Heterogeneous fault zone structure and flow localization in limestone successions

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Using outcrop constraints from Oligo-Miocene normal faults in Malta and mine data for Carboniferous normal faults in Zn-Pb Irish mineral deposits, this talk describes the heterogeneous nature of fault zone structure and content, concentrating on the importance of linear zones of high porosity-permeability. These zones of enhanced permeability are highly localized fault linkage-related features occurring on a range of scales, most often below the limit of hydrocarbon and mineral exploration datasets, that can be shown to promote highly localized fluid flow. Here we outline their geometry and formation, consider their potential impact on flow and how their presence might be predicted.

Our outcrop observations derive from superbly exposed normal fault zones in Malta, offsetting a pre- to syn-faulting succession of mainly massive limestones by up to 210 metres. The faults are usually relatively planar, containing mm-cm thick veneer of fine-grained breccia and cataclasite. However, marked heterogeneities in fault zone structure, characterized by increased brecciation and fracturing, are associated with specific fault linkage-related structures:
(i) Breached relay zones – characterized by high density arrays of antithetic and synthetic faults within massive limestone relay ramps that are one to two orders of magnitude greater than background.
(ii) Branch-lines - anomalous thicknesses of coarse fault breccia along branch-lines arising from relay breaching, with very high strains in the adjacent rock volume.
(iii) Bends – mechanical erosion at branch-lines, to produce cylindrical bends, causes anomalously thick fault zones comprising deformed lenses of footwall limestone.

Our outcrop observations therefore suggest that the evolution of segmented fault arrays within limestones tends to provide linear zones of enhanced vertical permeability at pre-existing segment boundaries. This view is supported by high quality 3-D data from the Lisheen Mine, in the Irish Midlands, for which ore distributions also provide constraints on fault-related fluid flow. Mineralization occurs as post-faulting replacements of Courceyan-aged carbonates, forming stratiform lenses at the base of a regionally dolomitised limestone. The main ore bodies are bounded to the SE by three en-échelon, north-dipping normal fault segments with maximum throws of ca. 220 metres, linked by intact relay ramps (up to 500m wide). However, smaller-scale fault segmentation has resulted in a series of breached relay zones (up to 150m wide) similar in character to those seen in Malta. Ore thickness and grade distribution patterns indicate that these strongly deformed breached relays, and related branch-lines and bends, were ‘feeder’ structures acting as the locus of upward flow along the main faults; outwith of these breached relays there is little evidence of focused flow of ore fluids along the bounding faults.

Our observational data indicate that although heterogeneities are restricted to relatively small areas of a fault, their flow significance is disproportionate. Fault zone heterogeneities can therefore be characterized by strong flow localization, acting as upward conduits for mineralizing or hydrocarbon fluids, or providing the high flow rates required in hydrocarbon production as a complement to the fluid capacities of adjacent less permeable fracture networks within fractured reservoirs. A potential major concern is however that their vertical persistence and high permeabilities could be responsible for early water breakthrough during reservoir production or leakage of hydrocarbon reservoirs on geological time scales. Though it is sometimes possible to identify the presence of such heterogeneities at the resolution of exploration datasets or to provide a rationale for their existence at sub-resolution scales, robust predictive modeling techniques, underpinned by refined mechanical and flow models, have yet to be developed and may, apart from for risking purposes, prove elusive.