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Dilation bands: A new form of localized failure in granular media

Xavier Du Bernard,[1] Peter Eichhubl, and Atilla Aydin

Rock Fracture Project, Department of Geological and Environmental Sciences, Stanford University, Stanford, California, USA

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[1] We report a structure that is characterized by a localized increase in porosity or dilation within a tabular band of on average 1–2 mm thickness in porous, poorly consolidated sand. These dilation bands formed in predominantly opening-mode and provide a sharp contrast to planar opening-mode fractures or joints with two discrete surfaces in consolidated, low porosity brittle rock. Our observation of dilation bands, together with previously recognized shear and compaction bands, complete the spectrum of localized deformation modes along tabular bands in poorly consolidated sand and sandstone consistent with recent theoretical predictions of deformation localization in granular media. *INDEX TERMS:* 5104 Physical Properties of Rocks: Fracture and flow; 5112 Physical Properties of Rocks: Microstructure; 5114 Permeability and porosity; 8020 Structural Geology: Mechanics; 8030 Microstructures. **Citation:** Du Bernard, X., P. Eichhubl, and A. Aydin, Dilation bands: A new form of localized failure in granular media, *Geophys. Res. Lett.*, *29*(24), 2176, doi:10.1029/2002GL015966, 2002.

1. Introduction

[2] Localized deformation modes of shear and compaction have been reported from granular materials deformed in the laboratory and under natural conditions [*Aydin*, 1978; *Antonellini et al.*, 1994; *Mollema and Antonellini*, 1996; *Mair et al.*, 2000; *Olsson and Holcomb*, 2000; *Wong et al.*, 2001] and from numerical simulations [e.g. *Regueiro et al.*, 1998; *Borja and Lai*, 2002]. The localization of deformation results in tabular bands generally referred to as deformation bands or, more specifically, as shear and compaction bands. Shear bands are characterized by a dominant shear displacement grachent that is accompanied by porosity reduction or compaction or, in some cases, by porosity increase or dilation [*Antonellini et al.*, 1994]. Compaction bands refer to tabular bands of localized porosity reduction or compaction that lack a macroscopic shear offset [*Mollema and Antonellini*, 1996]. Mathematical theories of deformation localization aimed at predicting the formation of shear and compaction bands as a function of material properties, loading conditions, and loading history [*Rudnicki and Rice*, 1975; *Issen and Rudnicki*, 2000]. These theories also predict the formation of dilation bands, i.e. bands of localized porosity increase that form in predominantly opening-mode with respect to their boundaries (Figure 1a). In this study, we present, to our knowledge, the first field evidence of dilation bands. These bands, forming in porous, poorly consolidated sand, are distinct from planar opening-mode fractures or joints (Figure 1b) [*Pollard and Aydin*, 1988] that are composed of two discrete surfaces and that are frequently observed in consolidated, low porosity brittle rock.

2. Structural and Textural Characterization of Dilation Bands

[3] We report dilation bands, a new form of localized failure, in poorly consolidated sand of late Pleistocene age exposed in the 83 ka Savage Creek marine terrace [*Cashman and Cashman*, 2000; *Harvey and Weppner*, 1992] near McKinleyville, northern California, USA. The sand contains abundant feldspar and lithic fragments, with sand grains subangular to subrounded, and a mean grain size of 0.2 mm [*Cashman and Cashman*, 2000]. Three sets of deformation bands exist in the footwall of the McKinleyville thrust, a fault that is considered seismically active [*Clarke and Carver*, 1992]: two apparently conjugate sets of bands [*Cashman and Cashman*, 2000] dipping approximately 30° in opposite directions and a third set of sub-horizontal bands (Figure 2a). All three sets of bands are preferentially cemented resulting in positive relief of the bands in outcrop (Figure 2b).

