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Finding the Continuum Scale in Highly Heterogeneous Rocks: Example of a Large Touching Vug Carbonate

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Abstract
Many of the world's oil fields and aquifers are found in carbonate strata. Some of these formations contain vugs or cavities several centimeters in size. Flow of fluids through such rocks depends strongly upon the spatial distribution and connectivity of the vugs. Enhanced oil recovery processes such as enriched gas drives and groundwater remediation efforts like soil venting operations depend on the amount of hydrodynamic dispersion of such rocks. Selecting a representative scale to measure permeability and dispersivity in such rocks can be crucial because the connected vug lengths can be longer than typical core diameters.

Large touching vug (centimeter-scale), Cretaceous carbonate rocks from an exposed rudist (caprinid) reef buildup at the Pipe Creek Outcrop in Central Texas were studied at three different scales. Single-phase airflow and gas-tracer experiments were conducted on 2.5 in. diameter by 5 in. long cores (core-scale) and 5- to 10-ft-radius well tests (field-scale). Zhang *et al*. (2005) studied a 10 in. diameter by 14 in. high sample (bench-scale). Vertical permeability in the bench-scale varied from 100 darcies to 10 md and in the core-scale averaged 2.5 darcies. The field-scale permeability was estimated to be 500 md from steady state airflow and pressure transient tests.

In the bench and core scales a connected path of vugs dominates flow and tracer concentration breakthrough profile. Tracer transport showed immediate breakthrough times and a long tail in the tracer concentrations characterized by multiple plateaus in concentrations. Neither flow nor tracer transport can be explained at these scales by the standard continuum equations (Darcy's law or 1D convection dispersion equation). However, interpreting field-scale measurements with standard continuum equations suggested that a strongly connected path of vugs did not extend past a few feet. In particular, the tracer experiment in the field scale can be modeled accurately using an equivalent homogeneous porous medium with a dispersivity of 0.5 ft. In our measurements, permeability decreased with scale, while vug connectivity and multi-scale effects associated with vug connectivity decreased with increasing scale. We concluded that approximately 5 ft could be considered the representative scale for the large-touching-vug carbonate rocks at the Pipe Creek Outcrop.

Introduction
Carbonate strata may contain vugs or cavities several centimeters in size. A vug can be defined as any pore that is significantly larger than a grain or inside of a grain. This definition includes moldic pores and intra-grain micro porosity. Vugs are commonly present as leached grains, fossil chambers, fractures, and large irregular cavities. Vuggy pore space can be divided into separate-vugs and touching-vugs, depending on vug interconnection. Separate vugs are connected only through interparticle pore networks and do not contribute to permeability. Touching vugs are independent of rock-fabric and form an interconnected pore system. Cavernous, breccia, fracture, and solution-enlarged fracture pore types are examples of touching-vug systems. Touching vugs have multiple origins and have little conformance to depositional models. There is no universal method to characterize petrophysical properties of touching-vug reservoirs (Lucia 1999).

Lucia (1999) classified touching-vug systems into two groups. The first includes non-tectonic fractures, karsts, caverns, and breccia. Continuum models like single and double continuum or multiple-interacting continua, and discrete fracture models have been suggested for the first group of touching-vug pore types. Another class of continuum models based on stochastic frameworks such as random walk, fractal, and percolation concepts have been implemented (Berkowitz 2002). The second group consists of interconnected molds that are more likely associated with selective dissolution of fossil fragments or voids within or between fossils that were never filled with sediment. Modeling flow and transport behavior in such systems is

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