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USING ISOTOPIC ALTERATION MODELING TO EXPLORE THE NATURAL STATE OF THE GEYSERS GEOTHERMAL SYSTEM, USA

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ABSTRACT

Oxygen isotope alteration of host rocks is a ubiquitous feature of hydrothermal/geothermal systems. This alteration can be used as a quantitative constraint in numerical models of geothermal systems, and is especially useful in determining system-wide pre-development characteristics. Fluid, heat and oxygen isotope transport models of the natural state of The Geysers system were made to better-understand its development and guide its long-term management. The unusual distribution of maximum oxygen isotope alteration low on the flanks of the main intrusive (felsite) at The Geysers requires caprock integrity to have been maintained throughout most of the system's lifetime. This served to limit hydrothermal circulation and isotopic alteration above the apex of the intrusion. In contrast, many fossil hydrothermal systems exhibit concentrated alteration above the apex. The lateral extensiveness of alteration along the top of the felsite requires good horizontal connectivity of permeable zones at depth to allow penetration of ^{18}O-depleted fluids. A maximum hydrothermal lifetime for the system is 0.5 million years (Ma), while the youngest dated intrusive is around 1.2 Ma. This supports the concept that as-yet concealed younger intrusions have continued to provide thermal input to the system. Petrologic evidence for high paleo-fluid temperatures (300 °C) within 1 km of the surface are difficult to reconcile with subdued ^{18}O alteration at depth in the same location. These vein occurrences may represent very limited penetration of the caprock during the liquid-dominated phase of The Geysers.. An alternative hypothesis is that boiling occurred early in the development of the system, halting rock isotopic alteration. Internet-accessible animations of model results are available at http://www.utdallas.edu/~brikowi/Publications/Geysers.

1. INTRODUCTION

Thermal structure in geothermal reservoirs often exhibits complex zoning and connectivity relationships. A variety of processes may be invoked to explain these structures, ranging from fluid dynamic (e.g. "heat pipe" phenomena at The Geysers, USA) to lithologic (e.g. permeability variations generating a "two-layer" reservoir at Kakkonda, Japan). These structures profoundly impact exploration and development in geothermal systems. Numerical models are often useful in resolving the origins of complex thermal structures, but many times lead to ambiguous solutions. This can lead to an uncomfortable level of scientific and economic uncertainty. At sites where the prevalent circulation paths can be determined, for example using rock alteration, the fluid dynamics of such systems can be much more accurately modeled, and the economics of development predicted with much greater certainty. Detailed modeling of fluid circulation and rock isotopic alteration at The Geysers geothermal system, USA offers a useful example of this approach.

The Geysers offer a unique opportunity in the U.S. to study an active hydrothermal system where the plutonic heat source is accessible. Natural state modeling of this system uses system-wide fluid mass and heat balances in space and time to derive a general view of system characteristics and lifetime. The benefits of such an approach at The Geysers are synthesis and advancement of our understanding of the nature and development of this important geothermal resource based on fundamental physical principles. This paper describes results of fluid and heat flow models for the pre-boiling state of The Geysers, including quantitative constraints on the hydrothermal system derived from vein-mineral geothermometry and observations of rock isotopic alteration. Our analysis begins from a geologically known condition, the initial appearance of the heat source (magma intrusion). From this starting condition, the models can calculate the dissipation of the original thermal and chemical energy of the intrusion into its host rocks. The models compute the temperature, pressure, fluid flow and chemical ($\delta^{18}O$) composition field for The Geysers geothermal/hydrothermal system from the time of its inception (magma intrusion) to a time immediately prior to boiling. These models are also constrained (calibrated) using the current state of the system, including the temperature and pressure fields, distribution of chemical and isotopic alteration, and distribution of fractures and permeability. Since the liquid phase is most efficient at isotopic alteration, these models treat only the pre-boiling, natural state of The Geysers.

