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# Evidence for paleoseismic slip on a continental low-angle normal fault: Tectonic pseudotachylyte from the West Salton detachment fault, CA, USA

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ABSTRACT

The potential of continental low-angle normal faults (LANF) to nucleate large (>6.0 $M_w$) earthquakes at low-angles remains unclear despite much focused research. We document evidence for ancient seismicity along a continental LANF (detachment fault) that formed and slipped at low-angles and produced tectonic pseudotachylyte. These thick and laterally persistent pseudotachylyte accumulations along the West Salton detachment fault (WSDF), Salton Trough, USA, preserve convincing evidence for a frictional melt origin including: spherulitic microlites, ductile-flow structures, preservation of high temperature phases as clasts, and injection veins. Cumulative thickness of pseudotachylyte along the fault ranges from 0.1 to 1.5 m, and pseudotachylyte–cataclasite in the fault core and damage zone are exposed along ∼2.6 km length of the fault. Reworked fragments of pseudotachylyte in cataclasites, and multiple generations of cataclasites provide evidence for the preservation of multiple earthquake cycles. The limited exposure (<3% of the total exposed length), and unusually large volumes of pseudotachylyte along this section of the WSDF suggest special conditions for generation of frictional melt. Prior work, documenting the low dip of the WSDF throughout its history and abundant evidence for ancient seismicity presented here, shows that research must focus on explanations for LANF formation and slip that incorporate seismic slip. A new synthesis of pseudotachylyte along detachment faults from diverse tectonic settings provides convincing evidence that repeated ancient seismicity is common along detachment faults. These data constrain models for low-angle normal fault formation and strength. These results also have important implications for the evaluation of seismic hazards associated with active examples of LANF.



## 1. Introduction

The presence of low-angle normal faults (LANF) or detachment faults in highly extended terranes has led to a large body of literature describing the orientation, rock types, pressure and temperature conditions, and their deformation history (Longwell, 1945; Armstrong, 1972; Davis and Lister, 1988; John et al., 1987; Wernicke 1981, 1995; Axen and Bartley, 1997; Sorel, 2000; McNulty and Farber, 2002; Cowan et al., 2003; Shirvell et al., 2009; Collettini, 2011; and many others). Detachment faults are low-angle normal faults with gentle dips, large aerial extent, large displacements (⩾5–15 km), that often exhume mid to lower continental crust in their footwalls (Davis and Lister, 1988). Debate has focused on whether low-angle normal faults formed and/or slipped at low dip angles (<30°) in the brittle crust against the general expectations of Andersonian fault mechanics (Anderson, 1951) that low-angle normal faults are unfavorably oriented for slip, and that seismic activity on low-angle normal faults is rare (Jackson, 1987; Jackson and White, 1989; Thatcher and Hill, 1991; Wernicke, 1995; Abers et al., 1997; Abers 2001, 2009; Collettini and Sibson, 2001; Axen, 2004; Collettini, 2011). A growing body of research shows that low-angle normal faults have nucleated moderate to large earthquakes, localized seismicity on coeval normal faults in their hanging walls, and slipped seismically when earthquakes propagate onto them (Abers, 1991, 2001; Rietbrock et al., 1996; Axen, 1999; Sorel, 2000; Boncio et al., 2000; Collettini, 2011). Additionally, the presence of Holocene fault scarps associated with modern examples of low-angle normal faults may be related to recent seismic slip (Johnson and Loy, 1992; Caskey et al., 1996, 2004; Axen et al., 1999).

