An investigation of porosity–velocity relationships in faulted carbonates using outcrop analogues

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Abstract: Porosity and permeability are notoriously difficult to predict in carbonates, especially prior to drilling when there is a lack of direct petrophysical data. The aim of this paper is to document the initial results of an integrated outcrop and laboratory study designed to investigate the relationships between pore systems and acoustic velocities in faulted Oligo-Miocene carbonates on the Mediterranean islands of Malta and Gozo. Depositional facies is shown to have a significant effect, with velocities in grain-dominated carbonates up to 1000 m s$^{-1}$ higher than those in micrite-dominated carbonates. Based on outcrop structural data, the fault zones can be separated into three architectural components: a fault core; an intensely damaged zone; and a weakly damaged zone, with the last passing into undamaged protolith. Our data suggest that only the fault core component can be identified using porosity–velocity data, with P-wave velocity ($V_p$) values of 5000–6500 m s$^{-1}$ at helium porosities of less than 5%. Our study is novel in that the prediction of elastic properties and acoustic velocities across fault zones is anticipated by linking laboratory-scale measurements with seismic-scale predictions through quantitative rock physics modelling.

Over many decades, a key to improving production from fractured carbonate reservoirs has been seen to be the understanding and prediction of fluid flow (e.g. Adams et al. 1968; Corbett et al. 2012). A critical factor in this endeavour is understanding the pore system, and how it relates to permeability and other petrophysical measurements, such as P- and S-wave velocities ($V_p$ and $V_s$). The petrophysical properties of carbonates, however, are notoriously difficult to predict due to the high variability in carbonate pore systems (e.g. Archie 1952; Lucia 1995; Lønøy 2006; Hollis et al. 2010).

One of the earliest pore classifications by Choquette & Fray (1970) was based on depositional and diagenetic textures, two of the key building blocks in understanding carbonate pore systems. Later, Lucia (1983, 1995) recognized that, by classifying carbonate pore systems on the basis of their geometry and particle/grain size, permeability could be predicted. Lønøy (2006) developed Lucia’s ideas further by recognizing the importance of pore size and the distribution of porosity when trying to predict permeability.

Over the past 10–15 years, rock typing has been developed as a method to improve production from carbonate reservoirs (e.g. Giot et al. 2000; Hollis et al. 2010). This method aims to group samples of similar lithology, diagenetic overprint, porosity, permeability and flow properties. Hollis et al. (2010), however, concluded that, although many studies of this type have been conducted, few are truly robust. Studies tend to focus on grouping samples with similar petrophysical properties rather than exploring how the pore system has evolved. Hollis et al. (2010) suggested that diagenetic modification of the pore systems is often overlooked.

Rationale

Most previous studies of the petrophysical properties of carbonates focus on the rock matrix and potential fluid flow through that matrix (e.g. Lucia 1995; Lønøy 2006). Fracture porosity, including the geometry and connectivity, is not always taken into account (e.g. Lønøy 2006) but it is a major issue in carbonates (e.g. Hollis et al. 2010). Another issue for conventional pore system and rock typing studies is the requirement for significant amounts of subsurface core material to achieve statistically significant results that honour
both the static and dynamic data. In the study by Hollis et al. (2010) of a giant carbonate field (85 km²; Hollis pers. comm.), initially about 1000 m of core was available from only 14 out of 400 wells, with no continuous core coverage through the entire reservoir section. For the purposes of their study, a further seven new wells were drilled with continuous core through the reservoirs adding a further 1800 m to the core database. Even with such a well-designed project that had relatively good core coverage, sampling was spatially limited in relation to reservoir size, and the general situation is usually worse than this.

A systematic investigation of the potential for P- and S-wave acoustic velocities ($V_p$ and $V_s$) to help predict porosity and pore types is another way forward. This is not a new approach (e.g. Anselmetti & Eberli 1993; Eberli et al. 2003; Fabricius et al. 2007; Weger et al. 2009) but it is one that has received very limited attention (e.g. Matonti et al. 2012). Anselmetti & Eberli (1993) and Eberli et al. (2003) showed how pore type had an effect on both $V_p$ and $V_s$. This work was further developed by Fabricius et al. (2007) who, using the Kozeny–Carman equation (Carman 1937), were able to make reasonable predictions of permeability in micritic-, but not vuggy-, dominated carbonates. Weger et al. (2009) quantitatively characterized carbonate pore systems through the development of digital image analysis. In that study, quantitative data for pore-space characteristics such as two-dimensional (2D) pore size, roundness and pore-network complexity were linked to permeability and sonic velocity. By carrying out these studies, Weger et al. (2009) showed that along with total porosity, the amount of microporosity, the pore-network complexity and the size of macropores influenced the acoustic behaviour of carbonates significantly. In their study, more than 80% microporosity in a sample was found to reduce the $V_p$ by 1000 m s$^{-1}$. In terms of pore-network complexity, given the same amount of porosity, carbonates with predominantly mouldic and/or vuggy porosity were found to have a $V_p$ 1000–1500 m s$^{-1}$ higher than those with intercrystalline and/or interparticle porosity. An even greater increase in $V_p$ of 2000 m s$^{-1}$ was seen where the dominant pore size increased from <200 μm to 600 μm.

