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Pulverized quartz clasts in gouge of the Alhama de Murcia fault (Spain): Evidence for coseismic clast pulverization in a matrix deformed by frictional sliding

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ABSTRACT

The fault gouge of the Alhama de Murcia fault (southeast Spain) shows a texture that resembles a mylonite, including a prominent foliation, S-C fabric, and isoclinal folds. It also embeds a large number of isolated pulverized quartz clasts (PQCs). Structural analysis indicates that the gouge fabric was mainly developed by slow frictional sliding along phyllosilicate-lined Riedel shear bands during continued shearing. In contrast, the PQCs show tensile fracture network features that are typically reported in seismically pulverized rocks found along seismogenic faults. This suggests that quartz-clast pulverization was due to a transient dilatational mechanism rather than shearing. We propose that the PQCs are the result of a rapid confined stress drop related to transient tensile stresses during coseismic ruptures that interrupt creep faulting along the gouge zone. The present study suggests that there is probably a large amount of evidence for paleoseismicity in fault rocks that is currently overlooked.

INTRODUCTION

The fabric of exhumed fault gouges offers the opportunity to understand how faults behaved during their slip history and to infer the mechanisms responsible for different types of slip behavior on active faults. Although there are few reliable criteria with which to distinguish between seismic and aseismic textures in fault gouges, significant progress in fault rocks studies is giving new insights into the identification of earthquake-related structures. Rowe and Griffith (2015) compiled several lines of evidence considered as indicators of paleoseismicity, including pulverized rocks (PRs). PRs are found in several seismogenic faults around the world, such as the San Andreas fault (e.g., Brune, 2001; Dor et al., 2006). Because they are characterized by a high density of tensile fractures, showing little or no shearing and preserving original rock fabrics, most authors have linked PRs to damage induced by transient stress perturbations during earthquake ruptures (e.g., Doan and Gary, 2009; Mitchell et al., 2011; Aben et al., 2016).

The Alhama de Murcia fault (AMF) in southeastern Spain is a well-exposed fault zone, offering the opportunity to study the associated fault gouge and processes related to its formation. This gouge is characterized by a penetrative shear foliation and includes a large number of isolated pulverized quartz clasts (PQCs), resembling mylonite. Based on comparative microstructures of natural and experimental gouges, Hall (1983) and Rutter et al. (1986) concluded that the AMF gouge fabric and quartz clasts mainly formed during continued shearing via gradual, as opposed to sudden, brecciation. In contrast, Rutter et al. (2012) suggested a coseismic origin for analogue pulverized clasts embedded in a sheared gouge of the Carboneras fault, located 80 km south of the AMF. According to Rutter's suggestion and the fact that PRs are collectively considered to be indicator of paleoseismicity, PQCs could record episodic coseismic ruptures that occurred intermittently during dominant longer-term shearing along the AMF gouge. However, it is unclear which process was responsible for clast pulverization, under which deformation conditions it occurred, and, more importantly, if PQCs could be associated only with coseismic deformation. In order to address these questions, we performed a detailed structural study of the AMF gouge and PQCs at various scales using field, optical, and scanning electron microscope observations, complemented by a fracture pattern analysis. We demonstrate that the microstructure of PQCs is almost identical to those found in PRs, making them a powerful tool with which to investigate the textural evidence for paleoseismicity in other fault gouges.

GEOLOGICAL SETTING AND SAMPLING

The AMF is a slow active crustal fault located in the eastern Betic Cordillera (Fig. 1A). It is characterized by instrumental seismicity of moderate to low magnitude capable of producing catastrophic events (e.g., Rodríguez-Escudero et al., 2014). Historical and paleoseismic data show $M_w > 6.0$ seismic ruptures during the Holocene (Martínez-Díaz et al., 2018).

