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Petrothermal and aquifer-based EGS in the Northern-German Sedimentary Basin, investigated by conservative tracers during single-well injection-flowback and production tests

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ABSTRACT

The use of artificial tracers in single-well tests in conjunction with EGS-related fracturing or stimulation of sedimentary and crystalline formations in the N-German Basin is evaluated. Conservative-tracer signal analysis is suggested as a tool to quantify individual fracture contributions to multiple-fracture discharge, and illustrated with preliminary data from the Groß Schönebeck site. The proposed approach helps to avoid investing in unnecessary wellbore completion-integrated devices used for inflow profiling, especially when the productivity of the target formation is uncertain. Conservative-tracer signal analysis is further applied to estimate the thermal-lifetime contributions from the petrothermal and the aquifer components of a hybrid EGS developed in sedimentary formations at the Horstberg site. Long-term observation of tracer signals is recommended for both sites.

1. Introduction

Tracer methods are important for measuring transport-related properties of subsurface flow systems. In the context of geothermal reservoir development, characterization and monitoring, tracer tests are used to determine a number of parameters governing reservoir productivity and commercial lifetime, e.g., inter-well connectivity, fluid residence time distribution, heat exchange area, and fluid-rock interface parameters controlling corrosion/scaling processes.

Whereas the use of tracer tests (TT) for assessing inter-well connectivity and fluid residence times is relatively well established, the use of single-well (SW) tracer tests for geothermal reservoir characterization still needs to resolve some issues (Tomich et al., 1973; Schroth et al., 2001; Ghergut et al., 2014a). These are primarily related to fluid flow reversal, common to injection-flowback or 'push–pull' tests, since this invalidates a direct relation between fluid residence time and reservoir 'size', and induces ambiguity between advection–dispersion and equilibrium-exchange effects when interpreting tracer data.

Originally, the work described here was driven by the idea of a tracer-based, or tracer-assisted estimation of reservoir parameters for the Groß Schönebeck and Horstberg geothermal research sites in the Northern-German Sedimentary Basin (NGB) where various HDR and EGS concepts were being tested. The parameters being sought were: (i) the thermal lifetime for various reservoir design schemes, including a SW system, and (ii) fracture-resolved discharge contributions (inflow profiling) from multiple fractures during SW flowback and production. Regarding (i), one may recall the thermal lifetime of a geothermal system, typically a geothermal well doublet, is defined (Pruess and Bodvarsson, 1984; Shook, 2001) as the duration until the produced-fluid temperature declines below a certain threshold, usually defined in terms of the ratio $p = (T_{\mathrm{outflow}} - T_{\mathrm{inflow}})/(T_{\mathrm{initial\ undisturbed\ reservoir}} - T_{\mathrm{inflow}})$, a common choice being $p = 75\%$. Regarding (ii), the terms 'flowback' and 'production' are not used synonymously; 'flowback' or 'puff' refers to fluid flowing back from the well, without a production pump, by virtue of sufficient pressure buildup during the prior injection

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Nomenclature for Section 2

a subscript referring to the horizontal 'aquifer' layer (shown as a cylinder in Fig. 1)
$C_{a'}$, $C_{m'}$ ratio between heat capacity of 'aquifer' or matrix bulk rock and heat capacity of water, at the reservoir operation temperature
D_m heat diffusivity in tight matrix adjacent to vertical fracture
FC 'frac circulation' experiment conducted at Horstberg
f subscript referring to the vertical fracture (shown as a dark-gray plate in Fig. 1)
H_a thickness of 'aquifer' layer (cf. Fig. 1)
H_f vertical distance between frac initiation well-screen and 'aquifer' layer (cf. Fig. 1)
InvErfc complementary inverse error function
L_f fracture half-length (cf. Fig. 1)
M_{inj} total quantity (mass, or activity) of artificial tracer injected at Horstberg as a short pulse during FC experiment
m subscript referring to rock matrix (not shown in Fig. 1) adjacent to the vertical fracture
p normalized relative temperature decrease level during geothermal reservoir operation: $p = (T_{outflow} - T_{inflow})/(T_{initial\ undisturbed\ reservoir} - T_{inflow})$ for defining thermal lifetime, a common choice is $p = 75\%$
Q flow rate (outflow rate at upper well-screen in the 'aquifer' layer)
R fraction of fracture flow that reaches the upper well-screen in the 'aquifer' layer (cf. Fig. 1)
$T_{thermal}$, thermal lifetime, and
T_{tracer} advective travel time of conservative tracer in the Horstberg FC scheme
w_f aperture of vertical fracture
X_a horizontal distance between the vertical fracture and the upper well-screen in the 'aquifer' layer(cf. Fig. 1); also referred to as '*aquifer bridge length*'
Φ_a transport-effective porosity of 'aquifer' layer

