basin and Range, epithermal mineral deposits are forming at the present time! It is generally thought that the temperatures are higher in mineral deposit formation than in Basin and Range geothermal systems. The temperature range of most of the developed Basin and Range systems is 200 to over 285°C. In fact modeling of the systems suggests that if they do not self seal or if the seals are broken over 10,000 year time scales then thermal systems can last for indefinite times at temperature of 150 to 200+°C (McKenna and Blackwell, 2004a). Fumaroles and local subsurface boiling with low TDS condensate are associated with many of the geothermal systems and are characteristic features of the epithermal deposits (Figure 1). The characteristic of low TDS fluid domination rather than steam domination also differentiates epithermal deposits from other types of mineral occurrences (porphyries, etc., see Figure 1).

The modulation of crustal fluid flow rates, depths, and temperatures in the Basin and Range by cycles of normal faulting in conjunction with the regional high heat flow and the local geology leads to ongoing geothermal system initiation and evolution, in some cases associated with epithermal mineralization events. In fact, Henley and Berger (2000, p. 690) argue that in epithermal deposits

> *"the timescale of mineral deposit formation is related to the timescales of crustal deformation rather than the longevity of crustal scale thermal events alone (measured, for example, by the time interval over which particular magmatic suites are intruded)."*

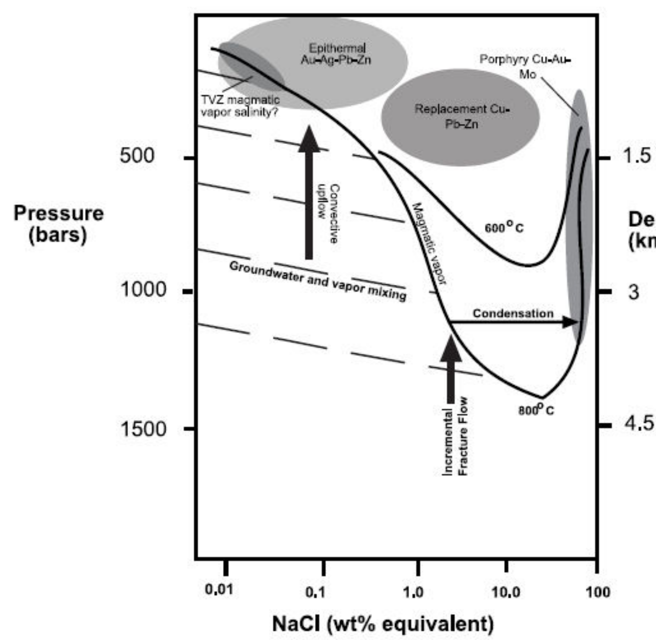

Figure 1. Pressure-Fluid conditions associated with mineral deposits (Henley and Berger, 2000). Note the similarity of fluid and chemical conditions and depths to Basin and Range geothermal systems and epithermal deposits and the contrast with direct volcanic associations (porphyries).

Therefore crustal scale fluid flow in Basin and Range geothermal systems represents a type setting for the formation of epithermal mineral deposits. And indeed, low grade gold mineralization has been found at Senator fumaroles (Johnson et al., 2000) and at the Dixie Comstock Mine (Vikre, 1994) adjacent to the 45-14 well 10 km south of the producing field.

The structure of epithermal deposits at depth should give examples of the deep characteristics of the associated geothermal systems. One of the recurring themes in those papers that do discuss structural setting is the role of very localized deformation patterns that result in large high permeability regions, i.e. a vertical conduit allowing large volumes of fluid to flow toward the surface. Localized areas of tension also fit with near-surface splaying of vertical structures, resulting in the flower or "Morel" near-surface pattern (Figure 2). This characteristic might explain why, while the Basin and Range is abundantly populated with normal faults, cross faulting and lateral fault splaying, only a few localized settings within these structures actually contain geothermal systems, and why some specific locations host recurring hydrothermal systems.

