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Effects of fluids on rock deformation and fault slip: From nature to societal impact (Louis Néel Medal Lecture)

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Understanding the effects of fluid-rock interaction on rock and fault mechanical behaviour is central not only to understanding natural tectonic and seismogenic processes, and phenomena such as resource trapping, but also to evaluating the impact of industrial operations in the Earth's crust. These include activities ranging from extraction of geo-energy to geological storage of fuels, CO_2 and wastes. For the assessment of both natural and induced geohazards, a physics-based approach to quantifying rock mechanical behaviour is unmissable.

Microstructural studies of rocks deformed naturally in the mid and upper crust, or at seismogenic depths in subduction zones, show widespread evidence for brittle deformation (cataclasis), dissolution-precipitation transfer, fluid-related reactions producing weak minerals, and dilatation/cementation of fractures, cracks and pores. In addition, experimental work on rocks and simulated fault gouges has shown that the presence of water strongly influences their mechanical and transport properties. This implies the operation of fluid-assisted deformation mechanisms, such as stress corrosion cracking and diffusive mass transfer (pressure solution). More recently, other fluid-coupled deformation processes have been recognised, in rocks from peridotites and granites to sandstones, limestones and shales.

In this lecture, I will give an overview of progress in this area. I will address the physics of pressure solution and stress corrosion cracking and how they contribute to the deformation and compaction of sandstone, carbonate and evaporite rocks in the mid and upper crust, under natural conditions and in the context of deformation caused by geo-resources production and geo-storage. New results on how these processes are affected by pore fluid salinity, gas content and CO_2 activity will also be considered, as will data on the effects of mineral-fluid reactions and associated volume changes on rock deformation, fracturing and transport. The effects of gas and CO_2 sorption on the stress-strain behaviour and permeability of clay and shale caprocks, recently reported in relation to seal integrity, will be addressed too, and compared with similar phenomena familiar in seen in coal seams.

Lastly, I will address the effects of fluid-rock interaction on the frictional behaviour of faults. Recent low velocity friction experiments (<100 μm/s) performed on simulated carbonate, evaporite and quartz gouges, with varying phyllosilicate content, indicate that pressure solution is key to determining whether frictional slip is velocity-strengthening (stable) or velocity weakening (potentially seismogenic). An important trend seen is a transition from velocity strengthening at low temperatures, to velocity weakening at intermediate temperatures, and back to velocity strengthening at high temperatures. This behaviour and the restrengthening observed when shearing is stopped are strongly influenced by water content. It is inferred that mechanistic models for the frictional behaviour of gouge-filled faults, under crustal conditions, must account for diffusion and stress corrosion cracking, and for slip on grain boundaries. First attempts to do this, assuming diffusive mass transfer as the fluid-assisted mechanism, successfully predict the steady state and transient behaviour seen in experiments and offer new perspectives for providing friction laws as for modelling earthquake rupture nucleation and evaluating seismic hazard, in the context of both natural and induced seismicity.