Nomenclature for Section 3

$c_{k,j}(t)$ the measured signal (flux-averaged concentration c as a function of time t), within overall backflow or production, of a tracer "j" that had been injected at fracture "k", where it had been followed by a chaser fluid volume $VOL_{IN;k,j}$.
$C_{k,j}(u)$ measured tracer signals (indexed similarly to $c_{k,j}$) as a function of normalized production volume u; i.e., a dimensionless-argument version of measured tracer signals $c_{k,j}(t)$, defined by the function transform $C_{k,j}(u) = c_{k,j}(t)$ with $t \to u = \int_0^t Q_{out;\Sigma}(\tau)\,d\tau/VOL_{IN;k,j}$
$G(u)$ 'SW pull-type' function (cf. Figs. 8 and 9)
j index for tracer slug
k index for artificial fracture (in a multiple-fracture system)
$M_{IN;k,j}$ total quantity of artificial tracer "j" injected as a short pulse at M_{IN} fracture "k" at Groß Schönebeck production well GrSk-4

$Pe_{k,j}$ Peclet number of reservoir matrix adjacent to artificial fracture, defined as the ratio between the advective travel radius reached into the adjacent rock matrix by tracer "j" during injection at fracture "k", and the longitudinal dispersivity of the rock matrix; different tracers injected consecutively at the same fracture "k" reach different radii and may therefore have different Peclet number values
$Q_{out;\Sigma}$ flow rate of overall flowback or production (from all fractures simultaneously) $Q_{out;\Sigma}(t)$ vary with time
t time variable (since the beginning of flowback or production); t_n times of discrete tracer signal sampling
$u(t)$ ratio between $VOL_{out}(t)$ and VOL_{IN} at a single fracture;
u dimensionless argument of 'SW pull-type' function G;
$u_{k,j}(t)$ dimensionless argument of transformed tracer signals $C_{k,j}(u)$, defined by $u_{k,j}(t) = \int_0^t Q_{out;\Sigma}(\tau)\,d\tau/VOL_{IN;k,j}$; all instances being generically referred to as 'normalized (cumulative) production volume'
$VOL_{IN;k,j}$ chaser fluid volume injected after tracer "j" at fracture "k" (indices sometimes omitted), i.e. the final 'push' volume (not a time-varying quantity, but a fixed parameter for each completed tracer slug injection at each fracture)
$VOL_{out}(t)$ cumulative fluid volume produced from a single fracture (or from fracture "k" in a multiple-fracture context), increasing monotonously with time t (Section 3.1, Fig. 8; indices and variables being omitted in figure axes' labels)
$VOL_{out;\Sigma}(t)$ cumulative fluid volume produced from all fractures simultaneously, increasing monotonously with time t (Sections 3.2 and 3.3, Figs. 9 and 12; indices and variables being omitted in figure axes' labels)
x_k relative contribution of fracture "k" to the overall outflow or production, i.e. the ratio between the fluid outflow or production flux originating from fracture "k" and the total outflow or production rate when producing from all fractures simultaneously

stage; 'production' or 'extraction' or 'withdrawal' refer to fluid produced from the well by means of a production pump (Karmakar et al., this issue).

At Horstberg, an artificial TT was conducted in a non-planar reservoir structure composed of a single large, artificially induced (man-made) fracture in 'less permeable' sandstone/claystone layers, and of a 'more permeable' sandstone layer, accessed by a single deviated well via casing and tube perforations, respectively (Fig. 1). At Groß Schönebeck, several artificial TT were conducted in a largely parallel flow field established across artificially induced (water and gel-proppant) fractures in crystalline and sedimentary layers.

This paper, however, is not meant to provide detailed case studies or the final evaluation of TT conducted at these two sites, but rather to explore the scope and limitations of a SWTT-based characterization of newly-created EGS, relying on tracers that are injected during fracturing operations. This is particularly relevant since most EGS projects would rely on extensive SW experiments to start with, and SW injection-backflow configurations are known to invalidate the direct relationship between tracer residence times