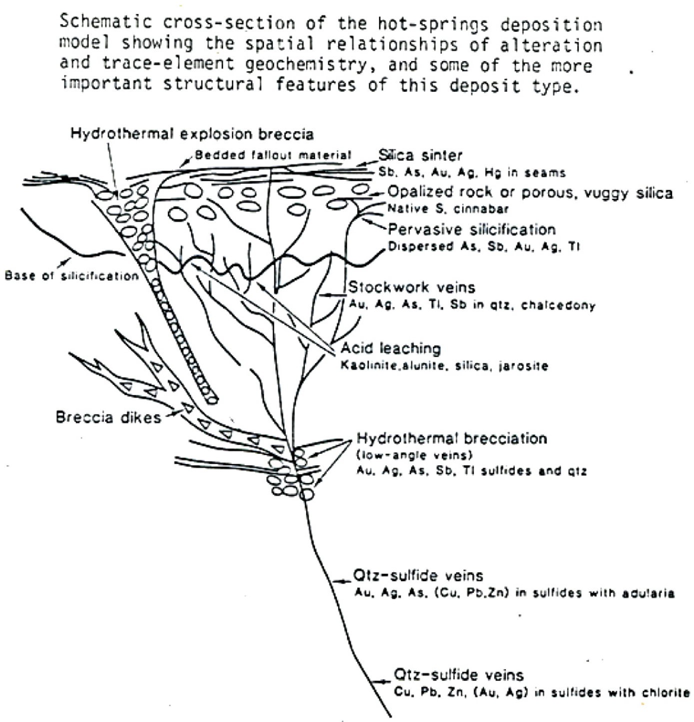

Figure 2. Hypothetical cross section of an epithermal mineral deposit (Berger and Emmons, 1983). In the specific case of the Basin and Range systems the desert environment means that surface springs are rare and much or all of the discharge is below the ground surface at the local water table with the formation of (large) plumes of thermal discharge offset from the surface expression shown in this diagram.

The Geothermal Model

The model proposed here is that the system shapes are more like mushrooms (morels) than planar fault features. The feeding "stems" may be quite small but are capable of very high flow when stimulated by drawdown of the pressure as the system is exploited. For example in Dixie Valley two such "stems" produce about 20 to 40 MW each. Thus one consequence of this model is that the reservoir "volume" may have little to do with any observable surface or shallow subsurface feature and the heat must be drawn from a large diffuse region that is presently uncharacterized. System size at shallow and intermediate depths does not uniquely reflect the overall "reservoir."

The typical model of a geothermal system is some volume of "reservoir" is tapped by the producing wells and sustained by injection that in some way maintains the pressure in the reservoir. In fact it appears that in many Basin and Range systems (and geothermal systems in general) the area of surface expression and/or structural association is bigger than the area tapped by production wells in the 1 to 3 km depth range. So in spite of the importance of the "reservoir" volume estimate in the system evaluation the determination of a "reservoir" volume based on exploration and early development data is in fact rarely based on empirical evidence. The evolving model is that Basin and Range systems are most commonly associated with regions that can be most clearly described as intersections or complexities in faulting patterns rather than planar parts of a fault zone. These complexities can be small (a fraction of a km^2) but have high flow rates. Examination of ore deposits associated with faulting has shown that the systems are associated with motion complexities and that they usually shrink rather than expand with depth.

A typical temperature-depth curve from a Basin and Range geothermal system is shown in Figure 3 from the Eleven Mile Canyon area in Southern Dixie Valley (Williams and Blackwell, 2012). These well sites were based on the location of the maximum gradient observed in shallow thermal gradient wells. Thus these deep wells do not intersect the thermal upflow feeding the shallow system. Unfortunately, as pointed out by Richards and Blackwell (2002b), the hydrologic conditions in the Basin and Range confuse the surface anomalies and overturns are ubiquitous at both shallow and deep depths in the Basin and Range. There are many examples of the location of deep wells on the basis of shallow thermal gradient wells that miss the system (Desert Peak (Benoit, 1982), Eleven Mile Canyon, Pirouette Mountain (Williams and Blackwell, 2012), Rye Patch (Waibel et al., 2003), etc., emphasizing the typical mushroom shape of the systems.

