Outcrop-Scale Variations in Petrophysical Properties of Faulted Carbonates: Exploring the Relative Influence of Lithology, Fault Displacement and Juxtaposition*

Dave Healy[1], Emma Michie[1], Tom Haines[1], Joyce Neilson[1], Ian Alsop[1], Nick Timms[2], and Moyra Wilson[2]

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[1]University of Aberdeen, Aberdeen, UK (d.healy@abdn.ac.uk)
[2]Curtin University, Perth, Australia

Abstract

Carbonate reservoirs are highly heterogeneous in their internal fabric and structure, due in part to the variety of depositional and diagenetic processes that affect these rocks. This intrinsic heterogeneity presents major challenges when characterising the physical properties of a reservoir, either from seismic or well data. An additional factor in many regions is due to the effects of fractures. Variations in fracture patterns, or damage, around faults, provide an extra source of heterogeneity in fractured carbonate reservoirs. Fault damage zones are often the main conduits for fluid-flow, whereas fault cores tend to be sealing and act as barriers to across-fault flow. High strains in the fault core tend to obliterate depositional and diagenetic textures, which consequently have little influence on fluid flow. In contrast, lower strains in fault damage zones mean that the effects of depositional and diagenetic textures are more apparent. Porosity and permeability will be controlled by the combination of original textures and fracture patterns in the fault damage zone. This contribution explores the relative effects of original lithology, fault displacement and juxtaposition on the key petrophysical properties (porosity, permeability and seismic velocities) of faulted carbonate reservoirs based on outcrop analogues in Malta. Our eventual aim is to provide a quantitative understanding of: a) the ways in which extrinsic brittle damage around faults combines with intrinsic lithological variation of different carbonate facies, and b) how these combinations are expressed in the petrophysical attributes.

Introduction

We chose outcrops in Malta for this study because of their limited degree of diagenesis and an overall low degree of tectonic strain. This improves the chances of being able to measure the effects of initial sedimentary facies on the pore systems, and to systematically measure and quantify the fault related deformation at accessible outcrops. The faulted rocks in our study are Oligo-Miocene carbonates that were deposited offshore Africa in a relatively low energy area of the palaeo-Mediterranean. There is only minor evidence of syn-sedimentary tectonic movements, with minor fault-controlled thickness changes and the development of sparse Neptunian dykes (Meulenkamp and Sissingh, 2003). The faults measured in our study were formed in the Pliocene, with the Tyrrhenian Basin opening to the north and rifting in the Pantellaria Rift to the south, and related uplift of the northern rift flank (i.e. present-day Malta and Gozo; Hill and Hayward, 1988). The faulted sediments we have analysed in Malta comprise the Lower Coralline Limestone composed of grainstones and bioclastic packstones, and the Globerigina Limestone, which is divided into the Lower (bioclastic wackestones/packstones), Middle (micritic) and Upper (micritic) Members. Each of these is separated by a hard ground with several intervening firm grounds. The limestones are capped by the Blue Clay, a Mid Miocene deep-water clastic unit deposited in up to 150 m water (Pedley, 1975).

Results

We present preliminary results from an ongoing field and laboratory study using spectacularly well exposed normal faults on Malta, with displacements ranging from ~20 cm up to ~95 m, spanning four orders of displacement magnitude. The deformation surrounding faults in two main lithofacies – mud- and grain-dominated carbonates – has been examined and quantified. The data have been used to evaluate the main deformation mechanisms observed in the two carbonate facies and inferences made about their differing responses to stress. In addition, these differences in deformation mechanisms change the scaling relationships of the fault zones. Mud-dominated carbonates show a plastic response in fault cores destroying any pre-existing fabrics; while in the damage zones the original fabric remains and is associated with large well-spaced fractures. Grain-dominated carbonates show a high degree of cataclasis and dissolution in the fault core, but with more localised deformation within the damage zones, with grain-scale Hertzian fracturing rather than large through-going fractures. Our preliminary data suggest that faults in grain-dominated facies have thicker cores and thinner damage zones compared to those in mud-dominated facies, which have thinner cores, and thicker damage zones (Figure 1).

In addition to the field data (maps, sections, scan lines and logs), we have analysed thin 170 sections and 204 core plugs taken from oriented samples. The core plugs have been analysed for porosity (Helium) and permeability at ambient pressure (Nitrogen, Klinkenberg corrected). To fully quantify the pore system, we need to know the pore types, their sizes, shapes and orientations (Lucia 1983, 1995; Lonoy, 2006). Critically, we need to understand the natural statistical distributions in all of these pore system attributes, as well as their spatial variation with respect to depositional facies and tectonic damage. This detailed characterisation of porosity will enhance our understanding of the permeability.

