A NEW MODEL FOR GEOTHERMAL EXPLORATION OF NON-VOLCANIC SYSTEMS IN EXTENDED TERRAINS

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ABSTRACT

Existing geologic models of geothermal systems work reasonably well for the exploration of systems clearly associated with active, or recently active, volcanic centers. The poor results of exploration drilling undertaken during the last few years in the non-volcanic systems of the western United States, however, indicate that the model being used for exploring these systems requires significant modification to be useful. Based on considerations of local and regional geology, as well as on drilling results, it is proposed that the presence of large tilted fault blocks, characteristic of extended terrains, are essential to the development of this type of non-volcanic geothermal system.

Groundwater, confined within tilted aquifers, can circulate to depths of thousands of feet and obtain temperatures of over 400°F even in areas with moderate temperature gradients. The heated, buoyant water flows up-dip in the aquifer until it reaches the impermeable barrier of a block-bounding fault. Flow then continues to the surface along the sloping intersection of the aquifer with the fault.

If future testing of this model proves it to be correct, it will provide a realistic conceptual model for guiding exploration and development drilling and for constructing more effective numerical models.

1. INTRODUCTION

Geologic models, or "conceptual" models as they are now more commonly called, form the basis for the exploration, development and management strategies required to find and produce a geothermal field. From the prioritization of prospects, through the design of geophysical and geochemical surveys, to the selection of drilling targets, decisions are based on a conceptual model which incorporates the geologic elements essential to the formation of the geothermal system being explored. Furthermore, the conceptual model forms the basis for constructing the numerical model needed for designing production and injection strategies and for predicting future changes of reservoir temperature.

During the past few years, a number of North American geothermal projects have been hampered both by unsuccessful exploration and development drilling and by unanticipated reservoir cooling after production start-up. These problems, undocumented in the public domain, have not only caused financial losses, but have led to the premature abandonment of exploration efforts in prospects that still hold considerable promise. These problem fields and prospects have the common characteristics of not being associated with young volcanism and of being located in the Basin and Range physiographic province. The cause of these problems, in the writer's opinion, is that the conceptual model being used to explore and develop these fields is unrealistic.

The lack of a realistic conceptual model to guide exploration and development of these non-volcanic systems has made geophysical surveys generally ineffective because there is no general agreement on: a) the type of surveys to use; b) what the survey should be looking for; and c) the relationship, if any, between the defined geophysical anomalies and the exploration objective. Inappropriate or misinterpreted surveys have resulted in negative or, at best, inconclusive results. The lack of a clear relationship between the survey used and the objective sought has led to the practice of undertaking geophysical and geochemical surveys to define anomalies, rather than validate models. Drilling targets are chosen in the area with the most overlapping anomalies. This strategy has the same chance of success as choosing targets on the basis of committee consensus.

In contrast to "anomaly-driven" exploration, oil geologist have practiced "model-driven" exploration for decades. This strategy, a product of some 80 years of industry experience, is based on a sound understanding of the geologic principles responsible for the formation, migration and accumulation of oil and gas in economic deposits. The anticlinal theory of oil accumulation became the cornerstone of oil exploration, giving coherence and logic to a multi-billion dollar industry.

The purpose of this paper is to propose a new geologic model for those non-volcanic geothermal systems which occur in extended terrains typified by the Basin and Range Province. It is hoped that this model, if it proves to be correct, will improve the design and effectiveness of geophysical surveys, the drilling success ratios in new prospects and developing fields, and the results of numerical modeling when used to design production and injection well fields and to predict future trends in reservoir temperature.

2. GEOLOGIC SETTING

The Basin and Range geothermal systems are developed in a region that has undergone tectonic extension characterized by normal faults. Extension produces horst and graben structures and, with fault block rotation, tilted blocks and half grabens.

Many of the world's geothermal systems located outside of the young volcanic belts associated with subduction zones occur in extended terrains. These terrains occur in three major regions: a) an E-W belt stretching eastward from Greece through Turkey, Georgia and Iran, into Tibet; b) a **N-S** belt extending from the Dead Sea Rift southward through the countries bordering the Red Sea and southward again through the East African Rift system; and c) on the North American continent, a N-S belt extending from the northwestern United States to northern Mexico. This last region coincides largely with the Basin and Range physiographic province.

Although young volcanism occurs in these extended terrains, it is not nearly as prevalent as the volcanism associated with subduction zones. For example, few active volcanoes occur along the African Rift as compared to the numbers occurring along comparable lengths of the Japanese, Philippine Indonesian or Andean subduction zones. In the Basin and

Range, young volcanism occurs only along its western margin, notably at Long Valley and Coso in California and, to a lesser extent, on its eastern margin at Roosevelt hot springs in Utah.

