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Fault-slip inversions: Their importance in terms of strain, heterogeneity, and kinematics of brittle deformation

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ABSTRACT

Heterogeneous deformation is intrinsic in natural deformation, but often underestimated in the analysis and interpretation of mesoscopic brittle shear faults. Based on the analysis of 11,222 faults from two distinct tectonic settings, the Central Andes in Argentina and the Sudbury area in Canada, interpolation of principal strain directions and scaled analogue modelling, we revisit controversial issues of fault-slip inversions, collectively adhering to heterogeneous deformation. These issues include the significance of inversion solutions in terms of (1) strain or paleo-stress; (2) displacement, notably plate convergence; (3) local versus far-field deformation; (4) strain perturbations and (5) spacing between stations of fault-slip data acquisition. Furthermore, we highlight the value of inversions for identifying the kinematics of master fault zones in the absence of displaced geological markers. A key result of our assessment is that fault-slip inversions relate to local strain, not paleo-stress, and thus can aid in inferring, the kinematics of master faults. Moreover, strain perturbations caused by mechanical anomalies of the deforming upper crust significantly influence local principal strain directions. Thus, differently oriented principal strain axes inferred from fault-slip inversions in a given region may not point to regional deformation caused by successive and distinct deformation regimes. This outcome calls into question the common practice of separating heterogeneous fault-slip data sets into apparently homogeneous subsets. Finally, the fact that displacement vectors and principal strains are rarely co-linear defies the use of brittle fault data as proxy for estimating directions of plate-scale motions.

1. Introduction

Mesoscale shear faults, notably slickensides (Fig. 1a), are widespread in geological terrains that are affected by brittle deformation. Shear faults permit the acquisition of so-called fault-slip data in the field. These data consist of orientations of faults and slip sense or direction from kinematic indicators such as slickensides (Fig. 1b). By now, fault-slip data are almost routinely acquired in structural, mostly neo-tectonic, field studies. The usage of such data sets for regional tectonic analyses is motivated by the availability of software packages enabling rapid processing of strain increments or states of paleo-stress from fault-slip data, known as fault-slip inversions (e.g., Gephart and Forsyth, 1984; Hardcastle, 1989; Marrett and Allmendinger, 1990; Gephart, 1990; Sperner et al., 1993; Ortner et al., 2002; Delvaux and Sperner, 2003). Depending on mechanical assumptions, the inversion of a given fault population provides reduced strain or paleo-stress tensors, which includes the orientations of respective principal axes, the ratio of relative principal axis magnitudes and statistical parameters describing the solution quality (Angelier and Mechler, 1977; Angelier and Goguel, 1979; Angelier, 1984; Sperner and Zweigel, 2010). Because brittle shear faulting is mostly friction-controlled, inversions aimed at paleo-stress solutions are chiefly based on the Mohr-Coulomb criterion (Reches, 1987). By contrast, solutions in terms of strain or kinematic axes rely on the geometry of faults and associated

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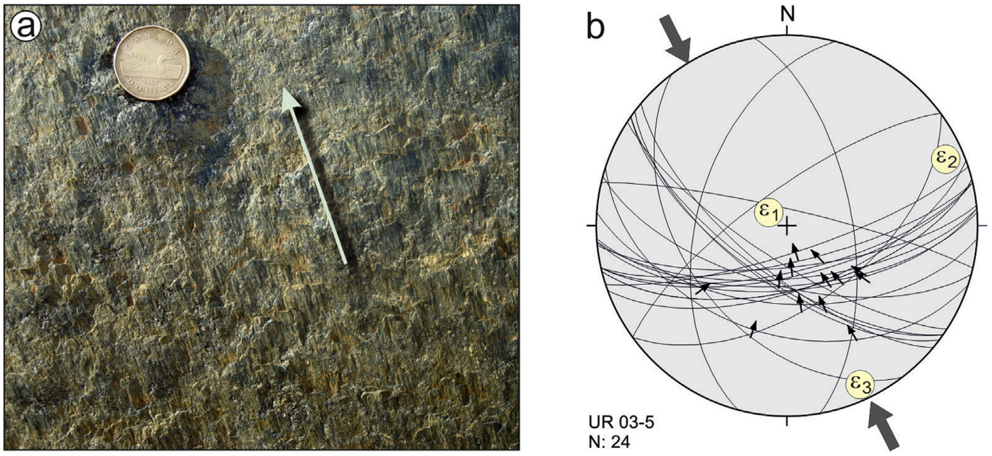

Fig. 1. Characteristics of fault-slip data. (a) Image showing an example of a brittle shear fault decorated with chlorite fibres from the Sudbury Igneous Complex, Ontario, Canada. Note the polarity of truncated mineral fibres indicating the sense of slip of the missing block on the fault surface indicated by the arrow. (b) Representation of fault-slip data in lower-hemisphere, equal-area projection. Great circles represent fault surfaces. Arrows on great circles indicate the senses of slip of hanging walls with respect to footwalls along a measured slip lineation. $\varepsilon_1 \geq \varepsilon_2 \geq \varepsilon_3$ are, respectively, maximum, intermediate and minimum principal strain axes. Grey arrows indicate the map-view shortening.

striations (Marrett and Allmendinger, 1990).

