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The signature and mechanics of earthquake ruptures along shallow creeping faults in poorly lithified sediments

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ABSTRACT

Seismic slip episodically occurring along shallow creeping faults in poorly lithified sediments represents an unsolved paradox, largely due to our poor understanding of the mechanics governing creeping faults and the lack of documented geological evidence showing how coseismic rupturing overprints creep in near-surface conditions. Here we describe the signature of seismic ruptures propagating along shallow creeping faults affecting unconsolidated forearc sediments. Field observations of deformation band–dominated fault zones show widespread foliated cataclasites in fault cores, locally overprinted by sharp slip surfaces decorated by thin (0.5–1.5 cm) black gouge layers (herein, black gouge). **[[SU: Ok as noun, as variant of "fault gouge"?]]** Compared to foliated cataclasites, black gouges have much lower grain size, porosity, and

permeability. Moreover, they are characterized by distinct mineralogical assemblages compatible with high temperatures (180–200 °C) due to frictional heating during seismic slip. Foliated cataclasites were also produced by laboratory experiments performed on host sediments at subseismic slip rates (≤0.1 m/s), displaying high friction ($\mu_f = 0.65$) **[[SU: friction coefficient is just μ in text; μ_f in Fig. 4 is defined as "residual" friction coefficient?]]** and strain-hardening behavior. Black gouges were produced during experiments performed at seismic (1 m/s) slip rates, displaying low friction ($\mu_f = 0.3$) due to dynamic weakening. Our results show that black gouges represent a potential diagnostic marker for seismic faulting in shallow creeping faults. These findings can help understanding the time-space partitioning between aseismic and seismic behavior of faults at shallow crustal levels.

INTRODUCTION

Most popular synoptic models of tectonic earthquakes assume that crustal faults compose a stable and aseismic region located at shallow depths (Marone and Scholz, 1988) up to the surface, and an unstable and seismic region extending at greater depths (Perfettini et al., 2010), down to the brittle-plastic transition. It is widely accepted that earthquakes can only nucleate within unstable, velocity-weakening regions (Kaneko et al., 2008). Seismic ruptures should not nucleate within the shallower portions of the crust (Scholz, 1998), due to the presence of stable, velocity-strengthening incohesive fault gouges for temperatures <100 °C (Marone et al., 1990; Saffer and Marone, 2003). However, the 2011 M_w 9.0 Tohoku-Oki earthquake (Japan) (Sato et al., 2011) demonstrated that large coseismic ruptures can propagate to the surface through shallow sediments of subduction zones (Ozawa et al., 2011), causing vast damage and destructive tsunamis (Avouac, 2011).

The discrepancy between the behavior of real earthquakes and model predictions is due to the lack of direct observations constraining the structure, rock physical properties, deformation patterns, and frictional behavior of fault zones in the shallow part of the crust.

Compelling numerical (Boatwright and Cocco, 1996), geophysical (Kodaira et al., 2012), experimental (Faulkner et al., 2011), and mineralogical (Yamaguchi et al., 2011; Sakaguchi et al., 2011) evidence has been presented to support possible scenarios and mechanisms that may lead a fault segment to host a seismic rupture in the shallow part of the crust. However, there is little documented geological evidence showing how seismic rupturing of shallow faults in unconsolidated sediments occurs in nature (Noda and Lapusta, 2013). Here we report field, petrophysical, mineralogical, and experimental evidence of past coseismic ruptures propagating along creeping extensional fault zones in the seismically active Crotone forearc basin in Calabria, southern Italy (Fig. 1A).

METHODS

Analytical procedures and graphics for laser diffraction particle size analysis, mercury-injection porosimetry, X-ray diffraction analyses, in situ permeability measurements, microstructural characterization, temperature rise calculations, and friction experiments are provided in the GSA Data Repository[1].