The AMF is an ~85-km-long, northeast-southwest, left-lateral reverse fault with a displacement history dating back at least to the late Miocene (Bousquet and Montenat, 1974). At the regional scale, the section of the AMF between Puerto Lumbreras and Totana is a complex fault zone of variable width (tens to hundreds of meters) dipping 55–70° to the northwest. It includes Betic basement rocks (developed as a thrust stack during the Alpine orogeny; Kampschuur and Rondeel, 1975) and underlying syntectonic deposits that filled Miocene to Holocene intermontane basins (Bousquet, 1979; Martínez-Díaz et al., 2012).

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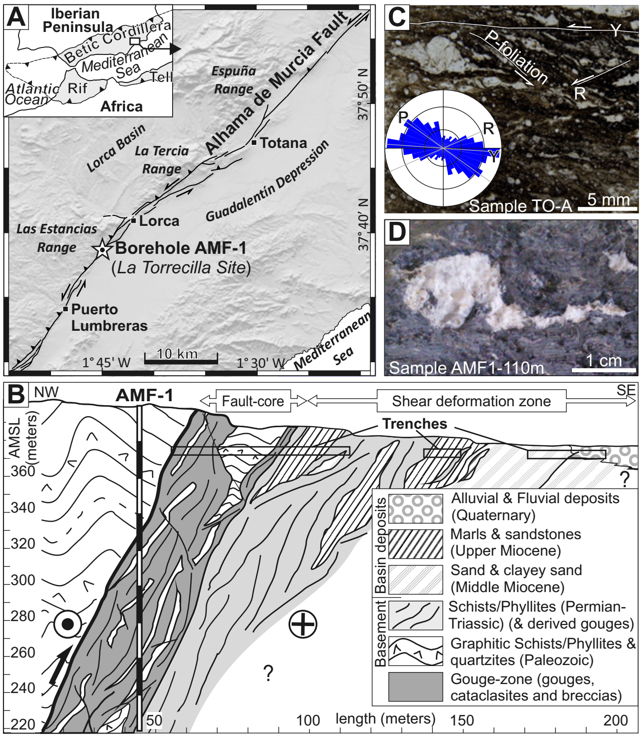

Figure 1. (A) Location map of Alhama de Murcia fault (AMF), Spain. (B) Schematic cross section of fault zone structure (AMF1 borehole is located at 37.638°N, 1.746°W). AMSL—above mean sea level. (C) Scan of thin section of sample TO-A (taken ~1 m from main fault plane; 37.638°N, 1.747°W) showing mylonitic texture of gouge. P foliation, as well as Y and R shears, are accentuated in white. Rose diagram of fractures in sample TO-A was constructed using FracPaQ toolbox (http://fracpaq.com). Trace of AMF is parallel to Y shear, and azimuth interval is 10° (for more detail, see Fig. DR3 [see text footnote 1]). (D) Detail of core sample AMF1–110 m showing sigmoidal pulverized quartz clast (PQC) with strain shadow.

Structural observations and samples were collected from several outcrops, but in particular from the La Torrecilla creek section, where the AMF is exceptionally well preserved (Fig. 1A). At this site, a borehole was drilled (AMF-1) through the hanging wall and fault-core rocks (Martínez-Díaz et al., 2016). In addition, trenches were excavated normal to the AMF to create a continuous and fresh fault zone exposure (Fig. DR1 in the GSA Data Repository[1]). Field and drill-core observations, and geophysical investigations (Martí et al., 2016) provided structural evidence for an asymmetric fault zone at the surface, where most of the strain is accommodated by a fault-core gouge zone on the north side of the fault (Fig. 1B). Toward the southeast, the fault zone contains a shear zone in sharp contact with the fault core, including uppermost tectonostratigraphic units (and derived fault rocks), as result of folding and uplifting of the Las Estancias and La Tercia ranges (Figs. 1A and 1B; Rodríguez-Escudero, 2017).

