

Design and development of nanoparticle tracers for geothermal reservoir exploration

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Successful and sustainable geothermal resource management depends on understanding subsurface reservoir characteristics, including geometry and fluid flow paths. Tracer techniques such as molecular dyes (e.g., uranine, eosin) are state-of-the-art for reservoir exploration. However, the variety of applicable tracers for geothermal reservoir exploration is restricted by limitations such as adsorption, retention, and degradation. These drawbacks can result in variability of transport properties and thus limit comparability. By merging nanotechnology with geoscience, we present an innovative tracer concept and demonstrate its applicability at the laboratory scale. Our concept of tracer multiplicity bears significant advantages for geothermal and hydrogeological exploration, for example by offering a greater variety of distinguishable tracers with designable transport behavior by encapsulating fluorescent dyes within mesoporous silica-based nanoparticle carriers. This approach improves the stability and transport uniformity of the tracers, which is shown in flow-through experiments. Additionally, the nanoparticle tracers show enhanced thermal resistance, reduced sorption, and greater modularity, making multi-tracer tests more reliable, accurate, and easier to interpret. A further advantage of nanoparticles is their adaptability. Unlike molecules, nanoparticles allow for surface modifications, i.e., tailoring the particles to specific geological conditions (e.g., mineralogy, fluid composition, flow dynamics). To improve the nanoparticle design process, we predict interactions with different reservoir minerals using the (extended) Derjaguin-Landau-Verwey-Overbeek ((X)DLVO) theory to assess dispersion stability, sorption tendency, and deposition behavior of nanoparticles within porous media. Based on DLVO and filtration theory, we show that nanoparticles should ideally be non-metallic and possess a strong negative zeta potential to minimize the risk of deposition and particle aggregation. By applying the XDLVO theory, we confirm the effectiveness of surface modification, which can lower the strength of the attractive forces by the formation of a steric barrier, thereby increasing stability and lowering deposition. In summary, integrating nanoscience into geoscience has the potential to enable the next steps toward smart, functional, and designable nanoparticle-based tracing technologies for holistic geo-reservoir exploration.