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Dilatant shear band formation and diagenesis in calcareous, arkosic sandstones, Vienna Basin (Austria)

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Abstract

The present study examines deformation bands in calcareous arkosic sands. The investigated units can be considered as an equivalent to the Matzen field in the Vienna Basin (Austria), which is one of the most productive oil reservoirs in central Europe. The outcrop exposes carbonate-free and carbonatic sediments of Badenian age separated by a normal fault. Carbonatic sediments in the hanging wall of the normal fault develop dilation bands with minor shear displacements (< 2 mm), whereas carbonate-free sediments in the footwall develop cataclastic shear bands with up to 70 cm displacement. The cataclastic shear bands show a permeability reduction up to 3 orders of magnitude and strong baffling effects in the vadose zone. Carbonatic dilation bands show a permeability reduction of 1-2 orders of magnitude and no baffling structures. We distinguished two types of deformation bands in the carbonatic units, which differ in deformation mechanisms, distribution and composition. Full-cemented bands form as dilation bands with an intense syn-kinematic calcite cementation, whereas the younger loose-cemented bands are dilatant shear bands cemented by patchy calcite and clay minerals. All analyzed bands are characterized by a porosity and permeability reduction caused by grain fracturing and cementation. The changed petrophysical properties and especially the porosity evolution are closely related to diagenetic processes driven by varying pore fluids in different diagenetic environments. The deformation band evolution and sealing capacity is controlled by the initial host rock composition.

Keywords

Deformation bands; Cataclasis; Diagenesis; Permeability; Cementation; Fluid flow

1. Introduction

Deformation bands are tabular zones of localized strain in porous sedimentary rocks (Aydin, 1978; Antonellini et al., 1994). These features nucleate close to larger faults or in broad zones of distributed deformation, but are due to their low width (mm to cm) and small offset (< 1m) generally not recognized in seismic data. Nevertheless, grain reorganization,

cataclasis, pore collapse or preferred cementation may lead to a significant loss of porosity and permeability relative to the host rock (Fisher & Knipe, 2001; Rawling et al., 2001; Fossen and Bale, 2007). As a result, deformation bands locally influence the migration of fluids into reservoir rocks or deteriorate reservoir quality by compartmentalization. Examples of these effects are well documented in literature (Eichhubl et al., 2004; Exner et al., 2013; Ballas et al., 2014), but their actual relevance for reservoir properties needs to be evaluated individually. Deformation bands are classified by their kinematic properties and dominant deformation mechanism. In terms of kinematic behavior, deformation bands are grouped into shear-, compaction- and dilation bands (Aydin et al., 2006). Based on the dominant deformation mechanisms band types are classified as disaggregation bands, cataclastic bands and dissolution/cementation bands (Fossen et al., 2007). Factors like composition, grain size, shape, sorting, initial porosity, cementation and kinematic boundary conditions determine the deformation mechanisms and band type. Natural samples are frequently mixtures between different end members. Several studies investigated different band types which developed under natural (e.g., Rawling and Goodwin, 2003; Tondi et al., 2006; Balsamo and Storti, 2010; Soliva et al., 2013) and experimental conditions (e.g., Vajdova et al., 2004; Baud et al., 2009; Ciloni et al., 2012) in different kinds of host rocks, or proposed constitutive models for their formation (e.g., Wong et al., 1997; Borja and Aydin, 2004; Nicol et al., 2013).

In uncemented, arkosic sediments we recently documented cataclastic shear bands, which influence fluid flow as a result of permeability reduction caused by grain fracturing and preferred clay mineral cementation (Lommatzsch et al., in press). The present study investigates deformation bands in overlying sediments, which formed under identical kinematic conditions and show equal siliciclastic content (arkosic sands), but additionally contain carbonate bioclasts and varying amounts of calcite cement. These bands show similar macroscopic distributions, but in contrast they show no significant influence on fluid flow or shear displacement. Our aim is to quantify the effect of initial composition on the deformation band evolution, by analyzing their deformation mechanisms, diagenesis and petrophysical properties.

2. Outcrop description

The investigated outcrop is located at the northern margin of the Eisenstadt-Sopron Basin (Austria), which is a satellite basin of the Vienna Basin (Fodor, 1995). The abandoned sandpit exposes terrigenous, carbonate-free sands and shallow marine, carbonatic sediments of Badenian age (Fig. 1B; Sauer et al., 1992). Both lithologies are crosscut by numerous deformation bands with identical orientation and kinematics, and were formed at shallow depths < 150 m (Strauss et al., 2006). The region is dominated by an extensional deformation regime (ESE-WNW) in the vicinity of the Eisenstadt Fault (Fig. 1A), which shows about 80 m of dip-slip displacement down to the southeast of the basin and postdates the deposition of the investigated units (Fodor, 1995; Decker 1996). The terrigenous and marine lithologies are divided by a normal fault with presumably several tens of meters of displacement into carbonate-free sediments in the footwall and a ca. 20 m thick carbonatic unit in the hanging wall (Fig. 2A). The main normal fault is composed of multiple, anastomosing fault planes marked by greenish marly cataclasites and slickensides indicating

