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INSIGHTS INTO EXTENSIONAL GEOTHERMAL SYSTEMS FROM NUMERICAL MODELING

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ABSTRACT

Numerical models are used to establish basic qualitative relationships between structure, heat input, and permeability distribution, and the resulting extensional geothermal system. Extensional systems rely on deep circulation of ground water (rather than cooling igneous bodies) for heat and extensional tectonics to provide permeable up-flow paths. This report focuses on the characteristics of the Basin and Range province of the United States, but the results apply to extensional settings in general. A series of steady state, two-dimensional models are used to evaluate the effect of permeability and structural variations on an idealized, generic Basin and Range geothermal system.

An extensional geothermal system only exists in a relatively narrow range of bulk permeability (10^{-15}-10^{-16} m^2). Outside of this window temperatures in the shallow sub-surface decrease rapidly. The presence of a relatively permeable upflow path (provided by geologically recent faulting) is a requirement for system development. Chemical self-sealing of upflow paths does not significantly affect the flow system as long as a central flow path is still available. While topography gives an extra, early "kick" to convective circulation, it is not a requirement for geothermal system development. A permeable fault in one valley can also induce cross-range flow from adjacent valleys if there are no equally good upflow paths in the adjacent valleys. When bulk permeability is high enough, additional deep circulation cells develop in adjacent valleys diverting heat and fluid from the fault and consequently reducing temperatures in the fault

1. INTRODUCTION

There are two major similarities in extensional systems of the Basin and Range: (1) strongly fault-related near-surface upflow, and (2) lack of any evident crustal magmatic heat sources (Yeamans, 1983). While there is general agreement that the upflow in most Basin and Range geothermal systems is fault controlled, the effect of the permeability structure on these systems is still debated (Wright, 1991). These non-magmatically driven, fault controlled geothermal systems are termed *extensional systems* in this report.

Most studies of extensional systems, including those based on numerical modeling, have focused on the near-surface reservoir with a view towards reservoir exploitation (Sorey and Olmstead, 1994). The generally accepted qualitative models of extensional systems postulate fluid circulation predominately perpendicular to, and occasionally within the range-front fault. There has been little effort to systematically determine the basic relationships between system configuration (e.g. permeability and structure) and the resulting thermal-flow behavior of the geothermal system. Notable exceptions are the studies of Forster and Smith (1988a&b, 1989), which considered mountainous terrain systems, and Lopez et al. (1994, 1995, 1996), Welch, Sorey and Olmsted (1981), and Sorey and Olmsted (1994), which simulated three-dimensional systems with a focus on in-the-fault-plane circulation.

Heat and water, two prime ingredients for a geothermal system, are present throughout the Basin and Range. Permeable upflow paths are also needed in order for the heated water to return quickly to the shallow sub-surface. Faulting provides these paths. The Basin and Range is heavily faulted throughout, so why then are geothermal systems only associated with relatively recent faulting? The answer is that self-sealing – the process where cooling, ascending fluids precipitate minerals in pore space (thereby reducing permeability) – will eventually limit or eliminate flow.

Field studies have found extensive sealing in exhumed faults. Parry et al., (1991) found extensive hydrothermal alteration and fracture filling at all scales on the exposed footwall of the Dixie Valley fault, south of the commercial plant. Similar pervasive geothermal alteration and sealing has been found on other faults in the region (Parry et al., 1988; Vikre, 1989). Precipitation would be orders-of-magnitude faster on the lateral boundaries of a flow conduit than along its length due to steeper temperature and pressure gradients. Thus it is likely that a conduit such as a fault would, for most of its lifetime, have low permeability lateral barriers.

