

## TRACER PROPERTIES, AND TRACER TEST RESULTS – PART 3: MODIFICATION TO SHOOK'S FLOW-STORAGE DIAGRAM METHOD

Horst Behrens, Iulia Ghergut, Martin Sauter

University of Göttingen, Geoscience Center  
Goldschmidtstr. 3  
Göttingen, D-37077, Germany  
e-mail: iulia.ghergut@geo.uni-goettingen.de

### **ABSTRACT**

Shook (2003, 2005) proposed a method for deriving 'reservoir geometry' from tracer test results. His method answers a major endeavor in reservoir characterization, and is extremely beneficial to the analysis of reservoir flow fields. We propose an additional step to Shook's diagram construction; it reveals some reservoir features that were not easily visible from the original FSR diagram. The modified FSR can occupy both regions, below and above the identity-function diagonal; the inflexion point of the modified FSR marks a switch from dominance of kinetic exchange processes between im/mobile fluid to dominance of advective-dispersive processes.

#### Abbreviations:

BTC: breakthrough curve (of a tracer in a test);  
RT: residence time;  
RTD, MRT: RT distribution, mean RT;  
FSR: flow-storage repartition.

### **DERIVING FSR FROM TRACER TESTS**

Constructing a FSR diagram from a measured tracer BTC is equivalent to taking truncated zeroth-order temporal moment of the tracer's RTD (derived from its measured BTC by appropriate means, including large-time extrapolation), as a function of truncated first-order temporal moment, in an incremental manner (with increasing RT as an implicit coordinate), and normalizing the incremental zeroth- and first-order moments by their last values (total recovered tracer mass, and MRT, respectively).

It can be shown that for any conservative tracer, under the conditions of a well-behaved flow field (advective-dispersive, with more or less influence from kinetic exchange processes between mobile and immobile fluid zones), this procedure always yields a monotonous function with curvature less equal zero. The identity function (straight-line diagonal in Shook's FSR diagram) corresponds to a perfectly

homogeneous, dispersion-free flow field (Peclet number going to infinity). Thus, a real-world FSR should always plot entirely in the region above the identity-function diagonal.

In his original works, Shook (2003, 2005) deems the (incremental, or cumulative) zeroth-order moment as 'flow capacity', and the first-order moment as 'storage capacity', and he takes the FSR to characterize 'reservoir geometry'. This indeed corresponds to a major endeavor in analyzing reservoir flow fields, and the abstraction introduced by Shook (2003) is uniquely beneficial to the analysis.

### **MODIFICATION TO FSR DIAGRAM**

We find that plotting 'flow capacity' against *the ratio between* 'storage capacity' and 'flow capacity' (rather than plotting it against 'storage capacity') is able to reveal some details of reservoir structure that are not easily visible from the original FSR.

This modified FSR can occupy both regions, below and above the identity-function diagonal. In all cases, the inflexion point (second derivative going through zero) on the modified FSR indicates a switch from dominance of kinetic exchange processes between im/mobile fluid zones to dominance of advective-dispersive processes.

To illustrate the proposed modification, we consider a three-parameter model of reservoir transport. We assume macroscopic heterogeneity of mobile-zone flow field to be characterized by a sole dimensionless parameter (Peclet number  $Pe$  expressing the importance of advection against dispersion processes), and kinetic exchange processes between immobile and mobile fluid zones to be described by only two parameters: fracture density (or fluid-rock contact surface area per volume), measured by dimensionless parameter  $\sigma$ , and the ratio between bulk rock matrix and mobile-fluid volumes, deemed  $\beta$ , equaling  $(1-n)/n$  (with  $n$  denoting the bulk porosity due to fractures).

