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A NOTE ABOUT "HEAT EXCHANGE AREAS" AS A TARGET PARAMETER FOR SWIW TRACER TESTS

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ABSTRACT

In fluid-based geothermal reservoirs, thermal breakthrough depends on mainly two parameters: fluid residence time, and heat exchange area density. However, "heat exchange area" is often used in a sense similar to residence times or their distribution; we examine the implications of that. Further, we discuss two non-equivalent meanings of "HEA density", depending upon reservoir structure and differing in respect to their determinability from SWIW or from inter-well tracer tests. In systems with negligible natural flow, SWIW tracer tests are a good method for measuring transport parameters other than advective-dispersive, out of which parameters associated with matrix diffusion are especially relevant to heat transport. In single-fracture systems, *HEA per fracture volume* is equivalent to fracture aperture, w. r. to which SWIW tracer tests indeed exhibit good sensitivity (better than from inter-well tests). In multiple-fracture systems, *HEA per bulk reservoir volume* is equivalent to fracture spacing, w. r. to which SWIW tracer tests also exhibit good sensitivity, yet heat transfer in such systems is controlled by both parameters, fracture spacing and individual-fracture aperture, with different weightings during early, late and very-late time stages. Thus, in order to reliably determine both parameters, multiple SWIW tests are recommendable, using tracers with contrasting diffusivities (like heat vs. solute tracers) and conducted at dual scales.

To be noted, *HEA* (fracture length $\times$ height $\times$ number of fracture walls) is completely independent upon *HEA density* (reciprocal of either aperture, or spacing). The mobile-fluid volume in the reservoir results from the product of fracture number, aperture, height, length, and porosity within fractures; while the latter three can be regarded as purely advective parameters, *MRT* and RTD will result from both AD and non-AD parameters, which makes the identification between "heat exchange area" and RTD features of a geothermal reservoir feel natural, but act highly confusing w. r. to what can or cannot be measured from SWIW tests.

ABBREVIATIONS

HEA: heat exchange area; *HEAd*: heat exchange area density (area per volume of fluid and/or rock, to be specified); BTC: tracer breakthrough curve (in a test); AD: advective-dispersive (parameters); *MRT*: mean residence time (of fluid within reservoir); RTD: residence time distribution; FSR: flow-storage repartition; SWIW: single-well injection-withdrawal (test), also deemed 'push-pull'; Bel: the popular belief quoted on page 2.

THE BACKGROUND

We apologize to the well-informed reader, to whom this paper will not present any new facts.

In fact, everything that matters about *HEA(d)* in geothermal reservoirs has already been identified and thoroughly analyzed by Pruess and Bodvarsson (1984), Kocabas and Horne (1987, 1990), Kocabas (2005), Carrera et al. (1998), Pruess and Doughty (2010), though with a different focus and using a different language. And almost everything that matters about SWIW tracer tests (especially within the realm of contaminant hydrology, but also relevant to their geothermal-field application) has already been explored in a major review work by Neretnieks (2007).

The focus of Pruess and Bodvarsson (1984) was on thermal breakthrough prediction for a reservoir dominated by one vertical fracture; they found that it depends on two parameters, both of which can theoretically be determined from inter-well tracer tests (and one of which is equivalent to *HEAd* in the first of 4 meanings discussed in the next sections).

Kocabas and Horne (1987, 1990), Kocabas (2005) conducted similar calculations on thermal breakthrough, but their main focus was on the design of a novel, single-well injection-backflow method for determining the "thermal parameter" (which by rewriting their parameter groups can be interpreted as *HEAd* in the first of 4 meanings discussed in the next sections); they also derived exact closed-form solutions for temperature signals from a particular type of SWIW test, and compared these with numerically-evaluated solutions.

Thermal breakthrough prediction was also addressed by Shook (1999, 2001a,b), whose “thermal retardation” formulae do not contain any *HEA(d)* parameter and are not equivalent to those derived by Pruess and Bodvarsson, or by Kocabas and Horne. The absence of a *HEA(d)* parameter is part of Shook's endeavor to ensure simplicity and robustness of reservoir prediction, requiring only a minimum of data, and ignoring inessential reservoir details. Later on, Shook (2003) proposed a universal formalism for deriving “reservoir geometry” (expressed as a FSR) from inter-well tracer tests, which is extremely valuable for interpreting tracer tests in a model-independent way, and for freeing geothermal reservoir characterization from all uncertainty associated with hydrogeological anecdotics; here, again, *HEA(d)* would not be part of that characterization. Behrens et al. (2010) proposed a small modification to Shook's formalism, to make it better reflect the effects of matrix diffusion processes, thus adding *HEAd* parameters (in the first and second of 4 meanings discussed in the next sections) to the FSR agenda. From Shook (2003) we shall quote, later on, a few sentences associated, in our interpretation, with the third and fourth meanings of *HEA* discussed in the next sections.