[4] The two sets of inclined bands consistently offset bedding laminations in a reverse sense and are thus recognized as shear bands. Single shear bands are a few grain diameter thick with slip of 1–5 mm and resemble shear or deformation bands described by earlier workers [*Aydin*, 1978; *Engelder*, 1974]. The third set of sub-horizontal bands is parallel or shallowly inclined to bedding along a direction that bisects the conjugate sets of shear bands (Figure 2a). Similar to shear bands, these sub-horizontal bands are 1–2 mm or 5 to 10 grain diameter thick. They are always spatially associated with shear bands, frequently originating at their tips and extending into their extensional quadrants. Sub-horizontal bands cut across but do not offset inclined markers such as cross beds, depositional unconformities and channel fill, and earlier shear bands. Lack of a macroscopic shear offset along sub-horizontal bands is consistent with a predominantly opening-mode failure. In analogy to opening-mode splay or wing fractures observed at the tips of faults [*Brace and Bombolakis*, 1963; *Pollard and Segall*, 1983], we conclude that the sub-horizontal set of bands form in predominantly opening-mode in response to slip along the inclined shear bands. The structural setting and the lack of macroscopic shear offset across sub-horizontal bands suggest that these bands represent a new class of structure in which dilation is localized within a thin tabular zone.

[1] Laboratoire de Géophysique Interne et Tectonophysique (UMR 5559), BP 53X, 38041 Grenoble cedex 9, France.

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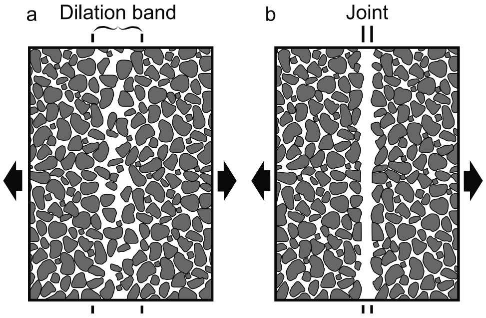

Figure 1. Dilation bands and joints as distinct classes of opening-mode failure. (a) Dilation bands are characterized by large pores that apparently grow from initial pores by grain displacement over a zone of finite width. (b) Joints are characterized by two discrete surfaces that form by inter- and transgranular fracturing and that move apart from each other.

[5] We collected oriented samples of all three sets of bands for micro-textural analysis in order to elucidate the micro-mechanisms of deformation and to quantify the inferred dilation. In-situ epoxy impregnation, followed by vacuum blue-epoxy impregnation in the laboratory, were used to preserve the original grain and pore geometry. In polished thin sections, shear bands are characterized by grain rotation and translation [*Cashman and Cashman*, 2000] and minor grain fracturing and grain size reduction. Grain rotation and translation resulted in porosity reduction and preferred orientation of elongate grains parallel to the bands. Remaining pore space in shear bands is preferentially filled with clay, predominantly kaolinite, chlorite, iron oxides, and organic matter. Sub-horizontal bands are identified in thin-section by an increased abundance of pore filling clay forming meniscus cement bridges across neighbouring grains (Figure 3a). In contrast to shear bands, no evidence of grain breakage was observed in sub-horizontal bands.

[6] To determine the amount of dilation within sub-horizontal bands, we point-counted the abundance of detrital grains (grain size >4 μm), clay, and residual pore space for 1500 points along transects across bands in four samples. Based on these point-counting transects, the abundance of detrital grains within sub-horizontal bands decreases by up to 7% (±3% 2σ) relative to the grain abundance outside of bands marked by line "A" in Figure 3b. The 7% reduction in detrital grain abundance correlates with an increase in clay abundance of 9% (±3% 2σ) with respect to the clay abundance outside the bands (line "B" in Figure 3b). Based on intact clay bridges across grains in sub-horizontal bands we infer that clay is largely a diagenetic phase resulting from mineral alteration and infiltration that occurred after band formation. Although part of the clay size fraction may predate band formation, we assume that the volume fraction of clay particles was uniform across the distance of point counting transects before band formation. We thus interpret the measured decrease in detrital grain abundance of 7% within the bands as the porosity increase or dilatancy associated with band formation. Subsequent precipitation and infiltration of clays may have prevented collapse of deformation-induced dilatancy after reverse slip on the inclined shear bands has seized. Based on the decrease in detrital grain abundance, the absence of grain fragmentation and of a macroscopic shear offset, and the preferred occurrence in dilational quadrants of shear bands, we designate the sub-horizontal bands as dilation bands.