ALHAMA DE MURCIA FAULT GOUGE

The fault core of the AMF is a 20–25-m-thick dark gouge zone in sharp contact with the hanging wall. It outcrops only adjacent to Paleozoic black schist/phyllite containing quartz veins from the Betic basement (Fig. DR2). The gouge zone is composed of a phyllosilicate-rich cataclastic matrix including millimeter- to decameter-scale fragments of the black schist/phyllite. At the mesoscopic scale, the gouge embeds asymmetrical PQCs within a strongly foliated matrix showing S-C fabrics, giving the gouge a mylonitic appearance (Figs. 1C and 1D).

The gouge and black schist/phyllite have the same mineral composition (e.g., Tsige et al., 2017). New mineral growth and plastically deformed quartz are not present in the gouge, indicating that both the latter and PQCs were produced by mechanical fragmentation of schist/phyllite and quartz veins. The inclusion of recognizable protolith fragments showing various stages of alteration suggests that the gouge was gradually developed by mechanical breakdown through processes of frictional sliding, cataclasis, and cataclastic flow, as described by Hall (1983) and Rutter et al. (1986). A fracture analysis of the AMF gouge using the FracPaQ toolbox (Healy et al., 2017) revealed that the gouge fabric was imposed by Riedel-type fracture patterns (Fig. 1C; see Fig. DR3 for more detail). Pervasive shear foliation is formed by the preferred orientation of phyllosilicates parallel to P-planes (orientation nomenclature sensu Rutter et al., 1986), which are truncated and deflected by Y and R shears defining S-C and S-C′ fabrics similar to those found in mylonites. The shear bands commonly propagate through schist porphyroclasts (Fig. DR4G), producing invasion of matrix into fractures, but not into the harder quartz clasts, the boundaries of which are normally sharp and undisturbed (Fig. 2; Fig. DR5).

PULVERIZED QUARTZ CLASTS

PQCs are only found within the fault zone, and they are predominantly associated with foliated gouges (either the black gouge or the locally purple gouge derived from Permian–Triassic schists in the deformation shear zone). These are nearly equidimensional clasts of white vein quartz up to 20 cm in diameter, with various degrees of pulverization. They are composed of noncohesive particles that, in the most deformed clasts, are easily disaggregated and show an icing sugar texture (Fig. 2). Quartz veins in the protolith, located only a few meters from the main fault plane, do not show such damage (Fig. DR2). Commonly, PQCs display sigmoidal shape, developed during shear. However, the samples collected from both trenches and the AMF-1 borehole contained numerous subangular centimeter-sized PQCs with no evidence for shear, except a possible clast rotation (Fig. 2; Fig. DR5C). They remained whole and preserve the crystal texture of quartz at the hand-sample scale, suggesting that little finite strain occurred during and after the pulverization process.

Microstructural observations show a very high fracture density in macroscopically unsheared PQCs, and in cores of sigmoidal porphyroclasts. Intragranular and grain boundary fractures reduced the clasts to angular fragments with sizes of tens to hundreds of micrometers (Fig. DR6). These fragments show no (or minor) rotation and display extinction in the same position under cross-polarized light, exhibiting the original rock fabric (Figs. 2C and 2D; Figs. DR2 and DR5E). On the contrary, the finer grains in strain shadows show random orientations, because of comminution and rotation during shearing (Fig. 3A; Fig. DR7). Microfractures cutting PQCs are opening-mode features, cross entire clasts, and have no obvious preferred orientation. They end at the clast-gouge contact. Original quartz grains show minor or no shear displacement. Locally, as shown in Figure 2C, short cracks terminate on sets of longer cracks, suggesting the longer ones formed first. A quantitative analysis of fracture pattern revealed a quasi-isotropic angular distribution of fracture segments (Fig. 2D; Fig. DR6), indicating that the tensile fractures formed in isotropic conditions and are not associated with the shear fabric in the matrix.

