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Directed Geothermal Drilling Using Temperature: Examples from Numerical Simulations

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Introduction

The geological models of geothermal systems are generally complicated and poorly known, particularly in the early stages of deep drilling. Deep wells often do not encounter the expected conditions/structures in the projected positions. As a result there are many "dry" wells or wells later used for injection. In other cases legs from a vertical well are subsequently directionally drilled in attempts to encounter nearby fluid active features. The directions of the legs are generally based on hypothesis of the structure as modified by the first vertical leg of that well. There is generally no confirmation that the correct direction was chosen until a fracture is actually encountered. There has long been a desire to be able to locate fractures near the well bore, but untapped by the well, by some downhole logging technique. However, no such technique has been successfully developed for operation for various technical and theoretical reasons (equipment difficulties, environmental problems, resolution limits, etc.). However, by the nature of geothermal systems fluid filled flow zones have to be hotter than their surroundings. Thus tracking the temperature change as a deviated well is drilled will indicate in many situations whether the bore is going toward or away from a zone of active fluid flow.

The objective of this paper is to demonstrate that such an approach is feasible by illustrating theoretical examples of such situations using a Basin and Range type of structure as an example. The practicality of such a procedure is based on the existence of temperature logging equipment that is accurate and can operate at high temperature (Wisian et al., 1999) and by the demonstration that the thermal recovery in a well can be used to estimate the temperature with relatively short well delays.

Results

Directed Reservoir Drilling

The 2-dimensional geometry utilized in subsequent numerical modeling is illustrated in Figure 1. The study area is a Basin and Range type of structure with three scenarios. In Figure 1a, a single fault dipping at 65° is present and serves as a conduit for subsurface fluids. A similar geometry is shown in Figure 1b, but instead of a single fault, two high angle faults (> 80°) are present, similar to those observed in typical producing Basin and Range geothermal systems, for example Dixie Valley, Nevada (see Blackwell et al., 2002). The convective models shown in Figures 2 and 4 were developed utilizing PetraSim by Thunderhead Engineering Consultants and solved numerically with TOUGH2 (Pruess et al., 1999). For a discussion of the modeling parameters, see McKenna and Blackwell (2004). Both the convective (Figures 2 and 4) and conductive (Figure 3) panels shown are a subset of a

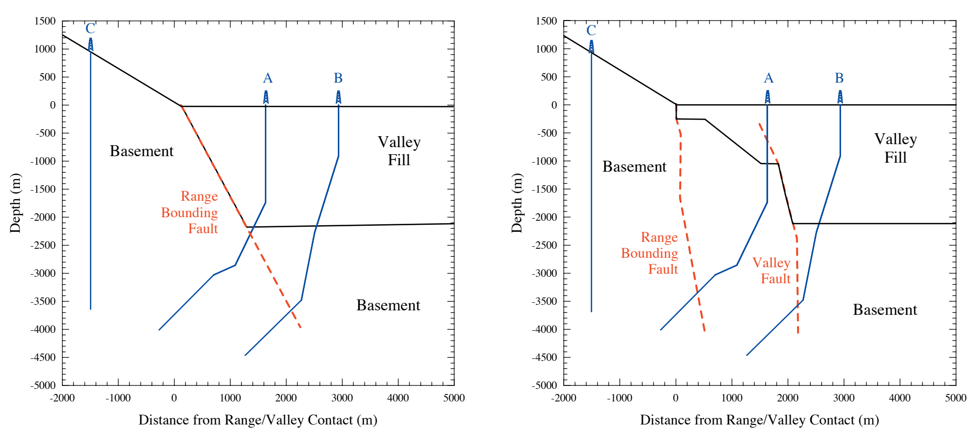

Figure 1. **(a)** Single fault model geometry **(b)** Two fault model geometry.

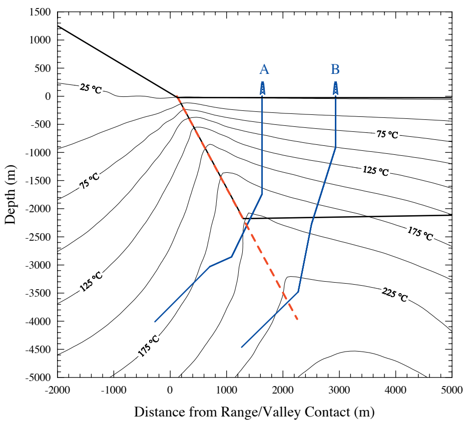

Figure 2. Single fault convective model.

