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Melting of fault gouge at shallow depth during the 2008 M_W 7.9 Wenchuan earthquake, China

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ABSTRACT

Typical rocks at shallow depths of seismogenic faults are fluid-rich gouges. During earthquakes, on-fault frictional heating may trigger thermal pressurization and dynamic fault weakening. We show that frictional melting, rather than thermal pressurization, occurred at shallow depths during the 2008 M_W 7.9 Wenchuan earthquake, China. One year after the Wenchuan earthquake, we found an ~2-mm-thick, glass-bearing pseudotachylyte (solidified frictional melt) in the fault gouges retrieved at 732.6 m depth from the first borehole of the Wenchuan Earthquake Fault Scientific Drilling Project. The matrix of pseudotachylyte is enriched in barium and cut by barite-bearing veins, which provide evidence of co- and post-seismic fluid percolation. Because pseudotachylyte can be rapidly altered in the presence of percolating fluids, its preservation suggests that gouge melting occurred in a recent large earthquake, possibly the Wenchuan earthquake. Rock friction experiments on fluid-rich fault gouges deformed at conditions expected for seismic slip at borehole depths showed the generation of pseudotachylytes. This result, along with the presence of a second slip zone attributed to the Wenchuan earthquake at 589.2 m depth, implies that during large earthquakes, frictional melting can occur at shallow depths and that seismic slip can be accommodated by multiple faults. This conclusion is consistent with the evidence from surface faulting that multiple ruptures propagated during the Wenchuan earthquake.

INTRODUCTION

The structure of major fault zones includes one or more localized meter-thick fault cores, surrounded by a damage zone cut by a dense network of fractures and minor faults (Faulkner et al., 2010). In the shallow crust, fault cores are commonly composed of fluid-rich gouges (Sibson, 1977; Wibberley et al., 2008). During individual earthquakes, seismic sliding localizes in millimeter- to centimeter-thick principal slip zones (PSZs) cutting fault cores (Sibson, 2003). The relative motion of fault wall-rocks occurs at average slip rates of ∼1 m/s, which results, given the lithostatic load, in frictional heating and thermal expansion of the granular material and the trapped fluid (Rice, 2006; Brantut et al., 2010). Because the thermal expansion of fluid is faster than that of solid components, the unbalance results in fluid pressurization, large coseismic weakening, and buffering of the temperature increase in the slipping zone (Rice, 2006; Brantut et al., 2010). Thus, frictional melting of fluid-rich gouges seems unlikely to occur during seismic faulting at shallow depths. In addition, post-seismic fluid percolation alters the pseudotachylyte (PT) fabrics due to glass crystallization and dissolution, and mineral precipitation, and may result in rock assemblages similar to those of common fault rocks such as cataclasites and gouges (Kirkpatrick and Rowe, 2013). As a consequence, in fluid-rich faults, the microstructural evidence of gouge melting may be rapidly lost from the geological record (Fondriest et al., 2020).

We report the occurrence of PT within fault gouges retrieved from 732.6 m depth from the first borehole of the Wenchuan Earthquake Fault Scientific Drilling Project (WFSD-1). The presence of PT is documented by focused ion beam–transmission electron microscopy. Rock friction experiments on fault gouges deformed at conditions expected for coseismic slip at borehole depths showed the generation of PT. These field, experimental, and microstructural observations suggest that frictional melting of fluid-rich fault gouges may occur at shallow crustal depths during large earthquakes.

GEOLOGICAL SETTING

The northeast-trending Longmen Shan thrust belt is a major structure along the eastern margin of the Tibetan Plateau, which hosted the catastrophic 2008 Wenchuan earthquake (Fig. 1A). To investigate the mechanics of seismic faulting, the WFSD project, including six boreholes along the ruptured Yingxiu-Beichuan and Guanxian-Anxian faults (Fig. 1B), was implemented quickly after the mainshock (Li et al., 2013). The WFSD-1 was drilled along the Yingxiu-Beichuan fault near Bajiaomiao village (Fig. 1B). During the Wenchuan earthquake, two seismic ruptures propagated from south to north along the Yingxiu fault and the nearby Shenxigou fault (Fig. 1A; Fig. S1 in the Supplemental Material[1]). The Yingxiu fault ruptured as pure thrust, while

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[1]Supplemental Material. Additional information about the surface rupture zones, sample collection and preparation, compositions of the fault rocks, friction experiments, and dissolution simulation of the pseudotachylyte. Please visit https://doi.org/10.1130/GEOL.S.21919407 to access the supplemental material, and contact editing@geosociety.org with any questions.

