Fluid flow in fractured rocks

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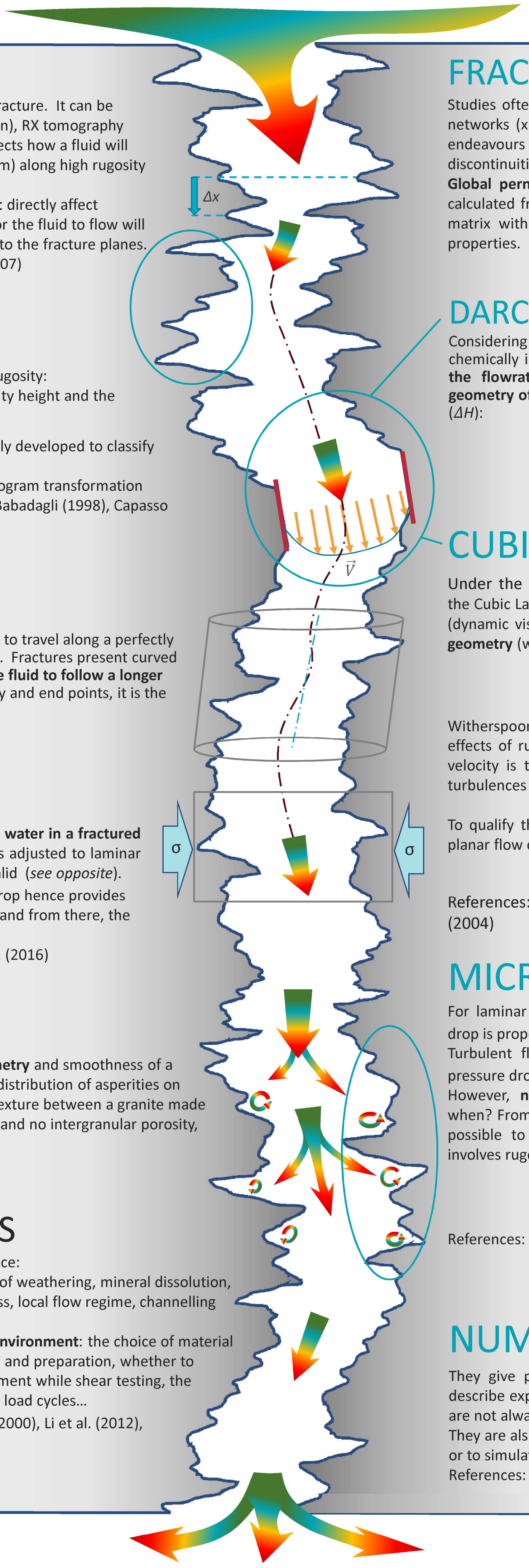
The understanding of fluid flow in fractured sedimentary rocks is essential in the modelling of **large fractured reservoir** (oil, water, gas), and even more relevant in medium scale applications where fractures significantly affect flowrate and local pressure regimes. Applications such as **underground pollution control, nuclear waste storage, hydro-fracturing, geothermal injection sites, hydrogeological water pumping…** call for the study of many key parameters that impact the fluid flow in fractured sedimentary rocks under known confinement stress: relative fracture apertures geometry, rugosity, tortuosity, asperities contact points, flow regimes (laminar towards locally turbulent)…

My thesis concerns the impact of different geometric configurations on fluid flow within rocks. It includes the evaluation of fracture surfaces disparity at the grain scale by use of laser profiles. Samples are submitted to flow tests under confinement in a triaxial press. Various textures, natural and artificial fracture surfaces are investigated.



FRACTURE GEOMETRY

The **mechanical aperture** is the physical opening of a fracture. It can be measured by laser profilometry (x10µm lateral precision), RX tomography (50-100µm) or image analysis softwares. It strongly affects how a fluid will flow within the fracture: for high apertures (0.35-1.2mm) along high rugosity surfaces, flow becomes non-laminar as low as Re=200.

Mismatched fracture surfaces and shear displacement directly affect permeability. The geometry of the volume available for the fluid to flow will also change depending on the confining stress applied to the fracture planes.

References: Rissler (1978), Xia et al. (2002), Legrain (2007)

ROUGHNESS

Three main methods are used to qualify rock surface rugosity:

- **Statistical evaluation** of R_a the mean average asperity height and the standard variation σ_a by use of their ratio $\frac{R_a}{\sigma_a}$
- The **Joint Roughness Coefficient** (JRC) experimentally developed to classify rough surfaces under ten standard profiles
- **Fractal mathematical models** such as the semi-variogram transformation

References: Nikuradse, Louis, Barton (1985), Develi & Babadagli (1998), Capasso (2000), Miao et al. (2015), Cao et al. (2016)

TORTUOSITY

In a natural porous rock or fracture, fluid won't be able to travel along a perfectly linear path unless the fracture's amplitude is very large. Fractures present curved surfaces, with shifts **and geometric changes forcing the fluid to follow a longer path than the straight line** between the fracture's entry and end points, it is the tortuosity:

$$\tau = \frac{l}{L} > 1$$

TRIAXIAL FLOW TEST

Permeability of a fracture can be assessed **by injecting water in a fractured rock sample under confinement**. Generally, flowrate is adjusted to laminar conditions so that the Cubic Law and Darcy's law are valid (*see opposite*).

