



The dual-tracer push-pull method for characterizing geothermal reservoirs

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Introduction

The success and long-term viability of any geothermal energy recovery scheme based on heat transfer from hot rock to circulating fluids essentially depends upon the contact surface between the host porous rock and the active fracture network. The size and properties of this surface cannot unambiguously be determined by hydraulic or geophysical methods, nor from the short-term temperature signals that are usually available (Ptak and Teutsch 1994).

One process this surface directly affects is the transport of solutes within fractures. The extent and the measurable effects of solute exchange between mobile water in fractures and immobile water within the rock matrix (by diffusion and/or physico-chemical interactions with surface minerals) will depend upon the size and spatial distribution of fracture surfaces. Thus one can attempt to quantify these unknown surfaces by measuring the transport of solutes (tracers) with known diffusion and interaction properties.

Yet the application of traditional tracing methods often faces itself the problem of parameter ambiguity (interplay), since the same typical effects on 'non-conservative' tracer breakthrough curves (BTCs), like retardation, signal damping and long tailings can be produced by a variety of processes (Behrens 1986) not uniquely related to the target contact surface. Hence the need emerged for a special tracing method that reduces the influence of non - surface-related processes upon tracer BTCs, while enhancing the effects of matrix diffusion and/or sorption. To this end the basic parameter

dependencies of tracer BTCs in fractured-porous reservoirs are briefly revisited below (for a more comprehensive review one may consult Carrera et al. 1997; for late-time approximations Haggerty et al. 2000; for BTC fitting examples and very-late-time approximations Maloszewski and Zuber 1990, 1993; for a special numerical treatment Kolditz 2003).

Early and late-time behaviour of solute transport in a fractured-porous reservoir: how many independent parameters?

The specific area (i.e., area per bulk volume) S_m of the contact surface between the adjacent continua of the hybrid (fractured-porous) system, i.e. between fractures and rock matrix, is equivalent to the effective size $L_m = (1-N_f)/S_m$ of matrix blocks (with N_f denoting the fractured porosity), or to the fracture density, taken as number of fractures per unit depth of the (local) flow cross section.

An adequate description of matrix diffusion and/or further processes at fracture surfaces and matrix inner pore surfaces may strongly depend upon the size and shape of rock matrix blocks.

At early ($t \ll$ diffusion time scale) as well as very late ($t \gg$ diffusion time scale) times, however, tracer BTCs are remarkably independent upon matrix block shapes. At very early tailing times, the effect of diffusion into matrix blocks of perceived infinite size will also be independent upon matrix block sizes (the well-known “ $3/2$ ” log-log BTC slope). Thus the desired specific surface area S_m cannot be determined from this slope.

At mid-early tailing times, the effective size of matrix blocks (L_m) will be perceived in the form of two independent parameters, for instance (several combinations are possible) the pair $\{R_m \cdot (L_m^2)/D_m$ and $N_m \cdot D_m/(L_m^2)\}$, modulated by some numeric factors characterising the geometry of matrix blocks (with D_m denoting an effective tracer diffusion coefficient within the rock matrix, R_m an equivalent retardation factor for equilibrium processes at matrix pore walls, and N_m the intrinsic matrix porosity). The first parameter represents an equivalent time scale for diffusion-sorption within the rock matrix, while the second parameter represents a measure for the strength of coupling between advection and diffusion. For tracer BTC interpretation, it is of major advantage that L_m (or, equivalently, S_m) multiplies different rock parameters (the physical size of rock matrix blocks is thus not easily ‘re-scaled’, other than by diffusion coefficients D_m), and that the two parameters play different functions in the tracer transport equations (that is, they will affect the measured tracer BTCs in two different ways): they yield, respectively, the rate of change and the relative magnitude of an equivalent ‘source-term’ describing diffusive fluxes to and from the rock matrix (in which diffusion-sorption takes place).