a dip-slip motion (Sauer et al., 1992). Following on previous studies in the terrigenous sands (Exner and Tschegg, 2012; Lommatzsch et al., in press), this paper is focused on the structures in the carbonatic sediments (Fig. 2). The investigated units comprise arkosic sands and gravels, which were reworked in a shallow marine environment (Sauer et al., 1992) and thus contain carbonate bioclasts. The beige carbonatic sands are intercalated with and gradually replaced by well cemented, massive limestone beds of several dm thickness towards the top of the outcrop, which are regarded as the base of the Badenian Leitha limestone due to their biogenic content (Fig. 1B). The planar bedding in the carbonatic host rocks dips gently to the southwest ($5-7^\circ$) and is characterized by a faint, cm thick layering and a parallel alignment of mollusk shells or accumulations of red algae (Fig. 2B). The quarry exposes two conjugated, intersecting sets of NNE-SSW trending deformation bands (Fig. 3). The main normal fault is parallel to the SE-dipping set of deformation bands and shows a similar orientation as the larger scale Eisenstadt fault. Due to the homogeneous host rock and limited outcrop conditions (ca. 8×6 m) in the carbonatic units, it is not possible to recognize full displacement or complete length of bands. The deformation bands continue as cracks with a few mm of opening mode displacement in the overlying limestone beds (Leitha limestone). Judging from the lack of shear displacement of the cemented beds and laminated calcareous sands along the bands, we infer a negligible shear displacement generally below a few millimeters. We identified two types of deformation bands in the carbonatic sands with mutually cross-cutting relationships (Fig. 2C), which differ macroscopically in distribution and cementation: loose-cemented bands (LCB) and full-cemented bands (FCB).

LCBs show a positive relief, slightly brighter colors and are not restricted to specific sediment layers. They occur in form of single bands and multistrand bands. Single bands are individual 0.5-2 cm thick zones (Fig. 2C). Several subparallel single bands can accumulate as multistrand bands, with interlinked eye and ramp structures. Their thicknesses range from 2 to 5 cm and they are often concentrated in 0.5-1 m broad zones (Fig. 2D). The single bands inside multistrands are separated by host rock material.

Multistrand bands commonly show a thickening, due to the continuous accumulation of single bands. LCBs offset FCBs by 0.5-2 mm in some rare examples, indicating a shear component (Fig. 2C).

FCBs appear as strong cemented single bands with thicknesses between 1.0 and 2.5 cm, but lack any observable shear displacement. The FCBs are straighter than LCBs and show a higher resistance against weathering (Fig. 2E). FCBs do not accumulate in multistrands and show in the most cases a similar orientation as the main fault in the outcrop.

3. Methods

Different deformation band types and related host rocks were sampled to conduct a combination of optical, mineralogical, petrological and chemical investigations. Polished thin sections were investigated under transmitted or reflected light with an optical microscope (Leica DM 4500PI) and the composition was determined by counting 300 points per thin section. Carbon coated thin sections were analyzed with a scanning electron

microscope (FEI Inspect S) at the Center of Earth Sciences, University of Vienna (Austria). We assessed back-scattered electron (BSE)/ secondary electron (SE) images and element distribution maps (EDX) to document the 2D/3D relationships between the components and the matrix. Quantitative chemical analyses (WDX-15kV/20nA) of detrital grains and carbonate cements were performed using a Jeol JXA 8530-F microprobe at the NHM-Vienna (Austria). Cathodoluminescence (CL) pictures were acquired by using a Lumic HC5-LM microscope (14 kV/ 5-7mA). In situ permeability measurements were performed by using a TinyPerm II portable air permeameter (New England Research Inc.) with a measuring range between 10^{-1} and 10^4 mD. For grain size analysis about 200-500 g material was treated with hydrogen peroxide (20%) and acetic acid (20%) in order to remove carbonatic bioclasts, cements and organic material. This procedure was chosen to evaluate the grain size reduction through fracturing and compare the results with the carbonate-free part of the outcrop. Therefore all grain size data refer only to the siliciclastic components, which are preferentially fractured in this material. The samples were analyzed with standard sieves (4- 2 -1 -0.5 -0.25 -0.125 -0.063 mm) in the range 4-0.063 mm. The silt/clay fraction was separated and the grain size distribution was obtained by a Sedigraph 5100 (Micromeritics) between 63 to 1 μm . X-ray diffraction (XRD) analyses were performed using a Panalytical PW 3040/60 X'Pert PRO diffractometer at the University of Vienna. Powdered bulk samples were measured between 2 to 70 $^{\circ}2\theta$ and clay fraction samples between 2 to 40 $^{\circ}2\theta$ (CuK α radiation, 40 kV, 40 mA, step size 0.0167, 5s per step). For clay mineral analysis, samples were carefully crushed by hand and disaggregated with EDTA (0.1 mol/L) to remove the carbonate and free iron oxides. The <2 μm fraction was collected by sedimentation in an Atterberg cylinder. Oriented samples on glass slides were prepared (8 mg sample in 1ml of distilled water) and analyzed after air-drying. Furthermore, the clay fraction were measured after saturated with K $^{+}$ or Mg $^{2+}$ ions, followed by ethylene glycol or glycerol saturation and/or heating to 550 $^{\circ}\text{C}$ (see Moore and Reynolds, 1997, for a full review). Major and trace element compositions were analyzed with a Philips PW2400 X-ray fluorescence spectrometer at the University of Vienna.

4. Results

4.1 Petrography and chemistry

The host sediment consists of detrital quartz, feldspar, metamorphic lithoclasts, bioclasts, biotite, sericite, authigenic clay minerals and calcite cements (Table 1). The bioclasts are coralline algae, echinoids, bryozoans, gastropods, bivalves, brachiopods and foraminifera. Bioclasts show different calcite cement rims and sparry calcite cements occur in pore space. Quartz grains are usually monocrystalline and feldspar grains are mainly albites with an intensive sericitization. Non-carbonatic lithoclasts are metamorphic in origin and consist of quartz, feldspar and mica. The host rock samples are friable coarse sands with mean grain diameters between 0.51-0.54 mm. Deformation band samples show mean grain diameters between 0.36 and 0.44 mm. The roundness of detrital grains is angular or subrounded, using standard charts by Pettijohn et al. (1987). All host rock as well as deformation band samples are poorly sorted (Folk and Ward, 1957). The host rock and deformation bands can be classified as calcareous, arkosic sandstones (according to Pettijohn et al., 1987). Deformation band samples show a relative increase of quartz grains and a decrease of

lithoclasts compared to the host rocks. The initial porosities of 20-27 % in the host rocks are reduced to 7-16 % in the related deformation bands. The loose-cemented bands (LCB) show an average porosity reduction of 8 % and the full-cemented bands (FCB) show an average porosity reduction by 15 %. The porosity reduction correlates with the average increase of calcite cements and authigenic clay minerals in the deformation bands (Table 1). FCBs are characterized by less than 10% authigenic clay minerals, less than 10% porosity and more than 25% calcite cement. In contrast, LCBs contain more than 10% authigenic clay minerals, more than 10% porosity and less than 20% calcite cement.

