The influence of fault geometry on small strike-slip fault mechanics

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Abstract

Meter-scale subvertical strike-slip fault traces in the central Californian Sierra Nevada exhibit geometric complexities that significantly contribute to their mechanical behavior. Sections of faults that opened at depth channelized fluid flow, as evidenced by hydrothermal mineral infillings and alteration haloes. Thin sections show a variation in the style of ductile deformation of infill along the fault, with greater intensities of deformation along restraining bends. Orthorectified photo-mosaics of outcrops provide model geometries and parameter constraints used in a two-dimensional displacement discontinuity model incorporating a complementarity algorithm. Model results show that fault shape influences the distribution of opening, and consequently the spatial distribution of fluid conduits. Geometric irregularities are present at many scales, and sections of opening occur along both releasing and restraining bends. Model sensitivity tests focus on boundary conditions along the fault: frictional properties on closed sections and fluid pressure within sections of opening. The influence of the remote stress state varies along a non-planar fault, complicating the relationships between remote stresses, frictional properties, slip, and opening. Discontinuous sections of opening along model faults are similar in spatial distribution and aperture to the epidote infill assemblages observed in the field.

1 Introduction

Faults have irregularly shaped surfaces, and often are composed of discontinuous segments. Such irregularities cause the mechanical behavior of faults to deviate from that of the idealized planar structure. Understanding opening and slip on faults at depth is crucial to many economic and scientific applications. For example, economic geologists have noted ore deposits along geometrically complex faults for nearly a century (Cox et al., 2001; Hulin, 1929; Mickelthwaite et al., 2010; Newhouse, 1940; Sibson, 1994). Fault shape also influences dynamic

rupture processes, affecting both earthquake and aftershock behavior (Harris et al., 1991; Mickelthwaite and Cox, 2004; Ryan and Oglesby, 2014; Sibson, 1985).

This study is motivated by new field observations of meter-scale left-lateral faults in the central Sierra Nevada, California (Figure 1). The faults considered in this study are within the Lake Edison Granodiorite (Kle), a fine- to medium-grained biotite hornblende granodiorite (Lockwood and Lydon, 1975) and one of several Late Cretaceous granitoid plutons in the area (Segall et al., 1990; Stern et al., 1981). Glaciation has exposed fractures meters to kilometers in length, exhumed from depths between 4 and 15 kilometers (Ague and Brimhall, 1988). Fracture is used here as a general term, and includes both opening-mode and shearing-mode structures. Earlier work in this area suggests that the faults developed from a single set of subvertical, subparallel joints that likely formed during cooling of the pluton (Bergbauer and Martel, 1999; Segall and Pollard, 1983a; Segall and Pollard, 1983b). The greater Bear Creek valley has been studied as a natural laboratory for investigations of fault mechanics for several decades (for example, Bürgmann and Pollard, 1992; Bürgmann and Pollard, 1994; Davies and Pollard, 1986; Griffith et al., 2008; Lockwood and Lydon, 1975; Martel et al., 1988; Pachell and Evans, 2002; Pennacchioni and Zucchi, 2013; Segall et al., 1990).

This study expands on previous work to elucidate the effect of non-planar fault shape on opening and deformation of fault infill. It is suggested here that fault shape controls opening, and therefore controls the spatial distribution of fluid flow along these faults, as evidenced by mineralized sections of opening and local alteration of the host rock (Bürgmann and Pollard, 1992; Christiansen and Pollard, 1997; Griffith et al., 2009; Griffith et al., 2010; Martel et al., 1988; Segall and Pollard, 1983b; Segall and Simpson, 1986; this study). Furthermore, fault shape may contribute to the localization of ductile deformation within fault infill. The mechanical

modeling presented in this study is constrained by field observations and the mechanical behavior of a representative fault from the study area is evaluated. The effect of several factors on slip and opening distributions along these faults are highlighted, including fault shape, two frictional properties, and fluid pressure within the sections of opening.

2 Methods

Field observations were collected from glacially polished outcrops of the Lake Edison Granodiorite using photomosaics and cylindrical core samples. Photomosaics were constructed by digitally orthorectifying each photograph along the outcrop, using a square metal frame included in each photograph as a guide and scale, then appropriately arranging and merging the overlapping photographs. Structures and textures were then mapped from these photomosaics, adding to the measurements and observations noted in the field. Core samples were drilled adjacent to and along several faults using a one inch diameter bit, and thin sections were made from those samples. Field work focused on an area in the Bear Creek valley along the Hilgard trail, which branches east from the Pacific Crest and John Muir Trail (Figure 1).

