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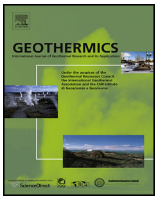

Full Length Article

Evaluation of inert tracers in a bedrock fracture using ground penetrating radar and thermal sensors

Adam J. Hawkins[a,*], Matthew W. Becker[b], Georgios P. Tsoflias[c]

[a] Cornell University, Earth & Atmospheric Sciences, 112 Hollister Drive, 2122 Snee Hall, Ithaca, NY 14853-1504, USA
[b] California State University, Geology Department, 1250 Bellflower Boulevard, Long Beach, CA 90840, USA
[c] University of Kansas, 1475 Jayhawk Blvd., Lawrence, KS 66045, USA

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ABSTRACT

The spatial distribution of fracture/matrix heat exchange was measured while hot water was circulated through a single bedding plane fracture in shallow bedrock. The field site is interpreted here as a simple model for a geothermal reservoir. Thermal breakthrough was recorded at the production well and Fiber-Optic Distributed Temperature Sensing (DTS) monitored temperature in the rock matrix. Conservative tracer tests revealed that the reservoir fluid volume in two separate experiments were nearly identical. Thermal breakthrough measurements, however, revealed that reservoir fluid volume did not correlate to thermal performance because the two experiments encountered different effective areas of heat transfer along the fracture. Ground Penetrating Radar imaging of subsurface tracer transport and DTS corroborate these findings.a cold reservoir

1. Introduction

Geothermal power plants commonly reinject production fluids in order to maintain reservoir pressure, prevent subsidence, and minimize waste water. A negative impact of reinjection is that short-circuiting of flow between injectors and producers can lead to premature production temperature decline as the rate of thermal energy extraction from the subsurface exceeds replenishment via natural thermal conduction and convection. When production well temperature declines below power plant design specifications earlier than expected, it is termed "premature thermal breakthrough." Premature thermal breakthrough can be economically disastrous for a well field. According to Stefansson (1997), examples of geothermal well fields that have observed cooling attributable to reinjection include Ahuachapan (El Salvador), Palinpinon (Philippines), and Svartsengi (Iceland).

Unfortunately, prediction of thermal breakthrough is often complicated by inherent uncertainties in subsurface characteristics. In reservoirs dominated by sparsely-spaced fractures, hydraulic connectivity through fracture networks is rarely known with any certainty. In addition to uncertainties associated with geometry and orientation of fractures, flow in individual fractures is highly heterogeneous and characterized by flow channelization (Tsang and Neretnieks, 1998). The combined effect of sparse fracture network connectivity and flow channelization in individual channels results in a reduced volume of fluid circulation and/or surface area available for heat exchange. As a consequence, premature thermal breakthrough may occur.

Flow channeling occurs in single fracture planes and is extended to fracture networks when channels within a plane intersect other hydraulically connected fractures. Thus, to understand flow channeling and thermal breakthrough in fracture-dominated geothermal reservoirs it is first necessary to understand flow channeling in single fractures. In addition, it is important to understand how flow channeling influences common subsurface characterization methods, including groundwater tracer testing.

Tracer testing is a common method employed by the geothermal industry (Axelsson et al., 2005; Robinson and Tester, 1984; Shook and Forsmann, 2005; Shook, 2001; Vetter and Crichlow, 1979). Tracer tests provide information on well connectivity which can provide early indication of injection/production well pairs that are prone to premature thermal breakthrough due to low reservoir fluid volume (Axelsson et al., 2001). Since conservative tracer breakthrough is strongly influenced by reservoir fluid volume, early arrival of tracer as indicated by the mean fluid residence time may suggest premature thermal breakthrough. Reservoir volume is esti-

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[*] Corresponding author.
E-mail addresses: ajh338@cornell.edu (A.J. Hawkins), matt.becker@csulb.edu (M.W. Becker), tsoflias@ku.edu (G.P. Tsoflias).

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mated by the product of the volumetric flow rate and the mean fluid residence time between injection and production wells.

Interpretation of tracer data is complicated, however, because heat exchange in fractured reservoirs is dominated by the surface area available for heat exchange. As discussed below, surface area cannot be directly interrogated by conservative tracer tests. This has major implications on the interpretation of conservative tracer tests, because flow channels may develop with a large volume, but relatively small surface area. In this case, a conservative tracer test would not provide early indication of premature thermal breakthrough.

The purpose of the experiments described here was to measure fracture/rock thermal exchange in the presence of channelized flow in a single fracture, demonstrate the effect of flow channeling on thermal breakthrough, and evaluate the relationship between mean tracer residence time and the rate of thermal breakthrough. Two experiments were conducted representing contrasting flow scenarios: a channelized flow path directly between two wells and a less direct path between two wells. Field experiments were conducted in a shallow sandstone bedrock site that was considered a reasonable experimental analog for a geothermal reservoir. Flow and tracer circulation was constrained to a single bedding plane fracture to focus the problem on individual fractures rather than fracture networks. Thermal exchange between fracture and rock matrix was measured using fiber-optic Distributed Temperature Sensing (DTS). Ground Penetrating Radar (GPR) images of saline tracer transport provide corroborating evidence of flow channeling and its influence on thermal breakthrough.