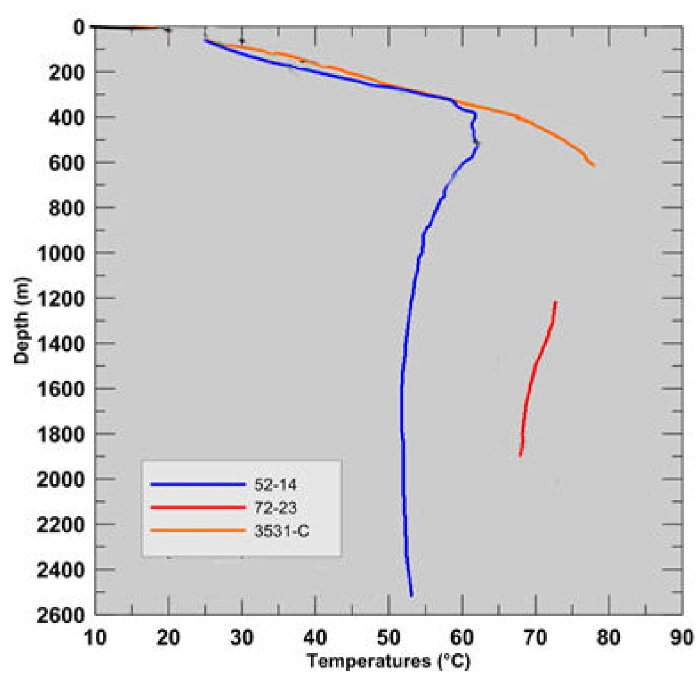

Figure 3. Temperature depth curves from the Eleven Mile Canyon Geothermal system, southern Dixie Valley, Nevada (Mitchell and Blackwell, 2012). The well 3531-C is an intermediate depth well near the site of the 72-23 deep well.

Basin and Range Systems and the Earthquake Cycle

The formation and evolution of Basin and Range geothermal systems is intimately related to the formation of the basins and ranges by normal faulting. The recurrence interval of faulting events ranges from 10,000s to 100,000s of years. This time scale is similar to the time scale for temperature effects over 10's of km. In a simple way, a single cycle consists of the breakage associated with a faulting event that opens a short circuit to distributed permeability in the larger system. Hot water flows up the fault driven by thermal and topographic effects with a velocity related to the detailed permeability distribution governed by the geometry of the fracturing and unit porosity along the fault. The more constricted permeability paths will be rapidly sealed by mineral deposits (silica, etc.) so that over longer periods the flow is confined to the highest permeability channels related to the details of the fault structure and the permeability of the various geological units in the system.

Perhaps surprisingly valley fill, except at shallow depths, is typically not involved in the flow system. This is in part because the active side of a basin range pair is generally the location of the playa lakes and even in the alluvial sediments along the active side of the basin, where the sediments might be expected to be the coarsest, the sediment contains a clay matrix that results in low permeability (Blackwell and Kelley, 1994). Therefore, most production is associated with fault related fracture permeability in basement types of rocks.

Size and Geometry of Epithermal Deposits

The general model of an epithermal deposit is shown in Figure 2. The ore grade deposits are generally found to be mushroom shaped with the acid alteration zone near the surface shrinking to the altered/ore bearing region below the fossil water table, shrinking further with depth to a feeder conduit. The shallowest parts are generally eroded away, so the upper parts illustrated in Figure 2 represent conditions below the water table.

The ore bearing volume of an epithermal deposit is typically quite small. This volume and the feeder presumably represent the area of concentrated fluid flow and so would be the drilling target in a geothermal system. For example, the Sleeper deposit in Humboldt County, Nevada is a typical bonanza epithermal gold deposit located and developed by AMAX (Wood, 1986). It is along a Basin and Range bounding fault between the Jackson Range and the Black Rock Desert. A map and a cross section of the deposit is shown in Figure 4. At its widest point it is about 150 m wide (narrowing less than 50 m wide to the north and south) and the extent is about 300 m N-S.

Another example of a plan view of a vein system is shown in Figure 5. The figure shows the typical vein structure associated with an ore body in the El Bronce mine in Chile (Camas et al., 1991). The complex effects of the superimposition of many different events lead to a pattern that is neither easily understood nor simply described. Furthermore, the location of the permeability necessary for a large, long-lived system of this type varies with time and as a result the ore bodies (maximum flow channels) are not uniformly nor logically distributed along the vein system in its final configuration. Many types of models for locating permeability may be useful in a given situation, i.e., the orientation of the fault, the position in time relative to the last large earthquake, etc. These are probably less relevant though than directly locating the thermal anomalies associated with the active flow paths at a given moment in the evolution of the system by using thermal techniques. As in the previous example the area of the veins is quite small and a random drill path through the area shown would most likely miss them!