GEOLOGICAL BACKGROUND AND FAULT ZONE STRUCTURE

Calabria exposes the southern segment of the Apennines fold-and-thrust belt (Fig. 1), characterized by ongoing northwestward subduction of the Ionian crust and backarc

Tyrrhenian rifting and regional uplift (e.g., Faccenna et al., 2004). The Crotone Basin (Fig. 1A) is a portion of the Ionian forearc region, filled by Miocene–Pleistocene continental to shallow-marine unconsolidated syntectonic sediments (e.g., Zecchin et al., 2004). Extensional fault zones in the study area developed in middle Pliocene–Pleistocene quartz-feldspathic unconsolidated sediments, which were exhumed from maximum burial depths of ≤1 km (Balsamo et al., 2012). Historical seismic records (Galli et al., 2008) and recent low-magnitude shallow seismicity (Italian Seismological Instrumental and Parametric Data-Base, http://iside.rm.ingv.it/iside/standard/index.jsp; Figs. 1A and 1B) make the studied fault zones an excellent field analogue of active deformation in shallow sediments. Fault zone structure in the Crotone Basin typically consists of deformation band–dominated damage zones encompassing narrow fault cores made of foliated cataclasites and gouges (Fig. 2A) (Balsamo and Storti, 2011). In three fault cores made of foliated cataclasites, 8–22 cm thick, we found sharp, localized principal slip surfaces decorated by a 0.5–1.5-cm-thick layer of black gouge (Fig. 2B). These fault zones have extensional displacements of 13.6, 21.3, and 41.7 m. Although it was not possible to discriminate where most slip was accommodated, we envisage that it was accommodated in the volumetrically more significant foliated cataclasites. Foliated cataclasites consist of subangular, coarse- to fine-grained granular material in which foliation is imparted by preferential clast orientation parallel to the principal slip direction (Fig. 2C). Black gouges consist of very fine grained matrix encompassing subrounded survivor quartz grains (Fig. 2D).

PETROPHYSICAL AND MINERALOGICAL DATA

Mean grain size ranges between 200 and 600 µm in the host sediments and between 100 and 450 µm in deformation bands and foliated cataclasites sands, and decreases to 70–80 µm within black gouges, independent of the cumulative displacement accommodated by each fault zone (Fig. 3A; Item DR1 in the Data Repository). The mean permeability of undeformed sediments is ~10^{-11} m^2, which reduces by 1–3 orders of magnitude in damage zones and foliated cataclasites, and to 10^{-15} m^2 in the black gouges (Fig. 3B). The undeformed sediments have a porosity of ~25% that reduces to 0.1%–4.5% in the foliated fault core and to 0.1%–0.9% in the black gouges. Mean pore size decreases from 20–50 µm in the undeformed sediments to 0.3 µm in the foliated cataclasites, and to 0.01–0.02 µm in the black gouges (Fig. 3; Item DR1).

X-ray diffraction (XRD) determined the bulk mineralogy of undeformed sands to consist of quartz, plagioclase, K-feldspar, clay minerals, chlorite, mica, and calcite. The relative abundance of mineral phases does not change significantly among fault structural domains, except for a slight increase in clay minerals in the black gouges (Table DR2 and Fig. DR4 in the Data Repository). Clay size fractions of undeformed sands show the presence of illite, kaolinite, chlorite, and random ordered (R0) mixed-layer illite-smectite (I-S; Fig. 3C; Table DR3; Fig. DR4D). Deformation bands in damage zones and foliated cataclasites in fault cores do not show significant variations of clay mineral assemblages with respect to the protolith in terms of relative abundances and mixed-layer I-S composition (Fig. 3C; Table DR3). Only samples located in the fault core next to the black gouge layer display short-range ordered (R1) mixed-layer I-S and the neoformation of palygorskite and mixed-layer chlorite-smectite (Table DR3). However, black gouges are characterized by the occurrence of long-range ordered (R3) mixed-layer I-S, accompanied by the formation of authigenic pyrophyllite (Fig. 3C; Fig. DR4F).