2. METHODS

The numerical code used to solve the coupled, non-linear equations of heat and fluid flow was TOUGH2. The code has been verified, as defined by Anderson and Woessner (1992). TOUGH2 (**T**ransport **O**f **U**nsaturated **G**roundwater and **H**eat **2**) is a multi-dimensional, Integrated Finite Difference (IFD) code for fluid and heat flow (Pruess, 1987, Pruess, 1991a). TOUGH2 is a refinement of the MULKOM code system developed at Lawrence Berkeley Laboratory. For this study a slight change was made to the published version of TOUGH2 for PCs. The maximum number of elements and connections was increased to accommodate the models in this study. A bibliography relating to TOUGH2 is available on the internet at http://ccs.lbl.gov/TOUGH2/BIBLIOGRAPHY.html. This site is part of a home page for information relating to TOUGH2. The FORTRAN77 source code for TOUGH2 is available (for a fee) from the Department of Energy. All the work for this study was performed on Pentium based PCs. Processor speeds varied from 90 to 200 MHz, and RAM ranged between 32 and 64 Megabytes.

The majority of the models covered a broad range in basal heat flow (30mW/m^2 to 120mW/m^2) and host rock permeability configurations (10^{-15}m^2 and 10^{-18}m^2). Host rock is taken to be all rock except the valley fill and fault zone. Other series were run to evaluate fault permeability (3.0*10^{-15} m^2 to 2.0*10^{-12} m^2), rock thermal conductivity (0.8 – 3.0 times the base configuration), degree of self-sealing along the upflow path (10^{-15}m^2 and 10^{-18}m^2), and valley fill permeability (ratios of horizontal to vertical permeabilities between 1 and 100). In all models, all rock properties, including porosity and permeability are constant within a given unit. In other words there is specifically no variation with depth or time (e.g. compaction or consolidation). All rock unit properties are also isotropic except for valley fill permeability.

The base model used in this report consists of a vertical cross section of a generic Basin and Range valley (Figure 1). The model is 27 km wide by 8.75 km deep (top of range to bottom of the model). The model has 4782 cells (or elements) and 4932 nodes. Elements range in size from 5762 m^2 in the fault zone to 30,1872 m^2 outside the area of interest (the models are assigned a thickness of one meter). While TOUGH2 can handle *n*-sided cells, all modeling was conducted with rectangular elements due to limitations with meshing algorithms in the Argus ONE software used to create the models.

The model domain is larger than often seen in system studies – it extends beyond the range and valley of interest to include part of the next range and valley to either side. The ranges are 5 km wide at the base and have a relief of 0.75 km. The valley floor is horizontal, and 9 km wide (Figure 1). These dimensions are representative of a typical basin and range.

The fault zone is planar, and dips 60°. The 60° dip was chosen to be representative of the upper portion of a typical Basin and Range fault. The fault extends to 4 km below the valley floor. This fault depth is somewhat less than might be expected for a typical fault. The fault depth was a compromise between the desire to allow for ample room below the base of the fault for fluid and heat flow such that the bottom boundary would not be abruptly truncating flow paths, and the need to keep the model less than 9km tall (due to the limits of the equation of state module). The surface break of the fault is at the base of the range, in the valley. There are separate zones on each side of the fault that are used to represent barrier zones. These barrier zones can be used to simulate self-sealing. The valley fill was divided into several layers to provide the capability of representing shallow outflow zones, but for the models reported here, the valley fill was treated as one unit (i.e. all four layers had identical properties).

Boundary conditions for all TOUGH2 models are as follows:

1) Top set at a constant pressure of 1E+05 Pa (atmospheric) and temperature of 20°C
2) Sides set at no heat or fluid-flow
3) Bottom set at no fluid-flow, with constant heat flux into the model.

The top boundary was set at representative surface conditions. No thermal lapse rate was included, as this would have an insignificant effect on the model. The water table was set at ground level in the model. No attempt was made to represent the unsaturated zone. The complexity that would be added to the model by representing the near surface environment in detail would add little to the understanding of a generic geothermal system.