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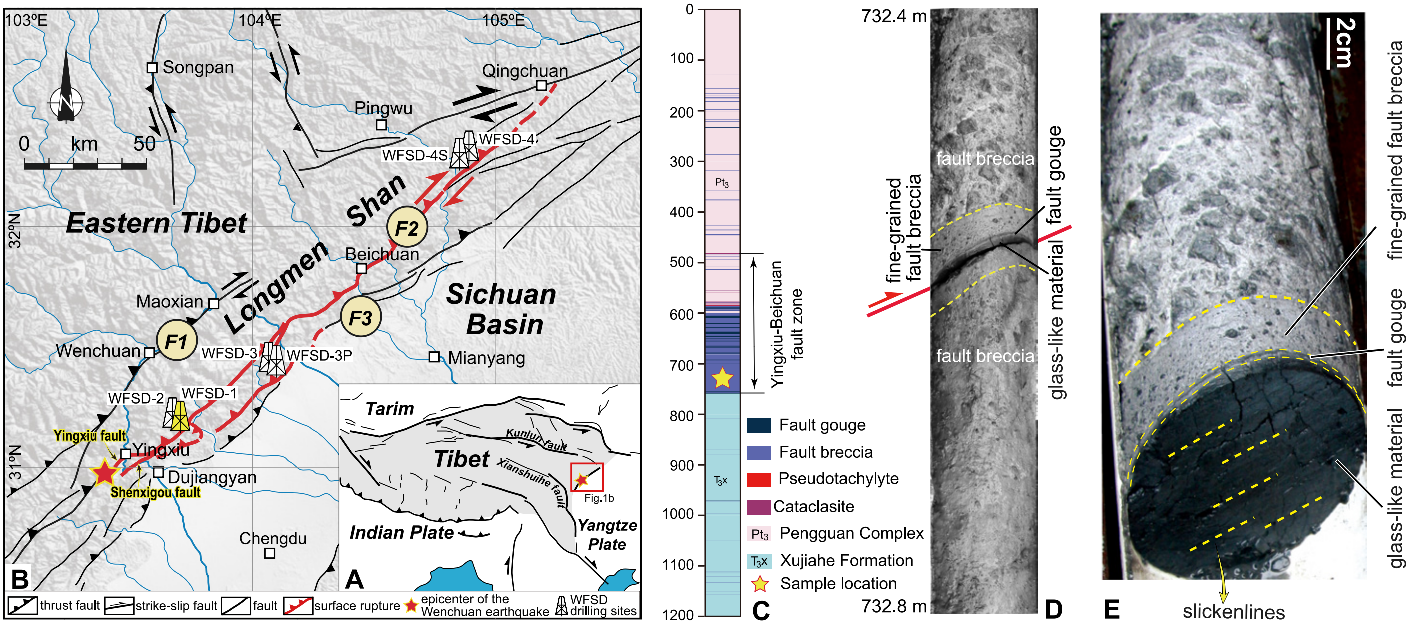

Figure 1. Tectonic setting and fault rocks in the first borehole of the Wenchuan Earthquake Fault Scientific Drilling Project (WFSD-1). (A) Active faults in the Tibetan Plateau. (B) Tectonic sketch of the Longmen Shan area in China and the WFSD drilling sites. F1—Wenchuan-Maoxian fault, F2—Yingxiu-Beichuan fault, F3—Guanxian-Anxian fault. (C) Fault rocks in the WFSD-1 core. (D) The core at 732.4–732.8 m depth, including a black 2-mm-thick layer bounded by (E) a striated, mirror-like principal slip surface.

the Shenxigou fault was a dextral transpressive fault (Pan et al., 2014). The two faults merged into one approaching the earth surface at Bajiaomiao village, where two sets of striae on the fault surface record the propagation of two ruptures. The fault accommodated vertical and horizontal displacements of up to ∼6.5 m and ∼2.5 m, respectively.