FRICTION EXPERIMENTS

Details of friction experiments performed on the undeformed medium-sized sands are provided in Item DR4. Experimental conditions range from seismic (to 1 m/s) to subseismic slip rates (to 0.1 m/s), normal stresses at 7 MPa and 14 MPa, displacements of ~1.3 m, and room temperature and humidity (Table DR5). The displacement of 1.3 m was chosen because it is the slip accommodated by a black gouge developed in the Crotone Basin (Balsamo and Storti, 2011). During experiments performed at subseismic slip rates, the friction coefficient (μ) **[[SU: correct?]]** increased with slip from initial values, μ_i = 0.59–0.65, to peak values, μ_p = 0.69–0.73, overall showing slip-hardening behavior (Fig. 4A). Samples sheared at seismic slip rates showed initial slip hardening (Fig. 4B), with μ increasing from μ_i = 0.63–0.69 to μ_p = 0.72–0.74, before weakening began and friction reduced to steady-state values μ_f = 0.32–0.47, for displacements d_w = 0.2–0.88 m **[[SU: friction coefficient is just μ in text; μ_f in Fig. 4 defined as "residual" friction coefficient? In Abstract, μ_f introduced as friction; use of variables should be consistent. What is subscript w in d_w?]]** (Table DR5). Cataclasites produced at subseismic slip rates (≤0.1 m/s) show overall slip-hardening behavior over the range of velocities tested (Fig. 4C), as opposed to black gouges, only produced at seismic slip rates (≥0.5 m/s), that showed dynamic weakening behavior.

Samples recovered after the experiments at subseismic slip rates show the development of a thin gray slip zone overlaying moderately comminuted cataclasite (Fig. 4A), as opposed to samples recovered after the tests at seismic slip rates that showed the development of black polished slip surfaces overlaying very fine grained gray gouge (Fig. 4B). At subseismic slip rates, the sheared sand consists of coarse-grained, very angular quartz and feldspar grains with jigsaw-fit geometry surrounded by a fine-grained matrix (Fig. 4D). The mean grain angularity value is 21.6 ± 3.7 (inset in Fig. 4D). Such an immature texture is similar to that observed within natural foliated cataclasites (Fig. 2C). At seismic slip rates, sheared sand is very fine grained, indicating higher grain comminution. Black gouge consists of subrounded quartz and feldspar grains floating within a fine-grained matrix. The mean grain angularity value is 18.7 ± 2.1 (Fig. 4E); i.e., grains sheared at seismic slip rates are more rounded than subseismic counterparts. The experimental black gouge layer **[[SU: correct “latter fabric”?]]** is similar to the fabric described for the natural black gouges (Fig. 2D).

XRD analyses performed on the experimental black gouges show the presence of amorphous phases as a result of extreme comminution (Fig. DR5A) and quartz, albite, K-feldspar, calcite, and ankerite minerals (Table DR4). In addition, in the <2 µm grain-size fraction, R3 mixed-layer I-S (Fig. DR5B) was recognized, as opposed to R0 I-S identified in the host sediments (Fig. 3C), similar to what was observed in the natural black gouges.

DISCUSSION

Our data show that creeping extensional fault zones can be overprinted by episodic seismic ruptures at very shallow depths, producing decoration of slip surfaces by black gouges. Creep faulting is inferred by the widespread occurrence of strain-hardening cataclastic deformation bands in damage zones (e.g., Fossen et al., 2007) and by the moderate reduction in grain size and pore size in foliated cataclasites (Fig. 3A; Item DR1). However, it is not possible to discriminate whether the studied faults have been partially or totally unlocked. We interpret the localized dramatic reduction of mean grain size, permeability, porosity, and pore size in black gouges as the evidence for transient fast slip during coseismic rupture propagation through creeping fault segments. This interpretation is further supported by recent field studies of high-strain-rate faulting in porous sandstones, where pervasive comminution of quartz grains, to ~10–100 µm, occurs without development of deformation bands (Key and Schultz, 2011; Balsamo and Storti, 2011). Coseismic slip-rate–dependent cataclasis inferred in the studied black gouges is also in agreement with numerical analyses on rock dynamic fragmentation processes showing that the average fragment size decreases with increasing strain rate (Zhou et al., 2005).

