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Clast-cortex aggregates in experimental and natural calcite-bearing fault zones

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A B S T R A C T

We investigated the formation mechanisms of rounded clast-cortex aggregates, a composite grain found in the slipping zones of faults hosted in calcite- and clay-rich rocks. The natural aggregates contain a central clast commonly made of host-rock fragments or reworked cataclasite from the slipping zone. The central clasts are surrounded by an outer cortex of calcite or clay grains a few μm or less in size. In laboratory experiments on calcite gouges using two rotary-shear apparatus we investigated the dependence of clast-cortex aggregate formation on the applied slip rate, normal stress, total displacement and ambient humidity. Clast-cortex aggregates formed at all investigated slip rates (100 μm/s to 1 m/s) but only at relatively low normal stresses (≤5 MPa). The aggregates were better developed with increasing displacement (up to 5 m) and did not form in experiments with water-dampened gouges. In the experiments, aggregates formed in low-strain regions within the gouge layers, adjacent to the highest-strain slip zones. We propose that clast-cortex aggregates in calcite-bearing slip zones form in the shallow portions of faults during shearing in relatively dry conditions, but our experiments suggest that they cannot be used as indicators of seismic slip. Formation involves clast rotation due to granular flow accompanied by accretion of fine matrix material possibly facilitated by electrostatic forces.

1. Introduction

A wide variety of micro- and meso-structural features are produced in fault zones from the interaction of deformation processes operating (often synchronously) across a range of time and length scales (e.g. Snoke et al., 1998). Recognizing (micro)structures that are characteristic of particular deformation conditions (e.g. of strain rate, total strain, fluid content) is a critical step towards interpreting fault mechanical behavior. For example, identifying seismic slip in the rock record (Cowan, 1999) relies on the identification of tectonic pseudotachylytes formed by frictional melting (Sibson, 1975; Di Toro et al., 2009), although many other fault-related structures and geochemical signatures are currently being investigated as potential seismic indicators, including, but not restricted to, injections of granular material (Lin, 1996; Smith et al., 2008; Rowe et al., 2012), pulverized fault zone rocks (Brune, 2001; Dor et al., 2006; Rempe et al., 2013), mirror-like slip surfaces (Boneh et al., 2013; Chen et al., 2013; Fondriest et al., 2013; Siman-Tov et al., 2013), localized zones of recrystallization (Kim et al., 2010; Brantut et al., 2011; Bestmann et al., 2012; Smith et al., 2013), graphitization of carbonaceous materials (Oohashi et al., 2013; Kuo et al., 2014) and thermal maturation of organic molecules (Polissar et al., 2011; Rabinowitz et al., 2013; Savage et al., 2014).

In this contribution, we focus on the conditions that determine the formation of rounded clast-cortex aggregates (CCAs; an abbreviation also used for *clay*-clast aggregates (Boutareaud et al., 2008)), a distinctive type of composite grain recognized in several different lithologies and geological settings (Table 1). CCAs have been found in the localized slipping zones of tectonic faults (e.g. Warr and Cox, 2001; Boullier et al., 2009; Smith et al., 2011) (Fig. 1)

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Table 1
Summary of naturally-occurring CCAs in tectonic fault zones and landslides. Modified after Han and Hirose (2012).

Location	Setting	CCA host-rock composition	Formation/ exhumation depth	Evidence of fluids	Reference
Tre Monti fault, Italy	Normal fault	Fossiliferous and micritic limestone	<2 km	Evidence of layer fluidization and syn-tectonic vein formation	Smith et al. (2011)
Alpine fault, New Zealand	Strike-slip fault	Mylonite-derived clay-gouge	2-4 km (attributed to the depth of growth of swelling clays)	Hydrous chloritization, dissolution, fluid-induced sub-critical cracking	Warr and Cox (2001)
Chelungpu fault, Taiwan	Thrust fault	Clay-rich gouge	1.11–1.14 km	Evidence for gouge layer fluidization	Boullier et al. (2009)
Palisades slide block, USA	Landslide	Basal layer where lithologies of upper plate (limestones) and lower plate (sandstone-conglomerate-like rock with clayey matrix) mix	<250 m	No evidence for or against involvement of fluids	Anders et al. (2000), Boyer and Hossack (1992)
Heart Mountain, WY, MT, USA	Landslide	Dolomite	2–4 km	Evidence for fluidization either with or without water	Beutner and Craven (1996), Beutner and Gerbi (2005) and Anders et al. (2010)

and in the basal detachment zones of large landslides (e.g. Beutner and Craven, 1996; Beutner and Gerbi, 2005; Anders et al., 2010). The main characteristic of CCAs is a central clast enclosed by an outer cortex of fine-grained material that defines the composite rounded structure (Fig. 1).