The relative paucity of seismicity associated with low-angle normal faults contrasts with compelling geologic evidence that some low-angle normal faults were active in the brittle-crust and has significant implications for fault mechanics and the evolution

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of highly extended terranes (e.g. Axen and Selverstone, 1994; Wernicke, 1995; Collettini and Sibson, 2001; Axen, 2004; Collettini, 2011; Selverstone et al., 2012; and many others). Models and data sets relevant to this paradox include: (1) models of low-angle normal fault formation in which the fault rotates from a moderate to low-angle during slip (Proffett, 1977; Davis, 1983; Buck, 1988; Wernicke and Axen, 1988), (2) existence of a small number of moderate-to-large magnitude earthquakes on low-angle normal faults (Abers 1991, 2001; Wernicke, 1995; Axen, 1999; McNulty and Farber, 2002), (3) the possibility of aseismic creep along low-angle normal faults (Jackson, 1987; Doser and Smith, 1989; Hreinsdottir and Bennett, 2009; Abers, 2009; Ikari et al., 2009; Smith and Faulkner, 2010; Lecomte et al., 2012), and (4) a rationale for especially long recurrence intervals between earthquake ruptures on low-angle normal faults, such that they exceed the historic record (Doser and Smith, 1989; Wernicke 1992, 1995). These hypotheses and data sets have different implications for expected fault-related deformation and structural relationships: option 1 requires evidence for large magnitude rotation about a horizontal axis during progressive exhumation (Davis, 1983; Buck, 1988; Fletcher and Spelz, 2009), options 2 and 4 predict evidence for ancient seismicity (Axen, 2004; Collettini, 2011), and option 3 predicts a lack of evidence for large magnitude seismicity (Axen, 2004; Lecomte et al., 2012).

Here we present evidence for ancient seismicity, in the form of substantial cumulative thicknesses of tectonic pseudotachylyte along the West Salton detachment fault zone, CA (Fig. 1) (Frost and Shafiquallah, 1989; Axen and Fletcher, 1998; Kairouz, 2005; Steely, 2006; Shirvell et al., 2009; Luther, 2012; Luther and Axen, 2013). Tectonic pseudotachylyte (rapidly-quenched frictional melt) provides the most convincing evidence for ancient seismic slip along exhumed fault zones (Cowan, 1999; Sibson and Toy, 2006; Lin, 2008; Marone and Richardson, 2010; Kirkpatrick and Rowe, 2013). Tectonic pseudotachylyte along LANFs are seldom reported, and where present they have important implications for the mechanics and seismic potential of active LANFs (Collettini, 2011; Lecomte et al., 2012). We use outcrop, microstructural, and compositional analyses to describe the nature of fault-related rocks, fault-zone evolution and test the hypothesis that low-angle normal faults preserve evidence for ancient seismic slip.

## 2. Methods

Detailed geologic mapping of the West Salton detachment fault at Yaqui Ridge, documents the presence of several strands of the detachment fault, and the development of thick and laterally extensive pseudotachylyte and cataclasite in the easternmost exposures of the fault zone (Schultejann, 1984; Kairouz, 2005; Steely, 2006; Janecke et al., 2008; Steely et al., 2009). We build on this work by collecting suites of oriented samples from the hanging wall and footwall of the West Salton detachment fault for microstructural, and compositional analyses (Fig. 1B). Sample characterization includes optical petrographic microscopy, scanning electron microscopy, X-ray diffraction (XRD) analyses, and X-ray florescence (XRF) analyses focused on microstructural, mineralogical, and chemical characterization of the fault zone. Scanning electron microscopy, back-scattered electron images (SEM–BSE) and energy-dispersive X-ray spectroscopy (EDS) analyses were conducted using a FEI Quanta 200 equipped with an EDAX EDS system at operating voltages between 15–20 KV at Weber State University. Calcite twin thickness measurements and analyses were conducted using a three-axis universal stage and methods described by Ferrill et al. (2004). The XRD analyses were conducted using an X Pert Pro Diffractometer system (45 kV/40 mA) at Utah State University. Major and trace element concentrations were determined using borate fused disk, and pressed pellet XRF analyses respectively. XRF analyses were conducted by SGS Canada.