3. Discussion and Conclusions

[7] A porosity increase or positive dilation has been observed previously for shear bands. Dilation of up to 8% was measured by *Antonellini et al.* [1994] for shear bands with little grain crushing in consolidated sandstone with porosity values of <12%. They observed locally enhanced dilation in the tip regions of shear bands which they interpreted as a transient effect at the tip of a propagating shear band. They explained dilation as a process associated with shearing within the framework of critical state theory of soil mechanics [*Wood*, 1990]. Critical state theory predicts failure at a critical porosity Φcr that is a function of effective mean stress $p' = [(\sigma_I + \sigma_{II} + \sigma_{III})/3 - p_f]$ where $\sigma_{I,\ II,\ III}$ are the principal stresses and p_f is the pore fluid pressure (Figure 4a and Figure 5). The porosity of undeformed sand in the Savage Creek terrace at the time of dilation band formation is not precisely known due to the unknown amount of clay contained in the sand at that time. Assuming that all clay was infiltrated after band formation provides an upper limit of porosity of 38% obtained by summing measured clay content and residual porosity. A lower bound value of the porosity is, of course, the present porosity of 22% (Figure 3b). Dilatant behaviour in the sand with a porosity of 22–38% occurred under shallow burial depth of the sediment and is consistent with low effective mean stress or confining pressure

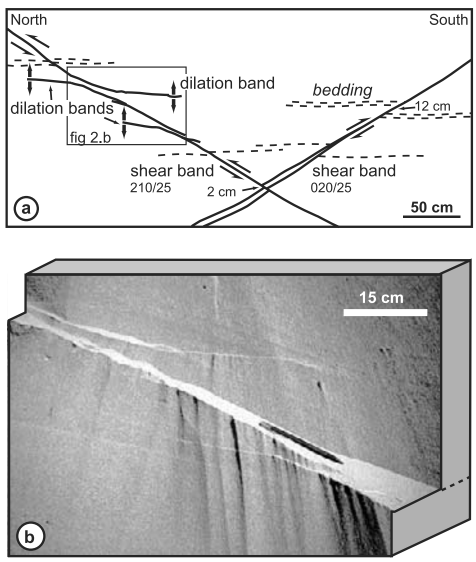

Figure 2. (a) Three sets of deformation bands in poorly consolidated sand exposed in the Savage Creek marine terrace, McKinleyville, California, USA. Dilation bands are sub-parallel to bedding and connected to the tips of shear bands with reverse slip. Slip along shear bands is indicated where observed. Orientation of shear bands is given as dip azimuth/dip. (b) Detail of (a) marked by rectangle.

