The Influence of Facies and Fracturing on the Petrophysical Properties of Carbonates*

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Abstract

The reservoir properties (especially permeability) of carbonates are notoriously difficult to predict. This arises from the well known and documented variability in pore systems in carbonates, partly the result of initial facies but also due to extreme variability in the effects of diagenesis (cementation and dissolution) and structural evolution (faulting and fracturing).

In order to investigate the effect that rock texture and fracturing has on the petrophysical properties of carbonates, an outcrop study has been designed to record facies, degree of diagenesis, style and amount of faulting and fracturing, and sampling to obtain porosity, permeability, Vp and Vs measurements in the laboratory. Oligo-Miocene carbonates cropping out on the island of Malta in the Mediterranean, were chosen because of their geological simplicity and limited degree of diagenesis. In this way it is hoped that the effects of initial facies on the pore systems and the faulting and fracture style and intensity can be identified and measured at outcrop and, using Effective Medium Theory, predicted in the subsurface.

During the Oligo-Early Miocene, major rifting and re-organisation occurred in the Western Mediterranean and to the east, the Gulf of Aden-Red Sea- Gulf of Suez rift system developed. The carbonates that now comprise the Oligo-Miocene of the present-day Maltese Archipelago however were deposited offshore Africa in a relatively quiet area of the Mediterranean. Only minor evidence of tectonic movement is observed, characterised by minor fault-controlled thickness changes and the development of neptunian dykes (Meulenkamp and Sissingh, 2003). By the Pliocene however, the Tyrrhenian Basin had opened up to the north of the Maltese Archipelago accompanied by rifting in the Pantellaria Rift just to the south with uplift of the northern rift flank (i.e., the present-day Maltese Archipelago). It is this movement that is the origin of the major faulting observed in the islands today (Hill and Hayward, 1988).

The Oligo-Miocene sediments in Malta developed in an outer-ramp setting around the northern margins of the Southern Peri-Tethys Platform (northern margin of the African plate) on a relatively stable platform. They comprise the Lower Coralline Limestone composed of

grainstones and bioclastic packstones and the Globigerina Limestone which is divided into the Lower (bioclastic wackestones/packstones), Middle (micritic), and Upper (micritic) Members. Each of these is separated by a hardground with several intervening firmgrounds. The limestones are capped by the Blue Clay, a Mid Miocene deep water clastic unit deposited in up to 150 m water. As such, a variety of initial facies types have been studied across the island. The nomenclature follows that of Pedley et al. (1976).

To date, 26 sedimentary logs at 3 locations across Malta have been constructed with associated geological maps and cross-sections of logging locations and accompanied by systematic stratigraphic sampling. In terms of structural data, 53 scan lines, 7 fault maps, and 5 cross sections have been constructed with systematic sampling across faults. In total, 244 samples have been collected for laboratory analysis. Of these, 170 thin-sections (standard and polished) have been prepared and screened for facies (grainstones, packestones, wackestones), degree of diagenesis, deformation mechanisms, and the amount of micro-fracturing. Preliminary work on the quantification and distribution of various porosity types, back-scattered electron microscopy, and cathodoluminescence has also been carried out.

As well as the thin-section analysis, 204 core plugs have been cut and, using in-house analytical equipment, all have been analysed for porosity (He) and permeability (N, atmospheric pressure, Klinkenberg corrected). In order to understand the pore system fully, as well as knowing the poroperm values, we need to know the type of porosity, its distribution (e.g. Lonoy, 2006) and the poroperm relationships with facies, grain size etc. (e.g. Lucia 1983, 1995).

As is the case with most carbonate datasets, a large range in porosity and permeability values have been observed, 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 damaged zone bound by slip surfaces in the hanging walls of the faults, and c) weakly damaged zone in both the hanging and footwalls. The weakly damaged zone passes gradually into undamaged protolith. The effect of faulting and fracturing on the poroperm of the carbonates appears to vary with lithology.

In the micritic Globigerina Limestone, although porosity can be quite high (up to 35%, Figure 1), 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 1).

In the underlying Lower Coralline Limestone however, the degree of damage appears to have more of an effect on plug scale poroperm values. Samples from the fault core (breccias, cataclasites) have much lower porosity and permeability values than the protolith (typically < 15% ф; < 10 mD k, Figure 2). Samples from the intensely damaged zone in the hanging wall of faults have moderate porosity but a relatively high permeability (typically < 20% ф, > 10 mD k, Figure 2). Current protolith samples have high poroperm but the data base is limited. Further sampling of the protolith is required to determine the degree of variability within the original samples and whether porosity in the intensely damaged zone has been destroyed (with permeability maintained) or maintained (with permeability increased, Figure 2). Samples from the weakly damaged zone follow the same trend of poroperm as the undamaged protolith.