2. Background and motivation

Tracer testing is a common reservoir characterization method with more than 100 geothermal tests conducted worldwide over the last 40 years (Shook and Forsmann, 2005). As discussed in Shook and Forsmann (2005), tracer test data has been applied to a variety of problems, including constraining numerical models, estimating heat transfer parameters, quantifying well connectivity, and defining inter-well volume and flow geometry. In addition, predicting thermal breakthrough using reservoir parameters inferred from tracer test data has long been a goal in the geothermal industry (Tester et al., 1986; Shook, 2001; Axelsson et al., 2005).

Shook (2001) used a thermal retardation factor in conjunction with a tracer Residence Time Distribution (RTD) to predict thermal breakthrough in heterogeneous porous media. This approach assumes that there is local thermodynamic equilibrium between the rock and fluid which implies that the surface area to volume ratio between the fluids and the rock surface is not a limiting factor. This approach is applied to heterogeneous media by assuming the tracer RTD curve is influenced only by varying flow paths and not by other dispersion mechanisms such as Taylor Dispersion and dispersion resulting from rough-walled fractures. With these assumptions, thermal breakthrough is influenced only by the reservoir porosity, fluid RTD, and the relative density and heat capacity of the bulk rock and fluids. A similar equilibrium model was developed by Wu et al. (2008) for densely fractured rock. However, equilibrium assumptions are not appropriate for sparsely fractured reservoirs where heat transfer from matrix to flowing fluid may be limited by rock/fluid contact area.

Tester et al. (1986) modeled heat transport and conservative tracer flow between well pairs at the Hot Dry Rock Project at Fenton Hill. Using a simple rectangular geometry and plug flow (no dispersion), they determined an effective surface area of heat exchange by examining the measured thermal drawdown curve and fitting the rectangular model to the observed data by varying the reservoir surface area. For comparing reservoir volume and surface area, they used a "modal volume" which corresponded to the peak breakthrough of the tracer. The rationale for this approach was that tracer and heat transport was dominated by a few permeable fractures connecting the well pairs. Heat transfer surface area (estimated from thermal decline) was found to be linearly related to reservoir volume (estimated from inert tracers). Although this result would suggest that the inert tracers can be used predict thermal decline in reservoirs, this particular application relied upon simple fracture geometry between a limited number of closely spaced well-pairs. To our knowledge, such a simple relationship has not been demonstrated in commercial scale geothermal reservoirs or in any other field setting.

In geothermal reservoirs characterized by sparsely-spaced fractures, a parallel fracture heat transport model may be more appropriate. Heat transport through parallel fractures separated by low permeability matrix can be described by the one-dimensional advection-dispersion equation with coupled heat diffusion perpendicular to fluid flow. Tang et al. (1981) presented a Laplace domain solution for solute transport in evenly but sparsely spaced fractures in a rock matrix. A modification of this equation for heat transport is

$$\overline{\Theta}(s) = \frac{1}{s}\exp\left[\frac{Pe}{2}\left(1-\sqrt{1+\frac{4\tau}{Pe}\left(s+\frac{\left(\rho C_p\right)_m}{\left(\rho C_p\right)_w}\frac{\sqrt{sD_m}}{b}\tanh\left(\sqrt{\frac{s}{D_m}}\left(\frac{L}{2}-b\right)\right)\right)}\right)\right] \quad (1)$$

where $\overline{\Theta}$is dimensionless temperature in Laplace space, Pe is the dispersional Peclet number for heat transport, τ is the mean fluid residence time of the fluid (or non-reactive tracer), s is the Laplace variable, b is the fracture half-aperture, ρ is density, C_p is heat capacity, D_m is the effective thermal diffusivity into the bulk rock matrix (fluid and solid), and L is the distance between fractures. The Peclet number is a dimensionless number representing the relative strength of advection and dispersion (i.e., the product of velocity and distance traveled over hydrodynamic dispersion of heat). The subscripts m and w refer to the bulk rock matrix and the fracture fluid (e.g., water), respectively. Dimensionless temperature is defined as

$$\Theta = \frac{T(t) - T_r}{T_{inj} - T_r} \quad (2)$$

where $T(t)$ is the mean fluid temperature across the fracture aperture at time, t, T_r is initial temperature of the rock, and T_{inj} is the temperature of injected fluid.

Becker and Charbeneau (2000) demonstrated that the boundary conditions imposed by Tang et al. (1981) are equivalent to those leading to a first passage time (FPT) problem, i.e. transport of heat is considered a transition probability distribution rather than a local concentration of heat energy. FPT functions are amenable to moment analysis, which provides a convenient reduction of parameters. Moments are readily found using Laplace solutions of FPT such as Eq. (1) (Becker and Charbeneau, 2000). The first moment, M_1, of Eq. (1) is

$$M_1 = \frac{\left(\rho C_p\right)_m}{\left(\rho C_p\right)_w}\frac{L\tau}{2b} \quad (3)$$