Journal of Structural Geology 76 (2015) 61–79

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Influence of host lithofacies on fault rock variation in carbonate fault zones: A case study from the Island of Malta

E.A.H. Michie*

School of Geosciences, King's College, University of Aberdeen, Aberdeen AB24 3UE, UK

ARTICLE INFO

Article history:
Received 27 November 2014
Received in revised form
2 April 2015
Accepted 22 April 2015
Available online 6 May 2015

Keywords:
Fault rock
Carbonates
Deformation mechanisms
Microstructures
Normal faults
Hydraulic behaviour

ABSTRACT

Relatively few studies have examined fault rock microstructures in carbonates. Understanding fault core production helps predict the hydraulic behaviour of faults and the potential for reservoir compartmentalisation. Normal faults on Malta, ranging from <1 m to 90 m displacement, cut two carbonate lithofacies, micrite-dominated and grain-dominated carbonates, allowing the investigation of fault rock evolution with increasing displacement in differing lithofacies. Lithological heterogeneity leads to a variety of deformation mechanisms. Nine different fault rock types have been identified, with a range of deformation microstructures along an individual slip surface. The deformation style, and hence type of fault rock produced, is a function of host rock texture, specifically grain size and sorting, porosity and uniaxial compressive strength. Homogeneously fine-grained micrtie-dominated carbonates are characterised by dispersed deformation with large fracture networks that develop into breccias. Alternatively, this lithofacies is commonly recrystallised. In contrast, in the coarse-grained, heterogeneous grain-dominated carbonates the development of faulting is characterised by localised deformation, creating protocataclasite and cataclasite fault rocks. Cementation also occurs within some grain-dominated carbonates close to and on slip surfaces. Fault rock variation is a function of displacement as well as juxtaposed lithofacies. An increase in fault rock variability is observed at higher displacements, potentially creating a more transmissible fault, which opposes what may be expected in siliciclastic and crystalline faults. Significant heterogeneity in the fault rock types formed is likely to create variable permeability along fault-strike, potentially allowing across-fault fluid flow. However, areas with homogeneous fault rocks may generate barriers to fluid flow.

1. Introduction

Fault zones in a variety of lithologies are commonly observed and modelled as having a single slip surface with a fault core surrounded by a damage zone (Chester and Logan, 1986; Caine et al., 1996). Damage zones accommodate lower strains by micro- and macro-fractures, tension gashes and secondary faulting, related to the fault growth and subsequent slip along the main fault (Caine et al., 1996; Chester et al., 2004; Agosta et al., 2007; Gaviglio et al., 2009; Hausegger et al., 2010; Mitchell and Faulkner, 2009; Faulkner et al., 2010). The fault core is a zone of high strain where most of the displacement is accommodated. It is usually accommodated by pervasive deformation that tends to destroy the original texture of the host rock, producing a variety of distinctive types of 'fault rock', such as fault breccias, cataclasites and gouge (Engelder, 1974; Caine et al., 1996; Evans et al., 1997; Agosta and Kirschner, 2003; Chester et al., 2004; Berg and Skar, 2005; Agosta and Aydin, 2006; Mitchell and Faulkner, 2009; Balsamo et al., 2010; Faulkner et al., 2010). Several fault rock types can occur in each lithology within a single tectonic and sedimentary setting. The processes that produce fault rocks can range from physical/mechanical comminution and particulate or 'granular' flow, to physico-chemical, such as pressure solution, cementation (including veining) and recrystallisation. Fault rock can also be produced by mixing different lithologies creating shale smears or clay gouge (e.g. Engelder, 1974; Aydin and Johnson, 1978; Lindsay et al., 1993; Antonellini and Aydin, 1994; Yielding et al., 1997; Fisher and Knipe, 1998; Storti et al., 2003; Agosta et al., 2007; Bonson et al., 2007; Bastesen and Braathen, 2010). Identification of the development of different fault rock types and their spatial distribution in fault cores is important when considering fluid flow

* Present address: Badley Geoscience Ltd, North Beck House, North Beck Lane, Hundleby, Spilsby, Lincolnshire PE23 5NB, UK. Tel.: +44 (0)1790753472.
E-mail address: emma@badleys.co.uk.

http://dx.doi.org/10.1016/j.jsg.2015.04.005
0191-8141/

in the subsurface, because it can significantly influence the permeability and frictional properties of the fault zones (Crawford et al., 2002; Agosta and Kirschner, 2003; Korneva et al., 2014).

The controlling factors for fault rock microstructural development include: fault zone architecture, displacement (total and on individual slip surfaces), slip rates, primary lithologies, distribution of mechanical properties, remote stress, residual stress, pore pressure, fluid content and temperature (Sibson, 1977; Childs et al., 1997; Fulljames et al., 1997; Fisher and Knipe, 1998; Childs et al., 2009; Michie et al., 2014). The fault zone architecture controls where and at what displacement fault rock production initiates (Childs et al., 1997; Hesthammer and Fossen, 2000). For example, a fault zone with multiple slip surfaces tends to have fault rock distributed as irregularly spaced lenses along their length and breadth (Childs et al., 1997).