The numerical results are calculated by a two dimensional displacement discontinuity boundary element model (DDM) in conjunction with a complementarity solver. These quasi-static experiments provide the horizontal deformation along vertical strike-slip faults and within the surrounding elastic host rock. Fault slip is driven by a remote stress loading. The Ritz et al. (2012) model is further developed to include fluid pressure along sections of opening, because evidence for fluid flow is observed in outcrop. Ductile deformation of the fault infill is not included in this elastic model, but can be indirectly modeled by adjusting contact boundary conditions along the fault; ductile deformation of the host rock cannot be taken into account. The

full model description is outlined in Appendix A. Matlab® code is provided in the supplementary material. Right-lateral shear stresses and tensile stresses are positive.

3 Field observations

3.1 Overview of study area and previous work

Studies of the geochronology, field relations, and hydrothermal mineral assemblages indicate that faults in the Lake Edison Granodiorite developed from subvertical cooling joints, which formed soon after emplacement (Bergbauer and Martel, 1999; Segall et al., 1990). The sheared joints are primarily left-lateral strike-slip faults, as evidenced by the offsetting of aplite dikes and mafic xenoliths, as well as exposed slickenlines which typically plunge less than 20° (Griffith et al., 2008; Martel et al., 1988; Segall and Pollard, 1983b). No evidence has been found to suggest that slip caused in-plane propagation of the shear fractures into intact rock. Instead, some small faults linked by oblique secondary opening fractures, called splay or wing cracks (Segall and Pollard, 1983b). Linked faults have been observed to form larger fault zones, up to thousands of meters long (Martel et al., 1988). Suggested mechanisms for fault development are reviewed by Pennacchioni and Zucchi (2013) and include a regional stress rotation, large-scale monoclinical kinking, or intrusion of younger plutons.

The joints were mineralized primarily with quartz and have preserved apertures generally less than 1 cm (Bergbauer and Martel, 1999; Martel et al., 1988). Later slip deformed the quartz infill and was accompanied by more opening along secondary fractures and between left-stepping discontinuous sections of the faults. Quartz mineralization continued, as evidenced by quartz-filled secondary structures, but later infill assemblages include mostly epidote with minor chlorite. Relative age of the two infill assemblages is observed from crosscutting relationships.

Multiple infill assemblages suggests multiple slip events, but the exact number of slip events along a particular fault is difficult to infer.

Both ductile and brittle deformation are observed along the meter-scale faults in the Bear Creek valley. Field and microstructural observations suggest that the epidote infill and localized hydrothermal alteration of the host rock represent a later, lower temperature stage of reactivation of small faults along which slip had been accommodated by ductile deformation (Griffith et al., 2008; Pennacchioni and Zucchi, 2013). The host rock adjacent to the fault tips may have experienced concurrent ductile and brittle deformation, with localized foliation development in contractional steps and contractional quadrants of the fault tips, and wing crack formation in dilational quadrants (Nevitt et al., 2014; Pennacchioni and Zucchi, 2013). Pennacchioni and Zucchi (2013) suggest that jointing and ductile shearing alternated, or developed coevally, in some locations in the Bear Creek valley. For example, ductile deformation along faults in the Lake Edison Granodiorite is more pronounced along the contact with the younger Mono Recesses Quartz Monzonite to the east (Bürgmann and Pollard, 1994; Pennacchioni and Zucchi, 2013). Because the faults in the Lake Edison Granodiorite may have spatially varying histories, this study focuses on faults in a small area along the Hilgard Branch trail (Figure 1).

Preserved pseudotachylyte veins along some of the small faults in the Lake Edison Granodiorite and nearby plutons indicate that they were seismically active (Griffith et al., 2008; Kirkpatrick et al., 2009). Pseudotachylyte is discontinuous and often overprints both the quartz and epidote-rich mineral infill (Griffith et al., 2008). Griffith et al. (2008) also found several occurrences of thin (~200 μm) undeformed zeolite veins which crosscut all other fault infill textures. Zeolites generally form under low-pressure conditions (Utada, 2001), and the thin zeolite veins likely formed and filled at lesser depths and temperatures, after the faults became

inactive. Kirkpatrick and Shipton (2009) suggest that exhumation of these faults occurred without significant reactivation of the faults, thus preserving evidence of deformation at depth. Late stage jointing, vertical and approximately perpendicular to older joints and faults, and subhorizontal sheeting joints are the most recent structural features to form in this area.

