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Sequential growth of deformation bands in carbonate grainstones in the hangingwall of an active growth fault: Implications for deformation mechanisms in different tectonic regimes

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ABSTRACT

Deformation bands in porous sandstones have been extensively studied for four decades, whereas comparatively less is known about deformation bands in porous carbonate rocks, particularly in extensional settings. Here, we investigate porous grainstones of the Globigerina Limestone Formation in Malta, which contain several types of deformation bands in the hangingwall of the Maghlaq Fault: (i) bed-parallel pure compaction bands (PCB); (ii) pressure solution-dominated compactive shear bands (SCSB) and iii) cataclasis-dominated compactive shear bands (CCSB). Geometric and kinematic analyses show that the bands formed sequentially in the hangingwall of the evolving Maghlaq growth fault. PCBs formed first due to fault-controlled subsidence and vertical loading; a (semi-)tectonic control on PCB formation is thus documented for the first time in an extensional setting. Pressure solution (dominating SCSBs) and cataclasis (dominating CCSBs) appear to have operated separately, and not in concert. Our findings therefore suggest that, in some carbonate rocks, cataclasis within deformation bands may develop irrespective of whether pressure solution processes are involved. We suggest this may be related to stress state, and that whereas pressure solution is a significant facilitator of grain size reduction in contractional settings, grain size reduction within deformation bands in extensional settings is less dependent on pressure solution processes.

1. Introduction

Deformation bands are tabular, mm-wide zones of localized shear and/or volume loss/gain that form in porous granular rocks through grain reorganization (disaggregation), grain crushing (cataclasis) and/or dissolution/precipitation (pressure solution, cementation) processes. Deformation bands have been mainly known to form in high-porous sandstones; natural examples are widely reported in the geological literature since the late 1970s (e.g. Aydin, 1978; Aydin and Johnson, 1978, 1983; Antonellini et al., 1994; Fossen and Hesthammer, 1997), and has later been supplemented by studies focusing on emulating deformation band growth through laboratory experiments (e.g. Mair et al., 2000; Mair et al., 2002; Vajdova et al., 2004) as well as in numerical models (e.g. Antonellini and Pollard, 1995; Klimczak et al., 2011; Chemenda et al., 2012). It is also well-established that deformation bands in porous sandstones may be associated with a bulk reduction in permeability in the range of 1–3 (occasionally up to six) orders of magnitude relative to host rock (e.g. Antonellini and Aydin, 1994; Taylor and Pollard, 2000; Sternlof et al., 2004; Fossen et al., 2007; Rotevatn et al., 2008; Ballas et al., 2012; Rotevatn et al. 2013); for pure compaction bands (sensu Mollema and Antonellini, 1996) in porous sandstones, up to 3 magnitude order permeability reductions have been reported (Baud et al., 2012; Deng et al., 2015).

Deformation bands in porous carbonate rocks, on the other hand, were first reported from laboratory experiments (Baud et al., 2000; Vajdova et al., 2004). Natural examples of these bands have been reported since the mid-2000s (Marchegiani et al., 2006; Micarelli et al., 2006; Tondi et al., 2006). Further studies have followed, including experimental work (Baxevanis et al., 2006; Baud et al., 2009; Vajdova et al., 2010; Zhu et al., 2010; Cilona et al., 2012, 2014; Ji et al., 2015) and field-based studies that document deformation bands predominantly in carbonate grainstones

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(Antonellini et al., 2008; Agosta et al., 2009; Cilona et al., 2012; Rustichelli et al., 2012; Tondi et al., 2012; Antonellini et al., 2014b), and recently also in chalk (Wennberg et al., 2013).

