Modeling Subsurface Flow and Transport: From Analytical Solutions to Field CO_2 Storage Imaging

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Abstract: Subsurface flow and transport are complicated either by the coupling between fractures and the rock matrix (F-M) and between aquifers and aquitards (A-A) in multilayered fractured reservoirs or by channelized two-phase flow and capillary/gravity equilibration in highly heterogeneous reservoirs. This talk includes two parts. The first part is focused on analytical solutions and physical conceptions of single-phase flow and solute/heat transport. Analytical solutions with F-M and A-A coupling can be unified by $G^*(x,s) = B^*(s)G_0^*\{x, s[1 + \vartheta g^*(s)]\}$, where $G_0^*(x,s)$ are the global transfer functions for advective-dispersive or diffusive transport in a single continuum, $g^*(s)$ is the unified-form memory function for F-M/A-A exchange, ϑ and $B^*(s)$ are the F-M/A-A scaling factor and the inlet boundary condition function, and x and s are the space and Laplace variable. We first show solution examples with four key $G_0^*\{x,s\}$: the Theis solution for 1-D radial flow, the Lapidus-Amundson solution for advective-dispersive transport in 1-D linear flow, the Tang-Babu solutions for advection-dispersion in 1-D radial flow, and the Hemker-Maas solutions for flow in multilayered systems. We then point out the limitations of first-order dual-porosity and mobile-immobile models that have long perplexed our community. Finally, we discuss how the unified solutions are applicable to flow and transport in heterogeneous reservoirs, with $G_0^*\{x,s\}$ representing numerical solutions in the Laplace domain.

In the second part, we present a consistent picture of dynamic channeling, invasion, lateral spreading, and breakthrough (CISB) of supercritical CO_2 in the hierarchical fluvial reservoir at Cranfield, Mississippi. The dynamic CISB with multiscale CO_2-flow channels were imaged by complementary hydrological-geophysical monitoring techniques during 221-day drainage with injection rate doubling twice and 81-day imbibition: (1) *small-scale CO_2-flow channels* in the crosswell section logged at the wells and imaged by daily electrical resistance tomography (ERT) and time-lapse crosswell seismic surveys, (2) *intermediate-scale CO_2-flow channels* normal to the crosswell section imaged by ERT during late-time drainage, and (3) a *large-scale, sinuous fluvial CO_2-flow channel* imaged by repeat surface seismic survey at the end of the imbibition. The fluvial sandstone channel sinuously bypasses but is connected, through the intermediate-scale sandstone channels, with the crosswell section in a point bar, leading to a complicated flow-channel network. The data-revealed multiscale flow-channel network enables us to consistently interpret the reversal of traveltime to two monitoring wells in three tracer tests. This interpretation of the CISB and flow-channel network will allow thorough modeling and data inversion to bridge their gaps with site-specific monitoring in the CO_2 storage system.