Fractured dirt: Deformation textures and processes in sediment and other unconsolidated deposits

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Structural geologists examine rock deformation to evaluate how Earth's crust responds to tectonic loads in the brittle, mixed mode (or the schizosphere of Scholz, 2002) and plastic regimes of the crust (Rutter, 1986). Recently, some researchers have turned their attention to unconsolidated and nonlithified deposits, elucidating how materials in the near-surface regime deform, and how the impact of this deformation may be felt in a variety of settings (Maltman, 1988; Rawling et al., 2001; Cashman et al., 2007, p. 611 of this issue).

The nature of exhumed fault-related rocks along the San Andreas fault and other faults has been examined for over 70 yr (Waters and Campbell, 1935), and for the most part, work has focused on exhumed fault rock in bedrock (Anderson et al., 1980; Chester and Logan, 1986; Chester et al., 1993; Wibberley and Shimamoto, 2003; Faulkner et al., 2003; Jeffries et al., 2006; Dor et al., 2006). These types of studies evaluate the processes at seismogenic depths where seismic energy is radiated (Scholz, 2002). Within the upper several kilometers, however, faults, while not radiating energy, transmit energy and displacement to Earth's surface, and this may pose significant hazards (Spudich and Olsen, 2001). Developing greater insights into the processes within fault zones in the upper 0–500 m of Earth's surface has important implications for hazards analysis, zoning, and paleoseismic studies. The ability to identify the textures in near-surface portions of faults that indicate whether a fault ruptures seismically, or fails by slow slip or creep, would be an important tool for paleoseismologists and structural geologists.

Cashman et al. document deformation in near-surface exposures of the San Andreas fault, and address two emerging topics: deformation in faults at the surface, and more generally, deformation processes in poorly lithified deposits prior to burial and diagenesis. Cashman et al. show that the microstructures of deformed sand in a creeping portion of the San Andreas fault reflect distributed deformation, and preserve no deformation bands, whereas siltstones and sandstones along a seismogenic portion of the fault exhibit deformation bands, which were the product of grain fracture and crushing. Cashman et al. indicate that the presence of brittle, localized slip in deformation bands may be an indicator of past rapid failure. If so, this would be an important finding, as few rock structures unequivocally document seismic slip (Cowan, 1999). Cashman et al. suggest that the behavior of the sediments at the seismic slip site can be explained in the context of the "grain bridge" model, in which stresses at grain boundaries fail under the concentrated stresses at the grain contact points (Gallagher et al., 1974; Sammis and Steacy, 1994; Morgan and Boettecher, 1999). The distributed deformation along the creeping segment lacks deformation bands, and fabrics within the multiple slip surfaces exhibit a grain-preferred orientation that may be the result of slow slip. Expanding these results to recent drilling of seismically ruptured faults (Ma et al., 2006; Sone et al., 2007) and other studies of shallow fault-related rocks (Dor et al., 2006) may provide significantly new insight into the processes that transmit seismic slip to Earth's surface along either very narrow slip zones or across zones 10–50 m wide.

Experimental verification of these results may be obtained from recent rock-on-rock friction experiments with gouge layers, deformed at normal stress values of 1–50 Mpa (Biegel et al., 1989; Anthony and Marone, 2005; Knuth and Marone, 2007). But, due to the strain rates needed to replicate co-seismic rupture velocities, and the difficulty in imaging deformed unconsolidated sediment, it will be challenging to evaluate the microscopic deformation mechanisms at most experimental conditions that approximate field conditions. Low confining pressure (*P*c) experiments are typically the domain of geotechnical engineers, who have produced strain localization in sand at *P*c of 10's to 100's kPa, and for a variety of material types (Finno et al., 1997; Alshibli et al., 2003). One of the interesting results from these experiments is that shear band localization in sand is suppressed by increasing *P*c, and the geometry of the load conditions are important for determining how strain is localized. Experiments can also examine the impact of gouge thickness and particle characteristics. Anthony and Marone (2005) showed that smooth grains deform by grain boundary sliding, whereas rough grains roll and dilate. In addition, stick-slip behavior is promoted by the presence of smooth grains. Knuth and Marone (2007) further documented the importance of grain material properties on the behavior of faults.

The other important aspect of Cashman et al.'s work is that it draws attention to the analysis of brittle deformation of nonlithified deposits. This has implications not only for earthquake studies but for hydrology, ground failure, deformation of saturated sediments in subaqueous and subarieal settings, and ultimately for interpreting deformed rock (Maltman, 1988; Cashman and Cashman, 2000; Rawling et al., 2001; Du Bernard et al., 2002; Rawling and Goodwin, 2003; Bhattacharya and Davies, 2004; Evans and Bradbury, 2004; Wilson et al., 2003; Schultz and Siddarthan, 2005; Aydin et al., 2006; Kirby et al., 2007). These researchers have documented that materials with little or no cohesive strength and, in some cases, with extremely high porosities, may sustain brittle slip localization, cataclasis, and dilatent fracturing.

The mechanics of deformation in these conditions has been elegantly described by Wong et al., (2004), Schultz and Siddarthan (2005), and Aydin et al. (2006). Instead of using the Mohr-Coulomb space familiar to most geologists, the deformation of unconsolidated porous deposits and rock can be examined with a yield analysis, where failure may occur by dilatency, shearing on localized surfaces, compaction, or distributed flow. Prediction of the mode of deformation depends on the relationships between differential stress (σ_1-σ_3) and the mean stress $[(\underset{\cdot}{\sigma}_1\underset{\cdot}{\sigma}_3\sigma_3)/3]$, as well as on grain properties, porosity, and water content. In this context, the style of deformation over a range of conditions can be predicted, and field and experimental observations confirm these predictions (Schultz and Siddarthan, 2005; Aydin et al., 2006).

The mode by which nonlithified materials deform is an increasingly important topic for geologists to consider, as such deformation has impacts on human-related activities such as groundwater resource development, waste isolation, and deep engineered structures. The implications for the rock record are also significant, because we must allow for the possibility that some of the brittle deformation we observe in rock may have developed before lithification. The analyses by Cashman et al., Cashman and Cashman (2000), and others cited above suggest that we might want to revise our conventional structural approach to examining deformed rocks, and admit the possibility of fracture, flow, and shearing in the nonlithified state.

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