Carrera et al. (1998) did not deal with heat transport, but they proposed a very efficient formalism for including a fluid-rock contact surface area-per-volume into the solute transport equations, as a distributed parameter (not associated with discrete features like major fractures), for various geometries of a porous medium (treated as a dual continuum). Their area-per-volume parameter need not be uniform but can vary in space and also in time (if the porous medium suffers deformation, for instance). This formalism can be particularly useful in shallow-geothermal porous-media modeling, but it also turns out to be useful for deep-geothermal models involving discrete permeability features. The distributed area-per-volume parameter of Carrera et al. (1998) is approximately equivalent to *HEAd* in the second of 4 meanings discussed in the next sections.

Besides the above-cited works, though not directly relating to interface areas as such, we would like to mention Neretnieks (1980) addressing matrix diffusion in the context of long-term solute transport from point sources, Sudicky and Frind (1982) who provided closed-form solutions to the solute transport IBVP in uniform parallel-fracture systems, as well as and Maloszewski and Zuber (1985, 1993) who contributed major insights concerning parameter determinability from inter-well tracer tests in single- and multiple-parallel-fracture systems (represented by their SFDM and PFDM models), and into the asymptotic behavior of SFDM and PFDM at early and large times. Regarding the latter, again Carrera et al. (1998) also wrote a very interesting comment on asymptotic behavior of tracer BTCs and on ambiguity of parameter determination from inter-well tracer tests, for dual-continuum geometries more general than in the SFDM and PFDM considered by Maloszewski and Zuber. Highly complex fracture network geometries and the possibility of representing them by equivalent continuum models have been dealt with by Kolditz (1997), equivalence being sought for w. r. to hydraulic and transport behavior, with matrix diffusion effects being assimilated to “dispersion” whenever feasible; various works by Maloszewski et al. also had demonstrated that a pure advection-”dispersion” model is often able to represent a variety of non-AD processes at certain scales.

Carrera's formalism for unifying the description of diffusive transport in porous media with various rock grain geometries was also used and extended by Haggerty et al. (2000, 2001) to describe “multi-rate diffusion”, which is of high relevance to solute (tracer) transport in the subsurface in general and to heat transport in shallow porous media, but of rather limited interest when dealing with heat transport in deep tight rock (of low permeability and high heat diffusivity). Remarkably, the foundation Haggerty et al. (2000, 2001) gave for their analysis on large-time asymptotics of tracer BTCs is identical for inter-well and for SWIW tracer tests.

Finally, Pruess and Doughty (2010) offer a thorough numerical analysis of *HEAd* determinability from heat SWIW tests (with *HEAd* having the first of 4 meanings identified in the next sections).

Is there anything still waiting to be “discovered”, regarding *HEA(d)*, or fluid-rock interface areas, in geothermal reservoirs? – Not really. What motivated the present paper is the growing popularity the following belief (subsequently abbreviated as Bel) is enjoying amongst (not solely) German geothermics professionals since a couple of years:

(Bel) “*Tracer SWIW tests provide the best method for determining heat exchange areas in geothermal reservoirs. Low HEAs are encountered in 'cigarette-shaped' reservoirs. High HEAs are encountered in 'balloon-shaped' reservoirs. Thus, tracer SWIW tests allow to determine whether the reservoir is 'cigarette-' or 'balloon-shaped'. Furthermore, repeatedly conducting SWIW tests during reservoir operation will allow to quantify how reservoir properties (including shape) have changed as a consequence of operation-induced, coupled THMC processes*.“

Maybe some papers like our own, disseminated in Germany on various occasions, have contributed to the first sentence of Bel becoming so popular; and maybe it is time to apologize, and intervene for a correction w. r. to Bel's other sentences; moreover, even the first sentence's validity is, in our opinion, limited. (Interestingly, Bel seems to be particularly popular in areas in which deep-geothermal energy is being promoted for reasons going beyond economics; it enjoys less attention in areas where geothermal projects are already working economically. Of course, a single-well, short-term push-pull test is attractive because it requires only one borehole and yields some results within a short time, in contrast with inter-well tests at geothermal doublets, that can only yield significant results after a time in the magnitude order of reservoir fluid MRT itself, which in Germany often means many years or decades.)

The cited Bel confronts researchers conducting tracer SWIW tests with great expectations on the side of geothermal project operators, that may be impossible to fulfill.

Why is *HEAd* so important?

In the deep-geothermal realm (not only) in Germany, it does not suffice to drill and find rock layers of good permeability and high temperature; it must also be ensured that the reservoir can be operated sustainably, for at least three decades, as a rule, otherwise a deep-geothermal project would be economically unattractive. 'Sustainability' involves at least four aspects:

(a) thermal lifetime (associated with production temperature drop, or 'thermal breakthrough'),

(b) hydraulic lifetime (associated with permeability reduction, typically by chemical processes),

(c) hydrogeomechanical lifetime (associated with pore pressure changes, etc. inducing seismic activity of 'undesired' kind),

(d) hydrogeochemical lifetime (associated with fluid-rock interactions, dissolution/precipitation etc., also impacting upon (b)).

