Final Report
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Transport and Clogging of Particulate Flow in Fracture Systems
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Abstract:

The aim of the project is to understand the effects of confinement in narrow rough-walled fractures on the transport behavior of fluids and suspended particles in subsurface hydrocarbon reservoirs. A key motivation for the study is that such fracture systems provide the highest throughput in oil and gas extraction and have been the focus of recent industrial activity. The scientific challenge is to understand how the confined geometry alters transport phenomena, and in particular its influence on (diagnostic) tracer transport and the effects of flow channeling and clogging on fluid motion. An important complicating feature of geological fractures is the self-affine fractal nature of their surface roughness, leading to irregular but correlated fluid and particle motion. The key technique used is computer simulation, augmented by analytical calculations and collaboration with outside experimental colleagues when possible. The principal topics studied were fluid permeability, tracer dispersion, flow channeling and anisotropy, particle transport in narrow channels and particle trapping in tight fractures.

Summary:

All of the research results were published in the open scientific literature, and may be conveniently summarized by the following list of publications and their abstracts.

- Permeability anisotropy induced by the shear displacement of rough fracture walls
  Harald Auradou, German Drazer, Jean Pierre Hulin and Joel Koplik
  Water Resources Research **41**, W09423 (2005)
  The permeability anisotropy that results from a shear displacement equation image between the complementary self-affine walls of a rough fracture is investigated. Experiments in which a dyed fluid radially injected into a transparent fracture displaces a transparent one are presented. A clear anisotropy is observed in the presence of shear displacements and allows us to estimate the ratio of the permeabilities for flows parallel and perpendicular to equation image. A simple model which accounts for the development of channels perpendicular to equation image qualitatively explains these results and predicts a permeability decreasing (increasing) linearly with the variance of the aperture field for flow parallel (perpendicular) to the shear displacement. These predictions are then compared to the results of numerical simulations performed using a lattice Boltzmann technique and to the anisotropies measured in displacement experiments.

- Flow channeling in a single fracture induced by shear displacement
  Harold Auradou, German Drazer, Alejandro Boschan, Jean-Pierre Hulin, Joel Koplik
  Geothermics **35**, 576 (2006)

The effect on the transport properties of a fracture of a shear displacement image between its complementary surfaces is investigated experimentally and numerically. The shear displacement image induces an anisotropy of the fracture aperture field with a correlation length scaling of image, which is significantly larger in the direction perpendicular to image. This reflects the presence of long fluid flow channels perpendicular to the shear displacement, resulting in a higher effective permeability in that direction. Such channels will have a strong influence on the transport characteristics of a fracture, such as, for instance, its thermal exchange area, crucial for geothermal applications. Miscible displacement fronts in shear-displaced fractures obtained experimentally display a self-affine geometry with a characteristic exponent directly related to that of the fracture surfaces. We present a simple model, based on the channeling of the aperture field, which reproduces the front geometry when the mean flow is parallel to the channels created by the shear displacement.

- Hydrodynamic interaction of two particles in confined linear shear flow at finite Reynolds number
  Yiguang Yan, Jeffrey F. Morris, Joel Koplik
  Physics of Fluids **19**, 113305 (2007)
  We discuss the hydrodynamic interactions of two solid bodies placed in linear shear flow between parallel plane walls in a periodic geometry at finite Reynolds number. The computations are based on the lattice Boltzmann method for particulate flow, validated here by comparison to previous results for a single particle. Most of our results pertain to cylinders in two dimensions but some examples are given for spheres in three dimensions. Either one mobile and one fixed particle or else two mobile particles are studied. The motion of a mobile particle is qualitatively similar in both cases at early times, exhibiting either trajectory reversal or bypass, depending upon the initial vector separation of the pair. At longer times, if a mobile particle does not approach a periodic image of the second, its trajectory tends to a stable limit point on the symmetry axis. The effect of interactions with periodic images is to produce nonconstant asymptotic long-time trajectories. For one free particle interacting with a fixed second particle within the unit cell, the free particle may either move to a fixed point or take up a limit cycle. Pairs of mobile particles starting from symmetric initial conditions are shown to asymptotically reach either fixed points, or mirror image limit cycles within the unit cell, or to bypass one another (and periodic images) indefinitely on a streamwise periodic trajectory. The limit cycle possibility requires finite Reynolds number and arises as a consequence of streamwise periodicity when the system length is sufficiently short.