For this simplified model, there is a closed-form, three-parameter solution to the tracer transport equation, which can be used to calculate tracer BTCs (instead of using measured ones). We compute them from the closed-form solution until attaining at least 80% tracer mass recovery (which can rarely be obtained from real-world reservoir tests), and use first-order asymptotic approximation of late-time BTC for times beyond (when singularities under the closed-form solution integral become difficult to handle numerically). Proper normalization is implicit to the use of an exact solution (instead of a measured BTC), since total tracer mass and MRT acted as parameters in its physical-dimensional (before rescaling to dimensionless) form. Parameters  $\sigma$  and  $\beta$  influence the solution in a largely similar manner, but are not reducible to a single parameter.

### **Visibility of processes in modified FSR diagram**

We compare how the original FSR, and the modified FSR respond to changes in each one of the three model parameters while keeping the other two parameters unchanged.

#### ***Influence of fracture density (or fluid-rock contact surface area per volume)***

The non-monotonicity (in parameter space) of tracer response w. r. to fracture density (change of direction somewhere between  $\sigma \sim 0.01$  and  $\sigma \sim 0.1$ ) is apparent from all representations (fig. 1): from the tracer BTCs themselves, from the original FSR diagrams, and from the modified FSR diagrams; in the modified FSR diagrams, signals do separate better (they are more sensitive) w. r. to  $\sigma$ , but this is not the important point. The FSR corresponding to highest  $\sigma$  value of 10 (plotted in violet) looks almost identical to the FSR of a perfectly homogeneous flow field (no difference between fractures and matrix). Thus from the original FSR it would be impossible to tell the difference between a situation with negligible immobile-zone contributions, and a situation in which immobile-fluid zones take a dominant role. This difference is clearly revealed by the modified FSR.

To be noted,  $\sigma$  was defined as the quotient between the solute exchange rate coefficient, and the fluid turnover rate of the whole reservoir ( $1/\text{MRT}$ ). A value of 10 is not untypical of real-world reservoirs.

#### ***Influence of immobile fluid (rock matrix) amount***

In figure 2, a monotonous behavior (in parameter space) w. r. to the rock/fractures volume ratio is apparent from all representations: from the tracer BTCs themselves, from the original FSR diagrams, and from the modified FSR diagrams; in the modified FSRs, signals do separate better (they are more

sensitive) w. r. to  $\beta$ , but this is not the important point. The FSR corresponding to highest  $\beta$  value of 1000 (plotted in violet) looks almost identical to the FSR of a perfectly homogeneous, dispersion-free flow field. Thus from the original FSR it would be impossible to tell the difference between a situation with negligible immobile-fluid contributions, and a situation in which immobile-fluid zones take the dominant role. This difference is clearly revealed by the modified FSR.

To be noted, a value of  $\beta \sim 1000$  (porosity due to fractures  $\sim 0.1\%$ ) is not untypical for geothermal reservoirs in rock depths up to few kilometers; the case plotted in violet in figure 2 does relate to real-world reservoirs.

### ***Influence of reservoir flow-field heterogeneity***

As seen from Figure 3, the non-modified FSR largely displays all the features apparent from the modified FSR. Here, the modified FSR does not bring major visual advantages compared to the original FSR, however the repartitions corresponding to different Peclet number values are better separated in the modified version, than in the original version. The modified FSR also allows to better cope with the ambiguity between effects from flow-field dispersion and from non-advective processes (matrix diffusion, or kinetic exchange of solutes between fractures and rock matrix); their relative contributions can be appreciated from the position of the inflexion point.

### **FINAL REMARK**

We believe the proposed FSR modification is not just of academic interest, but has a direct physical significance. The *specific* storage, i. e. the quotient between (incremental or cumulated) storage capacity and (incremental or cumulated) flow capacity, or in other words 'RT per recovered mass', as plotted by increasing RT, is clearly more sensitive w. r. to parameters characterizing kinetic exchange processes between mobile and immobile fluid zones, and these processes are better discerned from mobile-zone flow-field dispersion in the modified FSR diagram, than in the original FSR diagram.

