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Clay–clast aggregates in fault gouge: An unequivocal indicator of seismic faulting at shallow depths?

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ABSTRACT

A common problem encountered in studies of gouge-bearing natural faults is the difficulty of ascertaining whether the observed gouge was sheared seismically or aseismically; this problem arises because of the scarcity of indicators of fault slip rates for gouge. Recently, clay–clast aggregates (CCAs; a CCA comprises a clastic core mantled by a rim of ultrafine particles) were proposed as a possible indicator of seismic slip in gouge, on the basis of shear experiments on gouge at seismic slip rates. To examine the processes and conditions of CCA formation, we conducted rotary shear experiments on quartz and quartz–bentonite gouges under normal stresses (0.3–3.0 MPa) and slip rates (0.0005–1.3 m s^{-1}), and in both room-humidity (room-dry) and water-saturated (wet) conditions. We found that CCAs could be produced in room-dry gouges even at the lowest slip rates, which are considerably slower than actual seismic slip rates. This finding demonstrates that thermal pressurization and fluidization at elevated temperature during seismic slip are not necessarily needed for the formation of CCAs, contrary to previous views. Given the occurrence of CCAs over a wide range of slip rates, we suggest that the presence of CCAs is not an unequivocal indicator of fault slip at seismic slip rates.

1. Introduction

Fault zones commonly show internal structures consisting of a core and a damage zone (e.g., Chester et al., 1993). The core, which is the locus of shear displacements, consists of fault rocks such as fault gouge, breccias, cataclasites, and pseudotachylytes. These rocks can be an important source of information on the physicochemical processes related to the mechanical behaviors and slip modes of faults during past slip. However, except for pseudotachylytes, distinguishing between rocks that experienced seismic and aseismic slip is difficult (e.g., Cowan, 1999), and this uncertainty is a barrier to using fault rocks to infer mechanisms of faulting.

Recently, experiments to identify seismic slip indicators in fault rocks have been conducted using high-velocity shear tests that simulate fault slip on rocks and gouges at seismic slip rates (typically ~1 m s^{-1}). Potential seismic slip indicators in fault rocks, proposed on the basis of experimental results and/or natural fault observations, include the presence of thermal decarbonation products (Han et al., 2007a), clay–clast aggregates (CCAs; a CCA consists of a clastic core mantled by a rim of ultrafine particles) in clay-rich gouge (Boutareaud et al., 2008), grain size segregation structure (Ujiie and Tsutsumi, 2010), and a thin zone of plastic deformation adjacent to the principal slip zone (Kim et al., 2010).

CCAs, which are a main object of this study, have been reported in the literature (see Table 1 for details) not only on experimental faults (e.g., Boutareaud et al., 2008, 2010; Ferri et al., 2010, 2011; Kitajima et al., 2010; Ujiie and Tsutsumi, 2010; Togo et al., 2011; Sawai et al., 2012) but also on natural tectonic faults (Warr and Cox, 2001; Boullier et al., 2009; Boutareaud et al., 2010; Smith et al., 2011) and landslide soles (e.g., Hughes, 1970; Beutner and Craven, 1996; Beutner and Gerbi, 2005; Anders et al., 2000, 2010). The structures have been variously named: snowballed structure (Warr and Cox, 2001); armored grain (Anders et al., 2000, 2010); accreted grain (Beutner and Gerbi, 2005); mantled or rolled clast (Craddock et al., 2009); clast-cortex grain (Smith et al., 2011); clay–clast aggregates or CCAs (e.g., Boutareaud et al., 2008, 2010; Boullier et al., 2009; Kitajima et al., 2010; Ferri et al., 2010; Ujiie and Tsutsumi, 2010; Togo et al., 2011; Sawai et al., 2012). Also, CCAs have a structure quite similar to accretionary lapilli (e.g., Gilbert and Lane, 1994; Schumacher and Schmincke, 1995) or ash aggregates (Brown et al., 2010). Many studies of CCAs in fault gouges have reported so far that they were formed during shearing of gouge at seismic slip rates, and thermal pressurization and/or fluidization

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have been proposed as likely processes responsible for their formation (e.g., Boullier et al., 2009; Boutareaud et al., 2010; Ferri et al., 2010; Ujiie and Tsutsumi, 2010). However, previous experiments were performed over a limited range of conditions, mainly involving large displacements (10s of meters) and high velocities (generally >0.09 m s^{-1}), and the possibilities of CCA formation in conditions outside of these ranges were not critically tested; therefore, the studies were not able to conclusively determine whether CCAs are unique indicators of seismic slip or not.

