E08

Heterogeneous Fault Zone Structure and Related Flow Localization Within Limestones

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SUMMARY

High quality outcrop and mine data for normal faults within limestone sequences are used to highlight the inherently heterogenous nature of fault rock and fault zone structure. This heterogeneity is attributed to fault-related segmentation and refraction compounded by progressive breaching of segment boundaries (i. e. relays) and the removal of fault surface asperities with increasing displacement. Relay breaching and fault linkage is responsible for rapid changes in fault zone structure, with the generation of high fracture densities and increased host rock brecciation. Recent work on classic Zn-Pb Irish mineral deposits, hosted within Carboniferous limestones, suggests that the accentuated deformation associated with relay breaching and related fault bends is responsible for the creation of sub-vertical zones of high permeability which act as conduits for upward flow of mineralizing fluids from underlying basement rocks. These zones of enhanced permeability occur on a range of scales, most often below the limit of hydrocarbon and mineral exploration datasets. This talk considers the potential implications of the strongly heterogeneous nature of fault zone structure and related flow, for a variety of application areas, including hydrocarbon exploration/production and CO2 storage.

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 (Figs 1 & 2). The faults are usually relatively planar, containing a mm-cm thick veneer of fine-grained breccia and cataclasite (Bonson et al. 2007). However, marked heterogeneities in fault zone structure, characterized by more widespread brecciation and fracturing, are associated with specific fault linkage-related structures:
(i) Breached relay zones – characterized by dense arrays of antithetic and synthetic faults within massive limestone relay ramps; minor fault densities are one to two orders of magnitude higher 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 (Fig. 1).

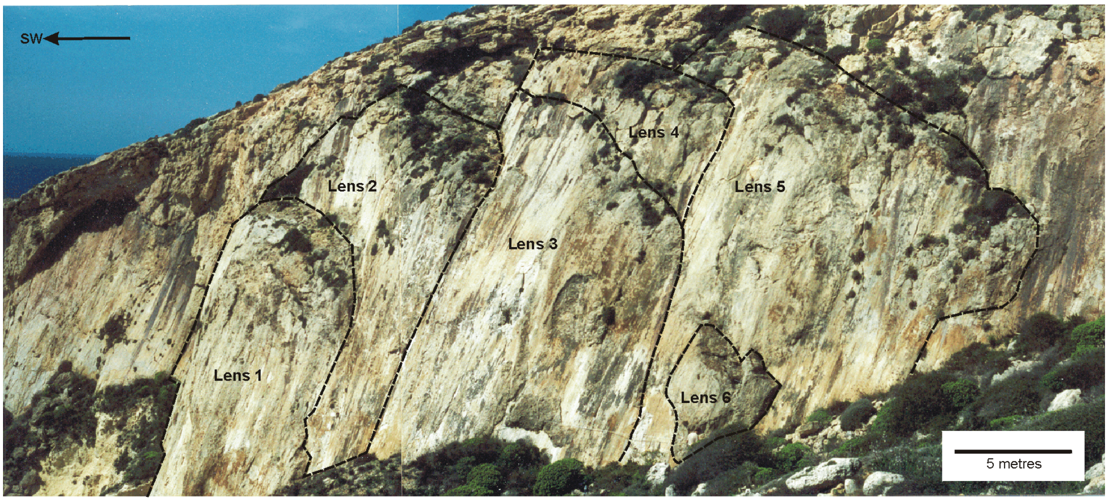

Figure 1 *Lenses of fault rock adjacent to a bend on the Maghlaq fault, Malta. This fault has an estimated vertical displacement of ca 200m and is characterised by frequent segments and associated breached relays and bends.*

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 (Carboni et al. 2003). 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 (Fig. 2) 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 disproportionately high. Fault zone heterogeneities can therefore be characterized by strong flow localization and may act as upward conduits for mineralizing fluids or hydrocarbons, or may provide the conduits required to focus flow during hydrocarbon production from 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, and leakage of hydrocarbon reservoirs and of CO2 storage sites. 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 mechanical or flow modeling techniques have yet to be developed and may, apart from for risking purposes, prove elusive.

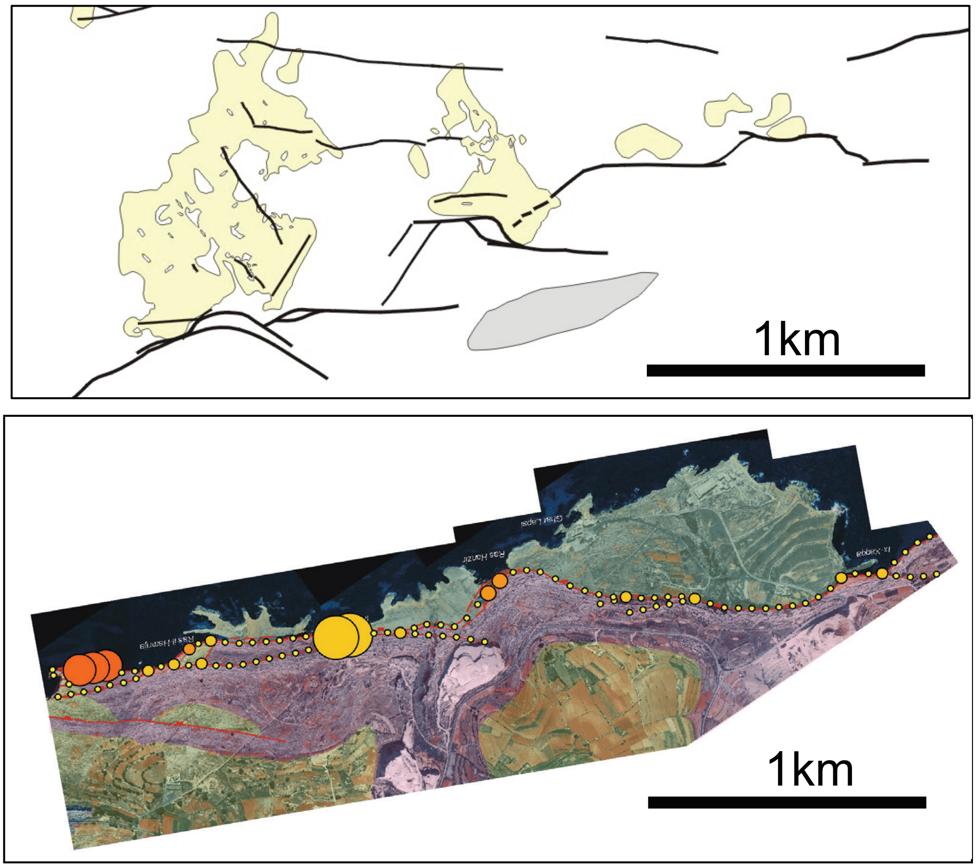

Figure 2 *Maps of ca 200m throw normal faults from Central Ireland and from Malta. The Lisheen Zn-Pb deposit (top diagram - ore shown in yellow) is bounded by a Lower Carboniferous normal fault which acted as a conduit for up-fault flow and for accentuated mineralisation adjacent to breached relays and associated bends. The Plio-Quaternary Maghlaq Fault is characterised by variable fracture densities along its length (in the above map bubble size is non-linearly related to density) which are related to breached relays and bends.*

References

Bonson, C.G., Childs, C., Walsh, J.J., Schöpfer, M.P.J. & Carboni, V. 2007. Geometric and kinematic controls on the internal structure of a large normal fault in massive limestones: the Maghlaq Fault, Malta. Journal of Structural Geology 29, 336-354.

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