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Short-term fluid, heat, and solute transport in deep 'georeservoirs' likely to become 'EGS': some challenges to ICDP hydrogeologists who might like using artificial tracers

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During Fall 2013, the *Integrated Continental Scientific Drilling Programme* (ICDP) set out to define a new *Science Plan* that shall replace its past-decade version (Harms et al., eds., 2005) for the decade to come. Geoscientists worldwide were welcomed to suggest new imaging and exploration methods, new sites to drill, new challenges to be addressed with a view at new 'societal needs' (Harms and Wiersberg 2013).

Save for two outstanding exceptions at the Mutnovsky volcano in Russia and the KTB site in Germany, the use of artificial tracers, especially within forced-gradient tests, has not been on the agenda of most ICDP projects so far (other than for purposes of monitoring microbial contamination in conjunction with drilling activities); deep-reservoir exploration and characterization efforts were restrained to non–fluid-invasive techniques on the one hand, and to sites featuring some unique earth-historical traits, on the other hand. Surely, this was not for lack of interest in quantifying fluid transport in the deep subsurface in general, but mainly due to operational, technical, and financial constraints (lack of resources / lack of opportunity for significant fluid turnover within the target, deep-seated georeservoirs, and fear of persistent, large-scale georeservoir contamination by non-pristine fluids). – This is likely to change during the forthcoming decade(s), owing to worldwide increased interest in some 'georesource' or 'georeservoir' play types (Moeck 2013) that have not been in the ICDP focus so far, including non-volcanogenic geothermal, and allowing for man-made design and intervention into how those 'georesources' or 'georeservoirs' shall work for us. Among the latter, petrothermal systems (Jung 2013, Huenges and Jung 2004) acquire growing recognition as a promising (and maybe unique) option for baseload energy supply in vast areas of the Northern hemisphere, at very low emissions and (in the long run) moderate costs. With petrothermal coming into play, forced-gradient turnover of significant fluid amounts shall be on the agenda, and with it also a more comprehensive use of artificial tracers, for far more ambitious tasks than just the monitoring of drilling-related contamination. Since any ICDP project is likely to start (and mostly also end) with not more than ***one*** deep well, ***single-well*** forced-gradient test experience gained within the non-ICDP areas of hydrocarbon and geothermal exploration and engineering seem predestined for a specific knowledge transfer.

Single-well 'push-then-pull' (SW) tracer methods appear as attractive for a number of reasons: less uncertainty of design and dimensioning, and lower tracer quantities required, than for inter-well (IW) tests; stronger tracer signals, enabling easier and cheaper metering, and shorter metering duration required, reaching higher tracer mass recovery, than in IW tests; last not least: no need for a second well! However, SW tracer signal inversion faces a major issue: the 'push-then-pull' design weakens the correlation between tracer residence time distribution (RTD) and fluid transport parameters, inducing insensitivity or ambiguity of tracer signal inversion against some of those georeservoir parameters that are supposed to be the target of tracer tests *par excellence*: pore velocity, transport-effective porosity, fracture aperture and spacing or density (where applicable), fluid/solid or fluid/fluid phase interface density. Hydraulic and geophysical methods cannot measure the transport-effective values of such parameters, because the signals they detect correlate neither with fluid motion, nor with material fluxes through (fluid-rock, or fluid-fluid) phase interfaces. Typically, pressure signals obtained in hydraulic tests do not enable to distinguish between geological formations with equal permeability, but different transport-effective porosity, nor between formations with equal permeability, equal transport-effective porosity, but different fluid-rock interface area. The ability to measure this latter parameter is crucial to lifetime predictability for geothermal, gas storage, waste disposal, or hydrocarbon reservoirs (especially in advanced depletion stages).

From IW tracer signals, fluid RTD can be derived, whose statistical moments relate to major hydrogeological properties of target georeservoirs. By contrast, SW tests can be used to quantify processes other than advection-

dispersion: typically, the exchange of some extensive quantity (mass, energy) between fluid and solid/fluid phases by matrix diffusion or sorption/partitioning, whose rate or amount depends on the phase saturation and/or interface area density. Flow-field reversal during the 'pull' stage of a SW test is supposed to largely compensate the effects of flow path heterogeneity, and to enhance the effects of tracer exchange processes at phase interfaces. However, it always destroys the equivalence between fluid RT and reservoir size; transport-effective porosities, closely relating to fluid RT, can only be measured reliably by means of conservative-tracer IW tests. The SW inability to determine porosity also (indirectly) impedes the SW-based ability to determine those complementary, non-advective parameters: increased sensitivity comes along with increased ambiguity.

Reactive tracers can aid overcoming some of the limitations to parameter determinability associated with the SW design. Specific use of reactive tracers has first been made by Tomich et al. (1973), for a SW-based measurement of residual-oil saturation in (depleted) oil reservoirs; later on by Robinson (1985), for tracking temperature fronts in laboratory-scale geothermal-reservoir IW-test 'analogues'; more recently by Schaffer et al. (2013), for tracking brine-(sc)CO_2 interfaces during CO_2 injection within CCS research projects.

The paper discusses some lessons derived from a twelve-year experience using artificial tracers in various IW and SW field tests in Germany, aimed at deep-georeservoir characterization and/or short- to mid-term process monitoring during reservoir operation:

– if those tests have been successful to a certain extent, it was primarily owing to ascertainedly *conservative* tracer transport behavior;

– if those tests have been of limited success, it was because of lack of *reactive* tracer species with well-defined, and reasonable properties (reasonable means: sensitive to 'something', but not to 'everything' that may 'happen' within the target georeservoir).

If the artificial-tracer–based quantification of deep-georeservoir hydrogeology and of induced (short- to mid-term) transport processes therein is to become a task for some future ICDP projects, they will need to effectively address this dilemma. Further, if EGS, and especially the petrothermal type shall be on the agenda, then SW tests will be 'unavoidable'. Finally, if the most is to be made out of a SW test, then *tailored reactive* tracer pairs (Tomich et al. 1973, Ghergut et al. 2013) are a must: not just reactive, not just retarded, but: conservative alongside with reactive, and with contrasting retardation behavior between product and reactant.

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