When considering flow in reservoirs, it is important to look at how pore systems vary on a larger scale. Matonti et al. (2012) explored the distribution of $V_p$ porosity and degree of cementation across the Castellas fault in SE France. In our study, data from outcrop analogues is evaluated to better understand controls on the variability of porosity in faulted and fractured carbonate rocks, and how these variations influence both $V_p$ and $V_s$ data. Separating the various factors that affect the petrophysical properties of carbonate rocks is non-trivial. Hence this outcrop study was designed to record depositional facies, degree and type of diagenesis and the style and intensity of faulting and fracturing. Careful and systematic sampling of oriented core plugs was conducted perpendicular and parallel to fault zones of varying displacement, from which laboratory measurements were obtained of porosity ($\phi$), permeability ($k$), and ultrasonic P- and S-wave velocities ($V_p$ and $V_s$).

Oligo-Miocene carbonates cropping out on the Maltese Islands (House et al. 1961) were chosen because of their geological simplicity and limited degree of diagenesis. The effects on the pore systems of the initial facies and the style and intensity of brittle fracturing can be identified and measured at outcrop and in the laboratory. The ultimate aim of our work is to use field and laboratory data to condition quantitative rock physics models (e.g. using Effective Medium Theory; Baechle et al. 2008) that can ‘upscale’ the ultrasonic (high frequency, low wavelength) velocities measured in the laboratory to seismic wavelengths for use in subsurface characterization.

The aims of this paper are to: describe the methods employed; review the facies studied including pre-fault diagenesis; characterize the nature and scale of the fault/fracture systems; and document porosity-velocity relationships in faulted carbonates.

Methodology

Detailed sedimentary logs from three separate areas on Malta and Gozo were constructed with associated geological maps and cross-sections, accompanied by systematic stratigraphic sampling. Structural fracture scan-lines, fault zone maps and cross sections were also constructed to complement the sampling across fault zones. 325 thin sections were prepared and screened for facies type and assessment of the degree of pre-fault diagenesis together with analysis of the deformation mechanisms and the amount of microfracturing. 283 core plugs were analysed for porosity (helium) and permeability (nitrogen, Klinkenberg corrected), $V_p$ and $V_s$. Pore-network characteristics and permeability data are not reported here, but form part of an ongoing study.

Ultrasonic velocity measurements

Ultrasonic acoustic velocities were measured using the pulse transmission technique of (Birch 1960). The measurements were recorded for dry samples under atmospheric pressure and temperature.
The velocity was measured using an ultrasonic pulser/receiver (Fig. 1a) in transmission mode, with two separate transmitting and receiving transducers on either side of the sample. The pulse generator and transducers were connected to a digital oscilloscope to visualize the waveforms (Fig. 1b, c). The velocities were measured with a voltage of 900 V and a gain of 60 dB. The transducers were connected to the sample with a constant, uniform pressure. In order for a good signal to be received, the ends of the core plug sample have to be completely flat and parallel. If large pores occur at the ends of the core plug, then a connection between the sample and transducer is poor and the signal is weak. In these rare cases, a small amount of silicon grease was applied to the plug ends to improve the signal.

Fracture intensity and density measurements

Scan lines were used to quantify fracture patterns across fault zones of varying displacements, in different carbonate lithofacies. The intensity and density of fractures were measured using circular scan windows (tens of cm to about 1 m across) along transect lines normal to, and along the
strike of, the fault planes (Mauldon et al. 2001; Rohrbaugh et al. 2002). Circular scan windows remove sampling bias from fracture orientation data, especially when compared to the traditional 1D scanline approach. Fracture intensity and density were calculated using the intersections and end points of each fracture trace within the circular scan windows of the line transects (Mauldon et al. 2001; Rohrbaugh et al. 2002). The density (P20) is the mean number of fractures per unit area. The intensity (P21) is the mean total trace length of fracture traces per unit area (Dershowitz & Herda 1992).