The WFSD-1 cores are composed of the Neoproterozoic Pengguan Magmatic Complex above 585.75 m depth, and the Late Triassic Xujiahe Formation sedimentary rocks below (Li et al., 2013). Fault rocks at depths of 482–759 m, containing PT, cataclasite, fault breccia, and fault gouge, compose the Yingxiu-Beichuan fault (Fig. 1C; Wang et al., 2019). The PSZ of the Wenchuan earthquake was proposed to be located at 589.2 m (PSZ589) within a black fault gouge (Li et al., 2013), where well-crystallized graphite was found; instead, amorphous carbonaceous materials were present in the adjacent host rock (Kuo et al., 2014). The graphitization of the carbonaceous minerals was associated with the high-temperature pulse generated during seismic slip (Kuo et al., 2017) and possibly contributed to the very low coseismic fault friction (Li et al., 2015).

NATURAL PSEUDOTACHYLYTE FROM WFSD-1

The drill core retrieved at 732.4–732.8 m depth on 9 May 2009 (i.e., one year after the Wenchuan earthquake) is made of sub-parallel layers of >20-cm-thick coarse-grained, and 2–3-cm-thick fine-grained, fault breccias, a 2-mm-thick fault gouge, and 2-mm-thick glass-like material cut by a lineated and fresh-looking mirror-like slip surface (Figs. 1D–1E). Fourteen thin sections were prepared from this core (see the Supplemental Material). The microstructural investigations of the fault rocks were conducted with optical, scanning (coupled to an energy-dispersive spectrometer, field emission scanning electron microscopy with energy dispersive x-ray spectroscopy [FESEM/EDX]), and focused ion beam–transmission electron (FIB-TEM; 20 nm rock slices) microscopy. The non-cohesive, fine-grained fault breccia contains mainly angular grains of quartz, feldspar, and ankerite, ranging from tens of microns to millimeters in size. The fault gouge is mainly made of angular to sub-angular quartz and feldspar clasts, as well as an ultrafine matrix with accessory minerals (Figs. 2A and 2B; Fig. S3; Table S1). The cohesive glass-like layer is composed of angular to sub-rounded quartz clasts from several microns to tens of microns in size (Figs. 2A and 2B) immersed in a matrix that is brighter in color than both the fault gouge and the breccia layers (Fig. 2B). The bright color of the glassy matrix is related to enrichment in heavier chemical elements (Fig. 2E; Fig. S4). The matrix is amorphous under the FIB-TEM beam (diffraction pattern with diffuse scattering intensity; Fig. 2F). The amorphous matrix includes 50–100-nm-thick, up to 1-μm-long, curved ripples resembling flow structures with a slightly different gray intensity color (Fig. 2F) that is likely associated with minor changes in K-content (transmission electron microscopy–energy-dispersive X-ray spectroscopy analyses; Figs. 2G and 2H). The amorphous matrix is cut by a pervasive network of randomly oriented, open microcracks spaced <1 μm apart (Figs. 2C and 2D) and by a few veins filled with barite (Fig. S5).

ARTIFICIAL PSEUDOTACHYLYTE FROM FRICTION EXPERIMENTS

To verify whether melting of fault gouge can occur at shallow depth, we conducted rotary-shear friction experiments with SHIVA, a tool to investigate rock friction during the seismic cycle (Di Toro et al., 2010), at the Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy, on powdered fault breccias retrieved at 706–732 m depth in the WFSD-1 borehole. The gouges were sheared by up to 5 m and at slip rates of 1 m/s under normal stress of 20 MPa (i.e., lower range of the stress normal to the fault at this depth) under room humidity and fluid-rich (by adding 20 wt% distilled water) conditions (see the Supplemental Material).

