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Mode I microfracturing and fluid flow in damage zones: The key to distinguishing faults from slides

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ABSTRACT

We have examined the distribution of microfractures in arenites and the evolution of vein forming fluids in the matrix of carbonate breccias within the damage zones of large detached blocks in order to characterize their modes of emplacement. Previous studies of microfractures in the damage zone associated with tectonic faulting have shown a clear pattern of increasing density as the fault is approached. Previous studies of carbonate breccia within damage zones of tectonic faults typically document evidence of multiple fluid events representing repeated rupture-healing processes. However, in this study, we find no change in the microfracture density with distance from the 45 km-displaced gravity-driven slide block at Heart Mountain, Wyoming. In a previous study of the same massive slide block there was no evidence of multiple fluid infiltration events related to emplacement. We interpret these observations as indicating the absence of rupture cycling that would be expected in the development of a process zone, instead being consistent with catastrophic emplacement of gravity-driven slide blocks. We use this distinct pattern of microfracture density and fluid infiltration to demonstrate that several large (>1 km^2) detached blocks in the Basin and Range, previously thought to be allochthons related to hyperextension detachment faults, are actually slide blocks whose detachment surfaces represent no crustal extension.

1. Introduction

Large slide blocks have often been misidentified as upper plates of tectonic faults, and the upper plates of tectonic faults have in turn been misidentified as slide blocks (e.g., Bucher, 1947; Zen, 1967; Armstrong, 1972; Boyer and Allison, 1987; Bird and Dewey, 1970; Beutner, 1972; Rowley and Kidd, 1981; Rodgers, 1981; Bosworth et al., 1988). Distinguishing between these two very different structures often requires detailed palinspastic reconstructions, kinematic indicators, and/or knowledge of the timing of metamorphism that is sometimes difficult to achieve. Geometrically, large slide blocks are similar to the upper plate of rooted low-angle normal faults, in that both typically have numerous high-angle upper plate normal faults that sole into a master detachment that is commonly in sharp contact with the lower plate (e.g., Pierce, 1980; Wernicke, 1981; Lister and Davis, 1989; Hauge, 1993). In many cases, distinguishing between tectonic crustal extension faults and slide block detachments is easy when toe structures or other geometric slide relationships are present. However, when the toe region is removed by erosion or buried, a massive slide block can easily be confused with a rooted extensional detachment (see Moores et al., 1968; Armstrong, 1972; Boyer and Allison, 1987).

There are numerous examples of large-scale slide blocks being interpreted as either large autochthonous and para-autochthonous masses or as large overthrust blocks. The most famous of these are Heart and Sheep Mountains of northwestern Wyoming, which were first mapped as large overthrust blocks (the largest over 30 km^2) lying on Eocene gravels and then later shown to be slide blocks (Bucher, 1947). Examples of large slide blocks within the Basin and Range that were originally thought to be partially or wholly para-autochthonous masses include blocks that slid off the Snake and Lemhi Ranges of Idaho; the Grant Range, Spring Mountains and Virgin Mountains of Nevada; and the Canyon Range of Utah (variously discussed in Secor, 1963; Moores et al., 1968; Seager, 1970; Beutner, 1972; Moore et al., 1987; Anders, 1990; Morris and Hebertson, 1996; Wills and Anders, 1999). Until the basal surfaces of these slide blocks were identified as resting on young gravels or lake sediments (e.g., Moores et al., 1968), or they

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were shown to be internally normal faulted where a thrust was previously interpreted (e.g., Bucher, 1947), the blocks were not recognized as being associated with gravity-driven slides.

Currently, there is controversy regarding the nature of the Mormon Peak detachment and the Castle Cliff detachment, which have been described as both slide block detachments as well as rooted detachments involving significant crustal extension (>25 km). The Mormon Peak detachment is located in the Mormon Mountains and Tule Springs Hills of southeastern Nevada (Wernicke et al., 1985; Axen, 1991; Anderson and Barnhard, 1993; Anders et al., 2006; Walker et al., 2007; Anderson et al., 2010; Diehl et al., 2010). The upper plate consists of a number of individual blocks of Paleozoic rocks resting on rocks mostly of Ordovician to Precambrian age (Wernicke et al., 1985). Wernicke et al. (1985), Wernicke et al. (1989), Anderson and Barnhard (1993), Axen (2004), Anderson et al. (2010) and Diehl et al. (2010) all suggest that the individual upper plate blocks are remnants of a Miocene extensional allochthon rooted in the mid-crust having anywhere from 4 km to 22 km of extension. In contrast, Tschanz and Pampeyan (1970), Carpenter and Carpenter (1994), Anders et al. (2006) and Walker et al. (2007) all have suggested that blocks assigned to the upper plate of the Mormon Peak detachment are individual gravity-driven slide blocks derived from the upper plate of the late Mesozoic/early Cenozoic Mormon thrust. Similarly, the Castle Cliff detachment in the Beaver Dam Mountains along the margin of the Basin and Range and the Colorado Plateau in southeastern Nevada and southwestern Utah is described as both a rooted detachment with as much as ∼30 km of extension (Wernicke and Axen, 1988; Wernicke et al., 1989; Axen and Wernicke, 1989; Axen et al., 1990; Anderson and Barnhard, 1993) as well as a slide block or multiple slide blocks (Jones, 1963; Hintze, 1986; Carpenter et al., 1989; Carpenter and Carpenter, 1994; Christie-Blick et al., 2007).