Calculation of percentage calcite in micrite-dominated carbonates

The percentage area of calcite was estimated for 25 samples using digital image analysis techniques, checked by energy dispersive X-ray analysis (EDX). The 25 selected samples represent a range of damaged and undamaged lithofacies. Digital image analysis was conducted on greyscale scanning electron microscope (SEM) photomicrographs. The greyscale values of these images correspond to the atomic number of elements and are therefore used to identify different minerals, such as calcite and impurity minerals (e.g. aluminosilicate clays) (Lloyd 1987). This was checked using EDX to identify the presence or absence of elements such as Si and Al, which would be present in the clay impurities but not in the calcite. Five photomicrographs were acquired for each sample, which equate to less than 1% of the total thin-section area. During digital image analysis, greyscale values were calibrated so that a range of values consistently represented the same mineral (e.g. calcite). The photomicrographs were collected at regular intervals along the length of the long axis of the thin section (spacing varied according to the length of the thin section but at intervals <8.5 mm). The area of porosity was quantified by systematically thresholding black areas at the darkest end of the greyscale range. The porosity of each of the five photomicrographs was averaged arithmetically and subtracted from 100% to define the mean total area of the rock ‘phase’ for each sample. The area of calcite was quantified by systematically thresholding the defined range of greyscale values that represent calcite, and checked by EDX analysis for the absence of Si and Al. The calcite percentage of each of the five photomicrographs was arithmetically averaged to define the mean area of calcite for each sample. The ratio of the mean area of calcite to the mean area of the rock ‘phase’ provides an estimate of the percentage area of calcite in each sample.

Oligo-Miocene sedimentology

The Oligo-Miocene sediments on the Maltese Islands developed as carbonate ramp facies in a relatively stable platform setting (Buxton & Pedley 1989; Pedley 1998; Brandano et al. 2009) around the northern margins of the African plate (the southern Peri-Tethys Platform). Vertical and lateral strata-stacking patterns were linked to sea-level changes, and the ramp was divided into inner, middle and outer zones. The sedimentology and pre-fault diagenetic pattern was studied in detail in the undeformed rocks so that accurate characterization and quantification of original porosity and pore networks could be achieved, and then compared with the effects of brittle deformation.

Lower Coralline Limestone

(grain-dominated carbonates)

The lowermost exposed formation on the Maltese Islands is the Oligocene Lower Coralline Limestone Formation (LCL). This formation consists of foraminiferal and coralline algal-rich wackestones, packstones, grainstones, floatstones and rudstones. Four members have been identified by Pedley et al. (1976): the Il Maqhaq, Attard, Xlendi and Il Mara members (from oldest to youngest). Owing to variations in the original depositional environment, not all members are seen at all locations. The focus of this study was on the Attard and Xlendi members at Qala Point and Madliena Tower (Fig. 2b), and the Il Mara Member at Ras ir Raheb (Fig. 2b & 3), along with the overlying Globigerina Limestone Formation (GL).

The Attard Member at Qala Point comprises massive rhodolith floatstones in a bioclastic packstone matrix. The rhodoliths are crustose in growth form and tend to be subspherical in shape. The bioclastic matrix contains abundant detritus of articulated coralline algae, larger benthic foraminifera, and fragments of echinoderms, bivalves and bryozoans. Rhodoliths have been observed in water depths from a few metres down to 150 m (Foster 2001). In modern western Mediterranean carbonate ramp environments, rhodoliths are most prolific in water depths of 40–90 m in the middle ramp facies (Fornos & Ahr 1997). In modern-day environments, larger benthic foraminifera facies can be found below the storm weather wave base at water depths from 40 to 60 m (Pedley 1998); however, heavily damaged and fragmented foraminifera tests (Beavington-Penney Taphonomic Scale ranking of 3) are indicative of allochthonous sedimentation. The lack of sedimentary structures and poor sorting of bioclasts suggests that this facies was reworked, transported down ramp and redeposited...
in a middle ramp setting, and/or were reworked in situ.

The Xlendi Member (Fig. 4a) is composed of planar to trough cross-bedded peloidal grainstones, packstones and rudstones. Coralline algae detritus include crustose and articulated forms. Deposits also contain varying amounts of benthic foraminifera, including larger benthic foraminifera (LBF) and miliolids. Articulated coralline algae are most abundant in water depths of less than 10 m in high-energy intertidal zones (e.g. Brandano et al. 2009). This observation is supported by the rounded nature of lithoclasts, the heavily damaged foraminifera tests (Beavington-Penney Taphonomic Scale ranking of 2 and 3; Beavington-Penney 2004) and the cross-bedding of the grainstones. Miliolids are more typical of shallow-water, lower energy environments, but are easily transported into higher energy areas (Hallock & Glenn 1986; BouDagher-Fadel 2008). Gatt & Gluyas (2012) suggested the miliolid foraminifera in Malta represent a water depth of less than 10 m. As such, the Xlendi Member represents part of the inner ramp, both high-energy barrier shoals and the back-barrier environment.

The Il Mara Member (e.g. Fig. 4b) is composed predominantly of LBF-rich packstones. Bioclastic beds can show swaley cross-stratification and LBF show a high degree of test damage (Beavington-Penney Taphonomic Scale of 2 or 3; Beavington-Penney 2004) and the cross-bedding of the grainstones. Miliolids are more typical of shallow-water, lower energy environments, but are easily transported into higher energy areas (Hallock & Glenn 1986; BouDagher-Fadel 2008). Gatt & Gluyas (2012) suggested a water depth range of 5–40 m. The heavily damaged foraminifera tests and cross-stratification in the upper beds of the Il Mara Member again suggests a relatively high-energy inner ramp origin, with many of the foraminifera being transported.