On the other hand, since heat transport is determined not by exchange between mobile and immobile fluid zones, but between mobile fluid and solid rock mass, processes of heat transport in the reservoir will not necessarily exhibit the same parameter influences as tracer (or fluid) RTDs do. Whereas a proper analysis of fluid (and solute) RTDs, and thus tracer tests are generally recognized as indispensable to geothermal reservoir characterization, there are several reasons not to rely on solute tracer tests for determining heat exchange areas (thermally-effective, as opposed to solute-transport-effective fracture densities). Some of

these reasons are thoroughly discussed, in the context of thermal breakthrough prediction, by Kocabas and Horne (1987, 1990), and further discrepancies between heat and solute transport are demonstrated by Graf (2005) in the context of analyzing thermo-haline flow in fracture networks.

Moreover, considering the several orders of magnitude difference between solute and thermal diffusivities, solutes will tend to yield distorted values for both  $\sigma$  (fracture density) and  $\beta$  (rock/fractures volume ratio), i. e., typically too large  $\sigma$  and too low  $\beta$  values, which is opposite to how thermal breakthrough in geothermal reservoirs depends on these two parameters. Thus, whereas FSR diagrams (either in the original or in the modified version) are very useful for characterizing reservoir structures, caution is indicated before deriving any thermal lifetime expectations from them.

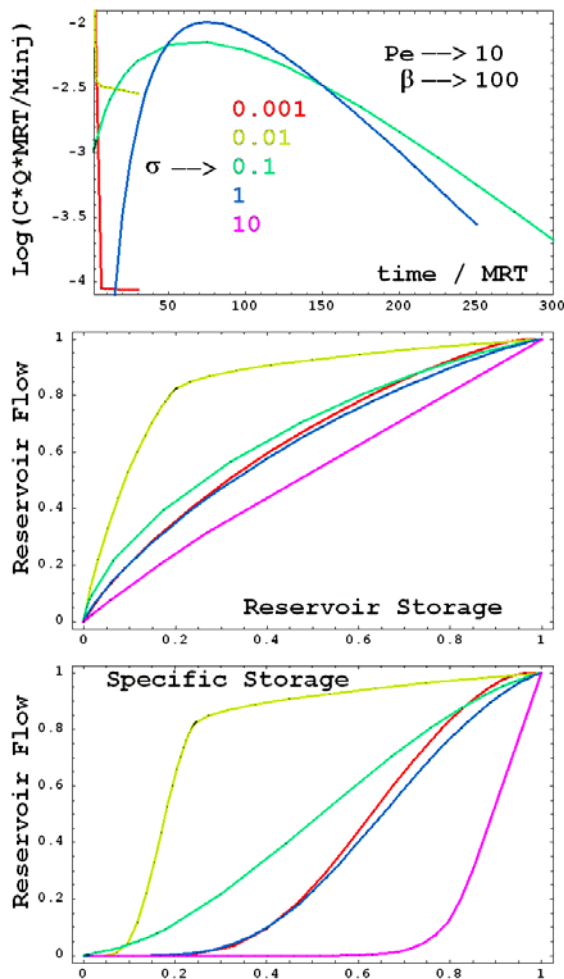


Figure 1: Influence of fracture density (or fluid-rock contact surface area per vol.) on tracer BTCs, on original FSRs, and on modified FSRs. Parameter values were chosen from a region exhibiting non-monotonous behavior in parameter space.