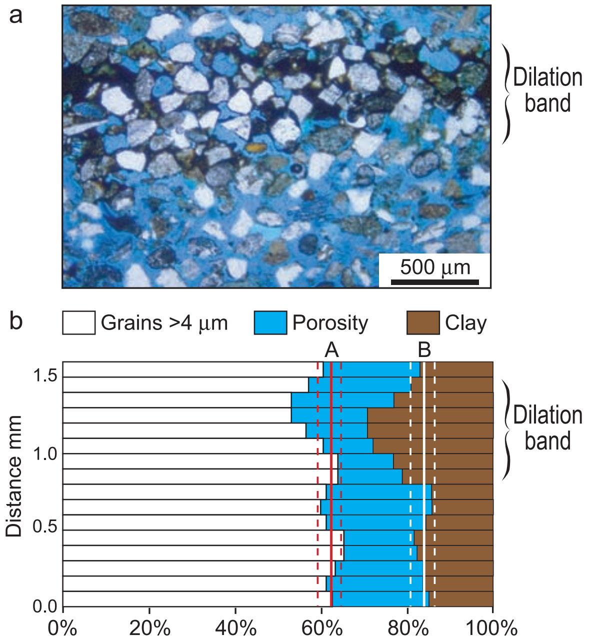

Figure 3. (a) Photomicrograph of a dilation band. Pore space is impregnated with blue epoxy. Interstitial space among sand grains within the dilation band is preferentially filled by a dark cement composed of clay minerals, iron oxide, and organic matter. (b) Frequency diagram of rock constituents and pore space based on point counting traverses across a dilation band. The band is characterized by a decrease in detrital grain (>4 μm in diameter) abundance compared to undeformed sand. Solid lines indicate mean values in detrital grain abundance ("A") and residual porosity ("B") away from bands, dashed lines indicate ±2σ error.

as predicted by critical state theory. The critical porosity at zero confining pressure Φcr_0 (Figure 4a) is not well constrained but a value close to 44% has been suggested [*Wood*, 1990]. Our observation of dilation band occurrence

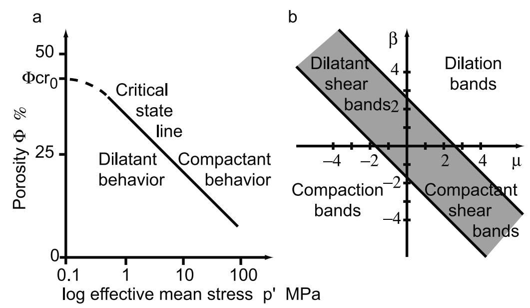

Figure 4. (a) Dilatant localized failure is predicted by critical state theory of soil mechanics for materials of porosity that is below a critical porosity Φcr defined by the critical state line. Dilatant failure in sand of the Savage Creek terrace with an inferred porosity of up to 38% at the time of dilation band formation required low effective mean stress which is consistent with an inferred low overburden stress. (b) Failure mode map based on bifurcation analysis after *Issen and Rudnicki* [2000], shown for Poisson ratio ν = 0.2. Dilation band formation is predicted for high values of β and μ where β is the dilatancy factor and μ the pressure sensitivity factor.

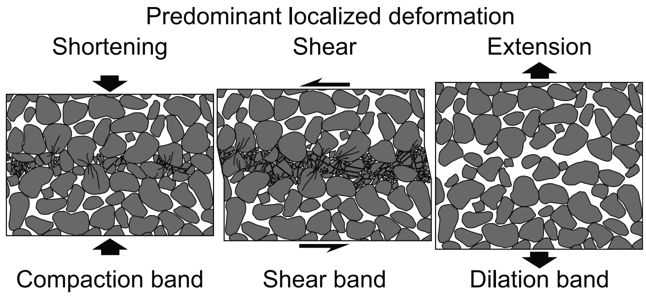

Figure 5. Tripartite classification of deformation bands based on the predominant displacement gradient: compaction, shear, and dilation.

in sediment of up to 38% porosity is high but is below the critical porosity value reported by *Wood* [1990].

[8] The localization of deformation in granular media along tabular bands has been treated by a series of workers using bifuration criteria. [*Wong et al.*, 2001; *Rudnicki and Rice*, 1975; *Issen and Rudnicki*, 2000; *Aydin and Johnson*, 1983; *Rudnicki and Olsson*, 1998; *Olsson*, 1999]. These models predict the occurrence of three end members of deformation bands-compaction, shear, and dilation bands-by defining a pressure-sensitivity parameter μ that characterizes the slope of the yield surface, and by a dilatancy factor β that characterizes the inelastic volume change associated with deformation. A positive value of β relates to a porosity increase or positive dilatancy with increasing loading. For axisymmetric loading the model predicts the formation of dilation bands perpendicular to the direction of the least compressive principal stress if

$$\beta + \mu > \sqrt{3}(2 - \nu)/1 + \nu \qquad (1)$$

[*Rudnicki and Olsson*, 1998; *Issen and Rudnicki*, 2000] where ν is the Poisson ratio.