Discussion

Our preliminary data show a large range in porosity and permeability values, partly related to facies but also related to the major faults and associated fractures. The structural data have allowed the fault zones to be separated into three major zones: a) fault core, b) intensely deformed damaged zone (IDDZ) bound by slip surfaces in the hanging walls and c) weakly deformed damaged (WDDZ) zone in both the hanging walls and footwalls. The WDDZ passes gradually into undamaged protolith. The effect of faulting and fracturing on the porosity and permeability of the carbonates appears to vary with lithology (Figure 2 and Figure 3).

In the micritic Globeriginid Limestone, although porosity can be quite high (up to 35%, Figure 2), permeability is generally low (< 10 mD) and the degree of damage does not appear to have any significant effect on reservoir quality at the core plug scale (Figure 2). In the underlying Lower Coralline Limestone however, the degree of damage appears to have more of an effect on plug scale porosity and permeability. Samples from the fault core (breccias, cataclasites) have much lower porosity and permeability values than the protolith (typically < 15 % porosity; < 10 mD permeability, Figure 3). Samples from the IDDZ in the hanging wall of faults have moderate porosity but a relatively high permeability (typically < 20 % porosity, > 10 mD permeability, Figure 3). Protolith samples appear to have high porosity and permeability, but the database is currently limited. Further sampling of the protolith is required to determine the degree of variability within the original samples and whether porosity in the IDDZ has been destroyed (with permeability maintained) or maintained (with permeability increased, Figure 3). Samples from the WDDZ follow the same trend of porosity and permeability as the undamaged protolith.

Conclusion

Porosity fundamentally influences the permeability but also the elastic properties and therefore the seismic velocities – V_p and V_s. One of our ultimate research aims is to predict the velocity structure across fault zones using Effective Medium Theory (EMT, Sayers and Kachanov, 1995) in a way that will allow us to span the frequency range from the ultrasonic (MHz, laboratory-scale core plug samples) to the seismic scale (in situ field scale outcrops). EMT equations require the size, shape and orientation of all pores and cracks as inputs, and we are quantifying attributes from image analyses of thin sections and data from mercury capillary injection (MCIP) tests. If our measured porosity data produce high frequency EMT predictions that match our measured ultrasonic velocity measurements in the laboratory, it will lend confidence to the lower frequency EMT predictions for the seismic scale using the same measured porosity data. We envisage this as an iterative process and will form the next phase of research.

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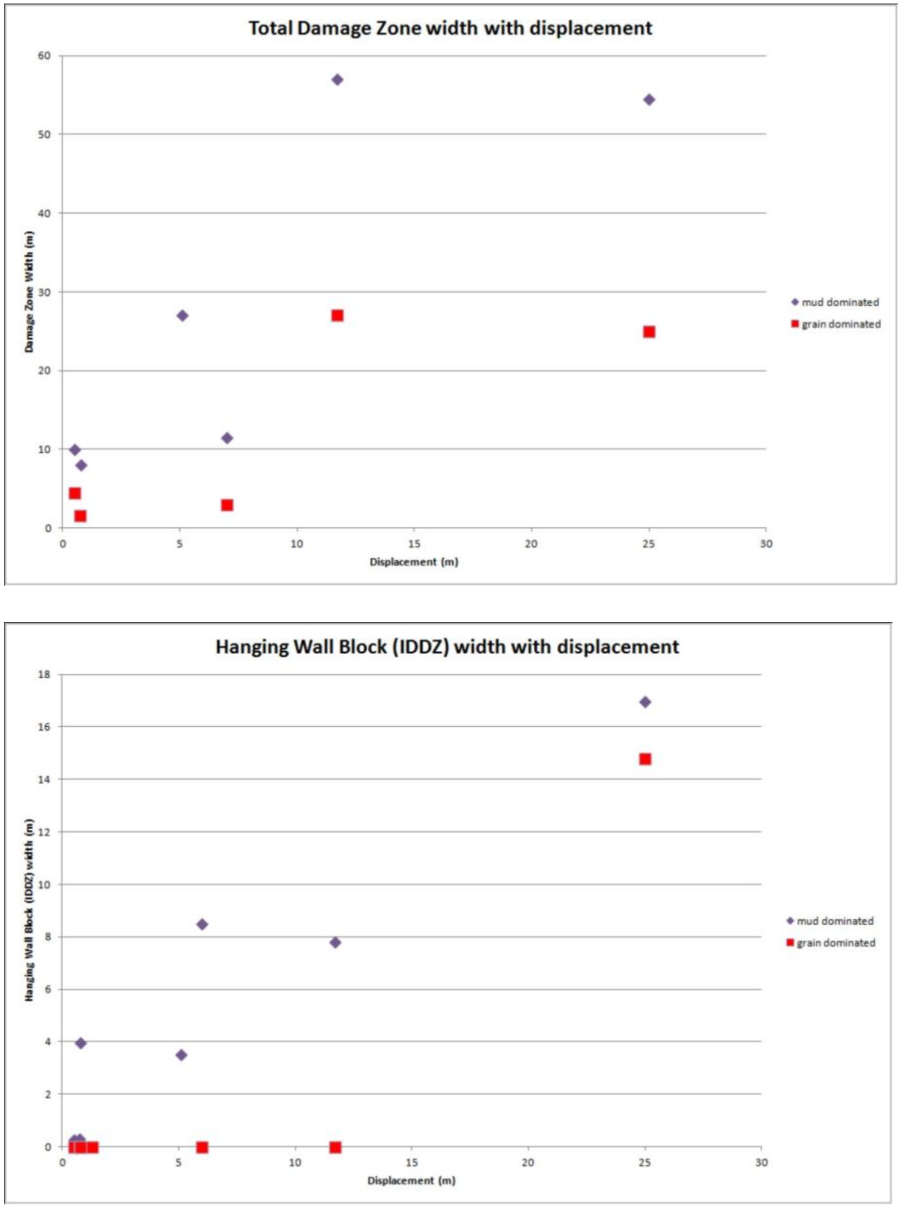