The detailed poroperm distribution (type and amount) is currently being studied across faults of different magnitude (90 m, 20 m, and 5 m displacement). Factors that have been found to vary are the degree of fracturing, cementation, and solution enhancement of both matrix and fracture porosity. To date, most solution enhancement has been found in the hanging wall but further study is required.

Porosity fundamentally influences elastic properties and therefore seismic velocities, V_p and V_s. The ultimate aim of the research is to predict elastic properties across fault zones using Effective Medium Theory (EMT, Kachanov, 1993) in a way that will allow us to link the frequency range from the ultrasonic (lab scale, core plug samples) to the seismic scale (in situ field scale samples). The data we are in the process of collecting (e.g. size, shape, and orientation of the pores and cracks) through thin-section image analysis and mercury injection analysis will be used as inputs. If the porosity data produces EMT predictions that match our measured laboratory ultrasonic velocity measurements, it will lend confidence to the EMT predictions for the seismic frequency range using the same measured porosities. This will naturally be an iterative process and will form the next phase of research.

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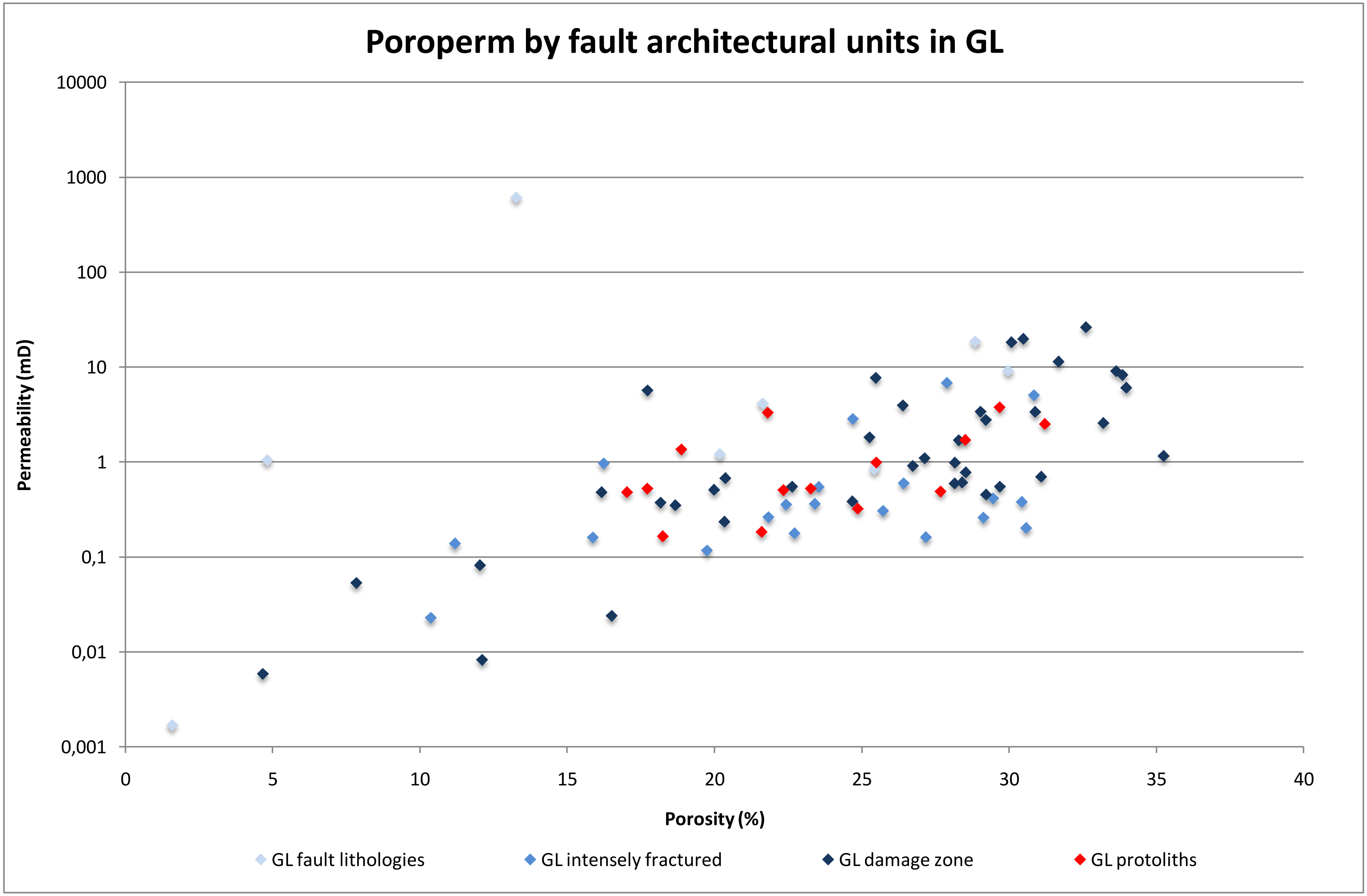

Figure 1. Poroperm data for the Globigerina Limestone, Malta. Samples have been collected across faults from the undamaged protolith through to the fault core.