**Globigerina Limestone Formation (micrite-dominated carbonates)**

The Miocene Globigerina Limestone Formation unconformably overlies the Oligocene Lower Coralline Limestone. It is composed of foraminiferal-rich lime mudstones, wackestones and packstones with differing bioclastic contents and ichnofabrics. The formation is subdivided into three members (Lower, Middle and Upper) separated by hardground and phosphatic conglomerate couplets (Pedley et al. 1976). The focus of this study is on the Lower and Middle Globigerina members.

The Lower Globigerina Limestone Member is subdivided into three beds (Pratt 1990) according to their faunal content (the Gnejna, Mgarr-ix-Xini and Reqqa beds). The Gnejna Bed (e.g. Fig. 4c) is composed of bryozoa wackestones and packstones, which are bioturbated but display no distinct ichnofabrics. The microfauna include both benthonic and planktonic foraminifera, while the macrofauna includes bryozaen, solitary corals, pectinids and the echinoid Schizaster. The Mgarr Ix Xini Bed (Fig. 4d) is composed of bioclastic wackestones and packstones, and contains specific ichnofabrics such as Ophiomorpha nodusa and Thalassinoides (Pratt 1990). Macrofossils include the irregular echinoids Scutella and Schizaster, pectinids and other bioclastic debris. The Reqqa Bed (Fig. 4e) is...
more micritic and comprises foraminiferal wackestones. It is heavily bioturbated including *Thalassinooides* and *Kulindrichnus*. Microfossils include planktonic and benthonic foraminifera. Macrofossils include *Schizaster*, *Scutella* and pectinids. Pratt (1990) suggested that the faunal content of the Mgarr ix Xini Bed indicates a shallow subtidal environment of deposition (*Scutella* and

**Fig. 3.** Summary log measured away from fault zones through the Oligo-Miocene carbonate succession at Ras ir Raheb.
Ophiomorpha nodusa), while Challis (1979) suggested that water depth could be slightly greater, assigning the Scutella echinoids to a water depth of 10–75 m, if they are autochthonous. The overlying Reqqa Bed was considered by Challis (1979) to be much deeper, with a minimum water depth of 140 m based on the faunal content (Schizaster and pectinids). Gatt & Gluyas (2012) suggested water depths of more than 50 m according to the planktonic foraminifera assemblages.

**POROSITY–VELOCITY IN FAULTED CARBONATES**

**Fig. 4.** Representative thin-section photomicrographs of undeformed samples taken away from the fault zones. Samples are impregnated with blue resin to highlight porosity. (a) Xlendi Member peloidal–bioclastic grainstone. Faunal components include coralline algae and miliolids. (b) Il Mara Member peloidal–bioclastic grainstone with *Amphistegina*. (c) Gnejna Bed bioclastic wackestone. (d) Mgarr ix Xini Bed bioclastic packstone with solution-enhanced porosity. (e) Reqqa Bed bioclastic wackestone with solution-enhanced porosity. (f) Ras Ir Raheb Bed bioclastic wackestone with intragranular porosity. Plane polarized light.
The Middle Globigerina Limestone, in western Malta, is composed of the Ras ir Raheb Bed (Pratt 1990), which comprises foraminiferal wackestones to calcareous foraminiferal lime mudstones and marls (Fig. 4f). Faint wavy laminations and scour structures are observed together with ichnofabrics such as *Chondrites*, *Planolites*, *Paleophycus* and *Thalassinoides*. Planktonic foraminifera include *Globigerina* with minor benthonic foraminifera and macrofossils such as *Schizaster* and pectinids. Again, the presence of Schizaster would suggest deeper water (Challis 1979). The contact between the Lower and Middle members of the Globigerina Limestone Formation marks a depositional hiatus (Bennett 1980; Pratt 1990). It consists of at least two hardground surfaces associated with phosphatic conglomerate bodies. The initial hardground surface, termed the Terminal Lower Globigerina Limestone Hardground (Pratt 1990), is intensely bioturbated and eroded. Immediately overlying this is a second hardground surface (the Qammieh Hardground: Pratt 1990) identified by francolite and glauconite mineralization. The francolite and glauconite suggest a period of non-deposition.

**Pre-faulting diagenesis**

The presence of caves and karstic surface depressions containing Pleistocene bones of land-dwelling mammals (Pedley et al. 1976) and the lack of significant sediment thicknesses suggest that post-Messian Malta and Gozo remained emergent to the present day (Bonson et al. 2007). In addition, based on the total thickness of the exposed footwall stratigraphy above the level of the present-day outcrop of the Il-Maghlaq Fault in SW Malta, burial depth during the Miocene is unlikely to have exceeded 300 m (Bonson et al. 2007). Diagenetic modifications to the carbonates have therefore been limited and restricted to shallow burial and surface processes.