Under room humidity conditions, the friction coefficient, μ, decayed with slip distance from a peak value of ∼0.6–0.7 at slip initiation, to a minimum value of ∼0.2 (experiment S1545: rock holders) or 0.45 (experiments S1541 and S1543: metal holders; Fig. 3A). Under fluid-rich conditions, the μ decayed from ∼0.6 to 0.7 at slip initiation to 0.3 (experiments S1547 and S1891: metal holders; Fig. 3B). After the experiments, regardless of the slip distance and the ambient conditions, the sheared gouges contained a brightly colored, glass-like layer that included micro- to nano-vesicles and clasts of quartz with angular to sub-angular shapes (Figs. 3C–3F). Vesicles are less abundant and

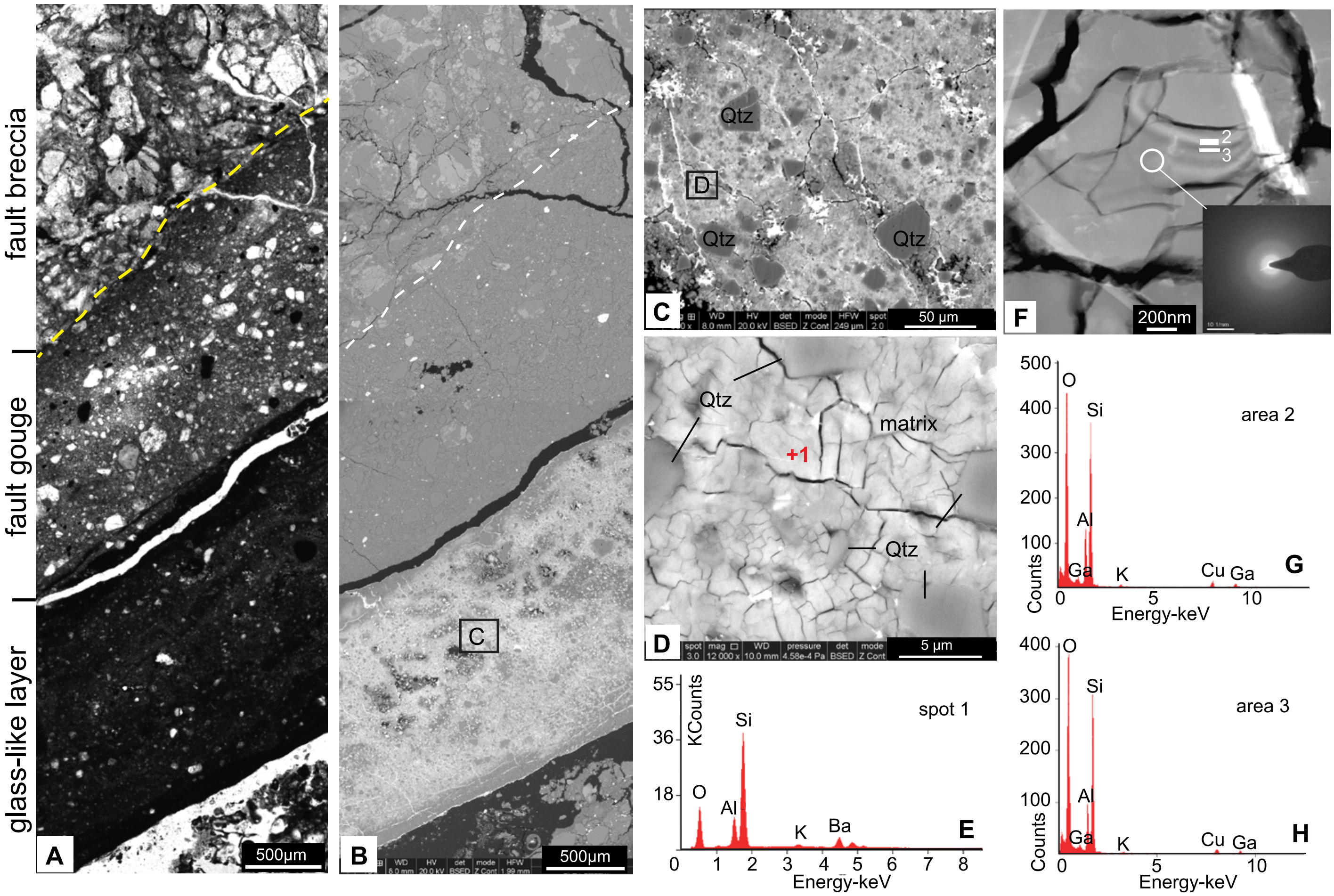

Figure 2. Microstructures of the fault rocks at 732.6 m depth in the first borehole of the Wenchuan Earthquake Fault Scientific Drilling Project (WFSD-1). (A,B) The slip zone consists of layers of fault breccia, fault gouge, and glass-like materials. Optical microscope image, parallel nicols. B–D are backscattered electron–scanning electron microscope images. (C) The glass-like layer is made of sub-rounded to angular quartz clasts immersed in a light gray matrix. (D) The matrix includes randomly oriented, open microcracks. (E) Scanning electron microscopy–energy-dispersive X-ray spectroscopy spectrum of spot 1 in image D. (F) Glass-like matrix with a few tens-of-nanometers-thick ripples and microcracks (transmission electron microscopy image). Inset shows the diffraction patterns. (G,H) Transmission electron–energy-dispersive X-ray spectra of areas 2 and 3 in image F. Ga and Cu are from the sample preparation by focused ion beam and transmission electron sample holders, respectively.

smaller in the gouges that were sheared under fluid-rich conditions.

DISCUSSION AND CONCLUSIONS

Fault Gouge Melting during the Wenchuan Earthquake

The formation of amorphous material in slip zones may result from ultracomminution or frictional melting (Wenk, 1978; Han et al., 2014). The fault gouges bounding the natural glass-like layer include quartz, feldspar, ankerite, chlorite, and mica (Table S1). The presence of only quartz clasts in the slip zone (Fig. S4) implies that seismic slip activated