1.1 Geologic Setting

The Geysers (Fig. 1) is one of a few productive vapor-dominated systems in the world, and currently produces approximately 840 MWe from a 150 km^2 area. The system has been extensively explored and developed, with data available from some 780 deep wells, many penetrating the underlying plutonic heat source. The Geysers system is developed in a structurally complex collection of Jurassic to Cretaceous metamorphic rocks, primarily metagreywacke, forming the Franciscan Complex (Fig. 2). Pleistocene intrusion of felsic rocks, collectively termed "felsite" (Schriener and Suemnicht, 1981; Thompson, 1992), provided the heat and reservoir permeability for the system. The felsite intrusive is found as shallow as 0.7 km depth in the southeastern Geysers, with minimum radiometric ages around 1.2 Ma (Dalrymple *et al*., 1999; Hulen *et al*., 1997). The geometry of the felsite top is relatively well characterized, and has been described in a variety of publications (Hulen *et al.*,1994; Hulen and Nielson, 1996). Permeability was generated in the roof rocks of the intrusive by hydrothermal dissolution of earlier metamorphic vein carbonate, and thermal fracturing in the upper felsite (Hulen and Nielson, 1995). A caprock is present, distinguished by undissolved metamorphic calcite and younger vein-filling calcite apparently related to the modern hydrothermal system. This system has left a strong alteration and metasomatic signature, forming a distinctive tourmaline-bearing hornfels along the contact of the felsite, and significant depletion of whole rock δ^{18}O along the lower flanks of the felsite (Fig. 2, lower portion).

The present-day distribution of the steam reservoir (i.e. highest elevation steam entries) is used as an initial estimate of the distribution of caprock and permeable zones above the felsite. Petrologic constraints on paleotemperatures are available from drilled core and cuttings (Hulen and Nielson, 1995; Moore *et al.*, 1989). Moore and Gunderson (1995) have outlined the distribution of δ^{18}O alteration at The Geysers, finding an $8^{o}/_{oo}$ decrease in rock δ^{18}O along the felsite-greywacke contact. Similar observations have been made for the Northwest Geysers (Walters *et al.*,1996). Modern fluid isotopic and non-condensable gas compositions have been cited as evidence of compartmentalization (i.e. faults form internal barriers) between the Northwestern and main Geysers steam reservoirs (Walters *et al*., 1996; Truesdell *et al*., 1995).

1.2 Model Geometry

In order to investigate the basic time and length scales for hydrothermal circulation at The Geysers using system-wide mass and heat balances, preliminary finite difference models of heat and fluid flow were made (Brikowski and Norton, 1999; Norton and Hulen, 2000). Modeling was carried out over a two-dimensional cross-sectional grid oriented SW-NE passing through Geysers Coring Project well SB-15D, and extending 10.8 km horizontally and 5.4 km vertically (line A-A', Fig. 1). Permeability zones were based on current distributions of steam reservoir and felsite (Fig. 2); a single instantaneous intrusion of granodiorite was assumed for the heat source. Caprock thickness was increased 10% over present values to account for erosion. Consequently, boiling conditions were not present in the reservoir and felsite in this model.

2. GOVERNING EQUATIONS

The governing relationships for heat and fluid transport are well established, and will not be developed here. Isotope transport can be modeled with the standard advection-dispersion equation, with minor variations in choice of variable and treatment of chemical reaction. Analytic solutions to the simplified chemical transport equation expressed in terms of rock ^{18}O/^{16}O ratio have been utilized to constrain ratios of transport parameters (Cook and Bowman, 1994). These methods use observed δ^{18}O gradients to determine apparent Peclet (ratio of advection over diffusion rates) and Damkohler (chemical reaction over advective rates) numbers. Norton (1988) developed an approximate Taylor's series based solution to the transport equation that can be utilized to constrain time and spatial scales of a hydrothermal/geothermal system given observed metasomatism, including δ^{18}O alteration (see an application to The Geysers in Brikowski and Norton, 1999).