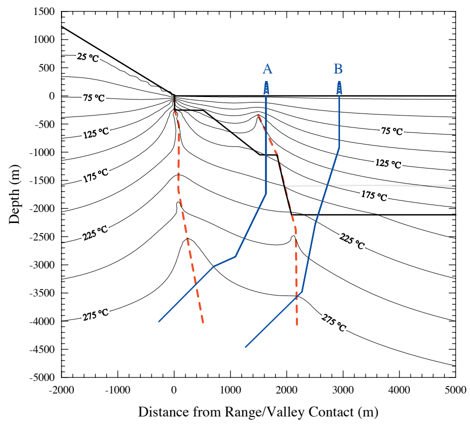

Figure 3. Two fault conductive model.

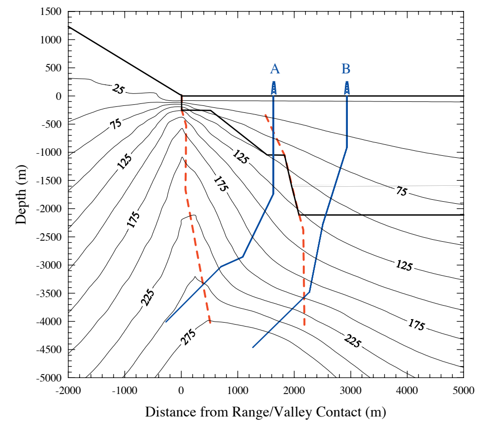

Figure 4. Two fault convective model.

larger model geometry consisting of a valley separated by two ranges. The modeling parameters specific to the conductive and convective models (thermal conductivity, permeability, etc.) are discussed in Blackwell et al. (2000), and McKenna and Blackwell (2004). All 3 models are penetrated by two wells: Well A close to the range/valley contact, and Well B farther out in the valley. Well C, which penetrates the models in the adjacent range, will be discussed in a subsequent section.

The convective model temperatures for the single fault geometry are contoured and shown in Figure 2. The maximum temperature predicted by the model in the likely reservoir area is about 240°C. The shape of the isotherms is diagnostic of a single high-permeability fault zone. Figures 3 and 4 are the contoured temperatures predicted by conductive and convective (very low permeability) models, respectively, utilizing a two fault geometry. The isotherms shown in Figure 3 were based the actual Dixie Valley Power Partners from measured well temperatures in 4 wells, including wells A, and B. Because the model is purely conductive, the actual shape of the isotherms will be slightly different, but not by much, as the measured temperatures are powerful constraints on *in situ subsurface temperatures.*

The temperature cross section shown in Figure 3 is derived from solving numerically for the fault positions constrained by the observed temperatures on the wells. This approach works in a convective system because the heat transfer is in some cases dominantly conductive (as proved by the complete lack of evidence of fluid loss or gain) away from fracture/fault zones. The temperatures in the convective models (Figures 2 and 4) however, are somewhat different than the conductive model. Future models will match the observed temperatures more closely, but the power of the temperature data in constraining the geothermal system model is reinforced by the difficulty in modeling it correctly. Both two fault models illustrate the important observation that the shape of the isotherms is quite different from the shape predicted by a single fault model.

The temperatures that would be measured in wells A, and B as each well is drilling progressively deeper are shown in Figures 5 and 6, respectively. In each figure, the first group of four plots corresponds to the single fault model, the second group of four the two fault conductive model, and the third group of four, the two fault convective model. Each plot in the figures corresponds to a temperature depth curve bottoming out at the depth show in the title bar. Each plot also contains any intersection the well track makes with any fault(s) present.

As each well is drilled deeper, the temperature changes in response to proximity of the reservoir; as drilling approaches the reservoir, temperatures will rise, and as the well is drilled away from the reservoir, temperatures will fall. The single fault convective model illustrates this concept. As both wells penetrate the fault (Figure 5a and 6a), the observed temperature rolls over, and the well begins to cool because the well is getting farther from the reservoir as drilling progresses. Compare these temperature depth curves to those predicted by the conductive two fault model of progressive drilling in well A (Figure 5b). As the well is drilled deeper, the well temperature increases. Only at the point at which the well passes through the reservoir, does it rollover and begins to cool. Note however, if the well temperature does not rollover and at least go isothermal, if not decrease, the well has not passed through the reservoir. Figure 6b illustrates this concept: well B gets hotter as drilling proceeds, indicating that the actual reservoir has not been exited by the well track. If this well was not "steered" into higher temperatures might not have found the highest temperature portion of the reservoir at all.

Thermal Regime Beneath the Range

McKenna and Blackwell (2004) note that one or two wells drilled in the range adjacent to fault-block hosted Basin and Range geothermal fields can impact exploitation in a fundamental way. By drilling in the range away from the reservoir, the background thermal and flow regime prior to faulting may be delineated; hence, the initial conditions for any regional/local reservoir modeling may be constrained, which is important for correctly placing the current reservoir in the temporal evolution of the geothermal system. We note here two other fundamental advantages of this type of drilling. First wells drilled in the range adjacent to production can help constrain the amount of downflow from adjacent ranges (if any), and second, wells situated in the range can help distinguish between competing fault models.