In the Attard, Xlendi and IL Mara members of the LCL Formation, syntaxial cementation on echi-noid fragments is the most volumetrically significant diagenetic process. Knoerich & Mutti (2006) used isotopic data to constrain the occurrence of syntaxial cementation to marine and marine burial diagenetic environments. Burial dissolution of aragonitic biota created mouldic porosity in the IL Mara Member (Knoerich & Mutti 2003). Primary porosity is also enhanced by a late phase of dissolution (Fig. 4a & b). The formation of the Lower GL Terminal Hardground required cementation of the Lower GL matrix. This cannot be observed at optical or SEM magnifications but small shifts towards lighter $^{13}\text{C}$ and $^{18}\text{O}$ isotopic values in the bulk rock of the hardground was used by Pratt (1990) to infer the presence of sub-micrometre-sized calcite, which is associated with the cementation of the hardground. The pore systems in some of the GL beds show a degree of solution enhancement (Fig. 4d).

**Tectonics and faulting**

**Regional tectonic setting**

During the Oligocene–Early Miocene, major rifting and plate tectonic reorganization occurred in the western Mediterranean, and also to the SE as 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 were originally deposited offshore Africa in a relatively tectonically quiescent area of the Mediterranean (Meulenkamp & Sissingh 2003). There is only limited evidence for synsedimentary tectonic movement from the mid-Miocene onwards, characterized by minor fault-controlled stratal thickness changes and the development of neptunian dykes (Dart et al. 1993; Meulenkamp & Sissingh 2003). By the Pliocene, the Pantellaria Rift had developed around Malta, with the major basin-bounding normal faults of the Pantellaria rift basin trending NW–SE (Fig. 2a). Uplift of the northern flank of the Pantellaria rift basin created the present-day Maltese Archipelago and is the origin of the major faulting in the islands today (Hill & Hayward 1988). This study targeted a set of subparallel, ENE–WSW- and WNW–ESE-trending normal faults that cut across the northern part of Malta, the southern part of Gozo, and are well exposed along the coastal sections at Ras ir Raheb, Qala Point and Madliena Tower (Fig. 2b). Similarly oriented faults occur throughout Malta and Gozo, and are conjugate to the NW–SE-trending basin-bounding faults that, with the exception of the Il Maghlaq fault system in the SW of Malta, only occur offshore.

**Fault zones studied**

A set of normal faults with a variety of displacements from across Malta and Gozo have been studied. Faults in the vicinity of Ras ir Raheb (Fig. 2b) have displacements ranging from 0.52 m up to 25 m. Qala Point Fault Zone, SE Gozo, has a displacement of less than 22 m, while the Victoria Lines Fault, which is well exposed on the NE coast of Malta at Madliena Tower (Fig. 2b), has a displacement of up to 100 m (Pedley et al. 1976) similar to the low offset faults (<40 m vertical displacement) that affect many of the reservoirs in the Middle East (e.g. Yose et al. 2006) and elsewhere (e.g. the Machar field in the UK North Sea: Casabianca et al. 2007). The Maltese faults, of varying
Fault zones can be described as one or more slip surfaces with more or less continuous fault cores surrounded by wider enclosing damage zones. The established view of deformation in fault damage zones stems from studies of faults in siliciclastic host rocks, in which the intensity of fracture damage decreases exponentially with distance into the undeformed protolith, or host rock (e.g. Chester & Logan 1986; Caine et al. 1996). In detail, the sudden spike in fracture intensity (Fig. 6c; also seen in fracture density, not shown) occurs solely in the hanging wall and only in the micrite-dominated carbonate facies. Different fault rock types are observed along a single slip surface, especially at low displacements with juxtaposition of different carbonate facies. Different fault rock types are also observed between the grain-dominated and micrite-dominated carbonates. Grain-dominated carbonates deform on a grain scale, breaking up individual grains and clasts, whereas micrite-dominated carbonates tend to deform with larger through-going fractures, and can be recrystallized.

A specific example serves to define these architectural elements more clearly (see Fig. 6). The fault shown in Figure 6 is at the southern end of the Ras ir Raheb section, and has a displacement of 11.7 m. Detailed field mapping of the fault zone and wall rocks has been combined with fracture scanline data. Fracture intensity rises abruptly close to the fault zone, rather than with the continuous or gradually exponential pattern reported elsewhere (Chester & Logan 1986; Caine et al. 1996; Savage & Brodsky 2011). Although variations to the Chester & Logan (1986) fault zone architecture have been described previously (e.g. Caine et al. 1996; Faulkner et al. 2010), normal faults in Malta show a distinct architecture that does not follow the exponential decay for damage zone intensity with increasing distance. The faults studied have a single slip surface surrounded by a fault core and damage zone at very low displacements (<1 m; Fig. 5). Where fault displacements are greater than about 1 m, fault zones develop an asymmetric hanging wall damage zone in the micrite-dominated facies, with a high intensity of fractures, containing several slip surfaces, and bound by two or more major slip surfaces (Michie et al. 2014: Figs 5b–d & 6). Either side of the bounding slip surfaces, deformation is much less intense in both the hanging wall and the adjacent footwall (Fig. 6). In the grain-dominated facies, the fault zones are again well represented by the orthodox fault zone model, with a single fault core and a relatively narrow, symmetrically distributed, damage zone in both the hanging wall and footwall.