This study was designed to better understand CCA formation; specifically, we tried to address the following issues: (1) are fault gouge CCA microstructures formed only at seismic slip rates, and (2) what materials and fault zone processes are required for CCA formation? Based on our experimental results and microstructural

Table 1
Summary of natural occurrence of CCAs and details of experimental CCAs.

Natural

Location	Remark	References
Tre Monti fault, Italy	Tectonic fault	Smith et al. (2011)
Alpine fault, New Zealand	Tectonic fault	Warr and Cox (2001)
Chelungpu fault, Taiwan	Tectonic fault	Boullier et al. (2009)
Palisades slide block, USA	Landslide	Anders et al. (2000)
Heart Mountain fault, USA	Landslide	Anders et al. (2010)
Heart Mountain fault, USA	Landslide	Beutner and Gerbi (2005)
Heart Mountain fault, USA	Landslide	Beutner and Craven (1996)
White Mountain fault, USA	Landslide	Hughes (1970)

Experimental

Experimental material	Source of material	Mineral composition	Wet/Room-dry	Normal stress [MPa]	Slip rate [m s^{-1}]	Fault displacement [m]	Remarks	Reference
Natural fault gouge	Usukitani fault, Japan	Quartz, K-feldspar, plagioclase, calcite, kaolinite, illitesmectite mixed layer	Wet	0.6	0.9	40.3	in non-foliated gouge (outside slip localization zones); run 521 at wet condition	Boutareaud et al. (2008)
Natural fault gouge	Usukitani fault, Japan	Quartz, K-feldspar, plagioclase, calcite, chlorite, muscovite, kaolinite, illite, illitesmectite mixed layer	Room-dry	0.6	0.09	5.6	in non-foliated gouge (outside slip localization zones); run 560	Boutareaud et al. (2010) [a]
				0.6	0.9	39.1	in non-foliated gouge (outside slip localization zones); run 553	
Natural gouge	Vaiont slide, Vaiont valley, Italy	Smectite, calcite, quartz	Room-dry	1.0	1.31	29.5	in non-foliated gouge (outside slip localization zones)	Ferri et al. (2010)
Natural gouge	Vaiont slide, Vaiont valley, Italy	Smectite, calcite, quartz	Room-dry	1.0	0.7 1.31	34.3 34.6	in non-foliated gouge (outside slip localization zones)	Ferri et al. (2011)
Natural fault gouge	Funaki, Awaji Island, Nojima fault, Japan	Quartz, plagioclase, kaolinite, smectite	Room-dry	1.2 1.3	0.009 1.31	18 21.9	in non-foliated gouge (outside s lip localization zones)	Sawai et al. (2012)
Natural fault gouge	Megasplay fault (Site C0004), Nankai subduction zone, Japan	Quartz, plagioclase, smectite, illite, chlorite	Room-dry	2.0	1.27	12.2	in non-foliated gouge (outside slip localization zones)	Ujiie and Tsutsumi (2010); see also Ujiie et al. (2011)
Natural fault gouge	Hongkou, Beichuan fault (SW part of Longmenshan fault system), China	Quartz, plagioclase, dolomite, chlorite, illite	Room-dry	1.0	0.43	~13	in non-foliated gouge (outside slip localization zones)	Togo et al. (2011)
Disaggregated natural ultracataclasite	Punchbowl fault, USA	Quartz, feldspar, smectite, clinoptillolite, chlorite, calcite, analcime	Room-dry/ Wet	–	–	–	in non-foliated gouge (outside slip localization zones)	Kitajima et al. (2010) [b]
Olivne aggregate	San Carlos	Olivine	Room-dry	0.5	1.3	23	in non-foliated gouge (outside slip localization zones); grain size >50 μm	Kinoshita and Hirose, unpublished data
Silica nanoparticles	Nanostructured & Amorphous Materials, Inc.	Amorphous silica	Dry	2.0	1.3	40.5	in non-foliated gouge (outside slip localization zones)	Our unpublished data

[a] They reported that no CCAs were observed in gouges sheared at slip rates of 0.014–14 μm/s and normal stresses of 20–45 MPa (their Table 2); we include in this table the sliding conditions (of CCA formation) that were clearly mentioned in the paper, although Boutareaud et al. (2010) conducted many experiments.
[b] Information on the exact sliding conditions under which CCA were produced could not be obtained from the paper by Kitajima et al. (2010).