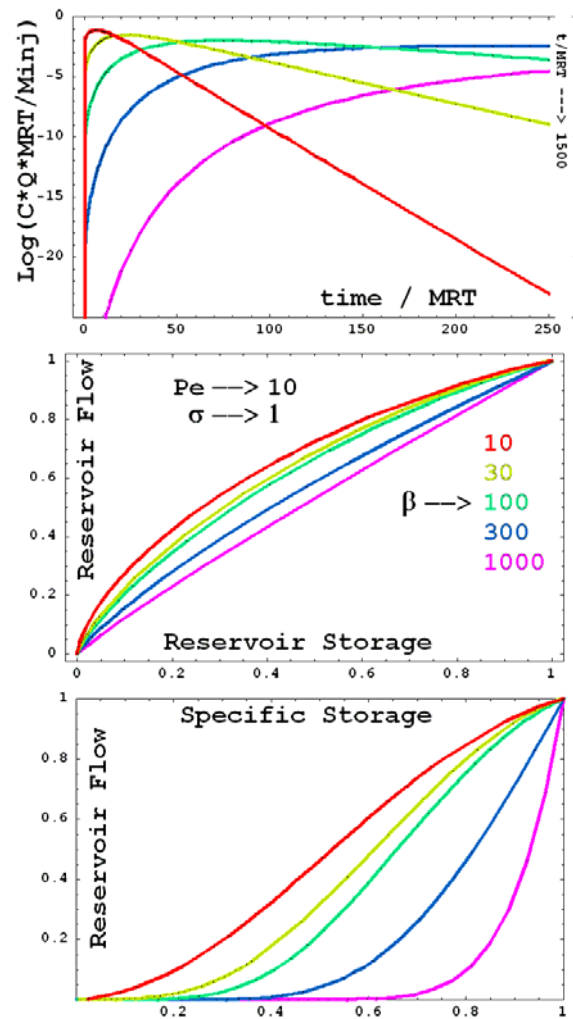


Figure 2: Influence of rock / fractures vol. ratio on tracer BTCs, on original FSRs, and on modified FSRs. Parameter values were chosen from a region exhibiting monotonous behavior in parameter space.

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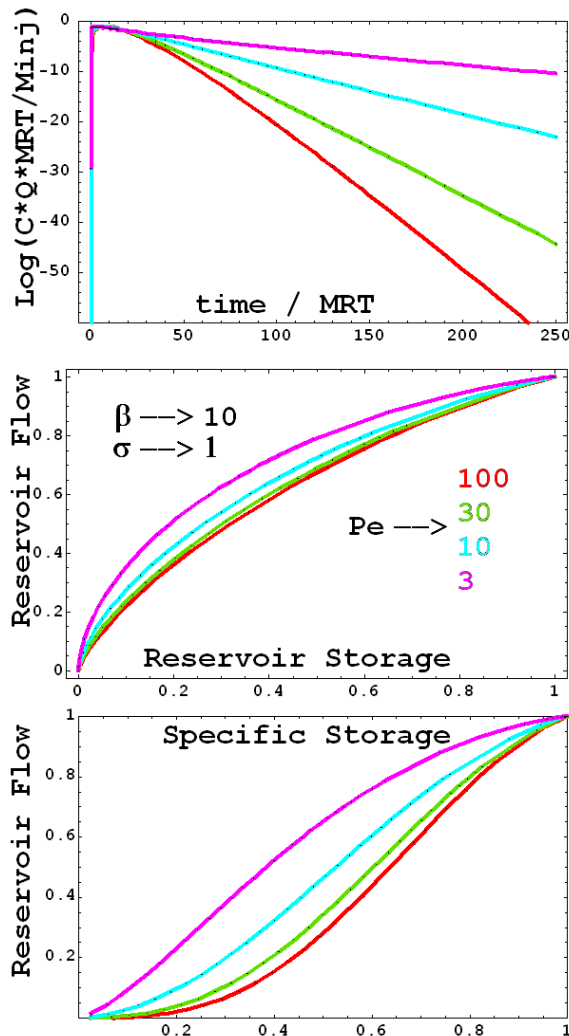


Figure 3: Influence of reservoir flow-field heterogeneity (measured by Peclet number) on tracer BTCs, on original FSRs, and on modified FSRs. W.r. to the Peclet number, behavior remains monotonous throughout.

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