A parameter closely resembling, but not identical to, and often mistaken for *HEAd*, namely the fluid-rock interface density (contact surface area per volume) is directly involved in (d), and indirectly involved in (c) and (b); we shall not deal with it any further within this paper. Parameter *HEAd* itself (with either of the first two meanings explained below) is directly involved in (a), and indirectly, yet significantly involved in (b) – (d) by virtue of coupled THMC processes. Thus, this parameter is definitely worthwhile developing field methods to measure it reliably. Since hydraulic and geophysical methods cannot measure it, tracer methods appear to be the first (or unique) option. And, since inter-well tracer tests notoriously suffer from ambiguity between AD and non-AD effects on tracer BTCs (an issue thoroughly investigated in many papers by Zuber and Maloszewski), a single-well method with flow-field reversal, reducing AD effects and enhancing non-AD effects, indeed appears as very promising. Now, let us have a look at what is meant by “heat exchange area” in various instances of Bel – would the SWIW tracer method work in any of them?

FOUR DIFFERENT MEANINGS?

Of the four different “meanings” identified below, the first two ones are legitimate and clearcut, and, with either of these two ones, the first sentence of Bel can be made true (if SWIW tracer test design and dimensioning matches the magnitude order of *HEAd* – which yet may be difficult to guess in advance –, and if field test execution follows the rules of the art). The further two meanings, of *HEA* rather than of *HEAd*, are somewhat problematic, being equivalent to *MRT* or RTDs, which makes them prone to misunderstanding; when such *HEA* are mistaken for *HEAd*, they may generate absurd expectations w. r. to SWIW test scope.

No. 1: *HEAd*, equivalent to fracture aperture in a single-fracture system

This meaning of *HEAd* was implicit in the thermal breakthrough prediction formula derived by Pruess and Bodvarsson (1984). If flow in the reservoir takes place in one major fracture, then the surface available for heat exchange will consist of the two walls of that fracture (say, each of area A). Their area, divided by the volume of the fracture, will equal $2/b$, with b denoting fracture aperture (or $1/b$, with b denoting half-aperture). One might choose to divide the area by the volume of mobile fluid within the fracture, instead of bulk fracture volume; then one would get $1 / (b\, f)$, with f denoting transport-effective fracture porosity, or with $b\, f$ denoting “effective aperture”. What matters, though, is how parameters b, f enter the thermal breakthrough prediction formula; there, they indeed act like 2 independent parameters.

Determinability of this *HEAd* from heat SWIW tests was given a thorough numerical analysis by Pruess and Doughty (2010), which we shall not repeat here. This *HEAd* can also be determined from inter-well tracer tests (as demonstrated by Maloszewski and Zuber 1993 with their single-fracture model SFDM), but with more ambiguity than from SWIW. To be noted, the fluid residence time in the fracture will be given by $A\, b\, f / q$, with q denoting fluid turnover rate. With given wall area A and given rate q, if fracture porosity were 1, both the residence time and the *HEAd* parameter become equivalent to fracture aperture b, and thus to each other, which looks paradoxical. This happens whenever a fracture is imagined as a entirely mobile-fluid-filled space between two rock walls. Yet we know that thermal breakthrough is determined by 2 parameters that are generally independent from each other. This could also be phrased in terms of 'effective apertures', allowing the 'transport-effective aperture' (which includes fracture porosity) to differ from 'exchange-effective aperture' (which defines temperature or concentration gradients between rock matrix and fracture, controlling exchange fluxes); this would formally add one more different meaning to the effective fracture apertures that were analyzed by Tsang (1991).

<u>No. 2: *HEAd*, equivalent to fracture spacing in a parallel-fracture system</u>

This meaning of *HEAd* was implicit in the formalism of Carrera et al. (1998), even though they do not consider fractures or fissures, but a porous medium consisting of pores and rock grains of various shapes. However, one can easily extend their definition from pores to fractures (as illustrated symbolically in fig. 1). A similar meaning was also implicit in the derivations presented by Maloszewski and Zuber (1985) for their 'parallel-fracture dispersion model' PFDM, though they never addressed any surface area notion, and their IBVP formulation, unlike Carrera's, did not contain this parameter in AD-transport PDE, but only in the locating of a BC transversally to flow direction. This *HEAd* differs from that of Pruess and Bodvarsson (1984), Pruess and Doughty (2010).

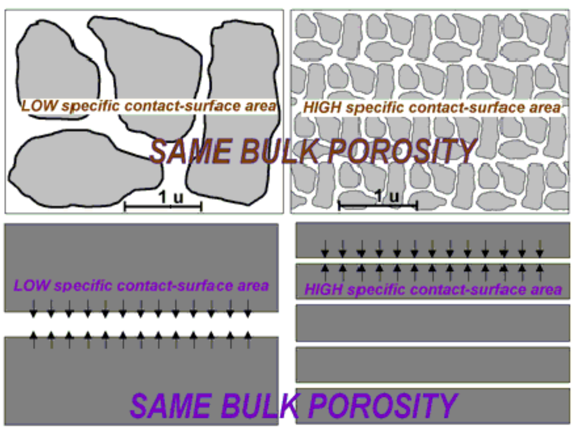

Figure 1: Resemblance between a parallel-fracture system and a porous medium regarding the definition of surface area density.