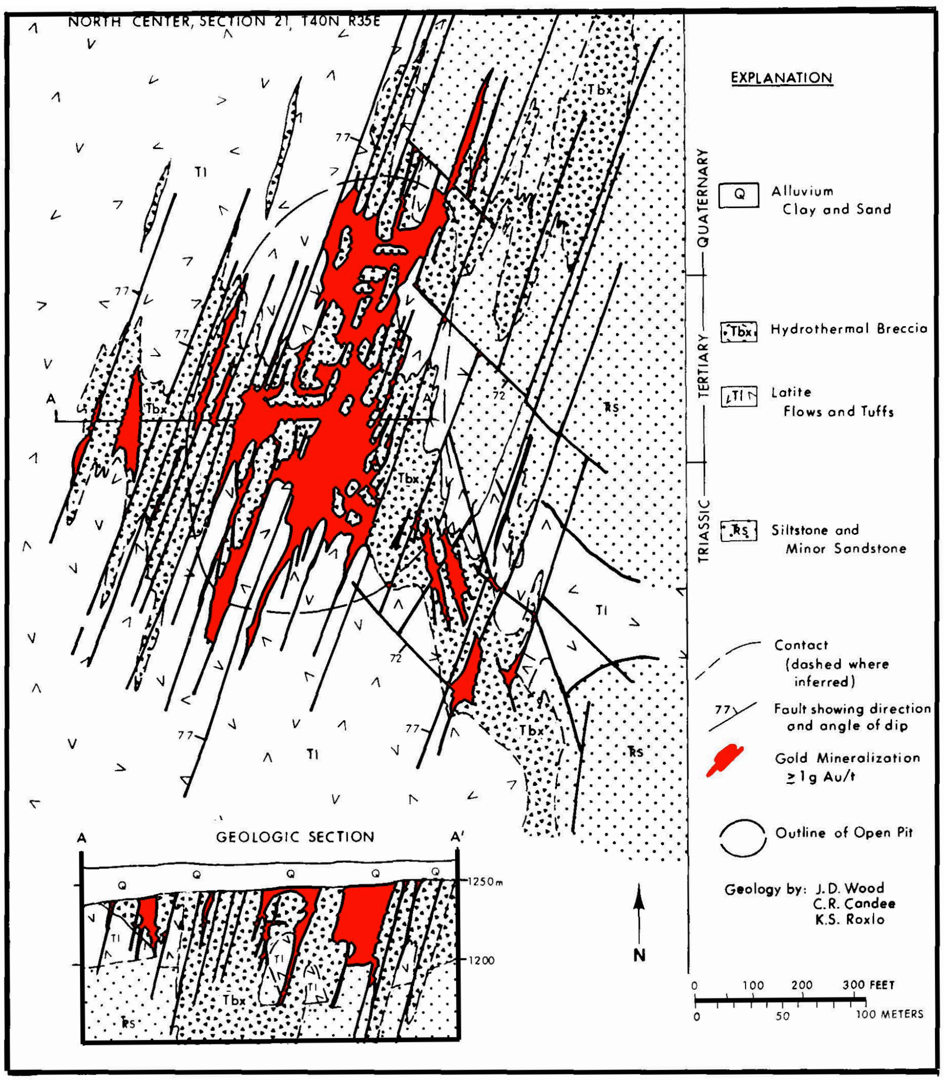

Figure 4. Map and section of the Sleeper deposit, Humboldt County, Northern Nevada (Wood, 1986).

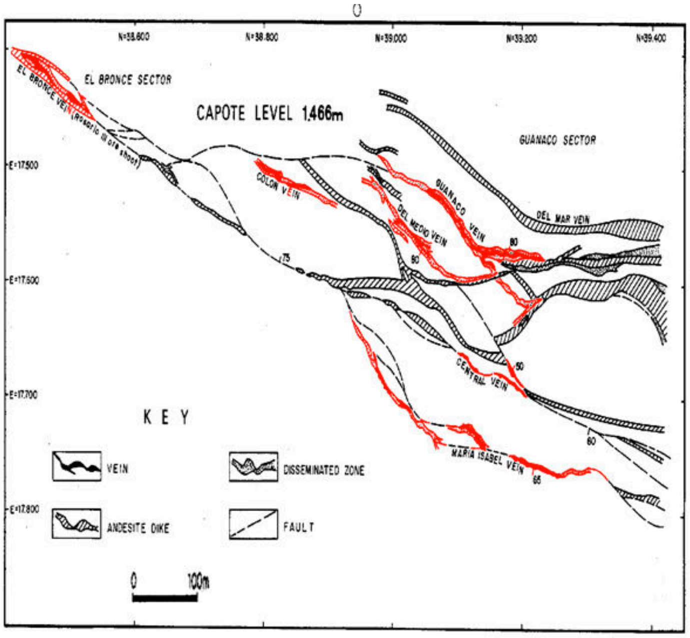

Figure 5. The veins and ore bodies at El Bronce District, Chile. Zones of permeability are shown in red (Camus et al., 1991). The area shown in the box is 0.5 km square, about the downhole size of the production zones in Sections 7 and 33 in Dixie Valley.