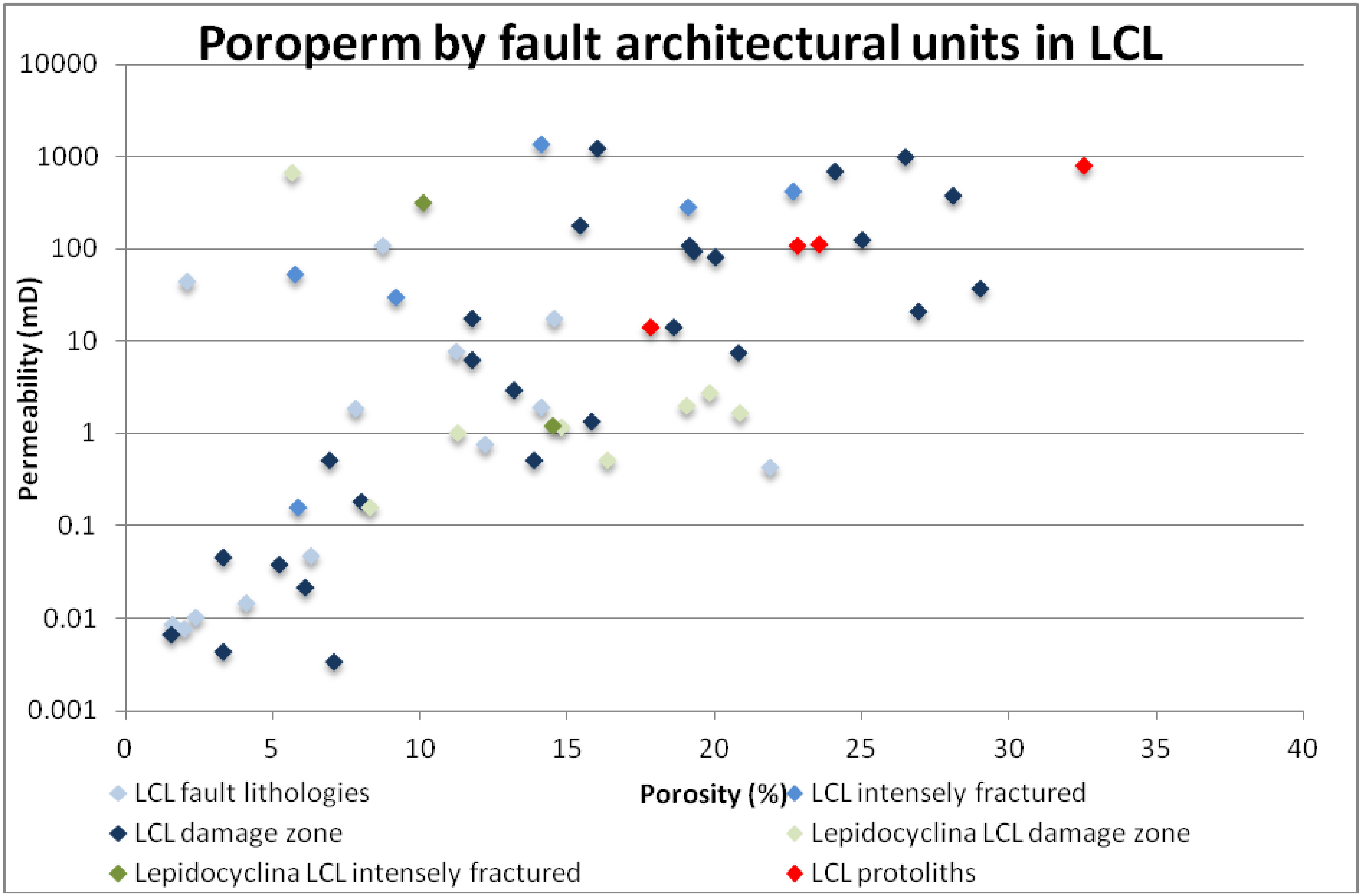

Figure 2. Poroperm data for the Lower Coralline Limestone, Malta. Samples have been collected across faults from the undamaged protolith through to the fault core.