For a parallel-fracture system, this *HEAd* is given by $1/a$, with a denoting half-spacing between adjacent fractures (considering that $a >> b$ in natural systems); it can also be called 'fracture density'. This density is referenced to the bulk fractured-medium volume, whereas the density in *HEAd* no. 1 was referenced to the bulk volume of a single fracture. To be kept in mind, fracture spacing effects upon heat or tracer transport in a different way than fracture aperture: whereas $1/b$ directly determines the matrix diffusion term's magnitude in the AD-transport PDE (as a factor multiplying this term), parameter a regulates the 'intensity' of matrix diffusion by 'turning it off' in distance a from fracture walls.

The determinability of *HEAd* no. 2 from SWIW tracer tests depends on the scale of the tests, as summarized in Table 1.

Table 1: On HEAd determinability of from SWIW tracer tests in parallel-fracture systems consisting of N>>1 fractures with spacing a, individual-fracture aperture b (b<<a), and fixed porosity value within individual fractures, for equal fluid slug volumes (i. e., same radial penetration distance into fractures) in all cases. T[a] denotes a squared divided by the tracer's effective diffusion coefficient D.

duration of push, pull phases, compared to $T[a] = a^2/D$	short injection pulse $T_{inj} << T[a]$	long injection pulse $T_{inj} > T[a]$
early pull signals $t_{pull} << T[a]$	• sensitive w. r. to $1/b$ • insensitive w. r. to a • single-fracture behavior like for isolated individual fractures	• sensitive w. r. to $1/(N\,a)$ • insensitive w. r. to b/a • single-fracture behavior for fracture bundle of total aperture ($N\,a$) and porosity (b/a)
late pull signals $t_{pull} \gtrapprox T[a]$	• sensitive w. r. to a • sensitive w. r. to $1/b$ • some ambiguity between parameters • parallel-fracture behavior like for $N \rightarrow \infty$	• sensitive w. r. to a and N • sensitive w. r. to $1/b$ • some ambiguity between parameters • parallel-fracture behavior like for finite N
very late pull signals $t_{pull} >> T[a]$	• sensitive w. r. to $1/(N\,a)$ • insensitive w. r. to b/a • single-fracture behavior for fracture bundle of total aperture ($N\,a$) and porosity (b/a)	• sensitive w. r. to $1/b$ • insensitive w. r. to a • single-fracture behavior like for isolated individual fractures

The relations in Table 1 can be explained as follows: with increasing injection time, the parallel-fracture system gradually becomes equivalent to a single fracture of total aperture Na, whose internal porosity (b/a) is computed from what previously represented *HEAd* no. 1 and no. 2; with increasing withdrawal time following a long injection time, it gradually resumes multiple-fracture behavior, until matrix blocks become highly depleted and the influence between neighboring fractures extincts, which resembles single-fracture behavior of multiply replicated, but isolated individual fractures. When following only a short 'push' time, long 'pull' time will just suffice to reach single-fracture behavior for the fracture bundle, but not for returning to single-fracture behavior of isolated individual fractures.

Since the effective diffusion coefficient *D* differs between heat and solutes (in deep geothermal reservoirs) by at least three orders of magnitude, what is 'early' for solute tracers may already be 'very late' for temperature signals, and what is 'late' for temperature signals may still be 'early' for solute tracers (example in fig. 2). This ensures possibilities to disambiguate, i. e. determine every *HEAd*-relevant parameter (*b*, *a*, *N*) independently from each other.

Thus, the design and dimensioning of dual-tracer, dual-scale SWIW should endeavor to meet as many different asymptotic behavior patterns (from Table 1) as possible. Also, to avoid uncertainty associated with physico-chemical “imponderables” of solute tracer behavior (sorption, brine-phase reactions etc.), it is recommendable to use tritiated or deuterated water as a fluid tracer: their transport behavior will resemble that of native reservoir brines closer than any chemical tracer; inert gases can also be a good choice. Density-driven effects could be compensated by using reservoir brine as a chaser, or adding salt in the tracer+chaser water slug.

This *HEAd* no. 2 can also be determined from inter-well tracer tests (as was demonstrated by Maloszewski and Zuber 1985), but with more ambiguity than from SWIW. The ambiguity affecting the determination of matrix diffusion parameters from inter-well tracer tests was discussed in detail by Maloszewski and Zuber (1985), though not in terms of *HEAd*, and also by Carrera et al. (1998).

Fig. 3 illustrates how three different values of *HEAd* no. 2 (i. e., of fracture spacing or fracture density) will be felt by incipient tracer signals from a SWIW test. Owing to symmetry, it suffices to consider only half of one matrix block between two fractures, adjacent to half of one fracture. The 3 cases shown in fig. 3 differ in their physical size; the lower (in blue) is 'short push, early pull', the upper (in red) is 'long push, early pull' in the sense of Table 1. To be kept in mind, one and the same physical SWIW test dimension (same volume, same duration) can turn out to be 'short' or 'long' in injection, and to remain 'early' throughout its pull duration or to attain 'late' stages during the same duration, depending upon the value of *T*[*a*], i. e., depending upon the value of spacing *a*, which is difficult to know in advance when dimensioning a SWIW test. Fig. 3 also illustrates the superposition between inward and outward matrix gradients; diffusion within matrix blocks continues both directions during 'pull' phases (until reaching uniformity over whole thickness).