At very late tailing times diffusion becomes irrelevant and the system responds like a single-continuum of mobile porosity N_f with a sole retardation factor $R_f \cdot N_f + R_m \cdot N_m$ acting synchronously for fractures and matrix. Such 'very late times' can hardly be realised in artificial tracings (yet they can apply to environmental tracer distributions, to which a perturbation signal is added).

Knowing the matrix porosity N_m , effective tracer diffusion coefficients D_m and tracer retardation factors R_f , R_m (from accompanying laboratory experiments), and with fracture porosity N_f assessed from hydraulic/geomechanical tests (cf. Ptak and Teutsch 1994, McDermott and Kolditz 2003, Kessels et al. 2004), it becomes possible to determine the specific contact-surface area S_m from artificial tracer BTCs, if the duration of the experiment is long enough for the tracer BTCs to show their 'mid-late' tailings.

The dual-tracer, push-pull (single-well, injection-withdrawal) method

A special single-well method, developed by Sauter and Herfort (2003) and abbreviated as D[ual]-T[racer] P[ush]-P[ull], can, even with relatively short-term tests, succeed to determine the specific contact area between circulating fluid and host rock. A selection of water-soluble tracers is injected into the reservoir (push), and left within it for some days or weeks (shut-in) during which the tracers can diffuse into the rock body and suffer further physico-chemical interactions (generically deemed as 'sorption') at fracture surfaces or at rock-inner pore walls. Upon withdrawal of the spiked water from the reservoir (pull), tracer concentrations will show different signals according to their different (dual) diffusion/interaction properties. From the relative difference of measured tracer BTCs, the size of the surfaces at which tracers diffused and/or interacted can be determined. Furthermore, it is this surface area parameter that the tracer BTCs will be most sensitive to, owing to the single-well design of the test. Here, D[ual]-T[racer] stands for theoretically at least two, in practice often more than two tracers with contrasting diffusion and/or sorption and/or further interaction properties, which must be ascertained from laboratory experiments (ideally, prior to their application in the field).

The push-pull tracer test concept has its origins in the representation that a tracer injected with flowing water into a heterogeneous fracture system will more or less follow the same heterogeneous fracture path(es) upon water withdrawal, thus reducing the influence of flow path heterogeneity while enhancing the influence of tracer diffusion and/or interactions at relevant fracture/matrix surfaces; tracer withdrawal signals are therefore expected to be much more sensitive to parameters relating to diffusion/interactions at fracture surfaces than to parameters relating to advection and dispersion in the fracture system. Metaphorically speaking, the effects of advection-

dispersion are thus partly ‘reverted’ (Haggerty et al. 2001); the part of ‘dispersion’ being reverted includes mid- and large-scale heterogeneities of the fracture network, but not hydrodynamic dispersion itself at the scale of a single fracture.

If, however, different compartments of a fracture system are mobilised differently, or one and the same compartment behaves differently under unequal injection/withdrawal rates and/or regimes, then tracer withdrawal signals can return further interesting information about this behaviour, or about the superposition of different flow systems, besides the major, surface-area information. Under equal injection and withdrawal rates, non-linear flow is more likely to occur during injection than during withdrawal, given the initial pressure distribution with high in-situ pressures in great depths.

Unlike traditional flow path tracings, push-pull tests cannot meaningfully aim at determining residence times that would characterise a given flow system, since the very test principle presupposes negligible natural flow, and the system volume ‘seen’ by the injected tracer is determined by the volume of chaser injected behind the tracer. Tracer ‘arrival’ times from single-well injection-withdrawal tests do not relate to residence times in the fracture systems themselves, but to the borehole volume between the tracer injection section and borehole-fracture intersections (the more this is important as packers are difficult to use in geothermal drillings). If multiple peaks are seen in a push-pull test, they are likely produced by different fracture systems intersected by the borehole in different depths, and peak arrival times or the corresponding water volumes withdrawn from the borehole can be used to localise the active fractures (applied in Urach-3 example below).