Regardless of their morphologies, the PQCs show sharp boundaries and do not mix with the enclosing matrix. Figure 3B illustrates how micrometer-scale phyllosilicates are concentrically distributed around PQCs. This phyllosilicate cortex holds the quartz fragments together,

[1]GSA Data Repository item 2020078, Figure DR1 (location of the AMF-1 borehole and trenches excavated in La Torrecilla creek area and features of gouge zone), Figure DR2 (structural and textural features of protolith), Figure DR3 (fracture pattern analysis of AMF gouge), Figure DR4 (structural features of AMF gouge at meso- and microscales), Figure DR5 (structural features of PQCs from outcrop to scanning electron microscope observations), Figure DR6 (fracture pattern analysis of PQC), and Figure DR7 (grain-size analysis of PQC tail), is available online at http://www.geosociety.org/datarepository/2020/, or on request from editing@geosociety.org.

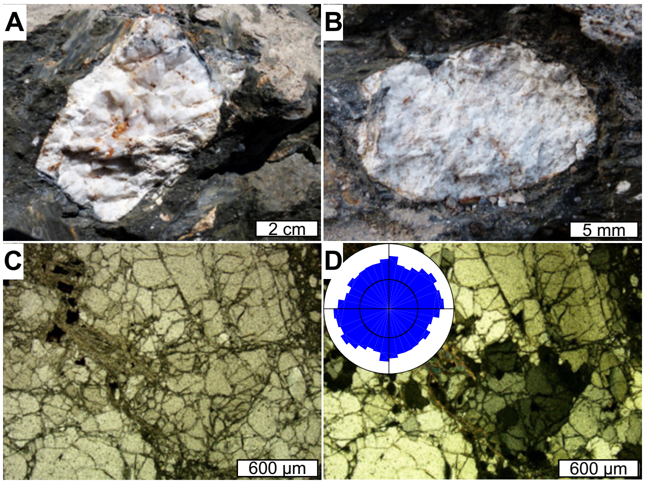

Figure 2. Structural observations of pulverized quartz clasts (PQCs) at meso- and microscales from trench excavated across gouge zone at La Torrecilla creek, Spain (Fig. 1; Fig. DR1 [see text footnote 1]). (A, B) Examples of near-equidimensional PQCs in phyllosilicate-rich fault gouge showing sharp contact between clast and matrix (37.638°N, 1.747°W). Offset on clast boundary is negligible, and there is no clear evidence of shear. Note alteration rind surrounds clast in B, suggesting rotation of clast. (C) Photomicrograph of part of a PQC, plane polarized light, from sample TO-1C (taken ~4 m from main fault plane; 37.638°N, 1.747°W), displaying network of inter- and transgranular opening-mode fractures. (D) Crossed-polarized view of C exhibiting original texture of protolith. Rose diagram, made using FracPaQ toolbox (http://fracpaq.com), displays frequency and angular distribution of fractures, revealing quasi-isotropic fracture pattern (for more detail, see Fig. DR6 [text footnote 1]). Trace of Alhama de Murcia fault (AMF) is parallel to horizontal reference line. Shear sense is left-lateral.

preventing them from mixing with the matrix and maintaining the integrity of PQCs, even after shearing (Fig. DR5). This leads to the idea that the fine-grained gouge matrix, and possibly its shear-related fabric, should have developed prior to the quartz clast brecciation to prevent intermixing.

Several PQCs deep in the section of the drill core, extracted from the fault gouge, show dilatation as a result of extraction of the core from the ground (Fig. 3C). This indicates release of elastic energy stored within the clasts, as might happen at depth if confinement is suddenly released during a seismic event.

DISCUSSION AND CONCLUSIONS

Mineralogy and frictional/brittle structures indicate that the AMF gouge formed primarily by progressive mechanical comminution of black schist in the shallow crust (<5 km). The frictional sliding along phyllosilicate-lined shear surfaces, assisted by particle size reduction by cataclasis, was responsible for the development of the sheared gouge fabric. The mylonitic texture of the gouge suggests that much of the strain in the AMF fault zone was accommodated through slow and stable slip (i.e., aseismic creep; e.g., Byerlee et al., 1978; Rutter et al., 1986). Friction experiments performed by Niemeijer and Vissers (2014) provided experimental data that support this interpretation by demonstrating that the frictional strength of the AMF gouge would inhibit seismic slip.