## 3. Geologic setting

The West Salton detachment fault lies along the northern half of the western margin of the Salton Trough, California, at the northern end of the Gulf Extensional Province and can be traced about 200 km-long (Fig. 1) (Schultejann, 1984; Frost and Shafiquallah, 1989; Axen and Fletcher, 1998; Kairouz, 2005; Shirvell et al., 2009; Steely et al., 2009; Luther, 2012; Luther and Axen, 2013). The late Cenozoic Gulf Extensional Province (Gastil et al., 1975) (Fig. 1), is a highly oblique, transtensional, 1000-km long continental rift (Stock and Hodges, 1989; Herzig and Jacobs, 1994; Axen, 1995; Winker and Kidwell, 1996; Martínez-Gutiérrez and Sethi, 1997; Axen and Fletcher, 1998; Dorsey and Umhoefer, 2000; Holt et al., 2000; Oskin et al., 2001; Oskin and Stock, 2003; Dorsey et al., 2007; Fletcher et al., 2007; Wong and Gans, 2008; Shirvell et al., 2009; Brothers et al., 2009; Dorsey, 2010).

The West Salton detachment fault was part of the southern San Andreas fault system from the latest Miocene to early Pleistocene, was the principal extensional structure in the western Salton Trough, and accommodated >8–10 km of top-to-the-east normal-oblique slip and 1.1–4.25 km of exhumation (Schultejann, 1984; Frost and Shafiquallah, 1989; Axen and Fletcher, 1998; Cox et al., 2002; King et al., 2002; Matti et al. 2002, 2006; Kairouz, 2005; Steely, 2006; Dorsey et al., 2007, 2011, 2012; Shirvell et al., 2009; Steely et al., 2009). The primary low-dip angle of the WSDF is evident from syn-detachment stratigraphy in the hanging wall of the detachment, and cross-cutting relationships between the detachment and Pleistocene strata (Steely, 2006; Steely et al., 2009; Dorsey et al. 2011, 2012). The latest Miocene to early Pleistocene age of the West Salton detachment fault is constrained by provenance analysis, magnetostratigraphy, cross-cutting relationships, direct dating of fault-related rocks, and cooling ages of rocks in the footwall and hanging wall (Axen and Fletcher, 1998; Kairouz et al., 2003; Kairouz, 2005; Steely, 2006; Dorsey et al., 2007, 2011, 2012; Luther et al., 2008; Steely et al., 2009; Shirvell et al., 2009; Housen and Dorsey, 2010). The cross-cutting San Felipe fault zone folded the detachment fault and exhumed what appear to be the deepest structural levels of the West Salton detachment fault at the east tip of Yaqui Ridge (Steely et al., 2009). This well-constrained history makes the West Salton detachment fault an excellent natural laboratory to describe the deformation associated with low-angle normal faults in the seismogenic crust.

## 4. Fault zone structure and fault rock assemblage

The West Salton detachment fault zone, exposed along the NE and SW limbs of the younger Yaqui Ridge antiform (Fig. 1) (Steely et al., 2009), has a thick damage zone, fault core, and anastomosing principal slip surfaces (Fig. 2). The damage zone, up to 250 m-thick, is composed of fault breccias and highly fractured and altered protolith, but the distribution of fault-related deformation is asymmetric. Small-offset faults in the WSDF core and damage zone (i.e. Riedel shear) confirm normal-sence-offset for the main fault.

The hanging wall of the detachment, defines a thick ($\leqslant$250 m) zone of fracture and discoloration (Steely, 2006; Steely et al., 2009; Luther, 2012). The footwall damage zone is significantly thinner than the hanging wall where fractures and alteration are less pervasive, forming a thin damage zone ($\leqslant$20 m) (Fig. 1) (Schultejann, 1984; Steely, 2006; Steely et al., 2009; Luther, 2012). The footwall of the detachment at Yaqui Ridge is composed of foliated quartzofeldspathic gneiss, metasedimentary rocks, and minor exposures of protomylonite (Supplemental material) (Steely, 2006; Steely et al.,