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Porosity variations in and around normal fault zones: implications for fault seal and geomechanics

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Porosity forms the building blocks for permeability, exerts a significant influence on the acoustic response of rocks to elastic waves, and fundamentally influences rock strength. And yet, published studies of porosity around fault zones or in faulted rock are relatively rare, and are hugely dominated by those of fault zone permeability. We present new data from detailed studies of porosity variations around normal faults in sandstone and limestone. We have developed an integrated approach to porosity characterisation in faulted rock exploiting different techniques to understand variations in the data. From systematic samples taken across exposed normal faults in limestone (Malta) and sandstone (Scotland), we combine digital image analysis on thin sections (optical and electron microscopy), core plug analysis (He porosimetry) and mercury injection capillary pressures (MICP). Our sampling includes representative material from undeformed protoliths and fault rocks from the footwall and hanging wall.

Fault-related porosity can produce anisotropic permeability with a 'fast' direction parallel to the slip vector in a sandstone-hosted normal fault. Undeformed sandstones in the same unit exhibit maximum permeability in a sub-horizontal direction parallel to lamination in dune-bedded sandstones. Fault-related deformation produces anisotropic pores and pore networks with long axes aligned sub-vertically and this controls the permeability anisotropy, even under confining pressures up to 100 MPa.

Fault-related porosity also has interesting consequences for the elastic properties and velocity structure of normal fault zones. Relationships between texture, pore type and acoustic velocity have been well documented in undeformed limestone. We have extended this work to include the effects of faulting on carbonate textures, pore types and P- and S-wave velocities (Vp, Vs) using a suite of normal fault zones in Malta, with displacements ranging from 0.5 to 90 m. Our results show a clear lithofacies control on the Vp-porosity and the Vs-Vp relationships for faulted limestones.

Using porosity patterns quantified in naturally deformed rocks we have modelled their effect on the mechanical stability of fluid-saturated fault zones in the subsurface. Poroelasticity theory predicts that variations in fluid pressure could influence fault stability. Anisotropic patterns of porosity in and around fault zones can – depending on their orientation and intensity – lead to an increase in fault stability in response to a rise in fluid pressure, and a decrease in fault stability for a drop in fluid pressure. These predictions are the exact opposite of the accepted role of effective stress in fault stability.

Our work has provided new data on the spatial and statistical variation of porosity in fault zones. Traditionally considered as an isotropic and scalar value, porosity and pore networks are better considered as anisotropic and as scale-dependent statistical distributions. The geological processes controlling the evolution of porosity are complex. Quantifying patterns of porosity variation is an essential first step in a wider quest to better understand deformation processes in and around normal fault zones. Understanding porosity patterns will help us to make more useful predictive tools for all agencies involved in the study and management of fluids in the subsurface.