The R0 illite-smectite mixed layers in high-porosity, permeable, and unconsolidated undeformed sediments indicate shallow burial depths (<2 km) and temperatures <70 °C (Środoń, 1999). The absence of significant variations of clay mineral assemblages with respect to the protolith in deformation bands and foliated cataclasites (Fig. 3C; Table DR3) indicates that such deformational structures formed without significant frictional heating, likely at subseismic slip rates. However, an energetic rupture could propagate through the poorly lithified sediments, using the distributed fault pattern. In this case, the rupture would quickly dissipate its energy and some sliding at low slip rates would occur before the rupture stopped. **[[SU: ok?]]** We believe that this scenario, although possible, should only have a local impact rather than affecting the entire fault population in the unconsolidated sediments. We think that it would be much more likely and plausible that the distributed fault pattern would have developed as a consequence of strain-hardening behavior of the sediments, and that most of the sliding along the studied faults would have been aseismic. However, the occurrence of R1 mixed-layer I-S and the neoformation of palygorskite in the foliated cataclasites next to the black gouges, and of R3 mixed-layer I-S in the black gouges, accompanied by the formation of authigenic pyrophyllite, indicate the attainment of higher temperatures during faulting (>180 °C for the black gouges; Fig. 3C) (Wang et al., 1996; Środoń, 1999). In this view, heat diffusion from the black gouge–decorated slip zones caused the temperature rise in the adjacent foliated cataclasites. These temperatures are comparable with the calculated temperature rise (to 211 °C) produced by moderate earthquakes ($M_w > 5$; Fig. DR6) that propagate under dry and fluid-saturated (hydrostatic fluid pore pressure) conditions **[[SU: not "respectively"]]** along localized slip zones with same physical properties and thickness as the black gouge layers observed in the field (gray shaded area in Fig. 3C). The lack of widespread mineralogical evidence supporting hydrothermal fluid circulation in the fault zones indicates that the inferred increase in temperature within the black gouges was attained by localized frictional heating during coseismic sliding (Fig. 3C).

When extrapolated to natural earthquake conditions, our experimental results suggest that M > 5 earthquakes (e.g., $d \geq 0.1$ m) **[[SU: not d_w, as in discussion of Friction Experiments?]]** nucleated at depth within velocity-weakening rocks (Niemeijer et al., 2012) would attain slip that is large enough to trigger dynamic weakening processes and facilitate rupture propagation along fault zones within unconsolidated, slip-hardening sands. This is consistent with temperatures inferred from the mineralogical assemblages observed in the natural black gouges and with temperature calculations for M > 5 earthquakes (Fig. DR6). The observed R0 to R3 I-S conversion in experimental black gouges is similar to the mineralogical assemblage of natural gouges and can be explained by localized temperature rise due to frictional heating (Fig. DR7).

We argue that, in nature, the progressive grain size and pore size reduction, porosity collapse, and permeability drop in foliated cataclasites reaches a threshold fabric that favors coseismic slip, black gouge development, and fault weakening. The different grain angularity values obtained from experimentally sheared gouges at different slip rates, and the resulting different friction coefficient, suggest that the wear and rounding of particles during coseismic slip may play an important role in dynamic weakening.