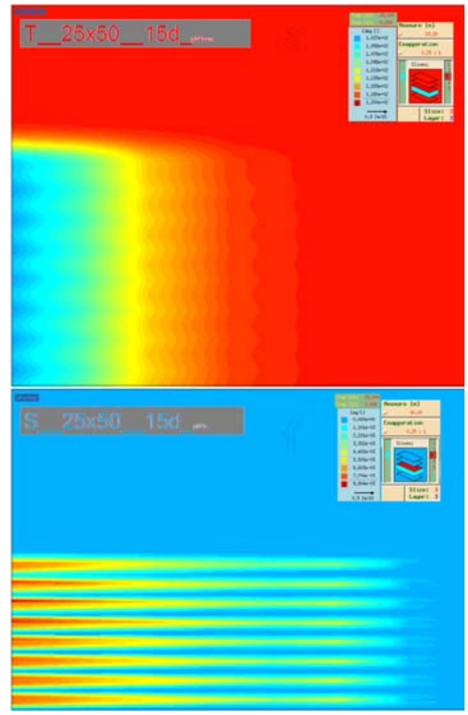

Figure 2: Heat vs. solute spreading, or 'late'- vs. 'mid late'-time transport in a parallel-fracture bundle of finite transversal extension.

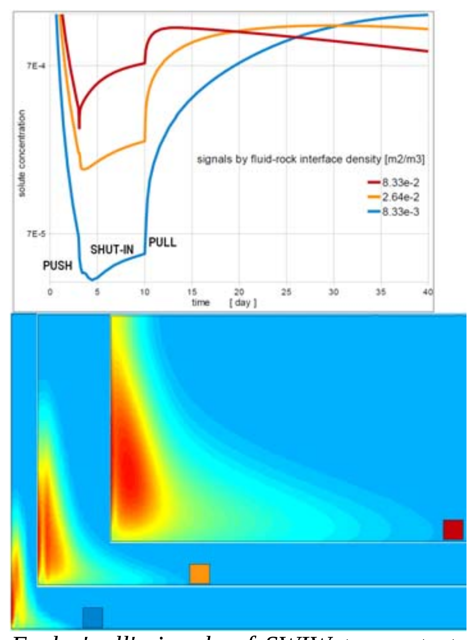

Figure 3: Early 'pull' signals of SWIW tracer tests in systems with different fracture spacing. Spatial tracer spreading within matrix half-block: pictures are re-scaled to approximately equal sizes, but differ in physical size. The lower case (blue mark) corresponds to the 'short push', the upper (red mark) to the 'long push' case from Table 1.

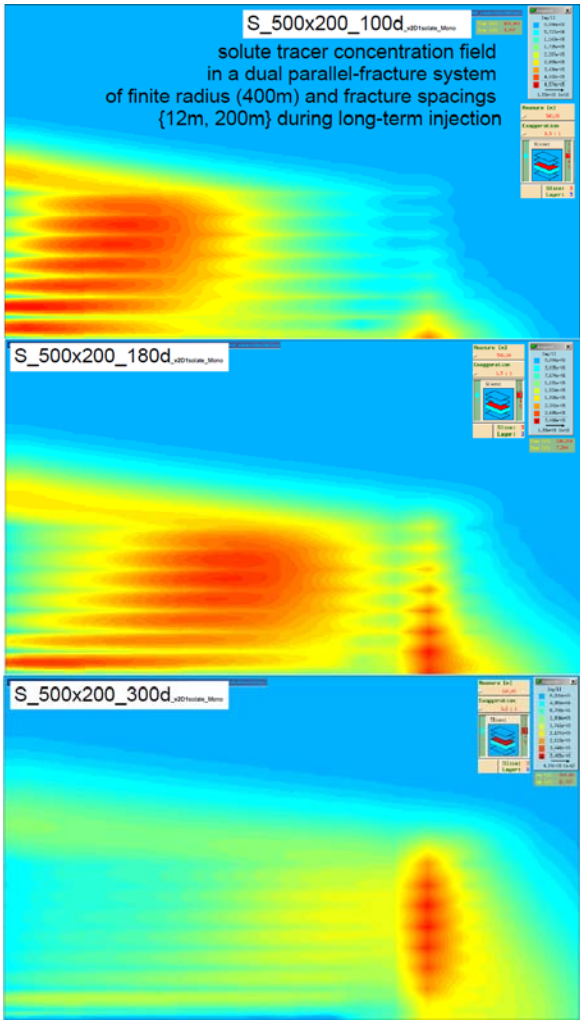

Figure 4: Example of tracer spreading in a dual-scale parallel-fracture system.