Initial conditions for the first model run in all series were a roughly linearly increasing (hydrostatic) pressure and temperature with depth. For subsequent runs in a series, the solution of the first run was used as the starting point. As a check some models were run from both sets of initial conditions. In these runs there was no difference in the final (steady state) solution. Default iteration and solution criteria, as defined in Pruess (1987, 1991a), and Moridis and Pruess (1995), were used in all models.

4) RESULTS

Representative model results for a basal heat flow of 90 mW/m^2 and 10^{-16} m^2 bulk permeability, are shown in Figures 2, and 3. The primary flow path in most models is from the ranges, to the bottom of the fault, and up. Secondary flow systems are present on the flanks of the ranges and in the valley fill. Most of the fluid circulates to depths below the bottom of the fault. Isotherms are depressed under the ranges and elevated near the fault (as would be expected). Figure 4 shows temperature-depth curves at various locations in the model. The character of the temperature-depth curves are dependent on where they are in relation to the upflow. Plots that cross the fault zone show an inflection of varying sharpness depending distance from the fault surface break. Note that temperature-depth plots from the range show only subtle indications of fluid recharge (the shallow isothermal section).

Before starting to discuss results for all the model series, it is necessary to determine what output is of interest. Flow fields and temperature isotherms are of course important to see, but it is not possible to keep dozens of graphs in mind. A more concise measurement of the results of many models is needed. To that end, total heat flow up the fault and fault temperatures have been used as overall measures of a model.

Heat flow and temperature vary continuously along and across the fault in all models, so some rational for quantifying these values is needed. Temperature and heat flow are measured 0.5 km below the valley floor. Heat flow is determined by summing the conductive and advective heat flux across the fault. Temperature is an average of the temperature in the cells that are in the fault zone at 0.5 km depth (plus or minus one cell). The 0.5km depth of measurement obviously impacts the values. As shallow a point as practical is desired so that, particularly for heat flow, all heat that is to be captured by the fault, is by this point. From the point of real-world applicability too, a shallow point is desired. Most temperature measurements are made in the upper one or two kilometers of the crust. Also, from an economic point of view, production is usually in the same depth range, so again it is the shallow thermal regime that is of interest. Model boundary effects and the shallow outflow zone need to be avoided when quantifying a model thermally. A depth of 0.5 km gets safely below the impact of any effects due to the coarseness of the air/surface interface.

The main feature apparent in Figures 5 and 6 is a peak in temperature and heat flow up the fault for bulk permeability in the 10^{-16} m^2 to 10^{-15} m^2 range. The peaks shift to lower permeability with increasing heat flow. Maximum temperature in the fault shows more dependence on basal heat flow than the heat output of the fault. In all cases the maximum temperature occurs at a slightly lower permeability than maximum heat flow, because of a trade-off between the volume of fluid moving up the fault and the temperature of the fluid.

5) DISCUSSION

For basal heat flow 30 mW/m^2 – 120 mW/m^2, temperature and heat flow in the fault versus bulk rock permeability are qualitatively similar. All start at a conductive state at 10^{-18} m^2 permeability. As permeability increases, convection starts (at lower bulk permeability with increasing basal heat flow). At 10^{-17} m^2, temperatures and heat flow are only slightly higher, in all cases, than at 10^{-18} m^2, but by $10^{-16.5}$ m^2 all the plots (except 30 mW/m^2) show clear increases from conductive states – indicating the onset of convection. From the start of convection, all the profiles increase steadily until the increasing convection starts to “wash-out” the system, there after the temperature and heat flow start to decrease. The decrease continues through 10^{-15} m^2, the highest bulk permeability that could be practically simulated. Above this value, fluid and heat flow was so vigorous that the code reduced the solvable time step to unrealistically short increments. Similar results across a (more limited) range of permeability and heat flow have been published for a low temperature mountainous environment, by Forster and Smith (1989), as previously mentioned. Lopez and Smith (1995), found the same type of dependence for their geothermal system models.