The equation describing water-rock exchange of ^{18}O in a system can be written in terms of δ^{18}O as a first-order rate law (Gregory *et al*., 1989; Brikowski, 2000):

$$\frac{\partial \delta^{18}\mathrm{O}_i}{\partial t} = k_{if}\left(\delta^{18}\mathrm{O}_f + \Delta_{if} - \delta^{18}\mathrm{O}_f\right) \qquad (1)$$

where the term on the left is the change in δ^{18}O with time in the *i*th reacting mineral in the volume of interest, k_{if} is the kinetic exchange coefficient (units 1/sec) modeled using an Arrhenius relationship (i.e. thermally controlled, Cole and Ohmoto, 1986). Δ_{if} is the equilibrium δ^{18}O difference between mineral *i* and fluid at current temperature and pressure. Then exchange between minerals and fluid is proportional to the reaction rate (which is strongly proportional to temperature) and the compositional difference between the current assemblage and a hypothetical one at equilibrium. Equation (1) describes the source/sink term in the standard advection-dispersion equation for transport of ^{18}O. This equation can be solved using finite difference or element methods. A much-modified version of the program Mariah (Brikowski, 2000) was used to model the system governed by this and the heat and fluid flow equations.

3. MODEL RESULTS

Two-dimensional models of heat and fluid flow and ^{18}O transport were made using a finite element model over the cross-section depicted in Fig. 2. To allow for maximum solution stability, approximately 1000 quadratic triangular elements were used to discretize the system, with grid density concentrated where high advection and reaction rates were anticipated (Fig. 3). The top boundary of the model was held at constant temperature and pressure, model sides and base were treated as impermeable and insulating. Specifying permeable sides made little difference in model results, since the permeable reservoir narrows and deepens considerably at the edge of the model grid. Repeated model runs were made, adjusting parameters until an adequate fit was achieved to observed δ^{18}O alteration, geothermometers, and general constraints on surficial heat flow in the system.

3.1 Heat Transport and Fluid Convection

Model results demonstrate a number of fundamental features of The Geysers hydrothermal system. Perhaps of greatest significance are constraints on system lifetime. Purely conductive models of the geometry shown in Figure 3 indicate a maximum lifetime of 0.5 Ma, convective models using the indicated permeabilities reduce this lifetime to 0.35-0.5 Ma (Fig. 4, column 1). The youngest dates available for the felsite are 1-1.2 Ma (Dalrymple *et al.*, 1999; Hulen *et al.*, 1997). This discrepancy supports the contention that The Geysers natural state system has had a complex, very recent, intrusive and hydrothermal history (e.g. . Dalrymple *et al.*, 1999; Stanley and Blakely, 1995).

Convection in the system is tightly constrained along the upward-sloping flanks of the felsite (vectors, Fig. 4). The lower boundary of this flow zone is controlled by the permeability contrast between reservoir and "basement felsite" rocks. The upper boundary of this zone is formed by localization of near-critical fluid properties. Recall that heat transport and fluid flow properties reach extrema near the fluid's critical point (374 °C and 22 MPa for pure water). These properties are computed in the model using an accurate numerical equation of state (Johnson and Norton, 1991). Heat capacity reaches near infinite values at the critical point, and is a useful indicator of near-critical conditions. The central column of Fig. 4 shows the development of a mantle of near-critical conditions in the host rock in the vicinity of the 375 °C temperature contour. This contour moves outward from the felsite until around 125 thousand years (Ka), at the peak of hydrothermal activity, and then slowly retreats downward. By 240Ka critical conditions are within the deep, low-permeability felsite, and effective hydrothermal circulation ceases in the system. Hydrothermal circulation above the apex of the felsite is limited by the presence of the caprock, forcing divergent flow in that area, and by the persistence of sub-critical fluid conditions in that area. Influx into the system is tightly channeled by these two phenomena, and is localized deep on the flanks of the intrusive.

