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The origin of anomalous transport in porous media - is it possible to make a priori predictions?

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Despite the range of significant applications of flow and solute transport in porous rock, including contaminant migration in subsurface hydrology, geological storage of carbon-dioxide and tracer studies and miscible displacement in oil recovery, even the qualitative behavior in the subsurface is uncertain. The non-Fickian nature of dispersive processes in heterogeneous porous media has been demonstrated experimentally from pore to field scales. However, the exact relationship between structure, velocity field and transport has not been fully understood.

Advances in X ray imaging techniques made it possible to accurately describe structure of the pore space, helping predict flow and anomalous transport behaviour using direct simulation. This is demonstrated by simulating solute transport through 3D images of rock samples, with resolutions of a few microns, representing geological media of increasing pore-scale complexity: a sandpack, a sandstone, and a carbonate. A novel methodology is developed that predicts solute transport at the pore scale by using probability density functions of displacement (propagators) and probability density function of transit time between the image voxels, and relates it to probability density function of normalized local velocity. A key advantage is that full information on velocity and solute concentration is retained in the models. The methodology includes solving for Stokes flow by Open Foam, solving for advective transport by the novel streamline simulation method, and superimposing diffusive transport diffusion by the random walk method.

It is shown how computed propagators for beadpack, sandstone and carbonate depend on the spread in the velocity distribution. A narrow velocity distribution in the beadpack leads to the least anomalous behaviour where the propagators rapidly become Gaussian; the wider velocity distribution in the sandstone gives rise to a small immobile concentration peak, and a large secondary mobile peak moving at approximately the average flow speed; in the carbonate with the widest velocity distribution the stagnant concentration peak is persistent, while the emergence of a smaller secondary mobile peak is observed, leading to a highly anomalous behavior. This defines different generic nature of non-Fickian transport in the three media and quantifies the effect of pore structure on transport. Moreover, the propagators obtained by the model are in a very good agreement with the propagators measured on beadpack, Bentheimer sandstone and Portland carbonate cores in nuclear magnetic resonance experiments. These findings demonstrate that it is possible to make a priori predictions of anomalous transport in porous media.

The importance of these findings for transport in complex carbonate rock micro-CT images is discussed, classifying them in terms of degree of anomalous transport that can have an impact at the field scale. Extensions to reactive transport will be discussed.