One series of models ,at 90mWm^2 basal heat flow, was run to evaluate the effect of self-sealing barriers. For these runs the permeability of the units on either side of the fault was varied between 10^{-18} and 10^{-15}m^2. The resulting heat flow and temperatures in the fault show relatively little variation. Thus, as long as a permeable central path exists, the degree of self-sealing has only a minor effect on the geothermal system (for this particular geometry).

There is a slight, but sharp decrease in temperature and heat flow up the fault at permeabilities slightly greater than that for the peaks in the respective curves (e.g. around $10^{-15.3}$ m^2 for 90 mW/m^2 basal heat flow). This drop is due to the development of secondary convection cells in the model. These cells start in the two outboard valleys when the bulk permeability is such that it is easier for the deep circulation under the valleys to exit within the valley rather than cross the range and exit at the fault. At this point the contrast between bulk and fault permeability is ~ one order of magnitude. Small cells initiate (with increasing permeability) in the lower outboard corners and rapidly expand to discharge at the surface. These models show that an easy “escape path” such as a permeable fault path can induce significant cross-range flow even without a regional topographic/hydrologic slope.

To isolate the effect of topography on geothermal system development, a series of models identical to the previous 90 mW/m^2 basal heat flow models were run, but with no topography. For this series, the top of the model was a flat surface at the level of the valley floor. All other variables and boundary conditions are the same. Figure 7 shows the results of the “flat top” models in terms of Nusselt number. The Nusselt number is the ratio of heat transferred by fluid movement to that transferred by conduction. As with other non-dimensional numbers used in porous media flow, *Nu* is defined in many subtly different ways according to circumstances. Here *Nu* is defined as;

$$Nu = \frac{HF_t}{HF_c}$$

Where HF_t is the total heat flow up the fault 0.5km below the surface, and HF_c is the heat flow up the fault at a bulk permeability of 10^{-18}m^2 (i.e. conduction dominated state).

The development of the system with respect to bulk permeability is qualitatively the same with and without topography. Topography provides an extra “kick” to convection compared to flat top models. Convection starts at slightly lower permeability with topography, and is somewhat stronger. The maximum Nusselt number (and similarly the maximum heat flow up the fault) for the system with topography is ~20% higher than for the flat system. Peak temperatures within the fault for the two systems are within 1°C (flat top systems are slightly lower). Besides being offset to higher permeability, the peak in temperature for the flat system is also broader. The occurrence of higher total heat flow up the fault, for the system with topography versus the system without, even though the maximum temperatures are nearly the same, indicates that the system with topography is pushing more fluid through the fault.

6) CONCLUSIONS

Basic qualitative relationships between structure, heat input, and permeability distribution, and the resulting extensional geothermal system have been determined based on numerical modeling of a typical basin and range. An extensional geothermal system is found to exist only in a relatively narrow range of bulk permeability (10^{-15}-10^{-16} m^2). Outside of this window temperatures in the shallow sub-surface decrease rapidly. The presence of a relatively permeable upflow path (provided by geologically recent faulting) is a requirement for system development. Combined with the need for above average (continental) heat flow, a fairly specific set of conditions for geothermal system development are defined.

Maximum temperatures in, and heat flow up the fault are proportional to basal heat flow (background or regional heat flow in geologic terms). While topography gives an extra, early “kick” to circulation, it is not a requirement for system development. In the generic geothermal system model, flow from the ranges to the fault dominates the circulation, while secondary flows exist on the range front slopes. A permeable fault in one valley can also induce cross-range flow from adjacent valleys if there are no equally good upflow paths in the adjacent valleys. When bulk permeability is high enough, additional deep circulation cells develop in adjacent valleys, diverting heat and fluid from the fault and consequently reducing temperatures.

While there are many factors that remain to be evaluated, the basic quantitative relationships are emerging.