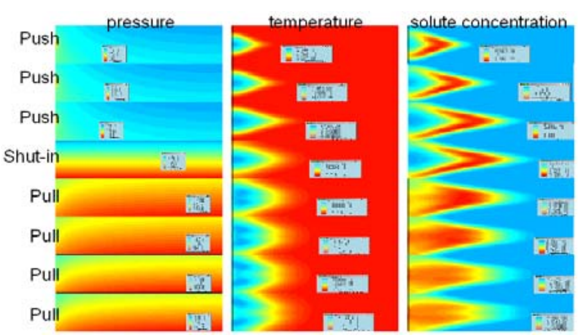

Figure 5: Example of a simultaneous heat and solute SWIW test in a highly-permeable aquifer layer (located in the middle of each plot) bounded by tight-rock layers.

To be noted, the definition of *HEAd* no. 2 implies infinite transversal extension of the parallel-fracture structure ($N \rightarrow \infty$, or $N >> 1$); small N bundles, or dual-scale parallel-fracture systems (example in fig. 4) would require a special treatment for early, intermediate and large times; yet the principles summarized in Table 1 would still hold, by and large. They may also be extended to the "aquifer-type" geothermal reservoir, consisting of a highly-permeable layer of macroscopic-scale thickness (not a fracture), bounded by tight rock layers; fig. 5 shows an example of heat and solute SWIW test in such a system. Generally, *HEAd* no. 2 or no. 1, though extendable in their meaning for such systems too, no longer suffice to characterize them w. r. to all aspects of transport.

We now turn to the 'cigarette or balloon' question from Bel.

No. 3: *HEA*, "equivalent" to fluid *MRT*

This "meaning" of HEA probably originates in the feeling that any *extensive* physical quantity describing the *size* of a geothermal reservoir is as good as any other. It may be a length, an area, a volume, or a time, say

– the effective distance L the fluid must "travel" from injector to producer,

– the surface area of hot rock that it "sweeps" or "contacts" while moving from injector to producer (perceived as *HEA*),

– the reservoir volume "seen" by the fluid between injector and producer, or the reservoir's turnover volume V (the volume of mobile fluid within the reservoir)

– the time the fluid "needs" to travel from injector to producer, or the reservoir's turnover time *MRT* (the time needed to once replace the mobile fluid within the reservoir);

they are all felt like equivalent to each other. For a reservoir whose only mobile-fluid region consists of a single rectangular vertical fracture of porosity f and of fixed dimensions (aperture b, or effective aperture $f\,b$, height h, connecting injector and producer in distance L), assuming parallel flow from injector to producer at rate q, one can write

$V = L\,h\,f\,b = HEA\,f\,b = MRT\,q$

For fixed "intensive" quantities (fracture cross-section, porosity, flow rate), all "extensive" quantities V, L, *HEA*, *MRT* will indeed be equivalent to each other.

It is easily seen that this *HEA* no. 3 is by no means equivalent, but complementary to *HEAd* no. 1 which was $1/b$.

To be noted, the idea that the variable expressing reservoir operation progress can be chosen from any of the above extensive quantities (measured from the injector to a variable location x between injector and producer, i. e., replacing the above-used distance L by a variable distance x) was already present in Pruess and Bodvarsson (1984). But they never stated that *HEA* thus defined would be determinable by SWIW tracer tests; they can by no means be made responsible for the misconception inhabiting Bel's last sentence.

Now, what about the 'cigarette or balloon' question? if one considers the dipole flow field between the injection and the producer of a geothermal well doublet, one may wish to say, for instance, 75% of the fluid flowing through the reservoir will be found within a narrow or within a wide “streamline volume” (depending upon a number of factors like permeability contrast etc.); consistently with the above definition of *HEA* no. 3, the (fracture-planar) flow-field dipole area containing, say, 75% of all streamlines could also be regarded as a measure of *HEA*. This illustrates how *HEA* becomes associated with 'cigarette or balloon' within <u>Bel</u>. More generally, this *HEA* could be associated with the degree of dipole flow-field focusing.

Clearly, this *HEA* is not determinable from SWIW tracer tests, but requires inter-well flow-path spikings for its (more or less ambiguous) “determination”. To be kept in mind, this *HEA* no. 3 is not a measure of the intensity of heat transfer from adjacent rock to the fluid flowing through the reservoir; it is completely independent from the factors multiplying the matrix diffusion gradient in the transport equation, as well as from fracture spacing in a multiple-fracture system.

No. 4: *HEA*, “equivalent” to fluid RTD

Once *HEA* was associated with “degree of flow-field focusing”, it is just a small step left to saying “flow-field heterogeneity”. From the point of view of <u>Bel</u>, a highly-dispersive flow dipole ('balloon') will enjoy a high *HEA*; a lowly-dispersive flow dipole ('cigarette') will be low in *HEA*. From the point of view of what can be measured by tracer tests (inter-well only), this means residence time distribution, rather than just *MRT*. And, from RTD, it is only one step left to FSR, according to Shook (2003): FSR is always uniquely derived from RTD. [However, this derivation of FSR from RTD ignores matrix diffusion processes; and, without matrix diffusion, any *HEA(d)* parameter looses physical meaning. From simulated matrix-diffusive tracer BTCs also, FSR are seen to be rather insensitive w. r. to matrix diffusion parameters, including *HEAd*. With the slightly modified FsSR suggested by Behrens et al. (2010), sensitivity w. r. to *HEAd* is regained.]