Figure 1. Preliminary data showing differences in fault zone scaling between mud- and grain-dominated lithofacies. Total damage zone width and intensely deformed damage zone (IDDZ) width both tend to be higher in the mud-dominated lithofacies, across a range of fault displacements.

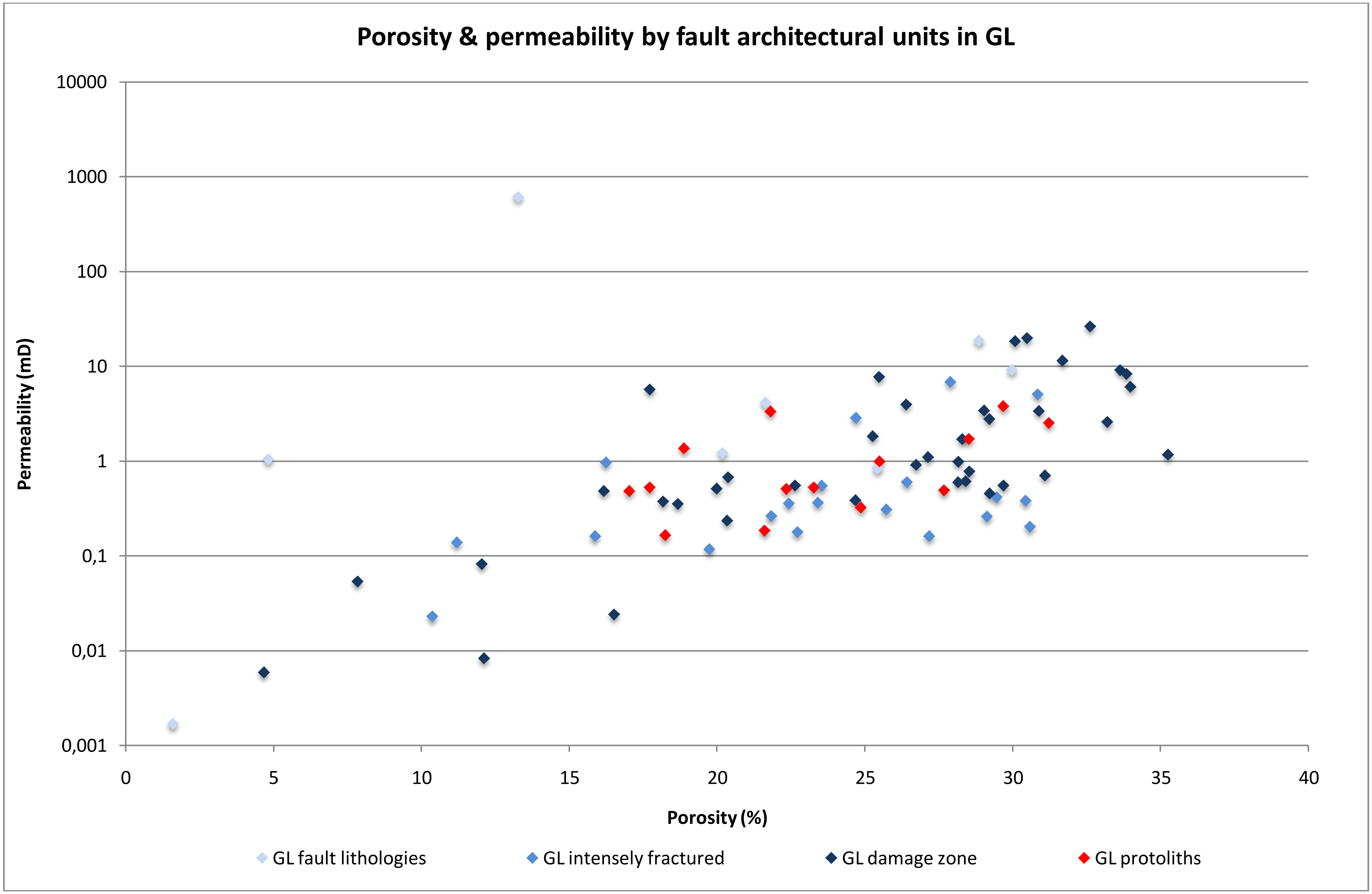

Figure 2. Preliminary porosity-permeability cross plot for the faulted Globeriginid Limestone, Malta.

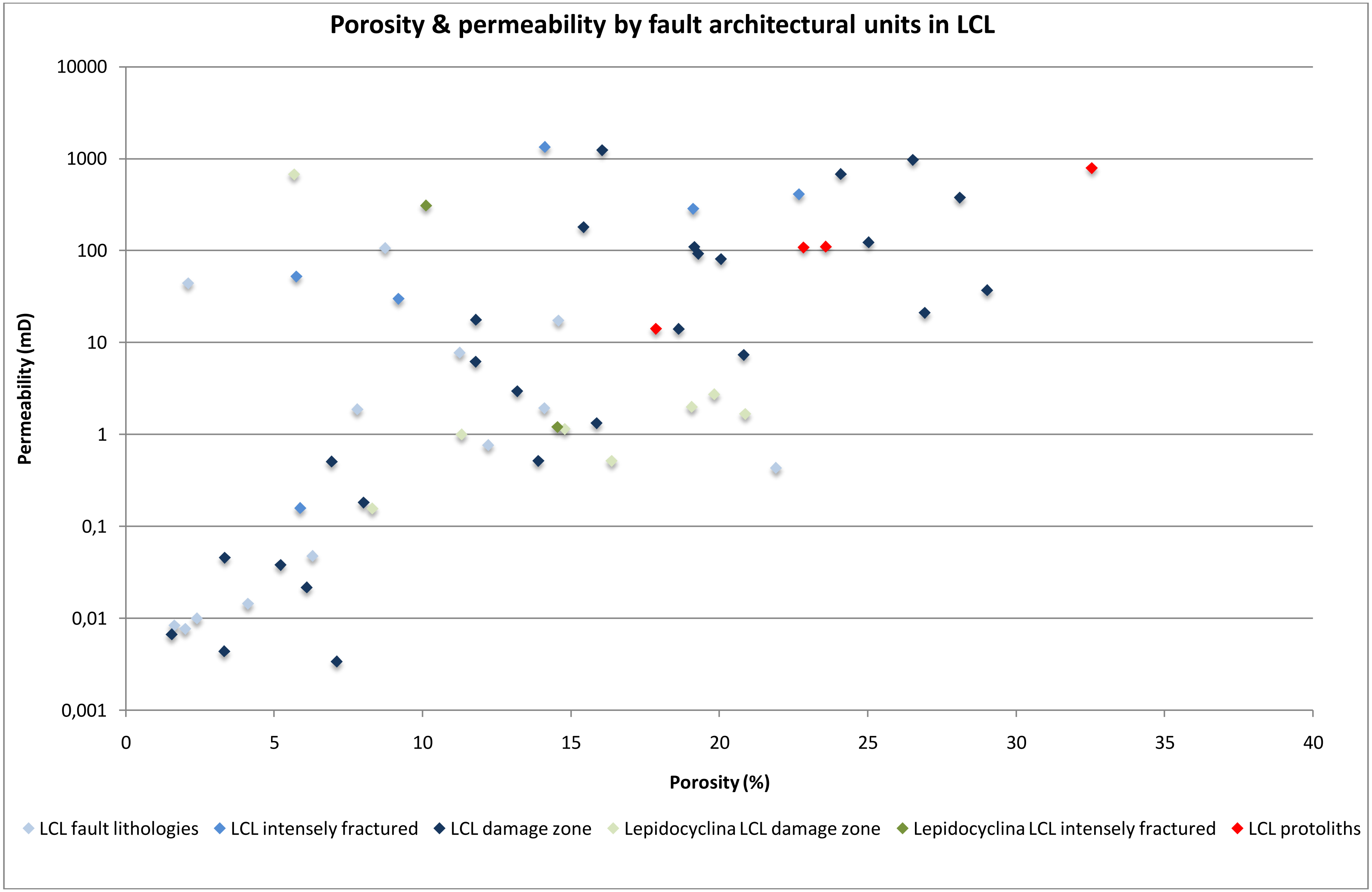

Figure 3. Preliminary porosity-permeability cross plot for the faulted Lower Coralline Limestone, Malta.