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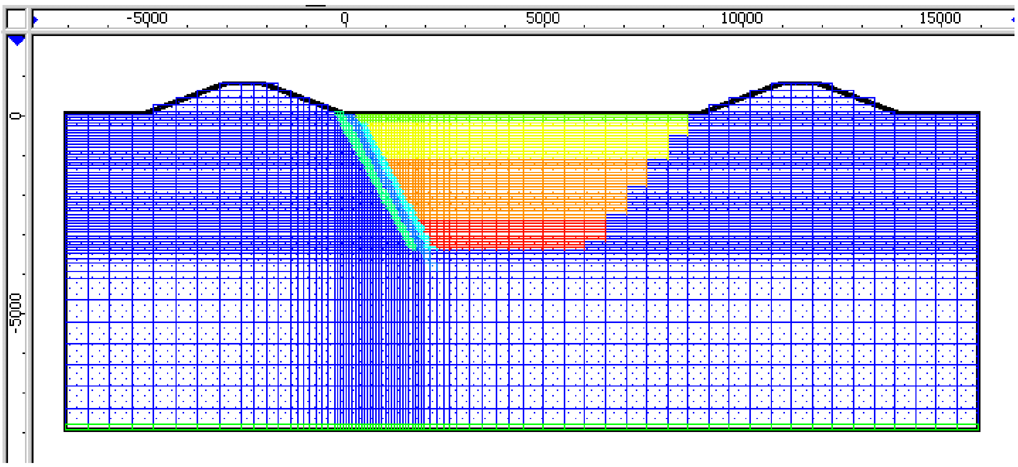

Figure 1. Model Mesh. Model dimensions are in meters. The bulk of the model consists of one rock unit (dark). The valley fill is divided into several units (shades of gray), but was treated as one for all cases. The fault zone is bracketed by barrier zones. Apparent gaps in element spacing in the high-density regions are a display artifact.

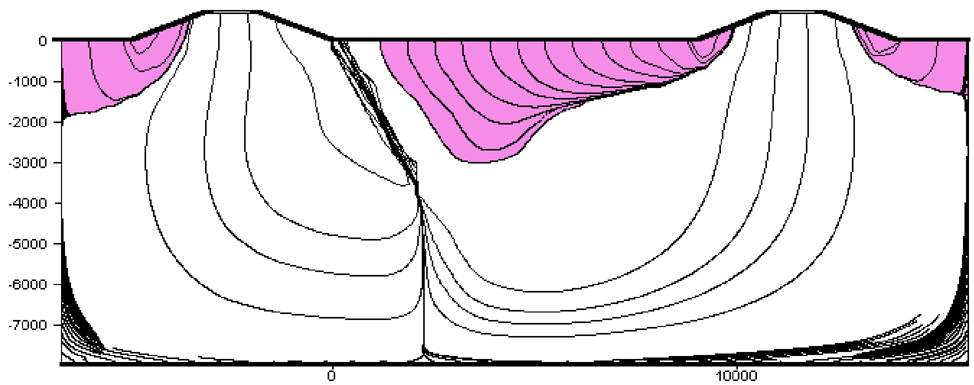

Figure 2. Flow paths for typical TOUGH2 model. Representative particle paths are shown (not stream functions). The bulk of the flow circulates to 4 to 7 kilometers depth before returning to the surface. The shallow flow systems (shaded) reach no deeper than 2km in most models.