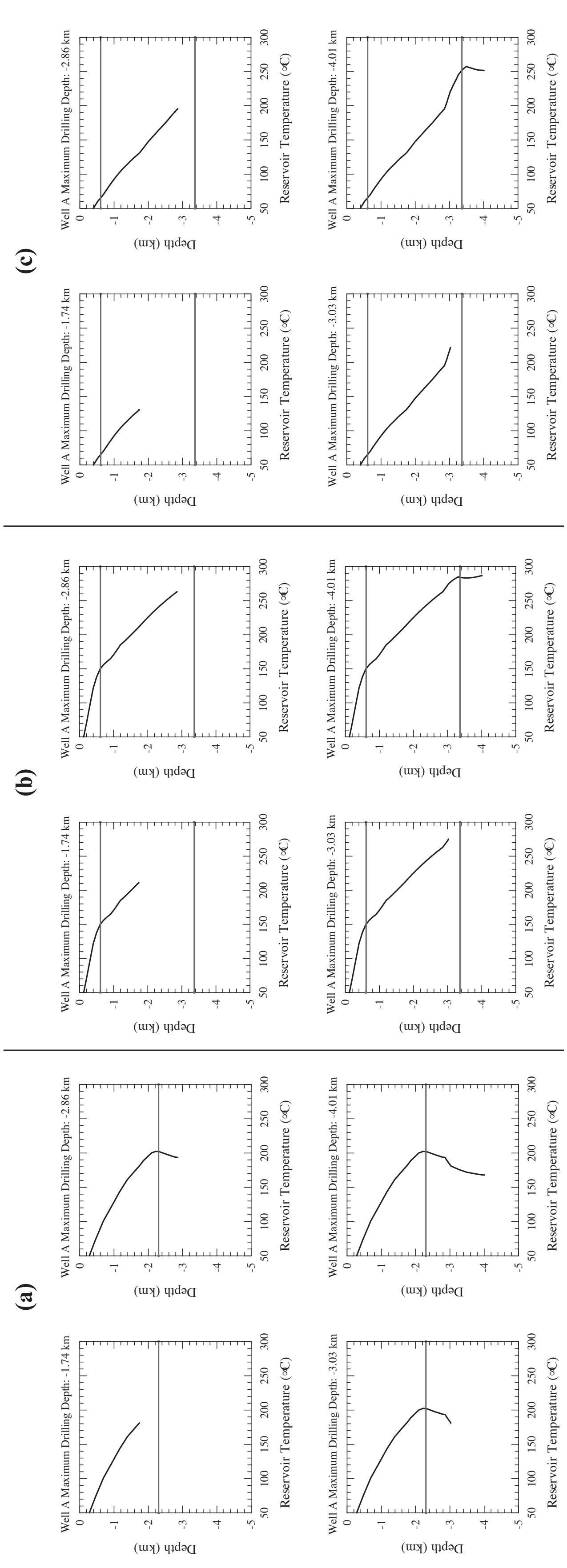

Figure 5. Well A progressive drilling paths from the **(a)** single fault conductive model **(b)** two fault conductive model and **(c)** two fault convective model. The horizontal solid lines are the depth at which a fault is intersected.

