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Influence of carbonate facies on fault zone architecture

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ABSTRACT

Normal faults on Malta were studied to analyse fault propagation and evolution in different carbonate facies. Deformation of carbonate facies is controlled by strength, particle size and pore structure. Different deformation styles influence the damage characteristics surrounding faults, and therefore the fault zone architecture. The carbonates were divided into grain- and micrite-dominated carbonate lithofacies. Stronger grain-dominated carbonates show localised deformation, whereas weaker micrite-dominated carbonates show distributed deformation. The weaker micrite-dominated carbonates overlie stronger grain-dominated carbonates, creating a mechanical stratigraphy. A different architecture of damage, the 'Fracture Splay Zone' (FSZ), is produced within micrite-dominated carbonates due to this mechanical stratigraphy. Strain accumulates at the point of juxtaposition between the stronger grain-dominated carbonates in the footwall block and the weaker micrite-dominated carbonates in the hanging wall block. New slip surfaces nucleate and grow from these points, developing an asymmetric fault damage zone segment. The development of more slip surfaces within a single fault zone forms a zone of intense deformation, bound between two slip surfaces within the micrite-dominated carbonate lithofacies (i.e., the FSZ). Rather than localisation onto a single slip surface, allowing formation of a continuous fault core, the deformation will be dispersed along several slip surfaces. The dispersed deformation can create a highly permeable zone, rather than a baffle/seal, in the micrite-dominated carbonate lithofacies. The formation of a Fracture Splay Zone will therefore affect the sealing potential of the fault zone. The FSZ, by contrast, is not observed in the majority of the grain-dominated carbonates.

1. Introduction

The details of fault zone architecture are important when considering fluid flow in the subsurface because faults can act as barriers, conduits or a combined conduit/barrier (Chester et al., 1993; Knipe, 1993; Antonellini and Aydin, 1994; Bruhn et al., 1994; Caine et al., 1996; Evans et al., 1997; Lockner et al., 2000; Billi et al., 2003; Agosta et al., 2007; Molli et al., 2010). Characterisation of the fault zone structure and analysis of fault propagation can help to provide a better understanding of the petrophysical properties of a fault zone, and therefore its influence on fluid flow.

The established fault zone architectural model was developed from observations of fault zones in siliciclastic and basement crystalline rocks, and describes a 'fault core' surrounded by a 'damage zone', with an exponential decrease in damage into the protolith (Chester and Logan, 1986; Caine et al., 1996; Vermilye and Scholz, 1998; Mitchell and Faulkner, 2009; Savage and Brodsky, 2011). The fault core is a zone (continuous or patchy) of intense deformation, where most of the fault displacement is accommodated. It is composed of fault rock, such as breccias, cataclasites and gouges, which commonly show little evidence of the primary fabric of the protolith (Engelder, 1974; Sibson, 1977; Groshong, 1988; Caine et al., 1996; Evans et al., 1997; Agosta and Kirschner, 2003; Chester et al., 2004; Berg and Skar, 2005; Agosta and Aydin, 2006; Tondi, 2007; Mitchell and Faulkner, 2009; Faulkner et al., 2010). The damage zone is an approximately tabular halo of fractured rock that accommodates smaller deformation by micro and macrofractures, tension gashes and subsidiary faulting, which are related to the fault growth (Caine et al., 1996; Chester et al., 2004; Agosta et al., 2007; Gaviglio et al., 2009; Mitchell and Faulkner,

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2009; Faulkner et al., 2010; Hausegger et al., 2010). It has been demonstrated that fault zones within carbonate facies can also conform to this architecture (e.g. Agosta and Kirschner, 2003; Storti et al., 2003). Conversely, other fault zones within carbonates are documented to have added architectural components, such as intensely and a weakly deformed damage zones (e.g. Micarelli et al., 2006; Ferrill et al., 2011).

Variations to this established fault zone architectural model are documented for all lithologies, including added and/or modified architectural components (e.g. Childs et al., 1997; Micarelli et al., 2006; Faulkner et al., 2010). Fault zone architecture also varies along fault strike due to interactions of faults, which creates segment linkage/relay zones (Peacock and Sanderson, 1991; Huggins et al., 1995). For example, dual fault systems bounding an intensely deformed zone may have a relay ramp (Larsen, 1988; Childs et al., 2009). The different fault zone structures influence petrophysical properties, such as porosity and permeability, of the faults (e.g. Faulkner et al., 2010).

The architecture of fault zones is controlled by how different lithologies and lithofacies deform (Aydin, 2000; Agosta and Aydin, 2006; Shipton et al., 2006; Riley et al., 2010; Loveless et al., 2011; Jeanne et al., 2012). In sedimentary rocks, the strength and texture (e.g. grain size, matrix, porosity) of the primary facies controls the deformation style (Hugman and Friedman, 1979; Shipton et al., 2006; Riley et al., 2010). The varied deformation styles causes the deformation mechanisms that accommodate the stress to differ in each lithology/facies. A mechanical stratigraphy also has a large influence over the evolution of the fault zone architecture, as the angle of dip will vary in layers of differing tensile strength, and the variable dip angles can create different architectures (Peacock and Zhang, 1994; Sibson, 1996; van Gent et al., 2010). These factors can create areas such as pull-aparts, dilatant jogs and asperity bifurcations (Childs et al., 1995; Peacock and Sanderson, 1995; Childs et al., 1996, 1997; Schöpfer et al., 2007a).