The fault core is primarily observed on the principal slip surface, especially at low displacements as, by definition, this is the slip surface with the most accumulated displacement. However, the development of several slip surfaces within the hanging wall in the micrite-dominated carbonates means that fault core can develop on any of these subsidiary faults, depending on their individual displacement. A variety of fault rock types are observed along a single slip surface, especially at higher displacements with juxtaposition of different carbonate facies. Different fault rock types are also observed between the grain-dominated and micrite-dominated carbonates. Grain-dominated carbonates deform on a grain scale, breaking up individual grains and clasts, whereas micrite-dominated carbonates tend to deform with larger through-going fractures, and can be recrystallized.

### Fault zone architecture

Fault zones can be described as one or more slip surfaces with more or less continuous fault cores surrounded by wider enclosing damage zones. The established view of deformation in fault damage zones stems from studies of faults in siliciclastic host rocks, in which the intensity of fracture damage decreases exponentially with distance into the undeformed protolith, or host rock (e.g. Chester & Logan 1986; Caine et al. 1996). In detail, the sudden spike in fracture intensity (Fig. 6c; also seen in fracture density, not shown) occurs solely in the hanging wall and only in the micrite-dominated MGL and LGL formations.

Different lithofacies – that is, the grain- and micrite-dominated carbonates – have different strengths, controlled by their texture; in the sections we have analysed, the grain-dominated carbonates are stronger and the micrite-dominated carbonates are weaker; and this is supported by in situ Schmidt hammer measurements (Aydin & Basu 2005). Schmidt hammer measurements are made on the surfaces of rock outcrops or samples and provide an approximate constraint for rock strength. However, these data form a useful relative guide for comparing a range of different rock types, especially in situ. Our Schmidt hammer data from Malta cluster into two distinct groups: calculated unconfined compressive strength (UCS) values of 33–45 MPa for the micrite-dominated units (e.g. LGL and MGL), and UCS values of 67–115 MPa for the grain-dominated units (e.g. LCL).
Different deformation styles are observed in the two lithofacies, caused by their different strengths and textures. The stronger grain-dominated carbonates show localized deformation, whilst the weaker micrite-dominated carbonates show more distributed deformation. Weaker micrite-dominated carbonates

Fig. 5. Annotated outcrop photographs showing the variation in fault architecture with increasing displacement for normal faults at Ras ir Raheb. Fault displacement for each location (a–d) is 0.52, 7, 11.7 and 25 m, respectively. Scale bars (m) refer to the cliff faces at the rear of the photographs and the width of the fracture zones. Red lines trace the key slip surfaces in the fault zones. Stereonets are lower-hemisphere, equal-area plots showing poles to measured faults (red) and other brittle fractures (black). Most faults and fractures trend ENE–WSW, and dip steeply to the north or south.
overlying stronger grain-dominated carbonates creates a mechanical stratigraphy at the length scale of the observed fault zones (Laubach et al. 2009). Note that we do not use the term fracture stratigraphy, as our fracture data (intensity and density from scanlines) shows significant lateral variation across fault zones within each stratigraphic unit (Laubach et al. 2009). The mechanical stratigraphy, based on the measured variations in UCS from the Schmidt hammer data and the different deformation styles observed in the grain- and micrite-dominated facies, produces the different fault zone architectures in these two stratigraphic units. An area of high strain occurs at the point of juxtaposition...
between the stronger grain-dominated carbonates and the weaker micrite-dominated carbonates, from which new slip surfaces nucleate and propagate upwards into the micrite-dominated hanging wall. This creates an intensely deformed zone in the hanging wall – or fracture splay zone – bound by discrete fault slip surfaces (Michie et al. 2014).

Relationships between $V_p$, $V_s$ and porosity

In order to understand the key controls on porosity and velocity in faulted and fractured carbonates, the contrasting effects of sedimentary facies, fault zone architecture and fault displacement need to be separated.

