Marine and Petroleum Geology 72 (2016) 62–82

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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

Research paper

Permeability evolution across carbonate hosted normal fault zones

Thomas J. Haines [a, b, *], Emma A.H. Michie [a, c], Joyce E. Neilson [a], David Healy [a]

[a] School of Geosciences, King's College, University of Aberdeen, Aberdeen AB24 3UE, UK
[b] Badley Ashton and Associates Ltd, Winceby House, Winceby, Horncastle, Lincolnshire LN9 6PB, UK
[c] Badley Geoscience Ltd, North Beck House, North Beck Lane, Hundleby, Lincolnshire PE23 5NB, UK

ARTICLE INFO

Article history:
Received 19 May 2015
Received in revised form
27 December 2015
Accepted 10 January 2016
Available online 13 January 2016

Keywords:
Permeability
Porosity
Pore systems
Carbonates
Normal fault zones

ABSTRACT

Carbonate lithologies tend to have highly heterogeneous and tortuous pore systems that are created and/or modified by diagenetic and tectonic processes following deposition. The correlation between porosity and permeability in carbonate lithologies is often poor as a result of their heterogeneous and complex pore systems. To effectively predict permeability, it is necessary to understand the processes that modify pore systems and quantify the impact of these modifications on permeability. Using outcrop exposures of normal fault zones hosted in carbonate lithologies on the Maltese Islands, this study documents the evolution of textures in contrasting carbonate lithofacies (wackestones, packstones and pack/grainstones) across two normal fault zones of varying displacement (*c.* 10 and 100 m). The pore system modifications associated with these textural changes are quantified using image analysis and point count methods, while porosity and permeability are measured across the studied fault zones using core plug porosimetry and permeametry techniques.

The fault related processes that occur within the fault zones are controlled by the primary lithofacies and to a lesser extent the fault displacement. Aggrading neomorphism is observed within the damage zones in the grain supported lithofacies and is postdated by fracturing. In the micrite supported lithofacies in the same damage zones, aggrading neomorphism is absent, but fracturing is prevalent. In the fault core, brecciation occurs in both lithofacies within the 10 and 100 m displacement fault zones, while cataclasis is only active in the grain supported lithofacies in the higher displacement fault zone. The mineralogical and textural compositions of the primary lithofacies dictate the processes that occur in the fault zones. These processes variably modify the pore systems and hence control the temporal evolution of permeability in the fault zones. Such observations can help understand reservoir quality distribution around fault zones in the subsurface reservoirs.

1. Introduction

Pore systems control the permeability of rocks. In carbonate lithologies, the pore systems reflect the depositional processes that form the rock and the diagenetic and tectonic processes that modify it. Immediately following deposition, permeability is higher in grainstones compared to packstones and wackestones because the grainstones contain larger quantities of connected interparticle macropores, while the packstones and wackestones host less macropores and are typically dominated by micropores due to the occurrence of lime mud (Loucks, 2002; Lucia, 1995). Additionally, the permeability in grainstones tends to increase with increasing grain sizes and better sorting (Lucia, 1995). Hydrodynamism controls on the quantity of lime mud, the grain size and the sorting and is hence a key depositional control on permeability (Loucks, 2002). Melim et al. (2001) shows that intraparticle macropores, such as those hosted within foraminifera, do not significantly contribute to permeability due to their isolated distribution. This indicates that the environmental conditions that promote the development of a given faunal assemblage, such as light and turbidity, also impose a depositional control on permeability.

Due to their metastable mineralogical compositions, carbonate lithologies are prone to significant diagenetic modifications following deposition. These textural changes can significantly modify the pore systems and drastically change the permeability. For example, calcite cementation has locally and pervasively occluded the primary interparticle macropore volume in shoal and

* Corresponding author. Present address: Badley Ashton and Associates Ltd, Winceby House, Winceby, Horncastle, Lincolnshire LN9 6PB, UK.
E-mail address: tj.haines.88@gmail.com (T.J. Haines).

http://dx.doi.org/10.1016/j.marpetgeo.2016.01.008
0264-8172/

marginal shoal deposits in the Natih E Member in Oman (Hollis et al., 2010). As a result of this calcite cementation, the average permeability decreases from 15.5mD to 2.84mD (Hollis et al., 2010). In similar shoal deposits in the Natih A and C Members, non-fabric selective leaching of the skeletal allochems has created abundant vugs and moulds; the pore system created by this dissolution hosts an average permeability of 324mD (Hollis et al., 2010).