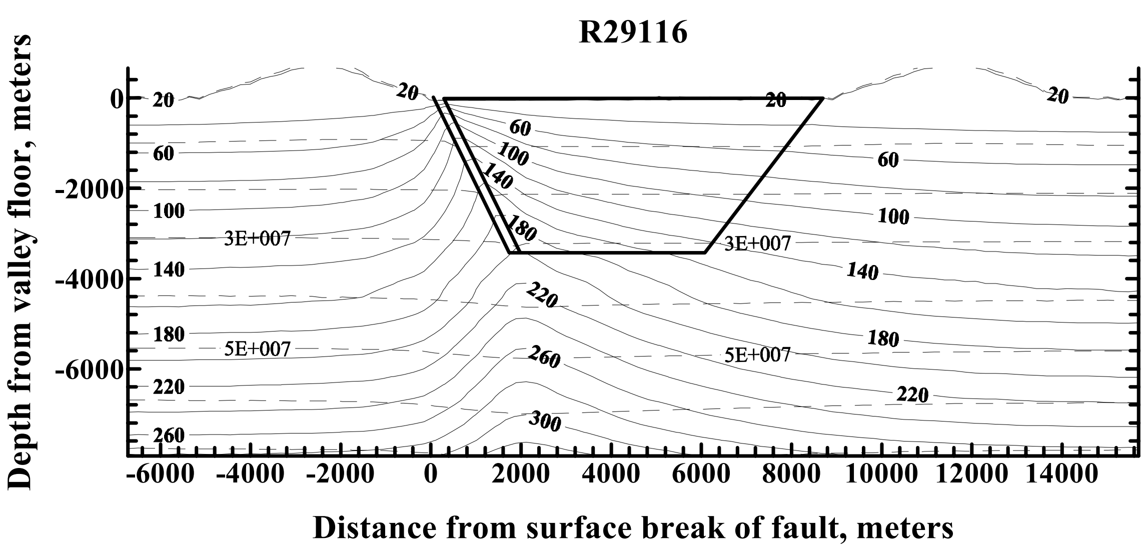

Figure 3. Temperatures and pressures in model R29116 (90 mW/m^2 basal heat flow, 10^{-16} m^2 bulk rock permeability). At this permeability, the thermal regime is between convection and conduction dominated states. The isotherms show significant depression under the ranges and pull-up in the fault due to fluid flow.

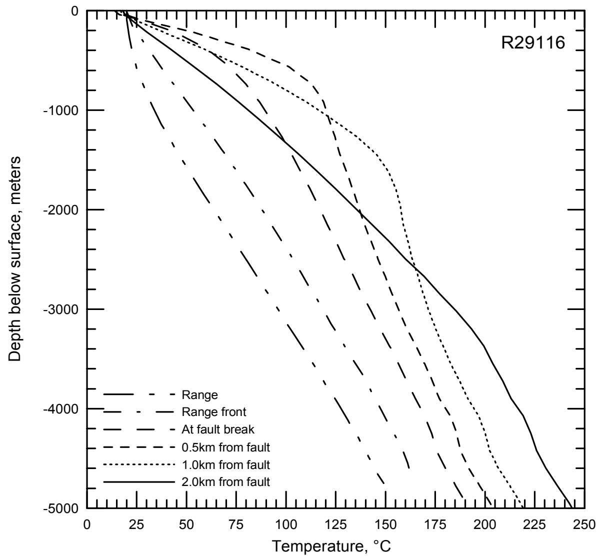

Figure 4. Temperature-depth curves for various locations in model R29116. Fluid upflow is clearly recognizable in the T-D plots from the fault and further into the valley. Even though there is strong downflow under the ranges, the range and range front T-D curves look qualitatively similar to conduction dominated cases.

