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Frictional properties of low-angle normal fault gouges and implications for low-angle normal fault slip

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ABSTRACT

The mechanics of slip on low-angle normal faults (LANFs) remain an enduring problem in structural geology and fault mechanics. In most cases, new faults should form rather than having slip occur on LANFs, assuming values of fault friction consistent with Byerlee's Law. We present results of laboratory measurements on the frictional properties of natural clay-rich gouges from low-angle normal faults (LANF) in the American Cordillera, from the Whipple Mts. Detachment, the Panamint range-front detachment, and the Waterman Hills detachment. These clay-rich gouges are dominated by neoformed clay minerals and are an integral part of fault zones in many LANFs, yet their frictional properties under in situ conditions remain relatively unknown. We conducted measurements under saturated and controlled pore pressure conditions at effective normal stresses ranging from 20 to 60 MPa (corresponding to depths of 0.9–2.9 km), on both powdered and intact wafers of fault rock. For the Whipple Mountains detachment, friction coefficient (μ) varies depending on clast content, with values ranging from 0.40 to 0.58 for clast-rich material, and 0.29–0.30 for clay-rich gouge. Samples from the Panamint range-front detachment were clay-rich, and exhibit friction values of 0.28 to 0.38, significantly lower than reported from previous studies on fault gouges tested under room humidity (nominally dry) conditions, including samples from the same exposure. Samples from the Waterman Hills detachment are slightly stronger, with μ ranging from 0.38 to 0.43. The neoformed gouge materials from all three localities exhibits velocity-strengthening frictional behavior under almost all of the experimental conditions we explored, with values of the friction rate parameter $(a-b)$ ranging from -0.001 to $+0.025$. Clast-rich samples exhibited frictional healing (strength increases with hold time), whereas clay-rich samples do not. Our results indicate that where clay-rich neoformed gouges are present along LANFs, they provide a mechanically viable explanation for slip on faults with dips $<20°$, requiring only moderate $(P_f < \sigma_3)$ overpressures and/or correcting for $\sim 5°$ of footwall tilting. Furthermore, the low rates of frictional strength recovery and velocity-strengthening frictional behavior we observe provide an explanation for the lack of observed seismicity on these structures. We suggest that LANFs in the upper crust (depth <8 km) slip via a combination of a) reaction-weakening of initially high-angle fault zones by the formation of neoformed clay-rich gouges, and b) regional tectonic accommodation of rotating fault blocks.

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1. Introduction

Normal faults with low dips ($<30°$) have been recognized in the field for over a century (e.g. Ransom et al., 1910; Longwell, 1945), but the shallow observed dips stand in apparent contradiction with two fundamental predictions from rock mechanics. For typical values of rock internal friction ($\sim$0.6–0.8), normal faults should not form at dips $<\sim 50°$; for typical values of sliding friction ($\mu = 0.6$) those faults should not then slip at dips much below 30°. The crust should fail instead by formation of new higher-angle faults (e.g., Anderson, 1951; Byerlee, 1978; Collettini and Sibson, 2001) (Fig. 1).

Several explanations for LANF slip have been offered. One set of explanations argues that the low dips observed in the field are caused by post-deformational rotation of the fault plane, either by the passage of a 'rolling hinge' (Wernicke and Axen, 1988; Buck, 1988), or by late-stage 'domino'-style rotation of normal fault blocks (e.g. Wong and Gans, 2008). A separate set

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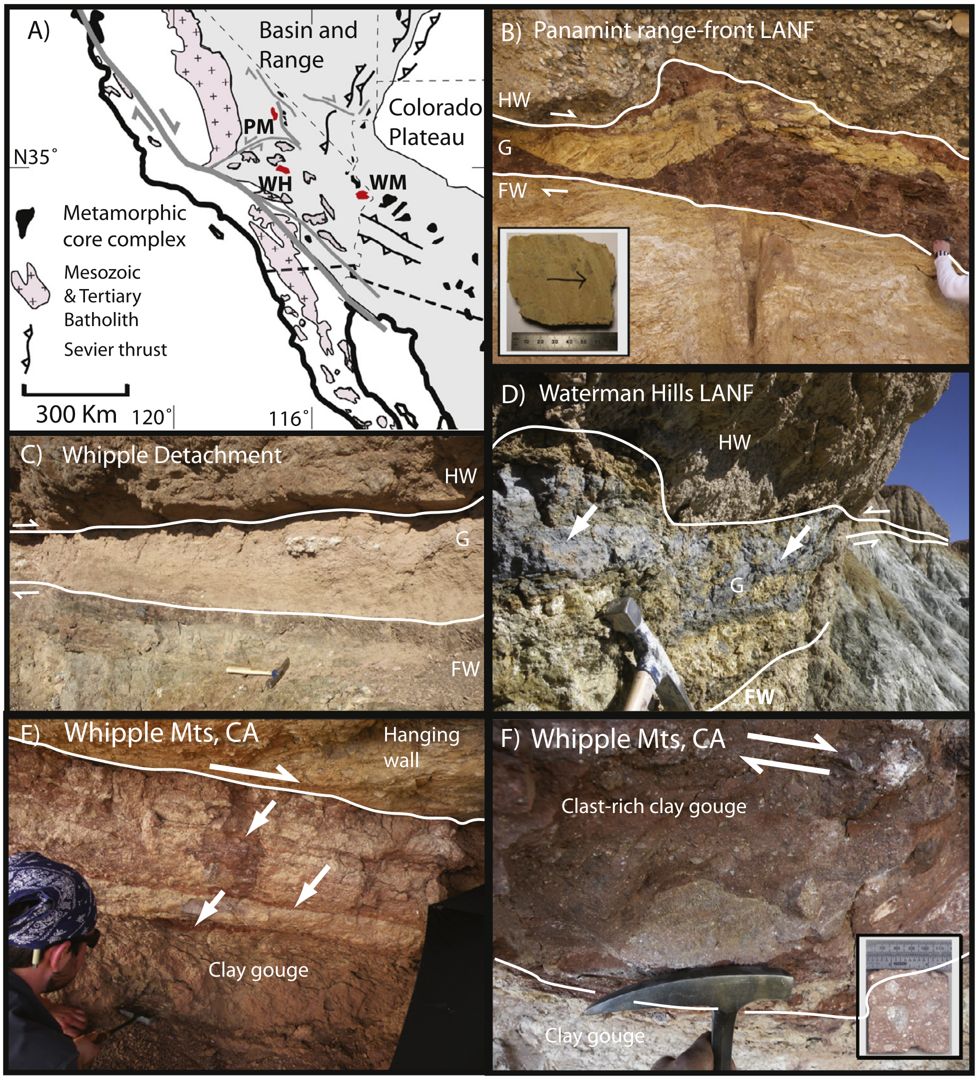