physical-chemical processes due to shear heating that leads to rock melting (Rice, 2006), mineral dehydration (Brantut et al., 2010), or decomposition (Sulem and Famin, 2009), resulting in the preferential consumption of feldspar, ankerite, chlorite, and mica. Instead, quartz clasts survived, as quartz has the highest melting point among these minerals (Spray, 2010). The curved ripples in the amorphous matrix may be due to melt migration or derived from the melting of minerals that have been stretched and folded as a result of viscous shearing (Wallace et al., 2019). The mineralogical and microstructural evidence reported above suggests that the glassy layer is the result of solidification of friction melts and thus can be called a PT (Sibson, 1975). Importantly, the PT is associated with a non-cohesive, fluid-rich fault gouge.

Previous experiments reproducing the Wenchuan earthquake deformation conditions but at a shallower depth (Kuo et al., 2014, 2017) or performed on more clay-rich gouges (Kuo et al., 2022) did not result in the production of PT. Instead, the experiments presented here confirm that PT may have formed during the Wenchuan earthquake, also in fluid-rich gouges, but at the larger confining stresses expected at 732 m depth (see the Supplemental Material).

The natural PT is quite similar to the artificial PT produced by the shearing of fluid-rich gouges (Figs. 3E and 3F). In the fluid-rich experiments, the presence of water should reduce the temperature of melting, resulting in larger amounts of melt produced (Allen, 1979). Moreover, the measured μ is lower when low thermal conductivity holders (experiment S1545, Fig. S7A) are used (e.g., Yao et al., 2016), which suggests that in natural faults under fluid-rich conditions, the μ could be lower than 0.2. Because of the limited amount of gouge available from the borehole, in the experiments we used gouges recovered at depths of 706–732 m, near the PSZ732. These gouges included 4–12 wt% of CO_2-bearing minerals (calcite, dolomite, ankerite, etc.; Table S1), which breakdown during frictional sliding and release CO_2 that is almost immiscible in silicate-built melts, resulting in the formation of vesicles in the artificial PTs (Gomila et al., 2021).