In both examples shown (Figures 4 and 5) the sizes of the target zones of maximum flow are closer to 10's of meters in scale rather than 100's of meters in scale. This size represents a small target to intersect at a depth of 1.5 to 3 km along a multi kilometer long structure. Following the zone of heat is the most direct way to accomplish the objective. The results in Dixie Valley show that the position of the permeable pathways will not necessarily be obvious, but they can be found thermally.

Temperature is a Boundary Condition

The flowing temperature of system is a thermal boundary condition, that is the highest temperatures are in the highest volume flow path, so that the maximum observed temperature must be found at the point of highest flow rate! Hence temperature can be used to direct the drill bit during drilling of an exploration or production well. As long as temperature is increasing the flow structure has not been reached or crossed. A number of numerical examples are given by McKenna and Blackwell (2004). If temperature starts to decrease the well track is moving away from the flow structure and has passed through it or beside it. The hottest bottom-hole geothermal well in Nevada was successfully drilled to TD based solely on surveys showing an increase in temperature with footage drilled. After 485ºF was passed (the assumed temperature of the target system), and once all possible 55° to 75° dipping normal fault projections were passed, increasing temperature with well footage was the only guide. (Blackwell et al., 2000). Furthermore the temperature pattern can be used to infer the geometry of the flow paths if the temperature on the flow path is known or can be inferred.

An example of how this information might have been used is illustrated in a thermal cross section at Brady's Hot Spring geothermal system, Nevada, from an online report by GeothermEx entitled "Evaluation Of The Resource Supply For The Mammoth, Ormesa, Steamboat, Bradys Hot Springs And Desert Peak Geothermal Projects, California And Nevada" for Lehman Brothers, New York, New York, Jan 2004 (http://www.sec.gov/Archives/edgar/data/1312500/000095013605000639/file034.htm, 2004).. The section (approximately West to East) crosses the producing normal fault at right angles and shows the production wells at about 360° F along the fault. The section also shows a well on the upthrown side that has a temperature of 395 °F (well 77-1) at approximately the same depth as the production. There is no structure shown on the section that can explain this situation. Yet there has to be a permeable zone bearing fluid at least 35° F hotter than the production zone in the vicinity of 77-1, even though there is no such structure is shown on the section!

Due to the small size of the deep flow paths, most geophysical surveys, particularly MT, cannot resolve these systems, particularly if the data are 2-d cross sections or have undergone smoothing associated with 3-D modeling. Another complexity the causes problems for MT is the low resistivity of valley fill that complicates resolution of modest electrical conductivity contrasts in the adjoining basement block. Techniques like MT, gravity and aeromagnetics can identify structures but cannot tell, over tens or hundreds of kilometers of structures, which few are the localized "Morel" structures. Shallow temp holes target the general area, but structure and deep temperature hole data provide the actual drilling target.

Discussion and Summary

Epithermal mineral systems are fossil geothermal systems and therefore have structural and geochemical characteristics and histories that compare directly to Basin and Range geothermal systems. The surface and shallow subsurface expressions are in general larger than the intermediate depth (1 to 4 km) upflow zones. The deep flow systems (> 4 km) are cryptic. Most epithermal deposits are found using grid drilling and sampling. In the geothermal case, the activity of the system is the key to location, it will be the hottest spot. There may be many structures and stratigraphic situations in a given area that might theoretically generate permeability suitable for geothermal system development, but the only ones that are effective at the present time will be the hottest ones! Because the footprint of the flow stem is often quite small, and the dip of the fluid bearing structures may be steep, vertical wells have a small margin for error and direction flexibility should be built into drilling plans.

Wisian et al. (2002) suggested using the empirically determined parameter of heat loss as an estimate of electrical size that can be used in early evaluation efforts. This approach was applied to Basin and Range systems (Richards and Blackwell, 2004) and compares favorably to the other evaluation techniques but involves many fewer assumptions. Heat Loss and an estimate of the system temperature determined by water chemistry in samples from springs or shallow test wells in the thermal gradient anomaly, appear to be the most helpful data at the early stages of exploration and development as directly measureable parameters that furnish estimates of system potential. This approach might be more widely useful in early evaluation efforts than the conventional approaches based on parameter assumptions.

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