The distribution and structural context of the PQCs indicate that they are associated with faulting. The high density of randomly oriented tension fractures with no shear displacement and the preservation of the original crystallographic orientations within the clasts suggest that the PQCs were created by rapid fragmentation in a quasi-isotropic tensional stress setting, similar to the process of formation of PRs (e.g., Dor et al., 2006; Mitchell et al., 2011; Xu and Ben-Zion, 2017; Griffith et al., 2018). Causative tensile stress may have been a result of reductions in fault-normal stress during earthquake ruptures (e.g., Ben-Zion and Shi, 2005; Griffith et al., 2018). A similar model may apply to the PQCs of the AMF.

The fact that the PQCs are competent inclusions in a weak matrix that experienced substantial shear distinguishes them from PRs, where the entire rock is pulverized. Although it cannot be ruled out that gradual brecciation due to shear occurred to some of the clasts included in the AMF gouge, and unsheared PQCs may simply reflect initial stages of that process, the quasi-isotropic tensile fracture pattern suggests that the PQCs formed due to rapid expansion, resulting in a release of stored elastic energy during transient reduction of confining pressure. It has been experimentally demonstrated that under isotropic, or quasi-isotropic expansion, high strain rates are not required for rock pulverization (Griffith et al., 2018). The expansion observed in the PQCs within drill cores is consistent with the elastic strain energy release that can induce tensile stress overcoming the tensile strength of the clasts as soon as confinement decreases. Since the PQCs are usually associated within foliated gouge of the AMF, and nonbrecciated quartz clasts are mostly found in breccias and cataclasites with random (or immature) fabric along the gouge zone (Fig. DR4F), the shattering process may have been governed by the gradient of confining effective stresses linked to the maturity of the gouge fabric. The quartz may have stored a high amount of elastic energy, because (1) it is known to have a high capacity for storage of elastic strain energy in relation to other minerals (Meng and Pan, 2007), and (2) quartz clasts are stiff inclusions in a soft matrix and therefore more likely to accumulate elastic energy (e.g., Eshelby, 1957; Eidelman and Reches, 1992). Regardless of the reason for elastic strain energy accumulation, the expanded clast in the extracted core (Fig. 3C) demonstrates that the clasts did accumulate elastic strain.

The fact that subangular PQCs in foliated gouge remain whole and preserve their preshattering geometries (Fig. 2A) suggests that pulverization may have occurred after development of the shear-related gouge fabric, and prior to the formation of strain shadows. We propose a model for their development within the AMF based on our observations (Fig. 4). Following initial incorporation of schist fragments into the fault core during fault movement, comminution caused by cataclastic and frictional processes formed a

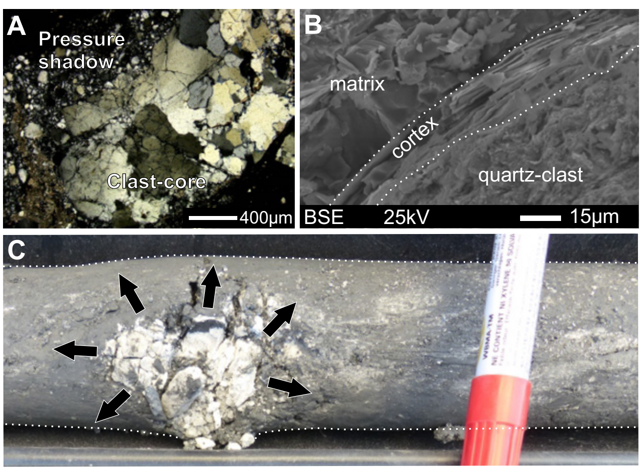

Figure 3. Structures within pulverized quartz clasts (PQCs). (A) Photomicrograph (cross polars) of sigmoidal PQC from sample TO-1A1 (taken ~4 m from main fault plane; 37.638°N, 1.747°W). Note clast core is highly fractured, but original texture of protolith is preserved (see Fig. DR2 [see text footnote 1]). In contrast, finer fragments that extend in left side as a tail are randomly oriented. (B) Scanning electron microscopy image of matrix-PQC contact, showing cortex formed by phyllosilicate. (C) Example of PQC that experienced dilation upon extraction from drill hole (sample AMF1–134 m).