All host rock samples show permeability values (Table 1) above 10000 mD, which is beyond the measurable range of the air permeameter (TinyPerm II). LCBs show permeability values between 2230-5260 mD, which equals a reduction by 1 order of magnitude in comparison to the host rock. FCBs show values between 780-3870 mD, which equals a permeability reduction by 1-2 orders of magnitude (Table 1). Specific microfabrics as well as the relationships between components can be distinguished for the different types of deformation bands and host rocks. The grains in the host rock (Fig. 4A) show minor fracturing as a result of slight compaction, and authigenic minerals are restricted to bioclasts or altered sheet silicates. The transitional region between host rock and deformation band is characterized by an increase of authigenic minerals and fracturing of detrital grains (Fig. 4B). The matrix in LCBs is dominated by fractured grains, authigenic clay minerals and patchy sparry calcite cements (Fig. 4C-D). The FCBs are characterized by a widespread cementation of the initially free pore space with granular sparry calcite cement and minor amounts of authigenic clay minerals (Fig. 4E-F). Bulk mineralogical XRD-analysis (Fig. 5) show no qualitative differences between host rock and band samples. The only continuous variances are increased calcite peaks in all deformation band samples, due to their carbonate cementation. Bulk major element XRF-analysis (Table 2), especially the CaO values, reflect the mentioned changes in composition for deformation band and host rock samples.

4.2 Authigenic minerals

4.2.1 Carbonate cements—The investigated samples contain variable amounts of different cement types, i.e. micrite cements, bladed isopachous rims, dog tooth cements, syntaxial calcite overgrowths and sparry calcite. All of these cements exhibit either a dull (micrite) or a bright (blades, sparry calcite) red-orange luminescence (Fig. 4F). Carbonatic bioclasts are usually fully or partly micritised and may show a micritic envelope (Fig. 6A). Fine-grained micrite cement can fill pore space nearby coralline algae (Fig. 6B). Pore-filling micritic cements are rare and occur very locally. The micrite envelopes are covered by bladed or dog tooth cements (calcite), which also occur as isopachous rims (Fig. 6B). The elongated crystals (blades) show brighter luminescence and occasionally a zonation in CL images. These cement rims show equal or asymmetric thicknesses between 20 and 50 μm . Syntaxial overgrowth cements around echinoderm fragments are also common. The sample types differ by the amount and distribution of sparry calcite cements. Sparry calcite cements in host rock and LCB samples show a patchy distribution (Fig. 6C) with plenty of free pore space in between. The host rock generally contains less patchy sparry cement than the LCBs. In contrast, FCB samples show an almost complete pore space cementation with granular sparry calcite (Fig. 6D), which consists of medium-grained crystals without a

preferred orientation. Both sparry cement types are usually mixed with fractured pieces of detrital grains (Fig. 6D), bladed cements and/or authigenic clay minerals (Fig. 6F). Moreover, some LCB samples contain late bladed cements around siliciclastic grains, which show meniscus geometries.

Representative microprobe analyses confirm that all cements have a homogenous chemical composition and are relatively pure calcite with minor variations in magnesium content (Fig. 7). The results of point measurements show that the CaO content ranges from about 53.75 to 55.51 wt.%. The amounts of MgO vary slightly between micrite pore-filling cements (mean 1.04 wt.%), micritic envelopes (mean 0.99 wt.%) and sparry calcite (mean 1.02 wt.%). Only unmicritized bioclasts (Fig. 8) show notable differences in MgO content between the fossil core (0.26 wt.%) and the surrounding cements (0.79-1.33 wt.%). However, all measured MgO contents stay low, ranging between 0.11 and 1.55 wt.%. The mean FeO content is 0.06 wt.% and increases up to 0.36 wt.% (Fig. 7). MnO values are 0.02 wt.% on average and reach a maximum of 0.09 wt.%. Variations in the MnO and FeO values seem to be not related to a specific cement types. The ratios between low MnO and low FeO contents are apparently in the right range to cause the mentioned luminescence (Boggs and Krinsley, 2006).

4.2.2 Clay minerals—Representative XRD-patterns of the clay fraction (Fig. 9) show that host rocks and deformation bands contain a variety of authigenic clay minerals like smectite, vermiculite, illite and kaolinite. Microscope and XRD analyses confirm that LCBs (Fig. 9A-B) contain more authigenic clay minerals than FCBs (Fig. 9C-D). This seems to be related to the available amount of unfilled pore space, where authigenic minerals grow preferably. This does not apply to the host rock samples, which contain less clay minerals that occur locally next to altered grains. Both band types show increased illite, vermiculite and kaolinite peak intensities compared to the host rock. LCBs show as well an increase of smectite peak intensities (Fig. 9B). Vermiculite and smectite appear in band samples together at cleavage planes or rims of altered biotite grains, in combination with a local reddening through Fe-(hydr)oxides. Moreover, minor amounts of smectite occur as grain coatings, pore-bridging structures and together with pore-filling kaolinite (Fig. 6E). Most illite is present as Fe-oxide-impregnated clay mineral (smectite+illite) grain coatings and next to altered sericite grains in pore space (Fig. 6F). The amount and distribution of kaolinite suggest an extensive transformation of smectite or illite to kaolinite. Kaolinite is replacing most of the earlier clay minerals and occurs close to altered albite/sericite grains or fills primary and secondary porosity (Fig. 6E). Kaolinite is usually present as stacks of pseudo-hexagonal plate or book structures.