3.2 *New observations of fault shape and opening at depth*

The faults in the study area are geometrically complex: they have curved traces, vary in thickness, and often are discontinuous. Figure 2 shows three meter-scale left-lateral faults mapped from photomosaics; A and B are new contributions, while LHF is a more detailed map of the Lower Hilgard Meadows Fault from Griffith et al. (2009). Possible causes of fault non-planarity may include non-planar joint formation (Pachell et al., 2003; Segall and Pollard, 1983b), linking of initially distinct joints by wing crack formation during shearing (Martel et al., 1988), and ductile deformation of the granodiorite surrounding the fault surfaces (Nevitt et al., 2014). The terms releasing bend and restraining bend are commonly used to describe fault geometry; Figure 3a illustrates the terminology. For right-lateral slip these designations are reversed.

The occurrence of opening at depth along the joints and faults is evidenced by mineralization and alteration, both due to hydrothermal fluid circulation. Mineralized sections of opening along small faults in the study area occur in two styles: lenticular opening due to separation of two adjacent fault surfaces (schematic in Figure 3a and field example in Figure 4), and rhombus-shaped openings connecting two fault segments at left steps (schematic in Figure 3b and field examples in Figure 5). Fault zone width that cannot be attributed to these two styles of opening is assumed to be due to mineralization of the initial joint openings.

Figure 4 shows two sets of field photos, maps, and aperture distributions along faults from the study area with mineralized sections of opening and accompanying alteration haloes; larger apertures are measured along releasing bends. Outcrop-scale observations indicate that the infill of these two faults is predominantly epidote, with little to no quartz infill. Apertures in Figure 4 are measured on the outcrop surface, approximately perpendicular to the general fault trace, and are therefore apparent apertures. Releasing bends along the faults generally have greater opening apertures, which can be categorized as lenticular sections of opening. Rhombochasms form after linkage between two initially distinct faults or slip surfaces by an extensional fracture (schematic in Figure 3b) (Griffith et al., 2009; Segall and Pollard, 1983b). Figure 5b shows a rhombochasm formed by linking of two initially separate faults, and Figure 5c shows a rhombochasm formed by linking of two slip patches along a single fault with earlier infill. Larger steps may produce dilatant zones with multiple rhombochasms and non-linking cracks. The dilational areas between faults in Figure 6 display closed, triangular, and rhombus shaped splay fractures, all surrounded by altered granodiorite. The rhombochasms in Figures 5 and 6, which were initially open cavities, have been mineralized.

In the study area, mineralized sections of opening are often surrounded by hydrothermally altered host rock (Figures 4, 5, and 6). The altered granodiorite appears lighter in color than the unaltered granodiorite, and these areas are commonly referred to as bleached or alteration haloes. Mineral infill and alteration haloes are also found around secondary fractures that have formed both along the faults and at fault tips (Figure 6). Hydrothermal alteration is not a regional feature, but a localized phenomenon, and is most pronounced along sections of fracture opening that display the epidote-rich infill. In general, the extent of hydrothermal alteration depends on host rock properties such as composition and permeability, and fluid

properties such as chemistry, temperature, and pressure. Within the alteration haloes, hornblende is commonly replaced by chlorite, epidote, and sphene. Biotite is replaced by chlorite, and the feldspars are altered to sericite. Figure 5 shows plane light petromicrographs taken from an array of samples through an alteration halo, away from the fault surface (1 through 3). Sericite, chlorite, and epidote all increase in abundance in the altered granodiorite, and the samples become less altered with distance from the fault. The feldspar to sericite alteration makes the altered granodiorite cloudy; photomicrograph 4 in Figure 5 shows the difference between highly altered host rock, below the fault, and nearly unaltered granodiorite, above the fault. Biotite from more distant samples are dark brown, but often alters to green chlorite closer to the fault.

Consistent with earlier studies, evidence suggesting that quartz is the earlier infill assemblage along fractures in the study area includes rhombochasms of epidote within quartz (Figure 5), discontinuous distributions of epidote infill and localized alteration, and epidote fingering into cracks and void spaces within the quartz infill and host rock. Furthermore, assuming that the boundary between infill and granodiorite was weaker than the solid infill of either assemblage, it follows that new sections of opening exploited these preexisting surfaces of weakness.

Figure 7 shows the apparent total aperture distribution for the completely exposed eastern fault mapped in B of Figure 2, and measured from the photomosaic. Quartz is the dominant infill assemblage along this fault, although discontinuous epidote rims on fault surfaces are observed (Figure 8). Photomicrographs from two prominent releasing bends of this fault, provided in Figure 8, show that epidote infill has a small but insignificant contribution to the total apparent aperture. The quartz infill is greater than one centimeter wide along some areas the fault, within releasing bends. No rhombochasms are observed along this fault. No conclusive evidence was

found to suggest that this fault either initiated as one continuous joint, or as several segments linked by wing cracks with ambiguously small take-off angles.