Detailed descriptions of different fault zone architectures, along with quantification of their petrophysical properties helps to predict fluid flow in fault zones. For example, a widely-held assumption is that the permeability in a damage zone increases into the fault zone with increased fracture-related porosity towards the principal slip surface (Caine et al., 1996; Evans et al., 1997; Lockner et al., 2000; Billi et al., 2003; Micarelli et al., 2006; Agosta et al., 2007; Agosta, 2008; Balsamo et al., 2010). However, fault zones may not conform to this traditional petrophysical characterisation of fault zones, because the spatial distribution of deformation will differ (e.g. Childs et al., 1997; Faulkner et al., 2003, 2010).

Not only can microstructures help to assess the hydraulic behaviour of fault zones, they can also be used to analyse the seismic versus aseismic behaviour of faults. For example, the occurrence of mirror-like slip surfaces, open or closed fractures, breccias/pulverised rock and/or pressure solution seams, and the cross-cutting relationships of these microstructures are used to interpret the seismic cycle of the fault (Agosta and Aydin, 2006; Billi and Di Toro, 2008; Fondriest et al., 2013; Gratier et al., 2013).

In this paper, we examine several normal fault zones on Malta, with varying displacement, from <0.1 m up to 90 m, so as to understand the propagation and evolution of faults in different carbonate lithofacies. Furthermore, we describe in detail the fault zone architecture and discuss the importance of fault zone architecture for fluid flow prediction. This analysis is achieved by using detailed field mapping, as well as spatial fracture analysis using circular scanlines. We will use these data to introduce a new architecture for fault zones. We also attempt to predict the fault zone architecture by understanding the influence of mechanical stratigraphy on deformation style.

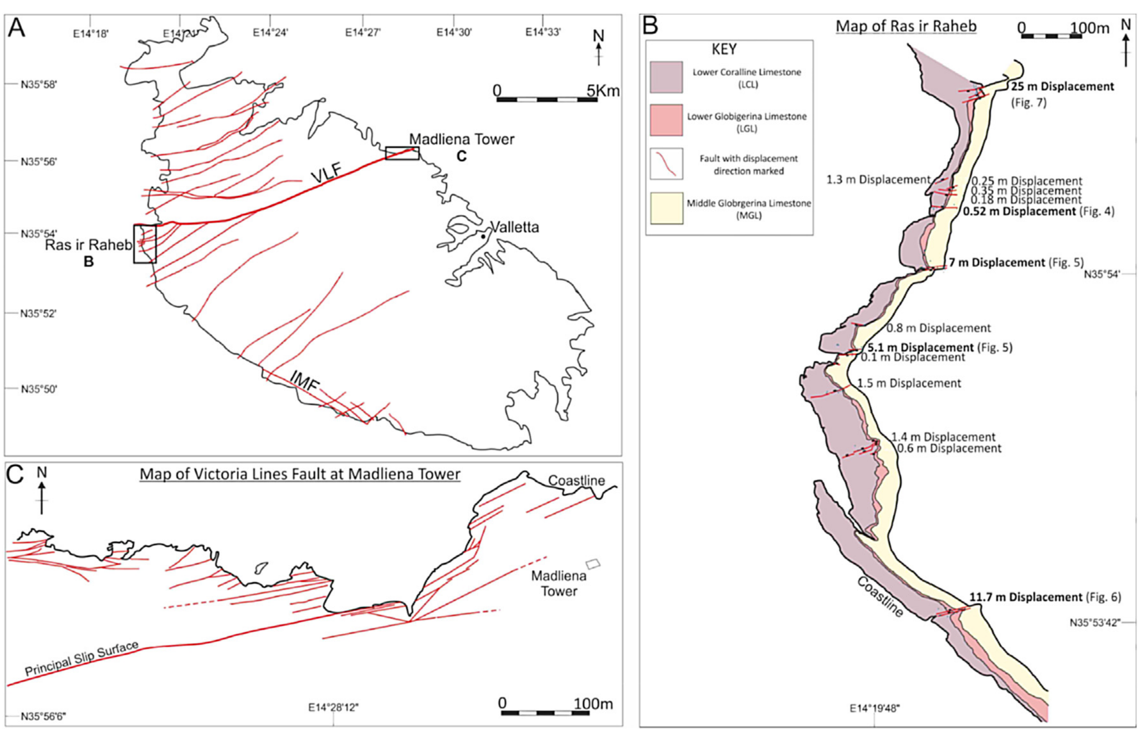

Fig. 1. A: Map of Malta showing the main faults (after Pedley et al., 1976), particularly, the ENE-WSW trending Victoria Lines fault (VLF) and the NW–SE Il Maghlaq fault (IMF). The two main localities on Malta used for examination of several faults are highlighted in boxes. Detailed maps of the two main localities are also shown; B: Ras ir Raheb exposing several normal faults and C: Madliena Tower exposing a graben bounding fault (the VLF). The fault zones studied in detail at Ras ir Raheb are shown in bold, and have 0.52 m, 5.1 m, 7 m, 11.7 m and 25 m displacement fault zones.