4.3 Microstructures

We investigated thin-sections of host rock, FCB and LCB samples to present the microstructural variations between them. Grain size distributions were measured to quantify the amount of cataclasis in the various band types. The pore space in deformation band samples is filled with detrital grain- or cement fragments and authigenic minerals (Fig. 4C), leading to porosity and permeability reduction compared to the host rock (Table 1). The host rock (Fig. 4A) shows just minor amounts of cementation and fracturing as a result of a slight

compaction. Deformation band samples show in general higher intensities of fracturing and cementation compared to the host rock.

Most of the resulting deformation structures are caused by collisions between weaker and stronger phases. Biotite grains show a strong exfoliation and spreading of the cleavage planes as a result of collisions with other grains or cements. All samples show fracturing of micritic rims, bladed rims and bioclasts (Fig. 10A). Pore-filling micritic cements locally show tensile fractures, which are often filled with late cements (Fig. 6B). Especially shell fragments are frequently fractured, which also affects (and thus post-dates) the surrounding authigenic calcite cements (Fig. 10A). Bladed or dog tooth cements often deform weaker biotite grains, indicating a prekinematic formation of these cements (Fig. 10B). Collisions with more rigid detrital grains break off pieces of the bladed or dog tooth cements. These fragments can fill pore space together with authigenic clay minerals or sparry calcite cements. In contrast, neither patchy nor pore-filling sparry calcite cements show deformation or fracturing features. Moreover, we do not observe any signs for deformation of authigenic clay minerals. Metamorphic lithoclasts are preferentially fractured along internal grain boundaries. Quartz as well as feldspar grains show intragranular fractures and mechanical abrasion (Fig. 10C). The release of sericite inclusions as a result of albite fracturing increases the amount of phyllosilicates in the matrix. Fractured grain fragments later deform less rigid grains like altered biotite (Fig. 10D).

The comminution of detrital grains and authigenic cements leads to grain size reduction in the deformation bands. We dissolved the carbonatic components with acetic acid (20%) and sieved the samples to evaluate the siliciclastic grain size reduction through fracturing. Mean grain diameters in LCB and FCB samples are reduced by 23.7 % on average (Fig. 11). For example the mean grain diameter is reduced down to 0.4 mm in a LCB (Fig. 11C), i.e. a reduction of 22.0 % compared to the host rock with a mean grain diameter of 0.51 mm. The example of a FCB (Fig. 11E) shows a mean grain diameter reduction from 0.52 to 0.38 mm, which equals a reduction by 26.6 %. All band samples (Fig. 11A-F) show a decrease in the 0.5-1 mm grain fraction and an increase of silt sized grains. Moreover, LCBs commonly show an increase in the 0.125-0.25 mm grain fraction. Microstructural observations indicate that the grain size reduction by fracturing is restricted to detrital grains and early cements. The fracturing processes took place before the pore space was partly or fully cemented by sparry calcite.

5. Discussion

In the following, we will discuss diagenetic processes and deformation mechanisms in the investigated calcareous, arkosic sands. Furthermore we will evaluate the influence of host rock composition on evolution and petrophysical properties of the deformation bands, in comparison to the deformation bands in the underlying carbonate-free sediments (Lommatzsch et al., in press). The siliciclastic grain content is identical in the carbonate-free part of the outcrop, as well as geometrical properties and kinematic conditions. The geometrical classification into single, multistrand and cluster bands is also applicable in both units, but cluster bands with the largest displacements are only exposed in the carbonate-free part. Accordingly we will only compare the properties of single and multistrand deformation

bands. Carbonatic and carbonate-free band types show a permeability reduction of 1-2 orders of magnitude in comparison to the host rocks. Apart from the composition, the most striking difference between the deformation bands of the two units is the magnitude of displacement: Non-carbonatic cataclastic shear bands (multistrands) show displacements up to 60 cm, whereas the carbonatic deformation bands (LCBs) just up to 2 mm in some rare examples.

5.1 Diagenesis

The changed petrophysical properties and especially the porosity evolution in the investigated band samples are closely related to diagenetic processes driven by varying pore fluids in different diagenetic environments (Fig. 12). The described differences between LCBs and FCBs are mainly caused by a different degree of authigenic cementation of primary pore space. Our observations suggest several pre-, syn- and post-kinematic cementation events, which generate the unique distribution of carbonate cements and authigenic clay minerals in the different band types. In accordance to Worden and Burley (2003), the term eogenesis refers to all interactions of detrital components with pore waters at surface or shallow burial under influence of the depositional system. Mesogenesis are diagenetic processes during burial at depths greater than 1 km, where the sediment is not anymore influenced by the depositional environment. The influence of effective burial diagenesis (mesogenesis) is thus negligible, since the deposits were most likely not buried deeper than 100-150 m (Exner and Tschegg, 2012). Telogenesis refers to all diagenetic reactions during exhumation- or inversion-related processes, which result in influx of meteoric fluids that are not related to the depositional environment.