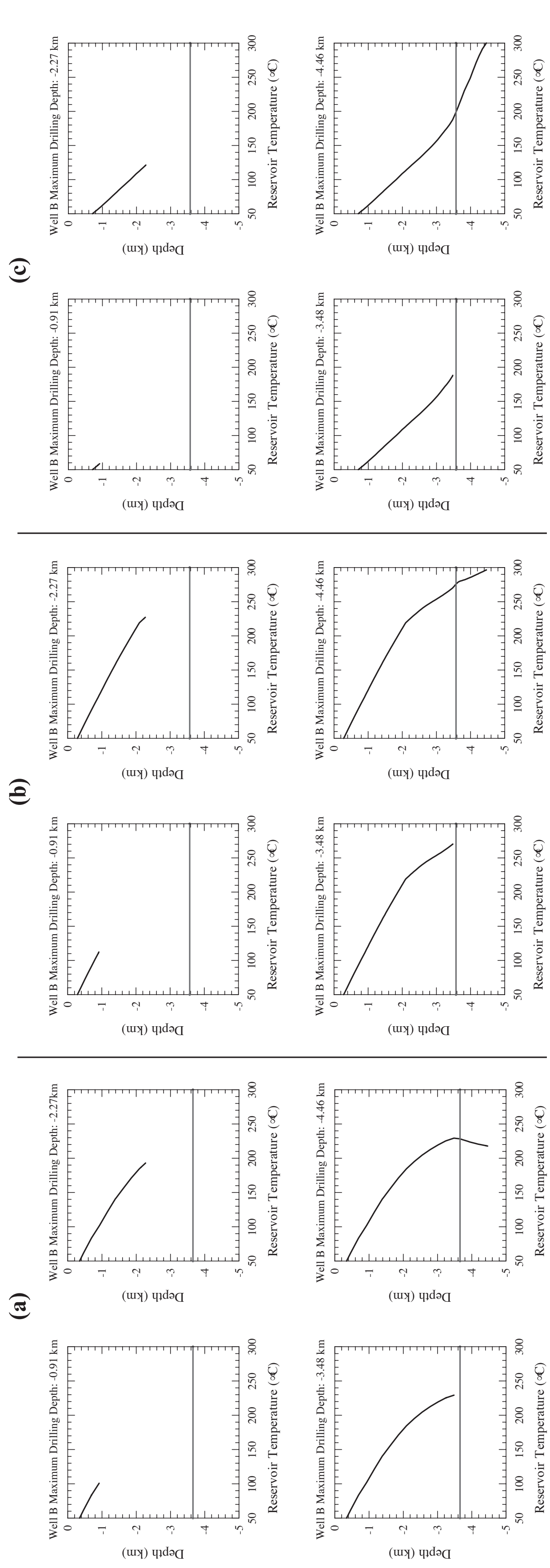

Figure 6. Well B progressive drilling paths from the **(a)** single fault convective model **(b)** two fault conductive model and **(c)** two fault convective model. The horizontal solid line is the depth at which a fault is intersected.

One of the observations from the type of convective modeling discussed here is that downflow from topographic highs (i.e., mountain ranges) near high angle faults tend to produce isotherms that don't mimic topography unless the permeability is very small. In contrast to the case in conductive modeling (see Figure 3) isotherms fold around permeable conduits (i.e., faults, see Figures 2 and 4). Well control of the thermal/flow field in this area would provide important constraints on the far-field thermal regime by delineating the permeability of the ranges. Furthermore, the concepts discussed above concerning directed drilling also apply to a well drilled in the range: as drilling proceeds from the range area towards the fault (particularly high-angle range-bounding faults common to the Basin and Range area), the observed temperature should get hotter until the high temperature reservoir is exited.

As another example of the importance of range drilling, consider the temperature obtained in well C (Figure 1) for the three models shown in Figures 2-4. Well C is a vertical well, so the temperature in the well is a reflection of the far-field thermal regime. For the models discussed here, it is clear that the highest temperatures encountered in well C at any given depth arise from the 2 fault conductive model, and the lowest arise from the single fault convective model (Figure 7). Both observations are expected, however, as the conductive model does not incorporate downflow from the topographically high ranges, and the single 65° fault focuses higher temperatures farther into the valley and away from the ranges. Drilling in the ranges, however, could help to determine if the thermal regime beneath the ranges is more conductive than convective, which would ultimately leas to better constraints on the extent and behavior of the high-temperature reservoir.

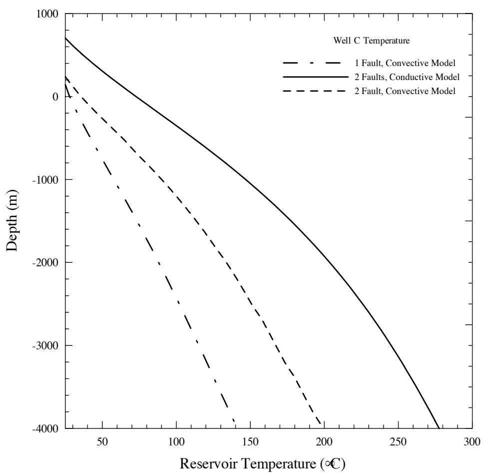

Figure 7. Temperature in Well C beneath the range adjacent to the valley. The modeled temperature in Well C was extracted from each of the 3 models shown in Figures 2-4. It is apparent that each model predicts a different thermal regime in the range adjacent to the reservoir. Information about the thermal regime of the adjacent range may help delineate the thermal/flow regime in the valley, and ultimately help direct drilling towards the high temperature reservoir situated in the valley.

Conclusions

Numerical simulations illustrate that "steering" a well into hotter regions regardless of how many flow zones are encountered is a viable technique for maximizing well success. Continued work understanding the detailed thermal regime within complex multi-zone geothermal reservoirs from numerical modeling and observed situations may therefore represent an important advance in increasing production well success rates.

Acknowledgments

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