Efforts to develop geothermal power in the Basin and Range began about 30 years ago. To date, 15 fields have been developed (Benoit, 1994) and, of these, only three are associated with young volcanism. The combined installed capacity of the 12 non volcanic fields is about 185 MW.

3. PROBLEMS WITH THE PRESENT MODEL

Simply stated, the present model used to explain the presence of geothermal systems in extended terrains is that meteoric water is heated by deep, convective circulation in a region of high heat flow (Hose and Taylor, 1974; Olmsted et. al., 1975). The vertical permeability needed for both downward and upward fluid movement is believed to be provided by the major normal faults caused by extension tectonics. Fault intersections are believed to be particularly favorable for creating this vertical permeability.

This model, however, does not adequately explain the following aspects of systems being explored and developed in the Basin and Range:

- Where sufficient data are available to reveal the pattern of temperature distribution on both sides of a range-bounding fault, the volume of high temperature rock is typically much larger in the relatively uplifted footwall block. If the fault acted only as a conductor of thermal fluid, a more symmetrical pattern of temperature distribution would be expected. Discharge from the fault to a shallow aquifer cannot explain this asymmetry because it is observed to extend to depths of thousands of feet and to exist in areas where aquifers dip away from the fault.

- Although the thermal systems are often associated closely with normal faults, fluid production is mainly obtained from specific stratigraphic horizons, rather than from the fault itself.

- Fluid production rarely occurs along the entire length of a fault segment, but typically occurs in laterally restricted zones. Furthermore, the permeable zones often do not extend down the dip of the fault, but plunge at moderate angles along or near the plane of the fault. Many exploration holes drilled to intersect a fault directly down its dip from the location of surface hot springs have been unsuccessful because of this characteristic.

- Although most geothermal systems are located along the fault scarps of the tilted blocks, some occur on dip slopes.

In addition to these characteristics, there are two concepts intrinsic to the fault model which are difficult to reconcile with geologic experience and production realities.

In oil fields, faults typically form impermeable barriers to fluid flow, thereby segmenting reservoirs into isolated compartments with each compartment requiring its own set of production and injection wells. In geothermal fields, on the other hand, faults are perceived as the main pathways for fluid transport. It is not clear how these two opposing roles can be reconciled.

A related problem is reconciling the small volume of fluid that can be contained within the fractures of a narrow fault with the vast volume of fluid which is typically produced from fields reportedly producing from a fault. Computer simulations of such fields have been unsuccessful in attempting to match long-term well characteristics by providing production only from a fault. If production is from a fault, it must be recharged from a much larger reservoir to sustain the observed long-term flows.

Because of the importance placed on fault permeability by the present model, geologists have a tendency to identify any permeability encountered in a well as fault permeability. This interpretation is made in spite of the absence of objective geologic criteria, such as recognizing a missing or repeated segment of stratigraphic section, to establish that a fault has actually been encountered. This practice perpetuates the concept that fault permeability is essential for production from systems located in extension terrains and frustrates objective evaluation of the true role of faults in these systems.

These observations have led the writer to develop a modified fault model which more adequately explains observed field characteristics than the model now in use.

4. PROPOSED TILTED FAULT BLOCK MODEL

It is proposed that the geologic elements unique to extended terrains, and vital to the formation of geothermal systems in this environment, are not only the faults, but also the aquifers which occur within the tilted blocks between the faults. Assuming a block width of 7 miles and a 20" tilt (typical of Basin and Range fault blocks), the down-dip edge of such aquifers can reach depths of almost 14,000 feet. Assuming a modest temperature gradient of 2.5°F/100 feet, water in the down-dip edge of the aquifer would be heated to 400°F. Provided the block is unbroken, or not broken sufficiently to isolate individual aquifers, the aquifers would provide a continuous permeable channel for thermal fluid to convect up-dip.

On reaching the fault bounding the up-dip edge of the aquifer, the fluid would continue to rise along one, or both, of two possible paths, depending on the permeability of the aquifer relative to the permeability of the fault: a) directly up the dip of the fault; and/or b) along the intersection of the aquifer with the fault. The relative lengths and permeabilities of the two possible paths would determine the amount of flow in each. For the reasons listed in Section 3 above, it is considered more probable that the fluid migrates along the intersection of the aquifer with the fault, rather than up the fault plane.

Although this model is more compatible with field observations than is the simple fault model, there are many unanswered questions. Two problems, however, may have one common solution:

1. In long fault blocks, the down-dip edge of the aquifer would be heated over a length of many miles, creating systems with much greater lengths than are normally observed.