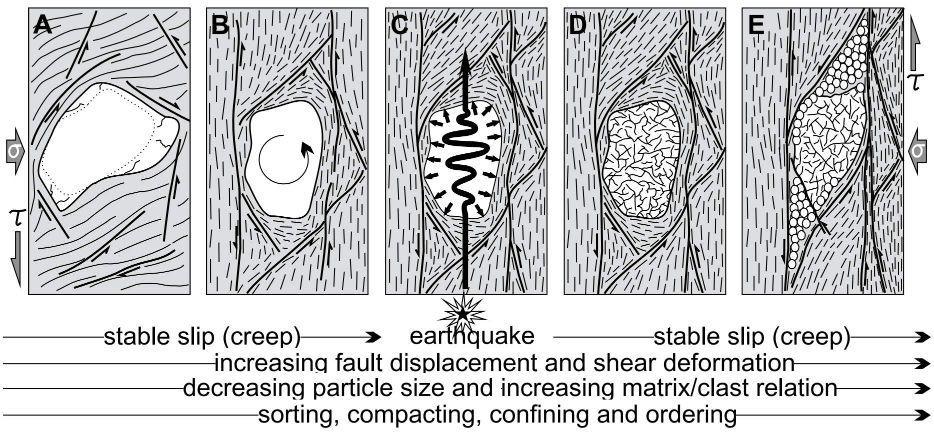

Figure 4. Model for formation of pulverized quartz clasts (PQCs) and gouge fabric. (A) Initial incorporation of schist/phyllites fragments into gouge zone during fault displacement is followed by progressive fragmentation and comminution, developing phyllosilicate/clay-rich matrix. (B) With increasing shear, most competent quartz clasts will tend to remain isolated within increasingly finer grained matrix, being forced to rotate by confined frictional sliding while phyllosilicates are arranged in favor of Riedel shear pattern and wrapped around clasts. Aseismic slip is then located along interconnected phyllosilicate-lined shear bands. (C) Because of presence of surrounding material, stresses will be present both inside and outside clasts, resulting in a great deal of elastic energy. Such accumulated energy can be suddenly released due to transient (coseismic) reduction in confining pressure, and a part of accumulated energy can be dissipated by rock failure, promoting shattering. (D) Once quartz clasts are subjected to pulverization, particles from clast edges will migrate to pressure shadows (E) by slow frictional sliding along clast-matrix contact, resulting in sigma-type geometries with progressive deformation. Meanwhile, the original texture inherited from protolith may be retained in core.

matrix increasingly finer and more enriched in phyllosilicate/clay than the protolith (Fig. 4A). Included fragments tended to be more quartzitic and therefore more resistant to mechanical breakdown than the micaceous fraction. Survivor quartz clasts were strained as the gouge matrix formed, flowed, and compacted around them, causing rigid body rotation, erosion of clast boundaries, and strain energy storage (Figs. 4B and 4C). A drastic confining stress reduction could have induced a sudden volume expansion of clasts, triggering *in situ* pulverization. Many of the proposed mechanisms for fault-normal stress reduction related to earthquake ruptures could theoretically lead to their formation, including asymmetric stress perturbations due to earthquake rupture on a localized surface (e.g., Ben-Zion and Shi, 2005), and acoustic fluidization (e.g., Xia et al., 2013). Hence, we propose that the PQCs are reliable indicators for paleoseismic activity, which could be extrapolated to analogous pulverized clasts associated with other faults, such as the Carboneras fault. This work provides evidence that the structural features of PQCs can be identified despite being subsequently sheared, which is undoubtedly important in creeping faults, where increasing strain tends to obliterate any preexisting seismic structure.

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