With these considerations, the fourth and last meaning of *HEA* (the one actually implied by the 'cigarette or balloon' question in <u>Bel</u>) can be regarded as equivalent, for instance, with a whole tracer BTC, or RTD, or Shook's FSR, etc.; obviously, it cannot be quantified by a single parameter, but reflects the interplay of all transport parameters: advective-dispersive, and diffusive.

Like no. 3, *HEA* measure no. 4 is not determinable from SWIW tests, but requires inter-well flow-path spikings for its determination.

To be noted, the idea of a direct correspondence between reservoir shape and thermal breakthrough was present also in Shook (2001), from whom we quote: “*optimal injection strategy [is] such that the injectate contacts a large volume of reservoir rock and extracts energy from the reservoir in a uniform pattern. Such uniform sweep efficiency can only truly be achieved in homogeneous media. Nevertheless, that is the goal of all injection projects: [...] maximizing sweep efficiency of the injectate. Premature thermal breakthrough is simply the undesired result of nonuniform sweep efficiency of reservoir rock by injected fluids*.” It seems difficult to tell which of *HEA* meanings no. 3 and no. 4 is expressed thereby; maybe both of them. But Shook (2001) explicitly stated that his FSR is “not yet” *HEA*, for which he was planning future research; he cannot be made responsible for the misconception inhabiting <u>Bel</u>.

In our opinion, *HEA* “meanings” no. 3 and no. 4 are not recommendable for further use: no. 3 merely duplicates an already existing parameter with unambiguous definition (the fluid's *MRT*); while no. 4 has no clearcut definition, it is equivalent to 'all parameters together'.

A final remark on *HEA* versus *HEAd*

Part of the confusion about the surface area vs. density notions probably arises from the fact that, for a fracture system, HE *area* (fracture length $\times$ height $\times$ number of fracture walls) is completely independent upon HEA *density* (reciprocal of either aperture, or spacing). The mobile-fluid volume in the reservoir results from the product of fracture number, aperture, height, length, and porosity within fractures; while the latter three can be regarded as purely advective parameters, *MRT* and RTD will result from both AD and non-AD parameters, which makes the identification between *HEA* and RTD features of a geothermal reservoir feel natural, but act highly confusing w. r. to what can or cannot be measured from SWIW tests.

Is the first sentence of Bel correct? and, if yes, is it useful?

Regarding *HEAd* no. 1 and no. 2 as a target parameter for SWIW tests, let us recollect: it is beyond doubt that in deep tight-rock reservoirs, in which most of the flow occurs in faults and large-scale fractures (but also in 'aquifer-type' systems like the one considered with fig. 5), and in which heat diffusivities exceed solute diffusivities by at least three orders of magnitude,

– heat spreads *transversally* faster (and farther) than longitudinally, and than solute tracers
– solute tracers spread *longitudinally* faster (and farther) than transversally, and than heat

(as also seen in fig. 2), which provides the foundation for predictability of thermal breakthrough from tracer tests. Further, it is beyond doubt that SWIW tracer tests are particularly suited for reducing the ambiguity of determination between AD and non-AD parameters (when natural flow is negligible compared to the applied forced-gradient flows during 'push' and 'pull' phases). The message from Table 1 is that SWIW tests *can* be used for determining fluid-rock interface densities around the testing well. The major question with all these valid principles is:

Does the reservoir-scale HEAd coincide with the test's push-scale HEAd? or: What 'push' volume would be necessary, in order to ensure a single-well push-pull test's representativity of reservoir scale, w. r. to HEAd?

From experiences so far, at least 5 significant deep-geothermal reservoir configurations can be named in Germany, for which the answer is: NO, single-well push-pull tests at scales feasible in practice cannot be representative of reservoir scale, w. r. to *HEAd*; the 'push' volume would in fact need to be as large as that of an inter-well test (for a geothermal well doublet). These examples will be discussed in separate papers; the present paper was purportedly kept independent of any site-related models.

Fortunately, the answer is YES for that type of reservoir that is nowadays regarded as most promising for Northern-Germany's deep-geothermal future: the one proposed, designed and analyzed by Jung and Sperber (2009), consisting of a sequence of hydraulically-induced, more or less vertical 'water-fracs' in deep-seated volcanics layers, all aligned along one more or less horizontal well, that are thereupon all penetrated by a properly-deviated second well; though not observing the requirement N>>1 (as in Table 1), its thermal breakthrough-controlling *HEAd* parameter will indeed enjoy highly-sensitive determinability from SWIW tracer tests. And the likely answer is “almost yes” for the geothermal well doublet at GroßSchönebeck (some 30 miles north from Berlin), involving a number of artificially-induced fractures in deep-seated sandstone and volcanics layers, intersecting a natural “parallel-fracture” system with a different prevailing orientation (as described by Blöcher et al., 2010).

SWIW TRACER TESTS AS A “RESERVOIR MONITORING TOOL”? WHAT ABOUT POROSITY CHANGES, W. R. TO WHICH SWIW TESTS WERE INSENSITIVE?