In general, deformation bands in carbonate rocks exhibit many similarities to their sandstone counterparts. This includes (i) that they are characterized by localized grain-scale shear in a mm-to-cm-scale zone rather than along a discrete slip surface (e.g. Tondi et al., 2006), (ii) strain hardening behaviour (Baud et al., 2009; Cilona et al., 2012; Ji et al., 2015), (iii) scaling properties (Tondi et al., 2012), (iv) magnitude of displacement (e.g. Tondi et al., 2006; Antonellini et al., 2008), (v) failure modes (Vajdova et al., 2004; Baxevanis et al., 2006; Cilona et al., 2014), (vi) sensitivity to changes in porosity and the shape and size of grains (Rustichelli et al., 2012; Cilona et al., 2014), and (vii) porosity-permeability reduction (Rath et al., 2011; Antonellini et al., 2014a; Tondi et al., 2016). However, there are other aspects of carbonate deformation bands that make them different from deformation bands in porous sandstones. *First*, whereas grain reorganization and cataclasis are the chief mechanisms for accommodating shear and compaction in porous sandstones (e.g. Antonellini et al., 1994; Fossen et al., 2007), pressure solution (in concert with cataclasis) seems to play a far more significant role in compaction- and shear localization in carbonate rocks, and appear to commonly occur at near-surface burial depths (e.g. Tondi et al., 2006, 2012; Cilona et al., 2012; Cilona et al., 2014). In fact, intergranular pressure solution is an important process that contributes to grain size and porosity reduction in deformation bands in grainstones (e.g. Tondi et al., 2006; Tondi, 2007; Rustichelli et al., 2012). However, there are also studies that report non-cataclastic and cataclastic deformation bands in porous carbonate rocks where evidence for pressure-solution processes is absent (Rath et al., 2011). Furthermore, Antonellini et al. (2014b) highlight a different micro-mechanism of deformation in carbonate rocks composed of soft micrite peloids, namely soft plastic deformation and subsequent smearing of the peloids, where grain crushing and pressure solution are subordinate micro-mechanisms. This plastic smearing is interpreted by Antonellini et al. (2014b) to occur due to the intragranular microporosity present in the peloids. *Second*, cataclasis, as a mechanism for strain accommodation in carbonate deformation bands, appears to be widespread at shallow burial depths (e.g. Micarelli et al., 2006; Tondi et al., 2012, 2016; Antonellini et al., 2014a). Contrastingly, in natural deformation bands in porous sandstones at shallow burial depths, grain reorganization is common (Mandl et al., 1977; Du Bernard et al., 2002; Bense et al., 2003); grain crushing in shallowly buried, poorly-consolidated sandstones have been reported in some cases (Cashman and Cashman, 2000; Rawling and Goodwin, 2003; Balsamo and Storti, 2011; Alikarami and Torabi, 2015) but is generally considered to be more common at greater burial depths (Mair et al., 2002; Fossen et al., 2007).

Third, and as a consequence of the former two points, permeability heterogeneity forming at shallow burial depths is more of a concern in carbonate rocks than in sandstones; deformation bands dominated by pressure solution and cataclasis, which may form at near-surface burial depths in porous carbonate rocks, may reduce permeability by 1–4 orders of magnitude (Rath et al., 2011; Antonellini et al., 2014a; Tondi et al., 2016). In poorly consolidated sandstones at shallow burial on the other hand, deformation is dominated by non-cataclastic bands that generally have little influence on permeability (Fisher and Knipe, 2001; Fossen et al., 2007). Rath et al. (2011) suggest that the reason for this difference may be that carbonates are able to accommodate strain by crystal plastic deformation (e.g. twinning, solution, and precipitation) already at shallow burial depths, in contrast to siliciclastic sediments where this is generally not possible.

Despite the significant progress made by previous workers, significantly less is known about the deformation bands in carbonate rocks compared to those of porous sandstones. Furthermore, the majority of existing studies of natural deformation bands in carbonate rocks clusters around a relatively small number of study areas predominantly in Italy (Table 1 and references therein). More outcrop studies are therefore needed in order to gain further insight to the structure, kinematics, and deformation mechanisms of deformation bands in carbonate rocks. This is particularly the case for extensional tectonic settings, since most previous studies have focused on contractional tectonic settings (Table 1).

The present study focuses on the structure and evolution of deformation bands in carbonate grainstones within syn-rift carbonate grainstones of the Globigerina Limestone Formation in Malta (Fig. 1), and we document for the first time the sequential development of compaction bands and compactive shear bands in the hangingwall of an extensional growth fault. In doing so, we aim to contribute towards improving the general understanding of the structure and evolution of deformation bands in porous carbonate rocks. This key aim is addressed through the following set of specific objectives; (i) to document and describe the geometry, morphology, microstructure and kinematics of the studied deformation bands; (ii) determine their porosity; (iii) elucidate their spatiotemporal evolution; (iv) discuss their mechanisms and conditions for formation, in light of previously published work.

Table 1
Overview of field areas where natural deformation bands in carbonate rocks have been studied.

Country	Region	Field location	References	Tectonic setting
Italy	Central Appenines	Majella Mountain	Marchegiani et al., 2006; Tondi et al., 2006; Antonellini et al., 2008; Agosta et al., 2009; Cilona et al., 2012; Cilona et al., 2014; Rustichelli et al., 2012; Tondi et al., 2016.	Contraction
	Northern Appenines	Cingoli Anticline	Antonellini et al., 2014b	Contraction
	NW Sicily	Favignana Island	Tondi et al., 2012; Tondi et al., 2016.	Contraction
		San Vito lo Capo peninsula	Tondi, 2007; Antonellini et al., 2014a	Contraction
	SE Sicily	Hyblean Plateau	Micarelli et al., 2006	Extension (syn-contractional)
Norway	Southern North Sea	Oseberg field	Wennberg et al., 2013	Extension
Austria/ Hungary	Austrian-Hungarian border	Eisenstadt-Sopron sub-basin of the Vienna Basin	Rath et al., 2011	Extension (subsequently also transtension and inversion)