- Flow of power-law fluids in self-affine fracture channels
  Yiguang Yan and Joel Koplik
  Physical Review E **77**, 036315 (2008)
  The two-dimensional pressure driven flow of non-Newtonian power-law fluids in self-affine fracture channels at finite Reynolds number is calculated. The channels have constant mean aperture and two values =0.5 and 0.8 of the Hurst exponent are considered. The calculation is based on the lattice-Boltzmann method, using a different tecnique

to obtain a power-law variation in viscosity, and the behavior of shear-thinning, Newtonian, and shear-thickening liquids is compared. Local aspects of the flow fields, such as maximum velocity and pressure fluctuations, are studied, and the non-Newtonian fluids are compared to the (previously studied) Newtonian case. We find a scaling relation between permeability and mean aperture in the low Reynolds number regime, generalizing an earlier result for Newtonian fluids. As the Reynolds number increases, we observe the same sequence of transitions to nonlinearity found in intergranular porous media. Furthermore, the permeability results may be collapsed into a master curve of friction factor vs Reynolds number, using a scaling similar to that employed for power-law fluids in porous media.

- Transport and sedimentation of suspended particles in inertial pressure-driven flow
  Yiguang Yan, Joel Koplik
  Physics of Fluids **21**, 013301 (2009)
  The dynamics of flowing suspensions of spherical particles in a channel, including their sedimentation under gravity, is studied using lattice Boltzmann simulations. Spherical particles confined to a three-dimensional periodic channel of constant width are driven through it by an applied pressure gradient while gravity acts to deposit the particles on the bottom wall. The particle diameter is 1/10 the channel width and bulk concentrations varying from 0.13 to 0.34 are considered. The simulations cover a range of buoyancy and Reynolds numbers and include the effects of inertia. In the neutral buoyancy case, we observe concentration profiles peaked at the center of the channel, plus secondary peaks near the walls due to layering effects, and velocity profiles which become increasingly blunted as particle concentration rises. Gravity produces a three-layer system with clear fluid, flowing suspension, and dense sediment regions having parabolic, pluglike, and nearly stagnant velocity profiles, respectively. In most cases, the fluid and particle fluxes decrease and the clear fluid region width increase with gravitational forcing, although nonmonotonic behavior is observed in some cases.

- Suspension flow and sedimentation in self-affine fractures
  Tak Shing Lo, Joel Koplik
  Physics of Fluids **24**, 053303 (2012)
  The transport and gravitational sedimentation of a particulate suspension in fracture joints with self-affinely rough walls is studied by lattice Boltzmann numerical simulations. We consider either homogeneous or bidisperse distributions of non-Brownian spheres in a Newtonian fluid, driven through a fracture by a pressure gradient, and acted upon by gravity. Most results concern the case of open fractures, in which the two walls of the channel do not approach closely enough to block the flow. We present profiles of particle density and profiles of particle and fluid velocities, along with total flow rates and characterizations of the sediment, for three values of particle concentration and a range of buoyancy and Reynolds numbers, principally in the inertial regime. We systematically study the effects of increasing the pressure gradient and the strength of sedimentation and compare the results to those for channel bounded by flat surfaces. We find that both the flow rate and the average particle velocity for flows through an open fracture, when suitably normalized, depend only on the volume

fraction of the particles and the buoyancy number in the steady state regardless of the pressure drop, and observe interesting scaling laws in the large buoyancy number limit. We also investigate the possibility for correlations between the surface morphology of the sediment region and the geometry of the underlying fracture surface in the strong sedimentation limit, but no evidence for correlation is found.

- Channeling and stress during fluid and suspension flow in self-affine fractures
  Tak Shing Lo and Joel Koplik
  Physical Review E **89**, 023010 (2014)
  The flow of fluids and particulate suspensions in realistic models of geological fractures is investigated by lattice Boltzmann numerical simulations. The walls are synthetic self-affine fractal surfaces combined to produce a tight fracture, the fluid is a viscous Newtonian liquid, and the particles are rigid noncolloidal solid spheres. One focus is channeling phenomena, where we compare the fracture aperture, the preferred paths for fluid flow, and the preferred paths for suspended particles. The preferred paths are found to be somewhat similar for pure fluid and particulates and not immediately related to the fracture aperture map. We further investigate the (tensor) stress exerted on the fracture walls. Wall roughness tends to decrease stress by reducing the flow velocities adjacent to it, an effect enhanced by the presence of particulates. Last, we examine the stress probability distributions and their spatial correlation functions.