Effect of sedimentary facies: undamaged samples

In addition to facies, the types, sizes and distribution of porosity need to be known (e.g. Lønøy 2006) to understand the pore system fully. As for most carbonate datasets, a large range in porosity values has been observed in both the grain-dominated (packstones, floatstones and rudstones, 5–30%: Fig. 7a) and the micrite-dominated carbonates (wackestones, 12–38%: Fig. 7a). This wide range is, in part, related to depositional facies and early diagenesis, and this variation is reflected in the ultrasonic velocity data of undamaged samples taken away from fault zones (Fig. 7). Both $V_p$ (6000–2000 m s$^{-1}$) and $V_s$ (3000–1500 m s$^{-1}$) decrease with increasing porosity, an observation that has been well documented elsewhere (e.g. Anselmetti & Eberli 1993). At any given porosity, however, $V_p$ in the packstones, floatstones and rudstones is typically 1000 m s$^{-1}$ higher than in the wackestones (Fig. 7a), which could be due to the microporous texture in the micrite. This measurable difference in $V_p$ signature is similar to that documented by Weger et al. (2009), and the phenomenon has also been documented by Anselmetti & Eberli (1993) and Eberli et al. (2003). A similar relationship is observed with $V_s$, although the difference is not so great (Fig. 7b). Cross-plots of $V_p/V_s$ ratio v. porosity and $V_s$ v. $V_p$ also show these wide ranges in velocity values (Fig. 7c, d). The differences are less clear when porosity is plotted against $V_p/V_s$ ratio (Fig. 7c). Significant overlap exists between different facies types, with the ratio appearing to be more dominated by porosity. When $V_s$ is plotted against $V_p$, facies tend to be more clearly separated (Fig. 7d). It should be noted that although grainstones and lime mudstones do occur within the stratigraphy, they are limited in extent and have not been encountered in the fault and damage zones.

Clay content (i.e. aluminosilicate clay, not fine-grained micrite) has also been shown to have an effect on velocity, especially in siliciclastic samples (e.g. Han et al. 1986). The mineralogy of the micrite-dominated facies has been found to vary with variable amounts of pure calcite (Fig. 7e) in relation to aluminosilicate clays. Samples with significantly more aluminosilicate impurities, defined as <50% calcite by area on SEM with back-scattered electrons (BSE) images, have $V_p$ values around 1000 m s$^{-1}$ lower than those with fewer impurities (i.e. 70–80% calcite by area on SEM BSE images).

Effect of sedimentary facies: damaged samples

Using our extensive database of samples, we have also analysed velocity–porosity data in damaged samples taken from within fault zones, with the data separated by lithofacies (Fig. 8). We display the data using both of our classification schemes: the Dunham classification as used for the undamaged protoliths shown in Figure 7, and the grain or micrite-dominated classification based on the mechanical stratigraphy. $V_s$–porosity plots for damaged samples are shown in Figure 8a, b. In terms of porosity, the damaged sample values range from 2 to about 36%, with a significant cluster of data at the lower end of this range. Figure 8b shows that these low-porosity values are dominantly in the grain-dominated facies, with micrite-dominated facies ranging to higher porosities. There is again a clear negative correlation between velocity and porosity, visible in both $V_p$ and $V_s$ (Fig. 8a–d). In the $V_p$–porosity data there is clear evidence of two separate trends: a higher velocity trend for the grain-dominated samples (packstones, floatstones and rudstones) and a lower trend for micrite-dominated (wackestones) samples. At a given porosity, the grain-dominated facies exhibit velocities up to 2000 m s$^{-1}$ higher than the micrite-dominated facies. As for the undamaged samples, we ascribe this difference to a combination of factors, including microporosity and a higher proportion of aluminosilicate clay minerals in the micrite-dominated facies. $V_s$ v. $V_p$ plots provide a stark separation of the two mechanical units, with the stronger grain-dominated samples at higher velocities and the weaker micrite-dominated units at lower velocities (Fig. 8e, f).