The microcracks in the natural PT are interpreted as resulting from rapid melt solidification and glass contraction, possibly caused by late coseismic to early post-seismic fluid influx. In fact, the natural PT of WFSD-1 was probably produced in a fluid-rich gouge layer, consistent with the evidence of vigorous fluid circulation

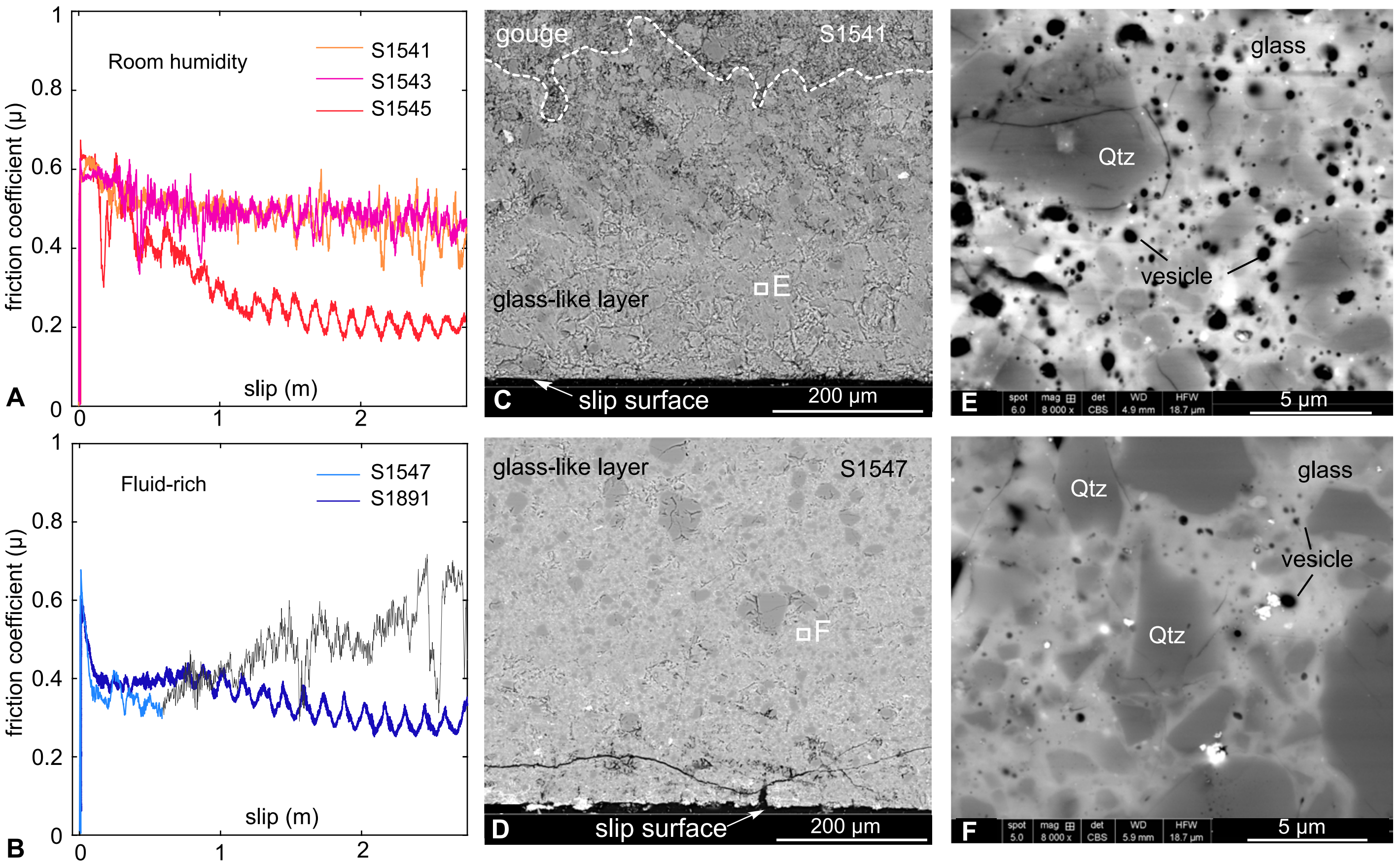

Figure 3. Experimental data and microstructures (backscattered electron–scanning electron microscope images) of the sheared gouges in the first borehole of the Wenchuan Earthquake Fault Scientific Drilling Project (WFSD-1). (A) Friction coefficient versus slip under room-humidity conditions (experiments S1541 and S1543: metal holders; experiment S1545: rock holder). (B) Friction coefficient versus slip under fluid-rich conditions (metal holders). Black curve is gouge extrusion. (C) Pseudotachylyte (PT) produced in experiment S1541. (D) PT produced in experiment S1547. (E) Close-up view of the PT of experiment S1541: the glass includes numerous vesicles and wraps rounded quartz clasts. (F) Close-up view of the PT of experiment S1547: compared to experiment S1541, the vesicles are smaller and less abundant, and the quartz clasts are more angular.