Experimental measure of displacement and pressure drop hence provides means to calculate an equivalent hydraulic aperture e, and from there, the sample's permeability k.

References: Descamps & Tshibangu (2008) , Caulk et al. (2016)

ROCK SAMPLING

The fine texture of rocks affects the microscopic geometry and smoothness of a fracture's surface. It conditions the shape, height and distribution of asperities on the fracture. For example, there is a big difference in texture between a granite made of angular minerals with very smooth cleaved surfaces and no intergranular porosity, compared to a chalk made of aggregated micro fossils.

References: Caulk et al. (2016)

EXPERIMENTAL STUDIES

Coupled hydro-mechanical are complex to put in practice:

- Many **parameters are difficult to assess**: the effect of weathering, mineral dissolution, actual mechanical aperture of a fracture under stress, local flow regime, channelling effects, tortuosity.
- Other elements must be set **to recreate a specific environment**: the choice of material (concrete, aluminium, rocks), the samples type, size and preparation, whether to conduct the test with or without flow, the measurement while shear testing, the confinement levels, temperature, duration, pre-test load cycles…

References: Barton & Bandis (1983), Barton & Olsson (2000), Li et al. (2012), Zoorabadi et al. (2015), Hofman et al. (2016)

FRACTURE FLOW

Studies often focus on **small scale** samples (cm) to generalise to **large scale** networks (x100m). Numerical generalisation however remain delicate as it endeavours to represent fairly large scale disturbances, fracture systems, discontinuities and structural variations within the rock mass.

Global permeability models use an homogeneous equivalent permeability calculated from either a representative elementary volume, an impermeable matrix with fracture permeability only, or combined matrix and fractures properties.

DARCY'S LAW

Considering stationary, laminar flow of an incompressible fluid that is chemically inert to the rock medium, in a planar fracture**, Darcy's law links the flowrate to fluid properties** (dynamic viscosity *µ*, density *ρ*)**, the geometry of the conduit** (flow area *A*, on a length *Δl*) **and the hydraulic load** (*ΔH*):

$$Q = -\frac{A\,(\rho\, g\, \Delta H)}{\mu\, \Delta l} = -\frac{A\, k\, \Delta_P}{\mu\, \Delta l}$$

CUBIC LAW

Under the same hypotheses as above, Navier-Stokes equations lead to the Cubic Law which expresses the **flowrate in relation to the fluid properties** (dynamic viscosity *µ*, density *ρ*), **the hydraulic gradient** ∇h **and the conduit geometry** (width *W*, inter-planar distance *E*):

$$Q = -\frac{\rho\, g\, W\, E^3}{12\, \mu} \nabla h$$

Witherspoon's correction factor attempts to take into consideration the effects of rugosity but this Modified Cubic Law cannot be used where flow velocity is too high (Re>400) or when rugosity is very high, creating local turbulences on the fracture surface.

To qualify the flow regime, the pressure drop coefficient λ under Poiseuille planar flow conditions can be calculated from:

$$\lambda = \frac{96}{Re}$$

References: Louis (1969), Witherspoon et al. (1980), Zimmerman et al. (2004)

MICRO-TURBULENCE

For laminar flow in a smooth conduit with small *Re* 200-400, the pressure drop is proportional to the fluid velocity $\vec{V}$.

Turbulent flow is observed when *Re*>4000 for smooth surfaces and the pressure drop is proportional to $\vec{V}^2$.

However, **non-planar interfaces induce premature non-linear flow**. But when? From the experimental measure of a fracture's aperture variation, it is possible to calculate an equivalent hydraulic aperture *e* which implicitly involves rugosity, tortuosity. Then, *Re* can be calculated:

$$Re = \frac{\vec{V}\, \rho\, 2e}{\mu}$$

References: Nikuradse, Louis (1976)

NUMERICAL STUDIES

They give powerful **simulations of hydraulic flow** in fractures. They can describe experimental flow tests on samples using mathematical routines, but are not always validated by experimental models.

They are also used to upscale small permeability models to a global rock mass, or to simulate fracture networks.

References: Kishida et al. (2009), Tan et al. (2015), Wang et al. (2016)

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