3.2 ^{18}O TRANSPORT MODEL

To investigate the alteration impacts of this localized convection, the ^{18}O transport equation was solved simultaneously with the heat and fluid transport equations. A single reactant mineral was assumed. Average groundmass mineralogy of The Geysers host rock metagreywacke is approximately 40% quartz, 30% plagioclase (Moore and Gunderson, 1995). Lambert and Epstein (1992) note limited reaction of quartz grains in the greywacke, suggesting the primary reactant mineral is plagioclase. Volume fraction of plagioclase in rock was assumed to be 0.30, and volume fraction of mobile water in rock $\phi_f=10^{-3}$. Isotopic parameters are the water-plagioclase isotope fractionation factor A = 2.61×10^6 and B = -3.7 (Javoy and Bottinga, 1973), unaltered rock $\delta^{18}O_r$ = 14 $^0/_{00}$ and maximum alteration $\delta^{18}O_r$ = 6 $^0/_{00}$ (Moore and Gunderson, 1995).

Alteration in the system begins quickly, with notable rock alteration visible by 20Ka. By 50Ka, depleted fluids have penetrated much of the way up the flanks of the felsite (upper right image, Fig. 4). Because temperatures are high, rapid isotopic exchange takes place, and the alteration progresses as a reaction front up the stream tube formed by the permeability contrast and critical-properties zone. As fluids approach the apex of the system, moving more sluggishly, they become enriched in $\delta^{18}O$ via exchange with the rock and no longer produce noticeable alteration. Had the caprock been permeable above the apex of the felsite, very strong convection would take place in that area, and a marked plume of ^{18}O -depleted fluids would alter the rocks in a vertical zone above the apex. The lack of such a pattern argues strongly for the presence of an unbroken caprock throughout the effective hydrothermal lifetime of The Geysers system. Although analysis of cores from well SB-15d in this area support high fluid temperatures, this is not consistent with the lack of strong ^{18}O depletion in the shallow reservoir. Instead it seems that the SB-15d veins record small zones of penetration of the caprock that were geologically short-lived.

4. CONCLUSIONS

This initial analysis of the natural state of The Geysers, constrained in particular by observed $\delta^{18}O$ alteration demonstrates a number fundamental features of the system:

- thermal system lifetime is considerably shorter than observed ages in the felsite, even for purely conductive models. Similar conclusions have been reached by other Geysers workers (e.g. Dalrymple *et al.,* 1999).
- low bulk permeabilities in the reservoir rock (0.05 md) are sufficient to allow the convective circulation of fluids required to produce observed alteration and vein mineralogies. Similar values were determined in steam-production models of The Geysers (Pham and Menzies, 1993; Williamson, 1990).
- enhanced heat and fluid transport related to critical fluid properties strongly focuses inflow and deep fluid convection into a "streamtube" along the felsite-greywacke contact
- isotopic rock alteration is strongly limited to the recharge zones of this streamtube, and becomes much weaker in the discharge zone of the streamtube near the apex of the felsite
- persistent integrity of the caprock is required to produce this pattern of alteration. Without the caprock, a vertical zone of strong alteration would be present above the apex of the felsite
- persistent horizontal hydraulic connectivity at depth is also required to preserve the streamtube effect along the low flanks of the felsite intrusive

The first feature indicates that the intrusive history of the felsite heat source at The Geysers is much more complex than indicated by available age-dates. The latter features are a consequence of the second: factors limiting fluid circulation at The Geysers are responsible for the unusual thermal and alteration structure above the intrusive. Consideration of system-wide heat, fluid and ^{18}O mass balances at The Geysers allows a fundamental understanding of the combined impact of these features. This in turn provides new insights regarding The Geysers as well as a firm basis for more focused reservoir engineering models.