[9] Formation of dilation bands perpendicular to the least compressive principal stress and parallel to the direction of greatest compression is consistent with the observed dilation band orientation bisecting the acute angle between the two sets of shear bands (Figure 2a) and at the extensional quadrants of the individual shear bands in the study area. Both parameters μ and β in (1) are material dependent and also dependent on loading conditions and history. Based on triaxial deformation experiments of Vosges sandstone with a porosity of 22%, both parameters μ and β were found to be positive at low confining pressure [*Bésuelle*, 2001]. In

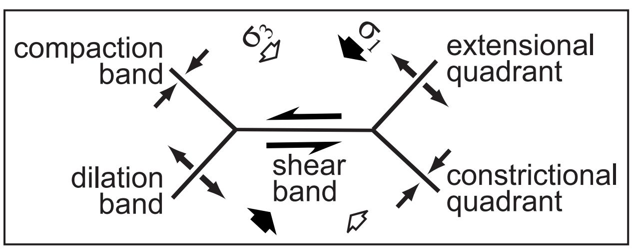

Figure 6. Idealized diagram depicting the coexistence of shear, compaction, and dilation bands similar to discontinuous modes of failure. Greatest and least remote principal stresses are indicated by σ_1 and σ_3, respectively.

extension tests, samples failed along surfaces perpendicular to the least principal stress direction at confining stresses below ∼20 MPa [*Bésuelle et al.*, 2000]. These experiments suggest formation of dilation bands under shallow burial conditions consistent with their occurrence in late Pleistocene unconsolidated sands where we estimate overburden stresses less than about 1 MPa at the time of dilation band formation. Alternatively, suitable subsurface conditions are expected at elevated pore fluid pressure resulting in low effective confining stress. Although currently exposed under unsaturated pore fluid conditions, dilation bands exposed in the Savage Creek marine terrace may have formed under saturated conditions in association with transient coseismic increases in pore fluid pressure due to slip on the nearby active McKinleyville thrust fault. Formation of dilation bands in association with slip on the main thrust fault is consistent with their spatial association with reverse shear bands that have been suggested to form coseismically [*Cashman and Cashman*, 2000].

[10] With the recognition of dilation bands as a natural mode of localized failure in granular materials, we propose a tripartite classification of deformation bands based on the predominant displacement gradient (Figure 5) across the band: compaction bands with predominant band-perpendicular shortening, shear bands with band-parallel macroscopic shear offset with or without volumetric strain, and dilation bands with predominant band-perpendicular extension described in this report. These three end member modes of localized failure with finite width correspond to equivalent modes of discontinuous failure with predominant shortening, shear, and opening displacement discontinuities in fracture mechanics: pressure solution seams, slip surfaces, and joints or dikes, respectively. Similar to joints forming in tensile and solution seams forming in compressive quadrants of terminating faults [*Pollard and Segall*, 1983], we propose that all three types of deformation bands may coexist under favourable conditions: Dilation bands in tensile quadrants of shear bands, and compaction bands in compressive quadrants (Figure 6).

[11] Shear and compaction bands have been recognized as potential barriers for subsurface fluid flow [*Antonellini and Aydin*, 1994]. Whereas shear and compaction bands are characterized by grain translation, pore collapse, and grain crushing that result in porosity and permeability reduction, the increase in porosity associated with dilation bands in this study is likely to render them as preferred fluid migration pathways at the time of their formation or immediately after. The increase in permeability may be transient, however, due to preferred infiltration and precipitation of clays along dilation bands as observed in the study area.

[12] In conclusion, we reported a new class of deformation band structure, the dilation bands, in poorly consolidated sand under near-surface conditions. This finding confirms earlier theoretical predictions and completes the spectrum of possible modes of localized deformation.

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X. Du Bernard, P. Eichhubl, and A. Aydin, Department of Geological and En-vironmental Sciences, Stanford University, Stanford, CA 94305, USA. (xduberna@ obs.ujf-grenoble.fr; eichhubl@pangea.stanford.edu; aydin@ pangea. stanford.edu)