Despite the popularity among structural geologists of conducting fault-slip analyses, considerable debate exists regarding assumptions underlying fault-slip inversion, analytical treatment of heterogeneous fault-slip data sets and interpretation of inversion solutions (Pollard et al., 1993; Twiss and Unruh, 1998; Marrett and Peacock, 1999; Liesa and Lisle, 2004; Lisle, 2013). Assumptions for fault-slip inversion, notably with regard to paleo-stress, include: (1) spatial and temporal homogeneity of a stress field during brittle faulting; (2) co-linearity of the slip direction and the maximum resolved shear stress on a given fault; (3) independence of slip among adjacent faults; (4) small displacement magnitudes compared to fault lengths; (5) small rotation magnitudes of faults and (6) formation of all faults at the time of the applied stress (Bott, 1959; Angelier and Mechler, 1977; Angelier and Goguel, 1979; Angelier, 1984).

The generation of a homogeneous stress field, i.e., the state of stress at which orientations and magnitudes of principal stresses are uniform over a specified area or volume, requires mechanical isotropy of the stressed material. The lithologically and structurally heterogeneous upper continental crust, which is the realm of brittle deformation, is mechanically rather anisotropic. Even in mechanically isotropic elastic materials, the presence of structural discontinuities gives rise to pronounced perturbations of an applied stress (Segall and Pollard, 1980; Olsen and Pollard, 1991; Homberg et al., 1997; de Joussineau et al., 2003; Okubo and Schultz, 2006; Misra et al., 2009), notably at fault tips (Fig. 2). An influence of stress perturbations on the configuration of secondary, i.e., higher-order, faults located close to master, i.e., lower-order, faults is also known from detailed field studies (Bürgmann and Pollard, 1994; Lee and Angelier, 1994; Roberts, 1996; Homberg et al., 1997; Gapais et al., 2000; Maerten et al., 2002; De Guidi et al., 2013). Collectively, experimental and field studies question the existence of stress homogeneity in the upper crust, particularly near structural discontinuities but also on the regional scale. Moreover, stress fluctuations associated with individual fault-slip events renders the temporal homogeneity of stresses over protracted times, such as the duration of brittle faulting phases, unlikely (Caputo, 2005).

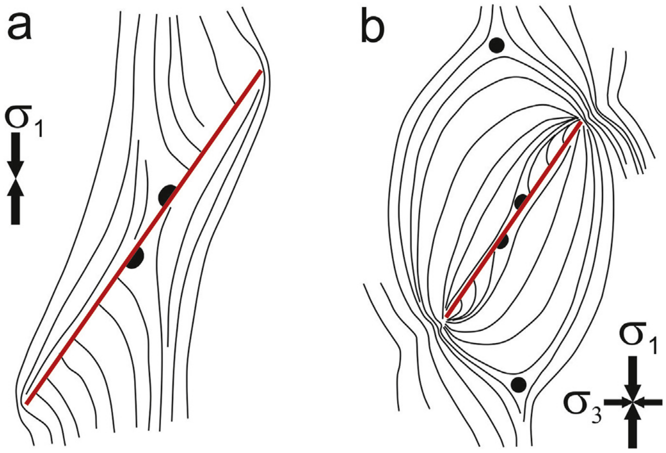

Fig. 2. Trajectories of maximum principal stress directions (σ_1) based on photoelastic and numerical studies of stress distributions by de Joussineau et al. (2003) illustrating stress perturbations at discontinuities. Solid circles and half circles indicate isotropic areas. (a) Perturbation at the tips of a single discontinuity caused by uniaxial loading. (b) Perturbation at the tips of a single discontinuity caused by biaxial loading.

Local stress perturbations near faults and mechanical interaction of faults were shown to result in significant angular departures of maximum resolved shear stresses and slip directions (Pollard et al., 1993). These departures may well exceed the precision of field data measurements and paleo-stress inversion analyses. This observation casts doubt on the fundamental assumption for stress inversion, i.e., that the slip on a fault surface is co-linear to the maximum shear stress vector on this surface (Lisle, 2013), known as the Wallace-Bott hypothesis (Wallace, 1951; Bott, 1959). Similarly, it cannot be ruled out that slip on an already existing fault is triggered by slip on a nearby, newly formed fault.

Displacement magnitudes of mesoscopic faults are likely on the order of a few centimeters and, thus, may indeed be rather small with regard to the size of a fault. By contrast, rotations of material planes and lines, which are intrinsic to any deforming body of rock and which includes shear faults and striations, may be variable and potentially amount to tens of degrees. For example, faults formed early in a protracted history of brittle faulting may accumulate significantly more rotation and displacement than later formed faults (Angelier and Colletta, 1983). This behavior applies particularly to secondary faults in fault damage zones, but also to regional-scale fault and deformation zones that may be many kilometers wide. Although such faults may well form under a potentially