Eogenesis—The investigated arkosic sands and gravels were reworked in a shallow marine environment in the Badenian (13-14 Ma, Fig. 1B), which led to an increased content of bioclasts and carbonatic material in the host rocks in comparison to the carbonate-free deposits in the northern part of the outcrop (Exner and Tschegg, 2012; Lommatzsch et al., in press). The first pre-kinematic cement precipitated shortly after the deposition. The eogenetic formation of micritic envelopes, micritization of bioclasts (Fig. 6A) and filling of pores with micritic cement takes place under shallow marine phreatic conditions (Moore, 2001). Isopachous bladed and dog tooth cements precipitated equally around carbonate grains and grew on already existing micritic cements (Fig. 6B), but rarely around siliciclastic grains. These cements are as well typical for shallow marine phreatic environments (Flügel, 2004). The chemical analyses (Fig. 7) and petrographic observations suggest that marine cement types such as aragonite or high-Mg calcite were replaced by more stable low-Mg calcite probably under meteoric conditions (Moore, 2001; Flügel 2004). Eogenetic cements occur in all sample types and are affected by compaction/fracturing in the following evolution of these sediments (Fig. 10B). Burial to a maximum depth of about 150 m leads to a slight compaction and porosity reduction in the host rock.

Telogenesis—The telogenetic evolution is dominated by strain localization and infiltration of meteoric fluids into the sediments. The granular sparry calcite filling the pore space in FCBs (Fig. 4E) forms under phreatic meteoric conditions (Moore, 2001). This syn-kinematic cement type precipitated exclusively along FCBs from calcium rich fluids which are not

related to the depositional environment anymore, but sourced by meteoric dissolution of overlying deposits (Leitha limestone). In contrast, the host rock and LCB samples are not affected by this intense cementation, but by the precipitation of a patchy sparry calcite (Fig. 6C) in the pore space. This patchy carbonate cement is clearly post-burial and post-kinematic (Fig. 12), since there is no petrographic evidence for deformation or fracturing. The patchy distribution of these cements indicates a precipitation after burial under meteoric vadose conditions, where both air and fluids are present in the pores (Flügel 2004). The patchy cement distribution reflects the distribution of fluids in the zone of capillarity (Moore, 2001). The partial dissolution of earlier cements through meteoric fluids in the host rock and limestones above are most probably the source for this cement type. The amount of patchy sparry calcite in FCBs is low, due to the previously widespread cementation by granular sparry calcite (Fig. 6D).

The syntaxial calcite overgrowth on echinoderm fragments could either be formed in a shallow marine or in a meteoric diagenetic environment (Flügel, 2004). We assume that the syntaxial overgrowths formed after burial under meteoric conditions (Moore, 2001), since they show no evidence for compaction or fracturing. Late low-Mg bladed cement rims in LCBs often show meniscus geometries and precipitate from a thin film of capillary water surrounding grains under meteoric vadose conditions (Flügel, 2004). These late rims do not occur in FCB samples, since there is no open pore space around the grains to precipitate cement rims. The intensity of telogenetic cement precipitation has to be related to the changed petrophysical properties, respectively the amount of porosity, permeability and grain size reduction in LCBs relative to the host rock. Either they act as preferred pathways for Ca-saturated fluids in the vadose zone or differences in capillarity facilitate fluid related dissolution and precipitation reactions. Several studies mention a preferred precipitation of authigenic minerals along deformation bands in the vadose zone, as a result of preferred fluid flow, fluid retention or capillary effects (Eichhubl et al., 2004; Ballas et al., 2012; Antonellini et al., 2014).

Authigenic clay minerals represent the latest telogenetic (Fig. 12) alteration products formed in a meteoric vadose environment. The amount of authigenic clay minerals in band samples depends on the available pore space. LCBs show accordingly the largest amounts of authigenic clay minerals due to their weak carbonate cementation and remaining high porosity (Table 1). Kaolinite is abundant in all band types and occurs close to altered feldspar, biotite and sericite (Fig. 6E). The alteration of detrital feldspar and sericite by acidic meteoric fluids is the main source for authigenic kaolinite in pore space (Brosse et al., 2003; Worden and Morad, 2003). Additionally, the deformation and alteration of biotite under meteoric vadose conditions facilitate the formation of vermiculite, smectite and kaolinite (Fordham, 1990), which we observe to a varying degree in all samples (Fig. 9). Smectite, vermiculite and illite precipitations are often partly or completely transformed to kaolinite as a result of a progressive diagenetic alteration in the vadose meteoric zone. Preferably in the LCBs, Fe-oxide-impregnated clay mineral grain coatings and bridge structures between grains can be observed, consisting of deformed biotite, smectite, illite and/or fractured pieces of albite, sericite and calcite cements (Fig. 6F). The grain size reduction by fracturing promotes easier bridging between the components. These clay bridges are clearly post-dating all compaction and deformation events. The pore-bridging

structures fill the remaining pore space between different carbonate cement generations and consequently reduce the porosity. The minor amounts of Fe-(hydr)oxides are restricted to clay mineral grain coatings/bridges and altered biotite. During the alteration of biotite, iron is oxidized and potassium is released, which forms iron precipitations and intercalated authigenic minerals like vermiculite or smectite (Wilson, 2004; Girty et al., 2013). FCBs show smaller amounts of authigenic clay minerals than LCBs, due to their widespread calcite cementation (Table 1).

5.2 Band evolution

The analyzed bands are characterized by a porosity and permeability reduction caused by grain fracturing and cementation. The only macroscopic differences between FCBs and LCBs are the deviant cementation and geometry (single or multistrand). The grain size reduction of 18-31% for siliciclastic grains is similar in both band types and depends just on the properties of the individual sample. Neither FCBs, single LCBs nor multistrand LCBs show significant differences in grain fracturing (Fig. 11). However, a clear age relationship can be inferred, since LCBs offset FCBs (Fig. 2C) and show a patchy sparry calcite cementation (Fig. 12). FCBs show in contrast no shear displacement and almost a complete pore space cementation with granular sparry calcite. We hypothesize that FCBs were formed in an early stage by grain reorganization and fracturing associated with dilation, which created pathways for Ca-saturated fluids and promoted the precipitation of syn-kinematic cements. Dilation as a result of band formation under low confining pressure has been reported from experimental (El Bied et al., 2002; Borja and Aydin, 2004; Cilona et al., 2012) and field studies (Du Bernard et al., 2002). Several studies reported as well a preferred fluid flow (Bense et al., 2003; Sample et al., 2006) and cementation (Wong et al., 1997) along dilation bands. Exner et al. (2013) described similar structures in dilation bands from the Matzen reservoir in the Vienna Basin, which turn into cementation bands caused by preferred dolomite cementation.