Clast-cortex aggregates composed of calcite have been found in the principal slipping zone of the Tre Monti fault, an active normal fault hosted mainly in limestones in the Central Apennines of Italy (Fig. 1a, b) (Smith et al., 2011). Geological constraints indicate that exposures of the principal slip zone of the Tre Monti fault were exhumed from depths of <2 km (Smith et al., 2011). The cataclastic principal slip zone (Fig. 1c) consists almost entirely of calcite (from Energy Dispersive X-Ray Spectroscopy in the Scanning Electron microscope (SEM) and X-ray powder diffraction (XRD)

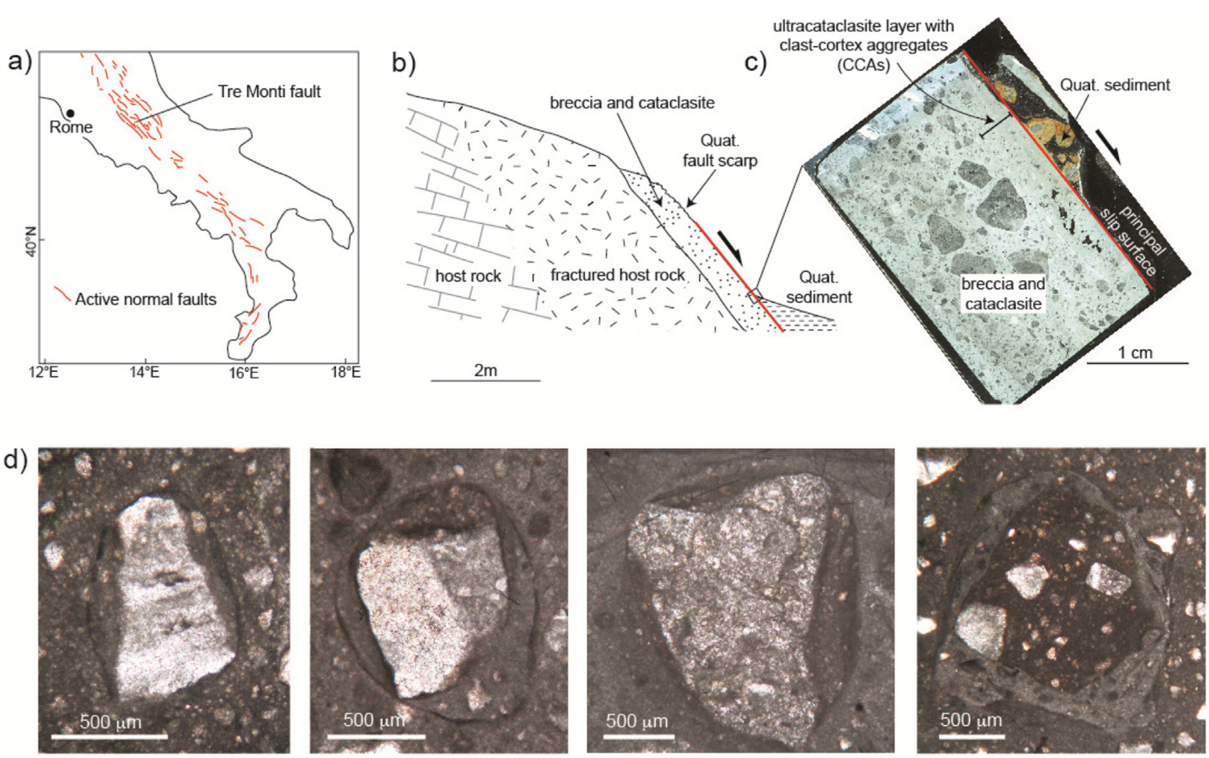

Fig. 1. Summary of the occurrence of clast-cortex aggregates (CCAs) in the Tre Monti normal fault, central Italy, (a) Map of southern Italy with red lines showing the locations of the Tre Monti fault and other active normal faults that cut Holocene deposits (modified from Roberts and Michetti, 2004), (b) Schematic cross-section through a segment of the Tre Monti fault showing the transition from intact host rock to breccias and cataclasites (modified from Smith et al., 2011). The active Quaternary fault scarp, corresponding to the principal slip surface in this fault, is marked in red. The hanging wall at the surface is composed of well-cemented Quaternary sediments, (c) scanned thin section image showing the principal slip surface and cataclastic to ultracataclastic principal slipping zone. The ultracataclasite layer closest to the principal slip surface contains well-developed CCAs. (d) Optical photomicrographs in plane-polarized light showing examples of CCAs from the ultracataclastic slipping zone of the Tre Monti fault. From left to right the CCAs increase in size and complexity. The central clasts can be composed of limestone host rock fragments (first three images) or reworked cataclastic material from the slipping zone (fourth image). In some cases, the cortex contains multiple laminations (third and fourth images and other examples in Smith et al., 2011). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)