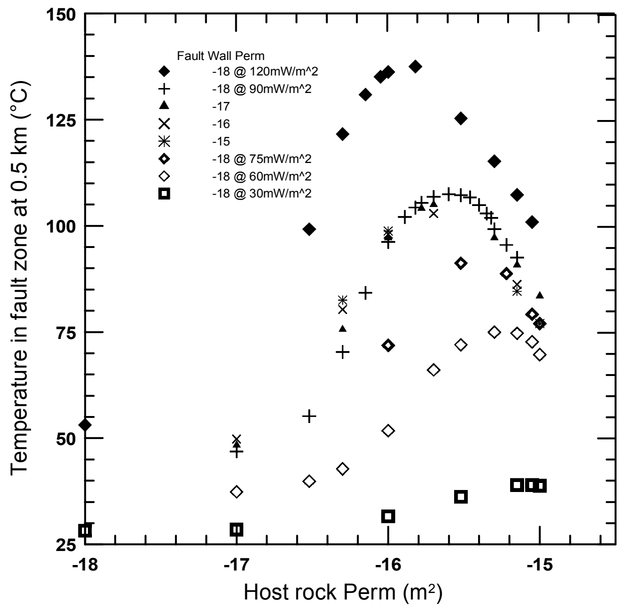

Figure 5. Fault temperature versus host rock permeability. At 10^{-18} m^2 bulk rock permeability temperatures reflect a conductive regime. As permeability increases, so does temperature in the fault, until reaching a maximum between 10^{-16} m^2 10^{-15} m^2 (depending on basal heat flow). At permeabilities higher than the peak, fluid flow is so vigorous that the models begin to "wash out" and the temperature declines.

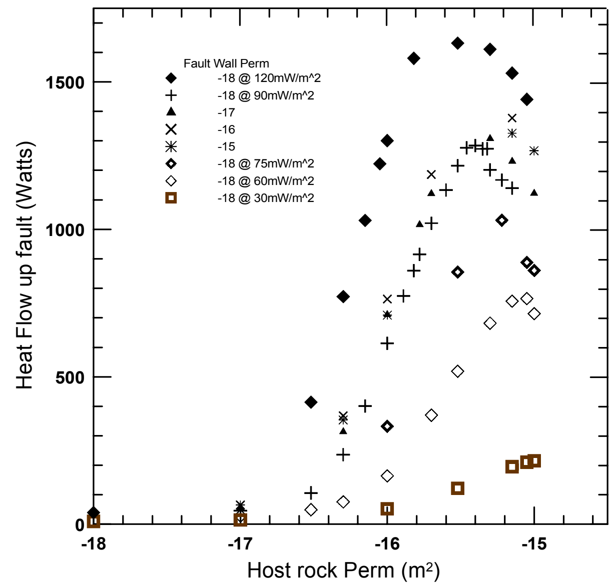

Figure 6. Heat flow up the fault versus host rock permeability. The pattern is similar to that for the temperatures in the fault.

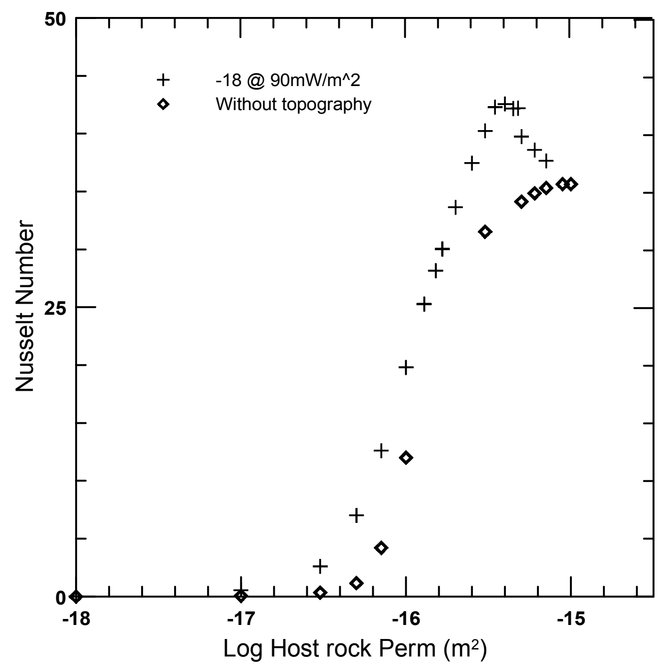

Figure 7. Nusselt Number for systems with and without topography. Qualitatively the convective heat transfer develops similarly for systems without topography compared to systems with topography. Topography gives an earlier start (around 10^{-17}m^2 bulk permeability) versus flat systems ($10^{-16.5}$m^2) and greater total heat movement up the fault.