In order to estimate the porosity increase caused by dilation, the minus cement porosity was calculated using the point counting data. The FCB samples show 4-6 % porosity increase by dilation, which is followed by carbonate cementation. The analyses of dilation bands by Du Bernard et al. (2002) present a comparable porosity increase of about 7 % followed by clay mineral cementation. Furthermore, Exner et al. (2013) reported even higher values of minus cement porosity, which are related to dilation, cementation and dissolution of detrital grains in sandstones. The preferred syn-kinematic cementation may lead to strain hardening and consequently terminate strain accumulation in FCB samples. This is most probably the reason for the fact that FCBs do not develop multistrand structures. The prevention of strain accumulation respectively band formation by syn-kinematic cementation is also described by Antonellini et al. (2014). According to the classification of Aydin et al. (2006) we thus classify FCBs as volumetric deformation bands, which show a positive volume change (dilation) with respect to the host rock. Moreover, we speculate that FCBs started out with a shear component, which is not well developed due to the inhibition of further strain accumulation by syn-kinematic cementation. In this case these deformation bands can be described as cemented shear dilation bands. The LCB samples show as well a porosity increase by dilation of 4 % in average (minus cement porosity) and shear displacements of

0-2 mm. Because of that LCBs are classified as dilatant shear bands (Antonellini et al., 1994; Borja and Aydin, 2004; Okubo and Schultz, 2005), which form after the syn-kinematic cementation with granular sparry calcite in FCBs. Dilatant shear bands are preferably formed at low confining pressures whereas compactional shear bands are formed at higher confining pressures (Fossen et al., 2007; Cilona et al., 2012). Our band samples show no evidence for pure- or shear-enhanced compaction like loading/shortening related band distributions, pore collapse, slip surfaces or stylolites (Baud et al., 2004; Tondi, 2006; Eichhubl et al., 2010; Soliva et al., 2013).

The deformation band evolution (Fig. 13), which leads to an average porosity reduction of 8% (p.u.) in LCBs and 15% (p.u.) in FCBs, has the following sequence: (1) FCB formation by grain reorganization and fracturing at shallow depth, associated with dilation. (2) Preferred syn-kinematic precipitation of a sparry calcite cement in FCBs. (3) Strain accumulation stops along FCBs. (4) Formation of dilatant shear bands (LCB), which offset FCBs and are not effected by prior syn-kinematic cementation processes. (5) Growth of authigenic patchy calcite cements and clay minerals in all samples under vadose meteoric conditions. The mean grain size reduction of 22 % in a multistrand LCB (Fig. 11C) is significant smaller than the reduction of 52 % for a carbonate-free multistrand band (Lommatzsch et al., in press, figure 8). If we look in particular at the increase of silt-sized grains, it is obvious that the carbonate-free deformation bands show more cataclasis due to more shear displacement. The increase of silt-sized grains for non-carbonatic single and multistrand bands is 11-14 weight%. In contrast LCB and FCB samples show a much smaller increase of 3-5 weight%. Porosity and permeability reduction by shear enhanced grain fracturing is only a dominant factor in carbonate-free deformation bands.

5.3 Fluid flow and reservoir applications

We described dilation bands with a preferred syn-kinematic calcite cementation and dilatant shear bands in calcareous arkoses located at the base of the Leitha limestone in the Eisenstadt-Sopron Basin. The investigated units can be considered as an equivalent to the Matzen field in Austria, which is the most productive reservoirs in the Vienna Basin (Kreutzer, 1992; Strauss et al., 2006). Investigations by Exner et al. (2013) in these reservoir rocks reported negative effects on reservoir quality as a result of deformation band formation. They described cataclastic dilation bands, which develop to cementation bands by the precipitation of ferrous dolomite, and create hydrocarbon baffles in the Matzen reservoir. Analysis of deformation bands in the overlying Leitha limestone by Rath et al. (2011) showed a porosity reduction of 1.5 orders of magnitude and a permeability decrease by up to 4 orders of magnitude within the deformation bands, caused predominately by grain reorganization and compaction, followed by post-kinematic cementation and subsequent marginal cataclasis. Both studies emphasize the formation of barriers in combination with reservoir compartmentalization, caused by changed petrophysical properties within deformation bands. These observations are in accordance with earlier studies, which described porosity and permeability reduction by grain reorganization, grain fracturing and cementation in deformation bands (Fisher and Knipe, 2001; Hesthammer and Fossen, 2001; Tondi 2007; Torabi and Fossen, 2009; Wennberg et al. 2013). Additionally, several laboratory studies on deformation bands in porous siliciclastic and carbonatic rocks

mentioned similar deformation mechanism and resulting structures under experimental conditions (Baud et al., 2004, 2009; Zhu et al., 2010; Vajdova et al., 2010). Recently we described the formation of fluid baffles in arkosic sands and gravels in carbonate-free sediments in the same outcrop (Lommatzsch et al., in press). These bands show a permeability reduction up to 3 orders of magnitude (Fig. 14) with respect to the host rock, caused by grain fracturing and intensive clay mineral cementation. The strong baffling effects in the vadose zone are demonstrated by hematite precipitations along multistrand bands, cluster bands and between conjugated sets of deformation bands.