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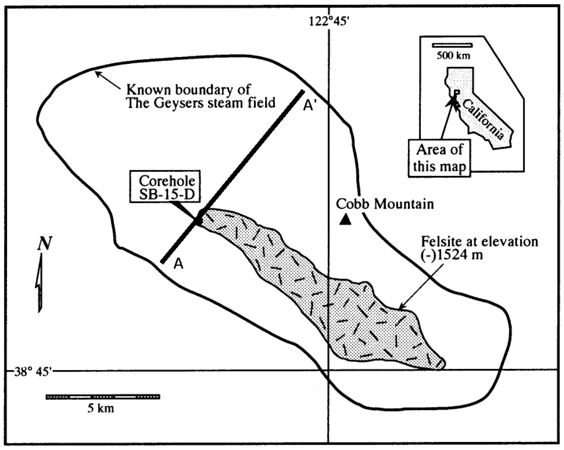

Figure 1: Location of The Geysers steam field, felsite at depth (after Hulen and Moore, 1995) and model cross-section. Coring project well SB-15d and location of model cross-section (A-A') shown near center of steam field.

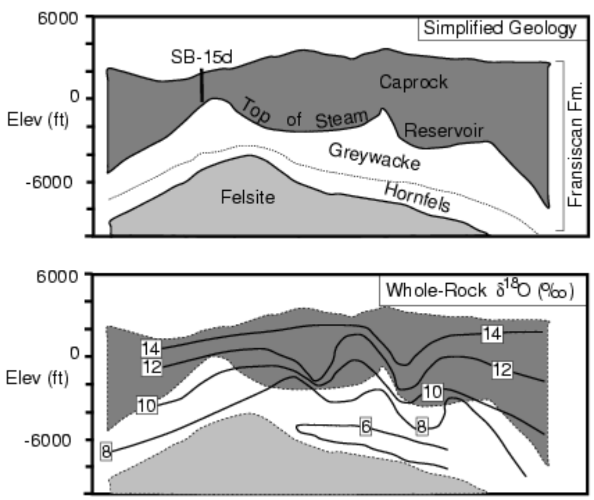

Figure 2: SW-NE cross-section of The Geysers, passing through well SB-15d, showing simplified geology and oxygen isotope alteration (after Hulen, *et al*., 1994). Location of well SB-15d and cross-section line shown in Fig. 1.

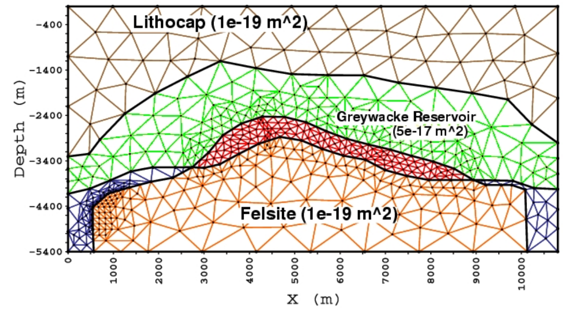

Figure 3: Finite element model grid, showing lithologic zones and modeled intrinsic permeability. Red zone is felsite reservoir, also modeled with 10^{-15} m^2, blue is cool bedrock with 10^{-19} m^2 permeability.). Well SB-15d TD located approximately at highest portion of steam reservoir-lithocap contact (see Fig. 2). The model contains 1071 quadratic triangular elements and 2188 nodes.