In addition to diagenesis, tectonic stresses can overprint carbonate textures, modify the pore systems and ultimately impact the permeability. At the field to basin-scale, tectonic stresses can create a range of different structures including normal fault zones and fold and thrust belts. This study uses outcrop exposures to understand the impact of normal faulting on the evolution of permeability in carbonate lithologies. Normal fault zones are traditionally characterised into architectural elements (e.g. Caine et al., 1996; Agosta and Aydin, 2006; Mitchell and Faulkner, 2009). Caine et al. (1996; and references therein) proposed a simple model that categorises fault zones into a damage zone and a fault core. Damage zones are networks of subsidiary fault related structures, including small faults, veins, fractures, cleavage and folds (Caine et al., 1996). Alternatively, they are defined as the areas surrounding a fault in which the fracture density is above the background regional fracture density due to the presence of fault related structural elements that are absent elsewhere (Agosta and Aydin, 2006). Damage zones can be subdivided into different architectural elements based on the abundance and/or connectivity of structural features, such as fractures (Agosta and Aydin, 2006; Micarelli et al., 2006). For example, Micarelli et al. (2006) subdivide damage zones into intensely deformed (IDDZ) and a weakly deformed (WDDZ) according to the density and connectivity of fractures. The fault core can be composed of single or multiple slip surfaces and a range of different fault lithologies, such as carbonate breccias, carbonate cataclasites, carbonate and shale gouges, secondary calcite cements, veins and host rock lenses (Bastesen and Braathen, 2010; Chester and Logan, 1987; Mitchell and Faulkner, 2009; Sibson, 1977). The types of deformation that occur within fault zones are a function of porosity and primary lithofacies texture (Fossen et al., 2007; Underhill and Woodcock, 1987). For example, fractures form in low porosity carbonates in the damage zone of the Venere Fault Zone (Agosta et al., 2007), while in high porosity grainstones deformation bands develop as a result of grain rotation, compaction and cataclasis (Rath et al., 2011). Due to the creation of connected fracture networks, damage zones tend to have enhanced permeability relative to the protolithology (Agosta et al., 2010; Caine et al., 1996; Chester and Logan, 1986; Larsen et al., 2010). For example, the creation of fractures in low porosity carbonates in the Venere Fault Zone results in an increase in permeability relative to the protolithology (Agosta et al., 2007). In the fault core, cataclasis can cause pore systems to collapse resulting in permeability decreases (Micarelli et al., 2006; Tondi, 2007). Rath et al. (2011) document porosity reductions of 20–30% and permeability decreases of 3 orders of magnitude, compared to protoliths, as a result of grain rotation, compaction and cataclasis in grainstones from the Eisenstadt-Sopron Basin (Austria and Hungary).

Due to diagenetic and deformation processes, carbonate lithologies have highly heterogeneous and tortuous pore systems, which result in complicated porosity-permeability relationships and a poor understanding of the controls on permeability (Hollis et al., 2010; van der Land et al., 2013). A key approach to understanding permeability in carbonates is to document pore system characteristics (Anselmetti and Eberli, 1999; Budd, 2002; Melim et al., 2001; van der Land et al., 2013). For example, Budd (2002) documents pore system modifications associated with cementation and compaction in carbonate grainstones to understand the evolution of permeability. However, no studies have quantified the evolution of pore systems according to fault damage and the associated diagenesis in carbonate lithologies. This study characterises textural changes and the resultant pore system modifications across outcrop exposures of two carbonate hosted normal fault zones on the Maltese Islands to understand the spatial and temporal evolution of permeability in carbonate lithologies according to fault damage and fault related diagenesis. Such an understanding can be applied to subsurface reservoirs to improve reservoir quality predictions.

2. Geological background

2.1. Stratigraphy

The Maltese Islands, which are located in the central Mediterranean (Fig. 1 a and b), are composed of a sequence of Oligo-Miocene shallow water to pelagic carbonates (Buxton and Pedley, 1989). The stratigraphy of the Maltese Islands is subdivided into four formations (Pedley et al., 1976) (Fig. 1 c). This study focusses on the two lowermost exposed formations: the Oligocene Lower Coralline Limestone Formation and the Miocene Globigerina Limestone Formation (Fig. 1 c). The Lower Coralline Limestone Formation is subdivided into four members, which are, from oldest to youngest: 1) Il Maghlaq (Lcm), 2) Attard (Lca), 3) Xlendi (Lcx) and 4) Il Mara (Lcim) Members (Pedley, 1978) (Fig. 1 c). The Lower Coralline Limestone Formation is dominantly composed of coralline algae and larger benthic foraminifera rich wackestones, packstones, pack/grainstones, grainstones, floatstones and rudstones. The Globigerina Limestone Formation is subdivided into three members (Pedley et al., 1976), which are separated by hardground-conglomerate couplets and include (from oldest to youngest) 1) Lower Globigerina (Lgl), 2) Middle Globigerina (Mgl) and 3) Upper Globigerina Limestone (Ugl) Members (Pedley et al., 1976) (Fig. 1 c). Bryozoa wackestones and packstones and planktonic foraminiferal lime mudstones and wackestones comprise the Globigerina Limestone Formation.

2.2. Normal fault zones

The carbonates of the Maltese Islands are dissected by normal fault zones, which trend either ENE-WSW or NW–SE and range in displacement from several centimetres to greater than 100 m. The normal fault zones are associated with the Pantelleria, Linosa and Malta Grabens, which formed due to crustal extension in the foreland of the Maghrebian-Apennine fold and thrust belt (Fig. 1 a), possibly related to either ridge-push/slab-pull and or pull-apart kinematics (Gatt, 2012 and references therein). Major fault activity occurred from the Late Miocene onwards and, despite the differing fault trends, it is thought to be caused by a single phase of deformation (Dart et al., 1993).

This study focusses on two normal fault zones that dissect the Oligo-Miocene carbonates: 1) the Ras ir Raheb Fault Zone, which is an 11.7 m displacement fault zone exposed on the western coast of Malta at Ras ir Raheb (Fig. 1 b and 2) the Victoria Lines Fault Zone, which is a c. 100 m displacement fault zone (Pedley et al., 1976) that crops out across Malta, but is particularly well exposed on the northeast coast at Madliena Tower (Fig. 1 b). Michie et al. (2014) classify the fault zones into architectural elements including the protolith, which is undeformed and displays no fault related diagenesis, the weakly deformed damage zone (WDDZ), the fracture splay zone (also known as the intensely deformed damage zone, IDDZ) and the fault core. The WDDZ presents elevated fracture intensities and densities compared to the protolith, while the fracture splay zone, which is positioned within the hanging wall (HW), is bound by fault surfaces and is characterised by the highest fracture intensities and densities within the fault zone (Michie et al., 2014). The fault core, which is distributed along slip