2. Flow along the intersection of an aquifer with a fault would occur only if the intersection were not horizontal. Horizontal intersections would result in traps that would stop convective flow. On the other hand, the steeper the angle of plunge of the intersection, the shorter the flow path to the surface and the greater the likelihood of significant flow occurring along the feature.

One probable geologic constraint on the model eliminates both these problems: as long as the strike of the aquifer and the strike of the fault are not parallel, the down-dip, heated portion of the aquifer will be restricted in length, thereby giving rise to smaller, more-realistic, upflow zones. Furthermore, the up-dip intersection of the aquifer with the fault will be tilted from the horizontal. Continuous changes in the orientation of tectonic stress fields through time make it improbable that the strike of beds within a fault block will exactly parallel the strike of the fault bounding the block. Exact parallelism would be coincidental.

The geologic features created by the non-parallelism of the strikes of faults and aquifers, and which, in turn, create the environment proposed herein for migration of thermal fluid in the Basin and Range, are illustrated in figure 1. This is a block diagram showing the orientation of an aquifer displaced by two faults. The faults produce three tilted fault blocks and cut the blocks at an acute angle to the strike of the aquifer contained within the blocks.

The large, central block in figure 1 illustrates up-dip flow of thermal fluid from the deepest (and therefore hottest) down-dip corner of the block. Up-dip convective flow of thermal fluid from this hot corner is vertically confined beneath the aquifer cap rock, but is laterally unconfined within the aquifer. On intersecting fault B, flow is diverted up the plunge of the inverted trough formed by the intersection of the fault with the plane forming the roof of the aquifer. Note that the flow path is not in the fault, but is in the footwall block adjacent to the fault. Downflow of cool water, infiltrating from aquifer outcrops in the range or across unconformable contacts of the aquifer with basin fill, recharges the system.

As long as the difference in strike direction between the aquifer and fault is not more than 20" or 30°, up-dip flow in an aquifer occurs transverse to the direction of Basin and Range faulting, whereas flow along an aquifer/fault intersection occurs longitudinally to the main direction of faulting. The relative amount of transverse compared to longitudinal flow in a system depends on the geometry of its fault block. The lengths of the transverse and longitudinal flow paths will be about equal in systems contained in equidimensional blocks. In relatively long and narrow blocks, however, longitudinal flow will dominate the system. In fault blocks that are isolated from deep upflow by cross faults, no thermal fluid flow will occur.

In summary, the tilted-fault-block theory of geothermal fluid migration proposes a geologic model which reconciles some of the problems with the simpler model and is compatible with the characteristics of many of the geothermal systems occurring in extended, non-volcanic terrains.

5. EXPLORATION IMPLICATIONS

The main similarity between oil and geothermal exploration is that both are concerned with finding accumulations of a buoyant fluid migrating in the earth's crust. Two of the main differences between the geology of oil fields compared to geothermal fields are: a) oil must be trapped to prevent its escape to the surface, whereas thermal fluid must flow continuously to prevent cooling; and b) oil fields occur in sedimentary basins, whereas the geothermal fields discussed in this paper occur in extended terrains.

Anticlines provide the closed structures needed for oil accumulations; it is proposed here that tilted fault blocks provide the open, leaky structures needed for the migration and concentration of thermal fluid. Because structure and stratigraphy control the location of thermal fluid concentrations, the objective of geothermal exploration, as in oil exploration, should be to define the structural and stratigraphic controls of the system under investigation.

The two most important implications of the proposed model relevant to exploration strategy are:

1. Permeable stratigraphic horizons and fractured basement rock overlain by impermeable cap rock form aquifers for

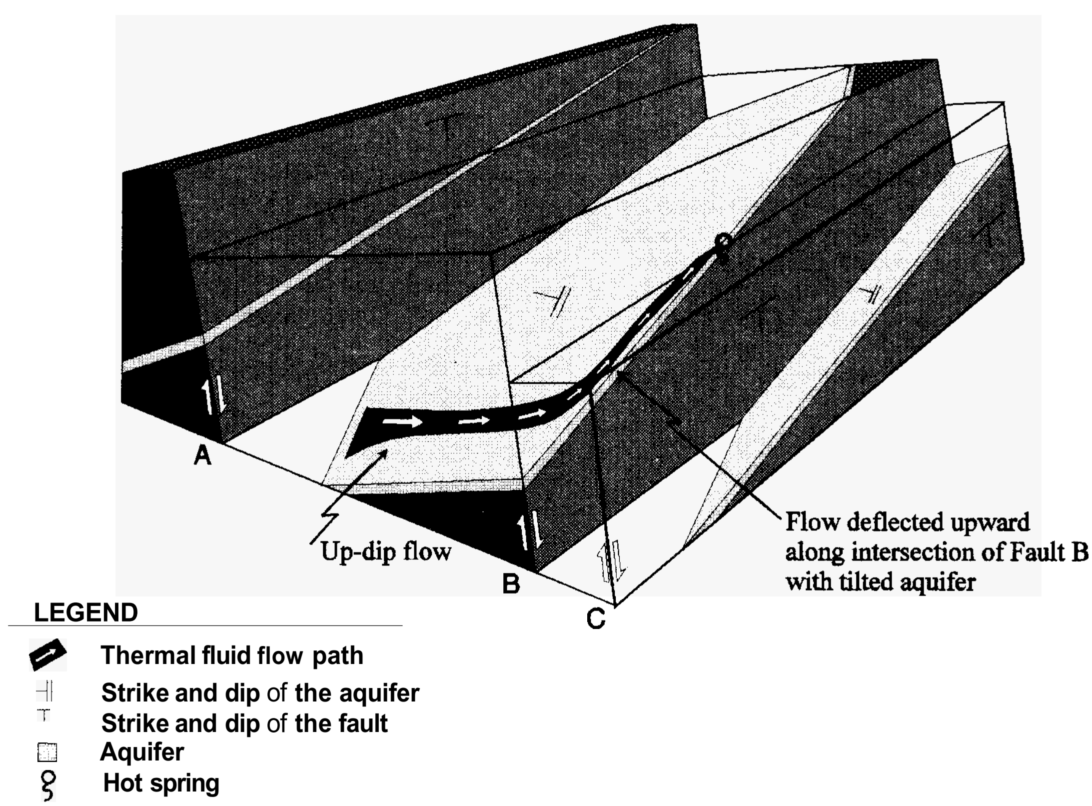

Figure 1: Block diagram illustrating the tilted fault block theory for the migration of thermal fluid

1995, GeothermEx, Inc. BRADNEW/CDR/H7897/010695/FTP the up-dip migration of thermal fluid; the function of faults, by offsetting aquifers against impermeable rock, is to intercept and divert the flow, still within the aquifer, toward the surface.

2. Because of its buoyancy, thermal fluid migrates along these paths toward structural highs formed by the up-turned edges and corners of tilted fault blocks. Structural highs buried beneath basin alluvium have been found to contain geothermal reservoirs. These highs may be the up-turned corners of tilted fault blocks. Reservoir permeability appears to be particularly high where the core of the structural highs consist of fractured, pre-Tertiary basement rock.

The most effective method of defining structure and stratigraphy is geologic mapping. Even where drilling targets are sought in basins, structures and stratigraphic sequences mapped in ranges can be projected to give important clues concerning the geologic features beneath the adjacent basin. Geologic mapping is inexpensive, but considerable time is required to cover large areas at the detailed scale required (one or two inches to the mile). Because mapping is time consuming, and because it requires experienced geologists specialized in that kind of work, it is best done by publicly funded geologic surveys. Although much of the Basin and Range has been mapped at regional scales, much more remains to be done on the detailed scale needed for exploration.

The best tool for defining geologic structure beneath the basins is gravity. Gravity is inexpensive, and much of the Basin and Range has been covered by publicly funded agencies at a reconnaissance scale. This scale, however, also is too small for siting exploration wells, and these agencies should be encouraged to undertake more detailed gravity mapping across those basins and ranges recognized as particularly attractive for geothermal development. Wide-spaced profiling is useless; an even areal coverage with a minimum station density of 4 per square mile is required for siting exploration holes.

Reflection seismic is also a valuable tool for defining structure; but it is expensive, and because it must be used in a profiling mode, results can be biased by the inadvertent selection of inappropriate profile directions. For these reasons, reflection seismic is best used for the detailed examination of buried structures projected from geologic mapping and/or detected from gravity surveys.
In summary, any exploration technique is appropriate that helps to define or confirm a geologic model of the prospect. No exploration technique is appropriate, however, if its only objective is to locate anomalies.

6. CONCLUSIONS

The conceptual model of a field forms the basis for deciding on exploration strategies; however, the geologic data from geothermal systems which have been developed in extended terrains indicate that the permeable fault model requires revision. The tilted fault-block theory presented herein gives an alternative in which thermal fluid migration is controlled by the intersection of dipping aquifers with impermeable faults. The significance of faults in extension terrains is that they deflect fluid upward; and as such, they form only one element of the exploration target.

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