Understanding the details of fault core production helps predictions of the sealing capacity of faults and, therefore, compartmentalisation within faulted reservoirs. Fault zone architecture, and hence location of fault rock, has significant implications for fluid flow pathways across and along fault zones (Childs et al., 1997; Færseth et al., 2007). On Malta, at displacements >1 m within weaker carbonates with lower uniaxial compressive strengths, fault zones have architectures with multiple slip surfaces. This causes fault rock development to be distributed over these surfaces and prevents a continuous fault core to be produced at displacements < 60 m, eliminating any sealing potential (Michie et al., 2014). The sealing capacity is also a function of the deformation mechanisms active in the production of fault rocks (Fisher and Knipe, 1998). Fault cores in general have often been interpreted as inhibiting across-fault fluid flow, because many fault rock types lower the hydraulic conductivity (e.g. Knipe, 1992; Antonellini and Aydin, 1994; Evans et al., 1997; Yielding et al., 1997; Gibson, 1998; Crawford et al., 2002; Bense et al., 2003; Billi et al., 2003; Flodin et al., 2005; Micarelli et al., 2006; Tondi, 2007). The deformation mechanisms that govern fault rock type can be inferred from the characteristically different deformation microstructures that are observed (e.g. Higgins, 1971; Groshong, 1988; Knipe, 1989).

Relatively few studies have examined fault rock microstructures in carbonate lithofacies (e.g. Tondi et al., 2006; Bonson et al., 2007; Agosta, 2008; Bastesen et al., 2009; Hausegger et al., 2010; Agosta et al., 2012) compared to studies in siliciclastic lithofacies (e.g. Engelder, 1974; Chester and Logan, 1986; Knipe, 1992; Chester et al., 1993; Hippler, 1993; Antonellini and Aydin, 1994; Caine et al., 1996; Evans et al., 1997; Fulljames et al., 1997; Yielding et al., 1997; Fisher and Knipe, 1998; Crawford et al., 2002; Flodin et al., 2005; Færseth et al., 2007). Previous studies show that deformation style varies with protolith porosity, creating different carbonate fault rock types. Porous carbonates have been documented to produce compactive shear bands by particulate flow involving grain rotation, translation and pore collapse, as well as pressure solution, lowering the porosity (Tondi, 2007). Low porosity carbonates are shown to cataclase and can be cemented, which also lowers the porosity and permeability (Agosta and Kirschner, 2003; Agosta, 2008). However, inherent host-rock heterogeneity, variety of pore types and increased diagenetic potential (Lucia, 1995; Lønøy, 2006) can also produce significant complexities recorded in carbonate fault rocks. These factors can result in a variety of deformation mechanisms occurring in similar carbonate lithofacies and the production of many composite fault rock types (e.g. Bastesen et al., 2009; Bastesen and Braathen, 2010). Each type of fault rock has a different hydraulic behaviour; therefore, along a single slip surface the fault core rocks could be both sealing and conductive.

Faulted carbonates outcropping on Malta were chosen for study due to their relative tectonic simplicity, the variation in lithofacies present, minimal background diagenesis and a range of fault displacements to analyse the controls on fault rock development. This study used field maps to identify the distribution and variety of fault rocks types in different lithofacies at increasing displacements. Optical microscope analysis of deformation microstructures is used to infer grain-scale deformation, to characterise how different fault rock types evolve in each lithofacies and to identify the controls on such evolution. The study addresses the following main points:

- Are different fault rock types consistently associated with the same magnitudes of displacement?
- How does variation of lithofacies juxtaposition influence fault rock evolution?
- What influence does the principal deformation mechanism(s) have on the evolution of fault rock types?

2. Geological setting

2.1. Regional tectonic background

Malta is located in the foreland of the Sicilian Apennine–Maghrebian fold-thrust belt. Normal faults present on Malta form part of a dextral transtensional system in the foreland. The ENE–WSW trending Maltese graben system within, and conjugate to, the NW–SE trending Pantelleria rift system, was formed during the Pliocene to Quaternary, creating many extensional basins with approximately N–S orientation of stretching (Pedley et al., 1976; Dart et al., 1993; Fig. 1). This study focuses on the ENE–WSW trending faults of the North Malta Graben. Depth of burial of the present day land surface at the time of faulting has been estimated to be 300 m, based on total thickness of exposed footwall stratigraphy above the level of present-day outcropping faults (Bonson et al., 2007). Normal faults on Malta have displacements ranging from 0.1 m to 210 m (Bonson et al., 2007), and have been shown to contain an architectural component with multiple slip surfaces, influencing fault core development, described below (Michie et al., 2014). The maximum displacement examined within this study is 90 m, at the eastern end of the Victoria Lines Fault (VLF) (House et al., 1961). Since studied faults range in displacement from 0.52 m up to 90 m, assuming that fault displacement accumulates with time, the range of displacements provides the opportunity to examine the evolution of carbonate fault core rocks.

2.2. Stratigraphy of Malta

The Maltese Islands are composed of different limestone lithofacies that were deposited on the shallow Mediterranean Pelagian Platform (Dart et al., 1993). Normal faults exposed on coastal sections propagate through two contrasting formations: the deeper Lower Coralline Limestone Formation (LCL) and the shallower *Globigerina* Limestone Formation (GL), of Oligocene to Miocene age (Pedley et al., 1976; Dart et al., 1993; Fig. 1). The LCL is a massively bedded, coarse grained, bioclastic-rich detrital limestone with limited sparite cement and a thickness of up to 140 m (House et al., 1961; Pedley et al., 1976; Dart et al., 1993; Bonson et al., 2007). The Lower and Middle *Globigerina* Members of the *Globigerina* Formation (LGL and MGL respectively) are fine-grained carbonates, dominated by G*lobigerina* foraminifera (Pedley et al., 1976; Dart et al., 1993). The thickness of the GL varies between 23 m and 207 m (Pedley et al., 1976).

To simplify the stratigraphy in order to document any controls on the deformation styles, the two formations (LCL and GL) have