Unfortunately hematite precipitations structures are not observable in the carbonatic sediments. The dominant porosity and permeability reducing process in LCB or FCB samples is clearly the cementation with calcite or clay minerals, rather than a combination of cataclasis and clay mineral growth. The changed band evolution in the carbonatic sands is caused by differences in host rock composition, cementation and deformation mechanisms. Non-carbonatic multistrand bands show 23 % porosity reduction, whereas the carbonatic multistrand LCBs have only 8 % reduction and thus porosities between 11 and 16%. Single FCBs end up in a porosity range between 5 and 10%, which is equal to carbonatic-free multistrand and cluster bands that act as fluid baffles in the vadose zone (Lommatzsch et al., in press). Host rock compartmentalization or long term baffling effects along bands are unlikely in the carbonatic host rocks, since both band types occur very local and just show a permeability reduction of 1-2 orders of magnitude compared to the host rock (>10000 mD), with a remaining high permeability of 780-5260 mD (Fig. 14). All band types show still high amounts of connected pores. A significant control on fluid flow or reservoir quality is only reported from deformation band networks with a continuous distribution (frequency, length, thickness, zoning) and permeability reductions of 3-5 orders of magnitude within the individual bands (Fisher and Knipe, 2001; Sternlof et al., 2006; Fossen and Bale, 2007; Ballas et al., 2014).

6. Conclusions

- The deformation band types can be kinematically classified as dilation bands (full-cemented bands) and dilatant shear bands (loose-cemented bands).
- Carbonatic sediments in the hanging wall of a normal fault develop dilation bands with minor shear displacements (< 2 mm), whereas carbonate-free sediments in the footwall develop cataclastic shear bands with up to 70 cm displacement.
- The dominant mechanism for porosity reduction in full-cemented bands is calcite cementation. In contrast porosity reduction in loose-cemented bands is achieved by a combination of grain fracturing, authigenic clay mineral growth and patchy calcite cementation.
- The reduction of permeability in FCBs and LCBs of 1-2 orders of magnitude relative to the host rock is apparently not enough to create fluid baffles or barriers.

- Intensive grain fracturing in combination with clay mineral cementation in carbonate-free bands is more effective in terms of porosity and permeability reduction than moderate grain fracturing in combination with calcite cementation in carbonatic bands.

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Figure 1.

(A) Map of the outcrop location at the northern margin of the Eisenstadt-Sopron Basin (after Schmid et al., 2001). (B) Stratigraphic chart of the Badenian in Austria modified after Piller et al. (2004).

Figure 2.

(A) Overview of the studied outcrop: The different lithologies are divided by a main fault (red line) into carbonatic sediments and carbonate-free sediments. (B) Overview of the sampling site in the carbonate-free sands at the base of the Leitha limestone. (C) Several LCBs crosscutting and displacing a FCB by few mm – marked by a grey square. (D) Broad zone of multistrand band accumulation (LCB) (E) Full-cemented band example. HR = Host rock; LCB = loose-cemented band; FCB = full-cemented band.

Figure 3. Stereoplot with sets of deformation bands (solid great circles), bedding (dotted great circles) and main normal fault (dashed great circle) orientations (equal area projection, lower hemisphere).

Figure 4.

Transmitted light (pore space = blue), CL images and BSE images (pore space = black) of characteristic matrix assemblages in thin sections. (A) Host rock, containing detrital grains and bioclasts. (B) Boundary zone between the host rock and a FCB. (C) LCB matrix filled with authigenic calcite and clay minerals. (D) Carbonate bioclasts and cements in the LCB matrix showing an orange luminescence. (E) FCB matrix nearly complete filled with calcite cement. (F) Carbonate cement in the FCB matrix showing an orange luminescence. Qtz = quartz; Ab = albite; Bt = biotite; Kln = kaolinite; Smc = smectite; CB = carbonate bioclast;

MC = micrite cement; SC = sparry calcite cement; BC = bladed calcite cement; Kfsp = K-feldspar; FCB = full-cemented band; LCB = loose-cemented band.

Figure 5. Representative bulk XRD-patterns of a full-cemented band (DB-C8) and the corresponding host rock (HR-C8). Qtz = quartz; Ab = albite; Bt = biotite; Ser = sericite; Cal = calcite.

Figure 6.

Transmitted light (pore space = blue), SEM and BSE images (pore space = black) of diagenetic features in thin sections. (A) Bryozoan fully replaced by micrite and overgrown by bladed isopachous cements. (B) Dog tooth cements growing at pore-filling micritic cements. (C) LCB matrix filled with patchy sparry calcite, fractured grain pieces and authigenic clay minerals. (D) FCB matrix filled with granular sparry calcite and fractured grain pieces. (E) Release and alteration of sericite inclusions as a result of albite fracturing in a LCB. (F) Formation of clay mineral bridge-structures between grains pieces and patchy

sparry calcite cements in a LCB. Qtz = quartz; Ab = albite; Bt = biotite; Ser = sericite; Hem = hematite; Smc = smectite; IL = illite; Kln = kaolinite; DC = dog tooth calcite cement; CB = carbonate bioclast; MC = micrite cement; SC = sparry calcite cement; BC = bladed calcite cement; FCB = full-cemented band; LCB = loose-cemented band.

Figure 7.

Ternary diagram showing CaO, FeO, MgO content (wt.%) of calcite cements in representative samples: DB-C8, DB-C3 and HR-C8 (see Table 1).

Figure 8.

(A) Representative EPMA point measurements of the MgO content in a bioclast and different calcite cements. (B) EDX - Mg distribution element map of the analyzed area. CB = carbonate bioclast; MC = micrite cement; BC = bladed calcite cement; Qtz = quartz.

Figure 9.