It is further believed that SWIW tests, repeatedly conducted during reservoir operation, are extremely valuable for monitoring purposes, for detecting changes of

– fracture number or spacing (fracture density or *HEAd* no. 2) induced, for instance, by cooling-induced 'thermal cracking',
– fracture aperture (or *HEAd* no. 1), whose change can be considered in the broader sense of pressure-dependent permeabilities,
– effective fracture aperture (i. e., porosity, w. r. to which, however, SWIW tests were supposed to be insensitive!) that may be induced hydrochemical and/or mechanical processes like precipitation/clogging etc.

It is the (re-)injection well(s) of a geothermal fluid (re-)circulation system, where most of such changes can be expected, because the injected fluid strongly differs from native reservoir fluids in temperature and chemistry (salinity, pH, gas content etc.); thus, repeatedly conducting tracer SWIW tests, at intervals during reservoir operation, would be particularly useful at geothermal (re-)injection wells.

At first sight, porosity changes that would occur within individual fractures cannot be seen by SWIW tracer tests, because porosity is a purely advective parameter, w. r. to which SWIW tests are insensitive. Indeed, we know from theory that SWIW tests are not fully insensitive w. r. to hydrodynamic dispersion (recall that weak dependency upon Peclet number in fig. 1-2 of Behrens et al. 2009), but w. r. to a purely advective parameter, like porosity or flow velocity, they should not exhibit any sensitivity (as was also seen by Pruess and Doughty 2010 in their numerical examples). However, this only holds in a homogeneous medium. The value of porosity determines the radial penetration distance into fractures, away from the borehole (higher porosity → smaller distance), for a given fluid slug volume ('push' volume in a SWIW test). When dealing with changes induced by cold- (and hydrochemically-altered-) fluid injection around a geothermal well, it is very likely that the change-driving gradient will rapidly decrease with radial distance away from the well. Thus, there will be strong change in the vicinity of the well, and less change farther away. The value of porosity will determine the length (radial distance) over which a particular SWIW test signal will be 'integrating' (higher porosity → smaller distance, i. e. a length interval containing more of 'total change'). Thus, by virtue of radial heterogeneity, SWIW tracer tests may also exhibit a dependency upon individual-fracture porosity, despite its being a purely advective parameter. Radially-decreasing profiles are always to be expected for processes induced by fluid injection (and especially by well stimulation treatments).

Complication (ambiguity) of interpretation may occur when all parameters are affected by coupled THMC processes at the same time:

– individual-fracture aperture (→ matrix diffusion intensity at low transversal scales),
– individual-fracture effective aperture (or porosity → radial penetration distance),
– fracture spacing (→ matrix diffusion intensity at large transversal scales),
– matrix porosity (→ matrix diffusion intensity at any scale).

In this case, it is useful to have some 'a priori' model (based on THMC process theory) telling what kind of changes are expected for each parameter, and how they will correlate with each other qualitatively, such as to reduce the number of degrees of freedom for

SWIW tracer test interpretation. Even if no formulas are available to relate between the parameters, prior knowledge of monotonicity relationships can help to reduce ambiguity; for instance, knowing that cold-water injection can only lead to an increase of fracture density and to a reduction of individual-fracture porosity (because of precipitation processes), while leaving individual-fracture aperture unaffected (but this sounds too simple to be true). Here, the geomechanical concepts of McDermott and Kolditz (2006), McDermott et al. (2007) could provide valuable help. And, again, *dual-scale* and *dual-tracer* tests can always help – but they are already necessary even for characterizing a static system. Whenever changes of more than two parameters occur simultaneously, the analysis will be non-trivial, with parameter determination ambiguity more likely to increase than to decrease. Tracer SWIW tests as a “reservoir monitoring tool”? looks promising, but the “tool” is yet to be developed.

SOME RECOMMENDATIONS ABOUT SWIW TEST DESIGN

The geometry of a reservoir is rarely known in advance with ultimate certainty. Real-life reservoirs (as were more realistically described, for instance, by Tsang and Doughty 2003) do not consist of “a single-fracture in a infinite matrix”, nor of a “parallel-fracture system” with spatially uniform properties. Will a particular reservoir behave more like the former, more like the latter, or none of the two? In order not to miss relevant features (at least in the sense of Table 1), SWIW applications should be designed both as *dual-tracer* and as *dual-scale*:

(A) using solute tracer pairs with different diffusion and/or sorption coefficients enables to characterize fluid-rock interface densities at scales comparable to that of hydrodynamic dispersion;

(B) using solutes and heat as a tracer, effective interface densities can be quantified at different scales *across* the flow direction;

(C) using either comparable tracers with different flushing ('push') volumes allows to characterize transport at different scales *along* the flow direction (sufficient 'pull' volume provided).

For multiple-fracture systems, when no estimate of fracture spacing a, and thus of the 'transversal' time scale $T[a]$ (cf. Table 1), is available in advance, the dimensioning of SWIW test sequences has to proceed heuristically. This is what renders the push- and pull-duration dimensioning for a SWIW test more complex, and less 'secure' than tracer-quantity and sampling-frequency dimensioning for inter-well tests.

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