First experiences with the dual-tracer push-pull method in Germany (crystalline reservoirs)

Two somewhat contrasting hydrogeological settings were chosen for a first application of the dual-tracer push-pull technique in Germany, also differing from each other in respect to potential influences on tracer behaviour through in-situ hydrochemical and mineralogical factors.

The very first dual-tracer push-pull test in Germany was carried out in August 2003 (in cooperation with the Communal Energy Supply of Bad Urach and the ETH Zuerich) in the 4,5-km deep, low-permeable HDR formation around the borehole Urach-3 in the south-west German crystalline (gneisses, anatexites, diatexites, with in-situ temperatures about 175°C as of 3200 m of depth), using uranine (sodium fluorescein), naphthol Green B and 1,5-naphthalene disulfonic salt, with a shut-in phase of about 11 days and withdrawal under artesian conditions (no pumping necessary) due to prior pressure build-up by massive water injection. The incipient tailings of tracer with-

drawal curves indicate that the experiment can be regarded as a short-term one (compared to diffusion time scales), the reservoir behaving like the superposition of two 'single-fracture'-behaved systems around the injection-withdrawal borehole; apparently at least one tracer did not behave conservatively. Tracer recoveries attained between 33% and 55% after five days of fluid outflow in which about the threefold of the injected chaser volume was recovered.

A second, small-scale dual-tracer push-pull test was conducted in December 2003 in the highly-permeable, hydrothermally-altered fault zone (along an ore dyke) of the Albtal plutonic granite at Lindau/Todtmoos in the Southern Black Forest. A parallel-plate fracture subsystem was chosen for the test and isolated from the surrounding flow system by creating a hydraulic short-cut between its designated boundaries. Uranine, naphthionate, 1,5-naphthalene disulfonate, bromide and lithium were used, with a two-week shut-in phase. Despite the very low tracer recoveries and about 90% of the inserted tracer remaining within the borehole and generating a persistent tailing 'noise', mid-late tracer tailings showed quite distinct slopes that can be consistently explained by the theoretically-expected contrast in tracer diffusivities (on grounds of their different equivalent ion radii) and sorptivities (cf. Behrens 1986). Relative to the tracer quantities actually entering the fracture system (about 10%), tracer recoveries ranged between 30% and 60% after few hours in which almost the tenfold of the injected chaser volume was recovered.

A complex dual-tracer push-pull test was conducted at the pilot hole of the Deep-Continental Drilling Programme in Germany (KTB-VB), intersecting a fluid-bearing fracture bundle in about 3.9 km depth in the crystalline formation (dominated by gneisses and amphibolites). The 'dual'-tracer cocktail was actually comprised of four thermally-stable tracers with contrasting molecular weights and sorption tendencies: tritiated water, 1,5-naphthalene disulfonate, uranine, and a further, non-commercial UV-fluorescent tracer (Netter and Behrens 1992, Machate et al. 1998). Tracer recoveries ranged between 29% and 44% after 18 days of pumping in which about the threefold of the injected chaser volume was recovered.

The mid-late slopes of tracer BTC tailings indicate specific contact surface areas or, equivalently, fracture densities in the range of 100 per meter for the test section of the Lindau granite, 0.1-1 per meter for the activated fractures at Urach-3, and 10-100 per meter for the shear zone around the pilot KTB hole.

The determination of contact surfaces from the tracer BTCs presupposes reliable knowledge of tracer properties. Diffusion, sorption and thermal degradation (match to Arrhenius law if applicable) must be quantified in laboratory experiments reproducing the reservoir in-situ physico-chemical conditions (temperature, pressure, mineralogi-

cal characteristics of rock surfaces, salinity). While diffusion coefficients increase with temperature (and also with increasing salinity due to reduced ion hydration), ion exchange is only weakly temperature-dependent (it may however become strongly limited with increasing salinity), and true sorption (van-der-Waals) is likely to decrease and become negligible beyond a certain reservoir temperature. The decision about the use of a tracer in the field can first rely on structure-activity considerations (Behrens 1986), before tracer thermostability, diffusion and sorption are quantified in laboratory experiments.

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