CONCLUSIONS

Discriminating between creeping and seismic faulting in poorly consolidated sediments strongly affects seismic hazard evaluation, especially for active fault segments in the shallow crust, where aseismic creeping behavior can episodically be overprinted by seismic slip during upward rupture propagation. Based on our data, we conclude that episodic seismic shear failure of creeping shallow fault segments is supported by field and laboratory evidence. The peculiar petrophysical and mineralogical signature of narrow black gouges described in this work makes them a potential new diagnostic marker for discriminating between aseismic and seismic faulting in shallow unconsolidated sediments. Our results can be applied, and improve our ability to estimate risks and hazards in many seismically active areas and tectonic settings, where fault segments cut across unconsolidated sediments in outcrop exposures, in cores retrieved from boreholes, and in paleoseismological trenches.

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FIGURE CAPTIONS

Figure 1. A: Calabria region with late Pleistocene faults (red lines) and historical earthquakes (A.D. 1630–1908) (white circles) (modified from Galli et al., 2008). **[[SU: what is KR in figure? Should spell out in caption.]]** B: Magnitude-depth distribution of small to moderate shallow (0–5 km) earthquakes (1983–2013) in Crotone area (from Italian Seismological Instrumental and Parametric Data-base, http://iside.rm.ingv.it/iside/standard/index.jsp). C: Schematic geological cross section of Calabrian subduction zone.

[[SU: need uppercase A–C labels in figure; no lat, long given. In Fig. A, Crotone Basin, not basin; “Plio-” should be Pliocene–; in Fig. C, “Undertrusted” should be underthrusted.]]

Figure 2. A: Structural domains in fault zone with 13.6 m displacement (FC—fault core; FWDZ—footwall damage zone; HWDZ—hanging-wall damage zone); red star shows location of fault rocks in B. B: Black gouge layer developed in foliated cataclastic sand. Diameter of coin used for scale is 24.25 mm. **[[SU: 50 cent Euro, correct?]]** C: Scanning electronic microscope (SEM) photomicrograph showing immature cataclastic texture in foliated sand. D: SEM photomicrograph of very fine grained fabric in black gouges. **[[SU: need uppercase A–D labels in figure; in Fig. A, reference to “Fig. 2b” should be “B”]]**

Figure 3. A: Progressive grain-size reduction from host sediments to foliated cataclastic sand to black gouges. B: Air-permeability data, plotted along idealized fault zone transect, show permeability decrease of as much as four orders of magnitude within black gouges. C: Clay-mineral association from undeformed and faulted samples, plotted versus estimated stability temperatures (Środoń, 1999), showing attainment of highest temperature within black gouges. Shaded gray area shows calculated range of temperatures produced by earthquakes up to $M_w > 5$, propagating under dry and fluid saturated (hydrostatic fluid pore pressure) conditions (Item DR4 and Fig. DR6 [see footnote 1]). R0 I-S—random ordered mixed-layer illite-smectite; C-S—mixed-layer chlorite-smectite; R1 I-S—short-range ordered mixed-layer illite-smectite; R3 I-S—long-range ordered mixed-layer illite-smectite. **[[SU: need uppercase A–D labels in figure; need space around = signs]]**

Figure 4. A: Slip-hardening behavior at subseismic slip rate (v) of 100 µm/s. B: Slip-hardening followed by slip-weakening behavior at coseismic slip rate of 1 m/s. C: Peak (μ_p) and residual (μ_f) friction coefficients plotted versus slip rate. D: Scanning electronic microscope photomicrograph showing microstructural features of sand sheared at 1 mm/s. Inset shows calculated mean angularity value of grains. Double arrows indicate sense of shear. E: Sand sheared at 1 m/s. **[[SU: Are Du206, Du207, Du210, Du211 sample numbers, experiment runs, or other? Should define in caption. Need uppercase A–E labels in figure.]]**

[1]GSA Data Repository items 2014, Item DR1 (petrophysical properties of natural undeformed and faulted sediments), Item DR2 (mineralogical composition of natural and experimentally sheared gouges), Item DR3 (temperature calculations within black gouges), and Item DR4 (experimental apparatus, sample assembly, and mechanical data), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.