in the fault zone during the seismic cycle (Xue et al., 2013). However, glass is rarely preserved in natural PTs (Scambelluri et al., 2017) and never found in the very few PTs associated with fault gouges (Otsuki et al., 2009). Most natural PTs are devitrified or altered because the glassy material is unstable under typical geological conditions and especially in the presence of percolating fluids (Kirkpatrick and Rowe, 2013; Fondriest et al., 2020). Therefore, the preservation of glass in the fluid-rich gouges, cut by barite-bearing veins associated with post-seismic fluid percolation, implies that the PT was produced recently, likely during the 2008 Wenchuan earthquake.

Implications for Seismic Faulting

Geological evidence supports the hypothesis that the glassy PT was produced at very shallow depths in Earth's crust. The PT is hosted in the Triassic Xujiahe Formation, where the exhumation rate is estimated at 0.4–0.65 mm/yr (Godard et al., 2009; Wang et al., 2012). Paleoseismic investigations show that large earthquakes occur in the Longmen Shan fault zone with a recurrence interval of $\sim$3000 yr (Shen et al., 2009). Assuming that uplift and erosion are in balance, the amount of denudation is roughly equivalent to the amount of the rock uplift (Godard et al., 2010), and thus the maximum uplift during a large earthquake is $\sim$4 m. This is in agreement with GPS measurements of deformation of 1–2 mm/yr accommodated over the entire Longmen Shan area, which is released abruptly in rare but large earthquakes (Zhang, 2013). If the PT formed during the last large seismic event before the Wenchuan earthquake, the formation depth could be $\sim$736 m, and, if older, the PT should have been partially or completely altered over thousands of years (see the Supplemental Material; Fondriest et al., 2020). This reasoning constrains the maximum formation depth of the studied PT to $<$1 km. Given that there was no earthquake $> M_W$ 7 in the Longmen Shan fault zone in the past 2700 yr (Zhang, 2013), we suggest that the PT at 732.6 m depth is a PSZ (PSZ732) associated with the Wenchuan earthquake. This conclusion challenges the common hypothesis that PTs are rare and limited to fluid-deficient environments (Sibson and Toy, 2006). The scarcity of PTs within fault zones may be because they are rarely preserved or simply rarely recognized, as their microstructural features are progressively obliterated on geologic time scales by successive faulting, alteration, and devitrification processes.

The Wenchuan earthquake was characterized by a complex rupture pattern similar to what has been recently observed from the Kaikoura 2016 M_W 7.8 earthquake in New Zealand (Hamling et al., 2017). Two coseismic surface rupture zones merged into one at Bajiaomiao village (Fig. S1), where a single fault surface with two coseismic striations (thrust- and transpressive-related) is exposed (Fig. 4B). This field evidence is consistent with the finding of two PSZs at depths in WFSD-1, which merged toward the Earth's surface (Fig. 4). As a consequence, during its complex rupture, the Wenchuan earthquake activated different on-fault processes in nearby fault-zone volumes (Fig. 4A), including coseismic gouge graphitization in the PSZ589 (Fig. 4C), and frictional melting of fluid-rich gouges (Fig. 4D) at greater, but still shallow, depth.