Effect of fault zone architecture

Our structural analysis shows that each fault can be separated into three architectural components: a fault core; an intensely damaged zone (IDZ) bound...
Fig. 7. Graphs showing relationships between laboratory measured porosity and velocity by sedimentary facies (Dunham classification) using undamaged samples taken far from fault zones. All velocities measured at 1 MHz on dry, unconfined samples, and porosity measured using helium. PF Wackestone is Planktonic Foraminiferal Wackestone and GCA is geniculate coralline algae. (a) $V_p$ v. porosity. (b) $V_s$ v. porosity. (c) $V_p/V_s$ ratio v. porosity. (d) $V_s$ v. $V_p$. (e) $V_p$ v. porosity, by the area of calcite visible in the thin section.
Fig. 8. Graphs showing relationships between laboratory measured porosity and velocity samples taken from fault zones. All velocities were measured at 1 MHz on dry, unconfined samples, and porosity measured using helium. (a) $V_p$ v. porosity by Dunham classification of the protolith. (b) $V_p$ v. porosity by grain or micrite dominated facies. (c) $V_s$ v. porosity by Dunham classification of the protolith. (d) $V_s$ v. porosity by grain or micrite dominated facies. (e) $V_s$ v. $V_p$ by Dunham classification of the protolith. (f) $V_s$ v. $V_p$ by grain or micrite dominated facies.
Fig. 9. Graphs showing relationships between laboratory measured porosity and velocity samples taken from fault zones. All velocities were measured at 1 MHz on dry, unconfined samples, and porosity measured using helium. (a) $V_p$ v. porosity by fault zone architectural component for grain dominated facies. (b) $V_p$ v. porosity by fault zone architectural component for micrite dominated facies. (c) $V_s$ v. porosity by fault zone architectural component for grain dominated facies. (d) $V_s$ v. porosity by fault zone architectural component for micrite dominated facies. (e) $V_s$ v. $V_p$ by fault zone architectural component for grain dominated facies. (f) $V_s$ v. $V_p$ by fault zone architectural component for micrite dominated facies.
Fig. 10. Graphs showing the relationship between laboratory measured porosity and velocity by fault zone displacement. All velocities were measured at 1 MHz on dry, unconfined samples, and porosity measured using helium. (a) $V_p$ v. porosity by fault displacement for grain dominated facies. (b) $V_p$ v. porosity by fault displacement for micrite dominated facies. (c) $V_s$ v. porosity by fault displacement for grain dominated facies. (d) $V_s$ v. porosity by fault displacement for micrite dominated facies. (e) $V_s$ v. $V_p$ by fault displacement for grain dominated facies. (f) $V_s$ v. $V_p$ by fault displacement for micrite dominated facies.
by slip surfaces in the hanging walls of the micrite-dominated layers; and a weakly damaged zone (WDZ) in both the hanging walls and footwalls in both the micrite- and grain-dominated layers. The WDZ abuts abruptly against the undamaged protolith (undeformed rock). In this subsection we consider whether different architectural components of the fault zones can be identified using the porosity–velocity data. Sampling bias could be an issue as porosity and velocity data cannot be obtained from intensely fractured incohesive samples; however, there is a considerable – and statistically significant – database with which to work \( n = 283 \) (Fig. 9a, b). The only fault zone architectural component with any semblance of definition in porosity–velocity space is the fault core, especially where porosity values are \(<10\%\) in the grain-dominated facies (Fig. 9a, c). These data also show that differences in \( V_p \) and \( V_s \) values observed between undamaged and weakly damaged micrite- and grain-dominated carbonates are lost as these different rock types are progressively deformed and incorporated into the fault core through the flanking damage zones (Fig. 9a–d). \( V_p \) v. \( V_s \) plots show overlapping fields for protolith, damage zones and fault core in both the grain- and micrite-dominated facies. It would therefore appear difficult to reliably separate different fault architectural components from an analysis of velocity–porosity data alone.

**Effect of fault displacement**

In terms of fault displacement, we can see distinct trends in the velocity–porosity data, especially for the micrite-dominated facies (compare Fig. 10a with Fig. 10b). However, there are important lithological differences in the stratigraphic units involved in these different fault zones. The micrite-dominated units in the low displacement fault zones (0.52 and 11.7 m) are richer in aluminosilicate clay impurities when compared to their stratigraphic equivalents in the high displacement fault zone (100 m). Therefore, mineralogy rather than displacement is the likely cause of the separate trends seen in Figure 10b. However, at higher fault displacements, the overall scatter of the data is progressively reduced in comparison to porosity–velocity at lower displacements (Fig. 10a–d). It is clear that variation in fault displacement over 3 orders of magnitude \((10^0–10^2 \text{ m})\) does not produce any significant ‘signal’ in the velocity–porosity data (Fig. 10).

**Summary**

Porosity is well known to fundamentally influence the elastic properties and, therefore, the seismic velocities \( (V_p \text{ and } V_s) \) of rocks. Based on an integrated outcrop and laboratory study, we show that different sedimentary facies and fault zones can be characterized in detail, and the factors that control \( V_p \) and \( V_s \) can be identified and separated. This preliminary study demonstrates that carbonate facies type – whether grain- or micrite-dominated – has a significant effect: that is, a difference in both \( V_p \) and \( V_s \) of up to 1000 m \( \text{s}^{-1} \) (Fig. 11a). Faults with relatively small displacements \((<20 \text{ m})\) do not impart a measurable effect on the acoustic
velocities of their fault rocks, but those with greater displacements (e.g. 100 m) can show increases in \( V_p \) and \( V_s \) by up to 1000 \( \text{m s}^{-1} \), especially in the micrite-dominated carbonates. Within a fault zone, it is clear that progressive localization onto one or more slip surfaces and the refinement of fault rock through the damage zone into the fault core, produces a systematic reduction in porosity and increase in velocity (Fig. 11b).

The ultimate aim of this research is to predict elastic properties across fault zones using effective medium models (Kachanov 1993) in a way that will allow linkage between the frequency range from the ultrasonic laboratory-scale core plug samples to the in situ seismic-scale prospect. Ongoing additional analyses include the collection of sizes, shapes and orientations of pores and cracks through a combination of quantitative orthogonal thin-section image analysis and mercury injection capillary pressure (MICP) analysis. These measured data will be used as inputs for effective medium models: if the measured input porosity data produce predictions that match the laboratory ultrasonic (high-frequency) velocity measurements, it will lend confidence to predictions for the seismic (low-frequency) range using the same measured porosities. This will naturally be an iterative process and will form the next phase of this research. Our approach is centred on the accurate quantification of porosity and pore networks in both the undeformed and the deformed rocks. We use these data as building blocks to construct better models of velocity and permeability in the subsurface.

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References


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