Fig. 1. A) Map of the southwestern US showing metamorphic core complexes with low-angle normal faults (LANFs). Core complexes with LANFs highlighted in red are those sampled in this study: PM: Panamint range-front LANF, WM: Whipple Mountains Detachment, WH: Waterman Hills LANF. B) Panamint Detachment outcrop; this is the same outcrop sampled by Numelin et al. (2007). Footwall is Neoproterozoic schist, hanging wall is weakly consolidated conglomerate. Clay gouge zone is 0.5–2.0 m thick. Inset is clay-rich wafer used in our experiments. C) WM: Whipple Mountains detachment fault exposed at Bowman's Wash. Hanging wall is quartz-cemented quartzite breccia (interpreted megabreccia deposits – Forshee and Yin, 1995). Footwall is Cretaceous granite with characteristic chlorite/epidote 'microbreccia' texture and alteration. Clay gouge zone is 0.5–2.0 m thick. D) Waterman Hills detachment fault. Hanging wall is Miocene rhyolite, footwall is Miocene granodiorite (Fletcher and Bartley, 1994). Clay gouge zone is 1.0–2.0 m thick. Grey material is smectite-dominated, brown is illite-dominated. Illite-dominated material was sampled. E) Field photo of Whipple Moutain Detachment at Bowman's Wash, showing clay-rich gouge horizons we sampled (white arrows). F) Whipple Mountain Detachment at Bowman's Wash, showing clast-rich gouge (inset is a wafer used in our experiments). Scale in insets in 1B and 1F are the same, upper scale units are in 10's of mm. Photo annotations: HW: Hanging wall. FW: Footwall. G: Gouge.

of explanations argues for the presence of unusual conditions within the fault core itself, through either: (a) rotation of principal stresses in the immediate vicinity of the fault core (Chery, 2002; Lecomte et al., 2012), (b) locally elevated pore-fluid pressures in the fault zone (Rice, 1992; Axen, 1992), or (c) the presence of low-friction materials in the fault core (Hayman et al., 2003; Numelin et al., 2007; Collettini et al., 2009a, 2009b).

Many LANF in the American Cordillera contain well-developed clay-rich gouges, ranging in thickness from cm's to >10 m (Haines and van der Pluijm, 2012, Fig. 1). These gouges are dominated by authigenic clay minerals (illite, illite–smectite, smectite and chlorite–smectite phases) formed at temperatures of 60–180 °C. Depth constraints on the formation of the neoformed clay gouges we sampled from three well-studied detachments for this work (the Whipple Mountains, Panamint range-front, and Waterman Hills detachments) are harder to establish, given uncertainties in heat flow and temperature gradients within exhuming LANF footwalls, but range from <2 to >8 km (Haines and van der Pluijm, 2012). The neoformation of clay-rich fault gouge, a low-temperature metasomatic process confined to fault zones, thus has a potential impact on the frictional strength of LANFs in the upper crust, where low-angle slip is mechanically most problematic. Although reaction-softening has been discussed as a possible explanation for LANF slip (e.g. Manatschal, 1999), the actual frictional properties of these neoformed clay-rich gouges and their implications for LANF slip remain poorly characterized.

Frictional properties of natural fault zones are commonly extrapolated or estimated from laboratory tests on synthetic gouges of similar composition (e.g. crushed illite shale as a proxy for illitic gouges; Brown et al., 2003; Ikari et al., 2009). Work comparing frictional properties of chlorite separated from natural fault gouge with crushed chlorite schist has highlighted dramatic differences in both the frictional strength and stability between phyllosilicate materials that have identical compositions, but very different parti-

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