In this paper, we propose a model for distinguishing between tectonic faults and detachments associated with slide blocks based on the microfracture characteristics associated with the detachment. At any point in the history of a tectonic fault, well-defined tips are sites of stress concentrations that, in low porosity rock, are sufficient to produce mode I fracturing in the surrounding rock (see Scholz et al., 1993; Scholz, 2002). This zone of fractures, called a process zone (Fig. 1a), forms an aureole of damage surrounding the fault (Scholz et al., 1993; Vermilye and Scholz, 1998). As the fault continues to grow in the brittle field by stress buildup and release, its displacement becomes greater and the damage zone deformation becomes more intense at a given distance from the fault (e.g., Scholz, 2002; Faulkner et al., 2011). In many low porosity rock types, this process results in an aureole of microfractures in the damage zone that increase exponentially or nearly so in density (e.g., fractures per mm) as a fault surface is approached (Brock and Engelder, 1977; Chester et al., 1993; Odling et al., 2004; Wilson et al., 2003; Faulkner et al., 2011). All of the faults in Fig. 2 and Table 1 were active at depths ranging from as little as 1.5 km to as much as 8–10 km of overburden (Brock and Engelder, 1977; Anders and Wiltschko, 1994; Coleman and Walker, 1994; Vermilye and Scholz, 1998; Anders et al., 2001; Faulkner et al., 2006; Mitchell and Faulkner, 2009). The width of the microfractured damage zone scales with fault displacement (Scholz et al., 1993). In addition, the repeated stress buildup-fracture process results in multiple fluid infiltration events, evidenced by cross-cutting veins and cathodoluminescence variations in fault breccia cements.

Prior to this study, no microfracture density data have been published for slide blocks. For comparison to tectonic faults, we document microfracture density associated with world's largest terrestrial gravity-driven slide, the 34,000 km^2 Heart Mountain slide block (which includes the smaller isolated Heart and Sheep Mountain blocks of Bucher, 1947; Pierce, 1973) located in northwestern

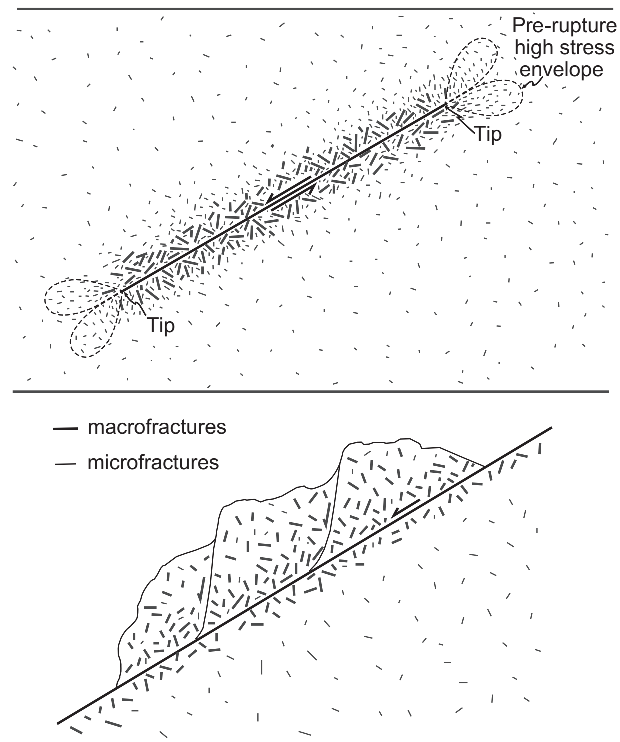

Fig. 1. Schematic diagrams of the difference between a tectonic fault (**a**) where stresses surrounding the fault tip result in the development of a process zone. The macrofractures (thick lines) and microfractures (thin lines) represent a density increase toward the displacement surface. Dashed lines represent stress concentrations associated with a mode II fracture propagation (see Scholz et al., 1993). (**b**) Representation of the distribution of macrofractures and microfractures found at the base of a slide block where there is no progressive fault tip. Macrofractures dominate in the upper plate of slides and microfractures that represent stress cycling are rare; in this figure, a regional background density is shown.

Wyoming. The Heart Mountain slide block moved at least 45 km across Eocene gravels about 50 million years ago; its upper plate during motion comprised 2–4 km of Paleozoic sedimentary rocks and Eocene Absaroka Volcanic rocks (Pierce, 1973; Hauge, 1993; Beutner and Gerbi, 2005; Aharonov and Anders, 2006; Craddock et al., 2009; Anders et al., 2010). Although Hauge (1985, 1993) proposed that the Heart Mountain slide block was emplaced slowly or incrementally, and Beutner and Hauge (2009) advocated for its emplacement by a combination of incremental and catastrophic processes, most researchers agree that the Heart Mountain slide block was emplaced catastrophically (e.g., Hughes, 1970; Pierce, 1973, 1980; Voight, 1973; Melosh, 1983; Beutner and Gerbi, 2005; Craddock et al., 2009; Anders et al., 2010, 2011; Craddock et al., 2012). For example, a previous study of carbonate breccias in the Heart Mountain detachment and adjacent rocks (Anders et al., 2010) documented cathodoluminescence evidence for a single fluid-infiltration event in the detachment, consistent with a single, rapid episode of emplacement of the slide block.

In contrast to rocks associated with tectonic faults, a slide block for the most part moves over pre-existing landscape. Catastrophically-emplaced slides can cut down into underlying rock, but do so at high velocities, leaving no chance for repeated stress cycling (see Shaller, 1991). Unlike tectonic faults, slide surfaces, commonly called "detachments" (a term also used for rooted low-angle normal fault surfaces), have no growth tips separating broken from unbroken rock and no associated stress concentrations. As a result no process zone is developed, and as we document here, there are no corresponding mode I fractures or multiple fluid infiltration events (Fig. 1b). Some slides do move incrementally (e.g.,