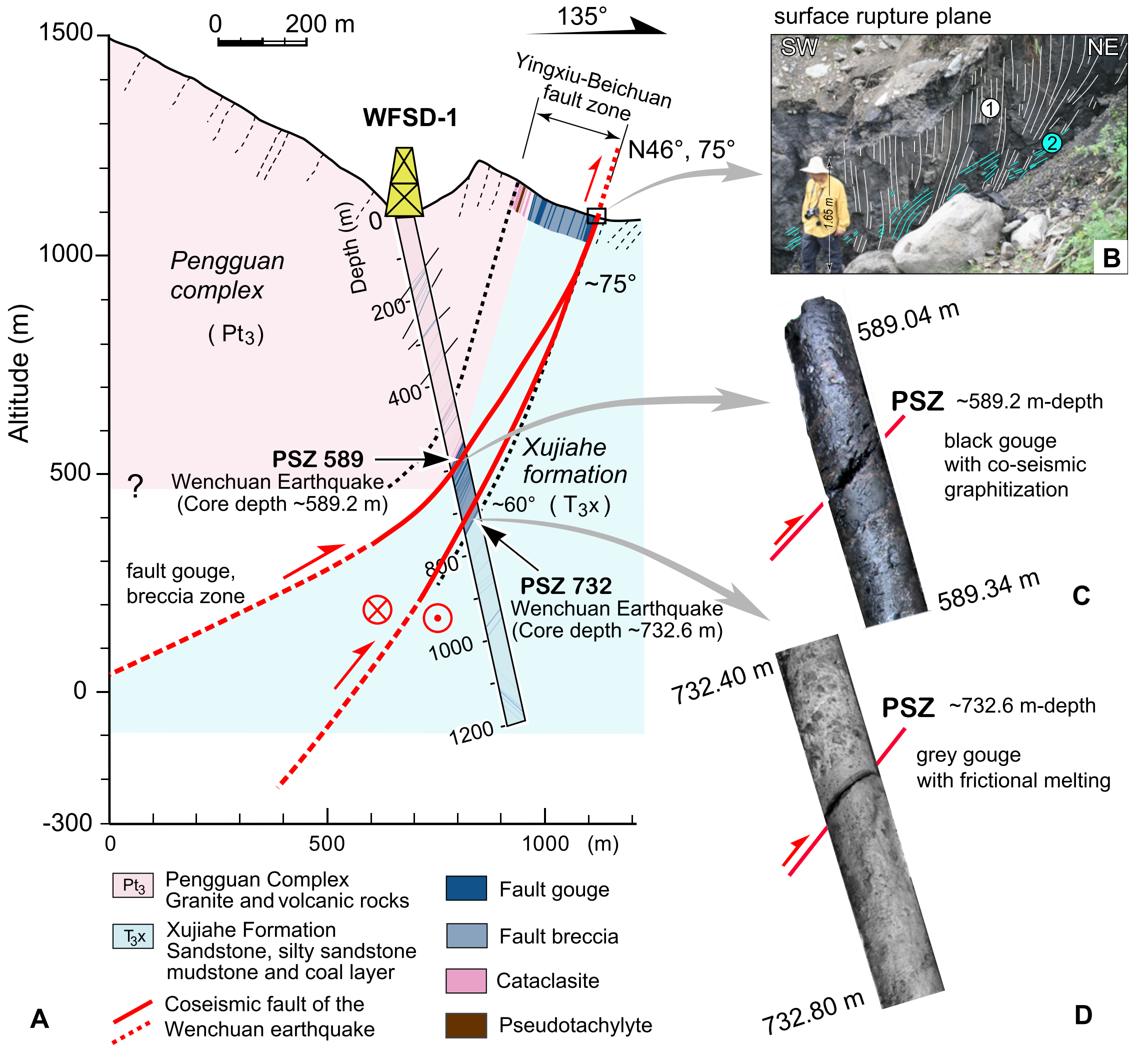

Figure 4. Two principal slip zones (PSZ) of the Wenchuan earthquake in the first borehole of the Wenchuan Earthquake Fault Scientific Drilling Project (WFSD-1). (A) Geological cross section across the WFSD-1 (modified from Li et al., 2013). (B) Surface rupture near the WFSD-1 drill site. Two sets of striae (1 and 2) decorate the fault surface. (C) Drill core from 589.04 m to 589.34 m depth includes the graphite-rich PSZ589. (D) Drill core from 732.40 m to 732.80 m depth includes the pseudotachylyte-bearing PSZ732.

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