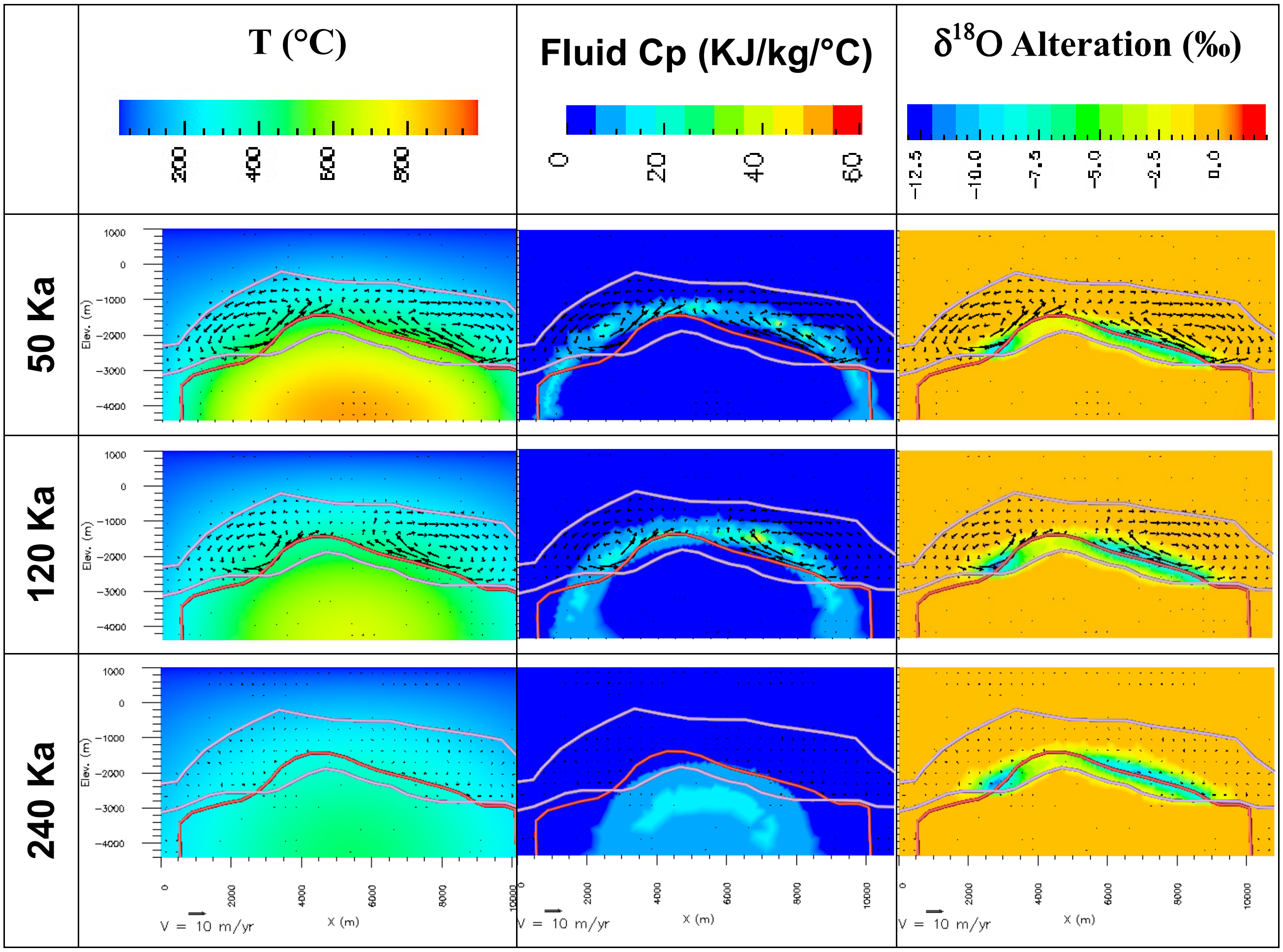

Figure 4: Temperature, heat capacity, and isotopic alteration results (columns) at 50Ka, 120Ka, and 240Ka (rows). Color scales given at top of columns. Black vectors show flow direction, length proportional to velocity (see scale arrow at base of columns). Horizontal scale given at base of columns, no vertical exaggeration, each panel is 5.4 km deep and 10.8 km wide. Felsite boundary shown by red line, reservoir boundary shown by white line. Alteration is initial value minus current, whole rock equivalent alteration is 0.3-0.5 time values shown in third column.