XRD patterns of < 2 μm fraction samples of host rocks and corresponding deformation band types. (A-B) Host rock versus loose-cemented band. (C-D) Host rock versus full-cemented band. Temp = heated to 550 °C; Mg-Gly = saturated with Mg²⁺ ions and treated with glycerol; K-EG = saturated with K⁺ ions and treated with ethylene glycol; Mg²⁺ = saturated with Mg²⁺ ions; K⁺ = saturated with K⁺ ions; N = non-treated, air-dried; Smc = smectite; IL = illite; Ver = vermiculite; Klin = kaolinite; Ser = sericite.

Figure 10.

Transmitted light (pore space = blue) and BSE images (pore space = black) of microstructures in LCB samples. (A) Fracturing shell fragments, which also affects (and thus post-dates) the surrounding authigenic cements. (B) Bladed calcite cements deforming weaker biotite grains, as a result of band formation or compaction. (C) Quartz and feldspar grains showing intragranular fractures and mechanical abrasion. (D) Released sericite inclusions deform less rigid biotite grains. Qtz = quartz; Ab = albite; Bt = biotite; Ser = sericite; CB = carbonate bioclast; MC = micrite cement; SC = sparry calcite cement; BC = bladed calcite cement; LCB = loose-cemented band.

Figure 11.

Grain size distributions of the siliciclastic components obtained by sieving and sedigraph analyses. (A) Host rock versus multistrand LCB. (B) Host rock versus multistrand LCB. (C) Host rock versus single LCB. (D-F) Host rock versus single FCB. FCB = full-cemented band; LCB = loose-cemented band; Gm = geometric mean grain diameter (Folk and Ward, 1957).

Figure 12.

Paragenetic sequence for the main diagenetic processes. FCB = full-cemented band; LCB = loose-cemented band.

Figure 13.

Deformation band evolution. HR = Host rock; FCB = full-cemented band; LCB = loose-cemented band; OM = order of magnitude; Φ = porosity; k = permeability.

Figure 14.

Air-permeability data of deformation band types in carbonate-free and carbonatic host rocks. All host rock samples show values above 10^4 mD, which is beyond the measurable range of the permeameter (TinyPerm II). FCB = full-cemented band; LCB = loose-cemented band.

Table 1

Point counted (300×) compositions of host rocks and corresponding deformation band types. Air-permeability data of host rocks and deformation bands. All host rock samples show values above 10 Darcy, which is beyond the measurable range of the permeameter (TinyPerm II).

Band-Type:		Loose-cemented band (LCB)						Full-cemented band (FCB)					
Component [%]	Host	DB-C3	Host	DB-C4	Host	DB-C5	Host	DB-C1	Host	DB-C6	Host	DB-C8	
Quartz	12.3	14.3	12.3	13.0	13.0	15.0	10.0	12.6	13.3	15.3	12.6	13.6	
Feldspar	23.6	20.3	23.6	22.0	25.3	23.6	24.0	19.6	23.0	21.0	24.6	22.6	
Biotite	6.3	5.3	6.3	4.6	5.3	3.6	4.6	2.6	4.6	3.3	4.0	3.0	
Lithoclast (meta.)	8.0	5.0	8.0	6.0	8.6	7.3	5.0	3.6	9.3	5.6	5.6	4.0	
Bioclast (carb.)	9.3	6.0	9.3	5.6	6.0	4.0	8.6	7.0	7.6	5.0	9.0	6.6	
Sericite	2.3	6.0	2.3	4.6	3.3	7.3	2.6	3.6	2.3	4.0	1.6	3.0	
Calcite cement	9.6	17.0	9.6	16.0	6.3	12.3	10.0	31.0	10.3	29.0	12.3	28.0	
Authigenic clays	8.0	14.0	8.0	13.6	6.0	10.3	7.6	9.0	6.0	7.6	6.0	8.0	
Fe-(hydr)oxide	0.3	1.0	0.3	0.6	1.6	0.6	1.0	2.0	1.0	1.6	1.0	1.6	
Porosity	20.3	11.0	20.3	14.0	24.6	16.0	26.6	9.0	22.6	7.6	23.3	9.6	
Permeability:													
Minimum [Darcy]	>10	2.23	>10	2.33	>10	3.00	>10	1.19	>10	0.78	>10	1.29	
Maximum [Darcy]	>10	4.57	>10	5.12	>10	5.26	>10	3.87	>10	3.34	>10	3.55	
Average (n=10)	>10	2.75	>10	3.59	>10	4.24	>10	2.50	>10	2.20	>10	2.69	

Table 2

Representative XRF bulk major element compositions of host sediments and corresponding deformation band types.

Band-Type:	Loose-cemented band (LCB)				Full-cemented band (FCB)			
	Host	DB-C3	Host	DB-C4	Host	DB-C1	Host	DB-C8
in wt. %								
SiO ₂	69.81	66.86	69.81	67.47	69.20	55.04	68.71	57.21
TiO ₂	0.22	0.23	0.22	0.22	0.21	0.17	0.20	0.17
Al ₂ O ₃	12.40	12.18	12.40	11.98	12.41	9.42	12.16	9.83
Fe ₂ O ₃	1.41	1.38	1.41	1.31	1.35	1.17	1.28	1.06
MnO	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.03
MgO	0.62	0.66	0.62	0.68	0.64	0.88	0.62	0.73
CaO	7.72	11.28	7.72	10.79	8.62	24.96	8.92	22.70
Na ₂ O	3.95	3.22	3.95	3.73	3.99	3.07	3.89	3.13
K ₂ O	1.60	1.61	1.60	1.58	1.64	1.21	1.56	1.28
P ₂ O ₅	0.07	0.07	0.07	0.07	0.07	0.06	0.06	0.06
LOI	1.45	2.11	1.45	1.98	1.43	3.73	1.57	3.28
Total	99.27	99.72	99.27	99.83	99.58	99.74	98.99	99.48