4 Parameter constraints for numerical modeling

Field observations from the completely exposed eastern fault mapped in B of Figure 2 constrain fault shape and stress boundary conditions for the model. The model fault tips are along the x -axis (geographical azimuth approximately 070°). The orientation of the remote maximum compressive stress is estimated from the wing cracks at the eastern tip of the fault. Although wing cracks may have a range of take-off angles (de Joussineau et al., 2007; Martel and Boger, 1998; Mutlu and Pollard, 2008), these secondary fractures turn to propagate toward the direction of the remote maximum compressive stress; the tips of the wing cracks of this fault are oriented 35° counterclockwise from the mean azimuth of the fault trace. Wing cracks in the Bear Creek valley generally strike between $15\text{--}35^\circ$ counterclockwise from the fault trace (Bürgmann and Pollard, 1994; Segall and Pollard, 1983b). Griffith et al. (2009) concluded from stress drop calculations on faults in this area that the faults are "strong" and estimated the remote shear stress $\sigma_{xy}^\infty \simeq -200$ MPa.

A discretized eastern fault from profile B of Figure 2 serves as the initial crack shape for the following numerical experiments. Although the natural fault currently exhibits sections of opening, the DDM simulates initially closed cracks. Therefore, the initial model fault surface is estimated to be equidistant between the two natural fault surfaces. The straight tip-to-tip length of the fault is $l = 3.05$ m, but the 1,200 boundary elements used to model the fault have a total length approximately 1 cm greater, due to non-planarity. The boundary elements vary in length to more accurately account for the natural fault geometry, but have an average length of 2.55 mm with a standard deviation of 0.54 mm.

The depth of the horizontal two-dimensional observation grid for the mechanical model is approximately 10 km, based on observations of Ague and Brimhall (1988). A least compressive principal stress of $\sigma_1^\infty = -100$ MPa is postulated. To be consistent with the stress drop findings, the most compressive principal stress is $\sigma_3^\infty = -525$ MPa. Such a large remote principal stress difference may have resulted from the intrusion of the Mono Creek pluton several hundred meters to the northeast. Postulating that the fluid pressure was no greater than the least compressive remote principal stress, the range between $0 \leq P \leq 100$ MPa is investigated. Fracture permeability is taken as several orders of magnitude greater than that of a granitoid rock (Kranzz et al., 1979; Pratt et al., 1977), so fluid from the fracture network would fill the newly created sections of opening much more quickly than fluid from within the host rock; therefore, only fluid within the fault openings is considered. All numerical experiments utilize the elastic moduli of Westerly granite, with a Young's modulus of $E = 70$ MPa and a Poisson's ratio of $\nu = 0.25$ (Gercek, 2007).

Along every closed boundary element, the shear and normal stresses are related to the frictional properties following:

$$|\sigma_{ns}| \leq -\mu\sigma_{nn} + S_f \quad (1)$$

where μ is the unitless coefficient of friction and S_f is the frictional strength with units of stress (Pollard and Fletcher, 2005). Again, positive normal stress is tensile. For slip on pre-existing structures, the frictional strength may be only a few megapascals (Hoskins et al., 1968), while the internal frictional strength of unfractured rock is approximately 50 MPa (Byerlee, 1978). Although these faults formed from preexisting joints, mineralization of the joints may have increased the frictional strength, so the range $0 \leq S_f \leq 50$ MPa is investigated. The range of

uniform coefficients of friction applied here is $0 \leq \mu \leq 1$, because the coefficient of friction for this fault is unknown.

The total slip observed along fault B is due to a combination of both ductile and elastic processes, and multiple slip events. Evidence of both elastic and inelastic deformation along this structure includes intense foliation localized between the two faults in B, and large slip gradients toward the tips (Figure 2). The modeling approach employed in this study does not capture the effect of inelastic deformation of the host rock, multiple slipping events, or joint infill. Instead, the mechanical model is used to investigate the latest brittle slip event, when the fault geometry most closely resembles what is observed in outcrop today. Therefore some numerical results, including the magnitudes of slip, are not directly compared to the field example. The distributions of slip and opening, and the change in their magnitudes, are the focus of the following discussion.

5 Numerical results

5.1 The influence of fault shape

In this section the mechanical behavior of faults with no frictional properties and no fluid pressure, $\mu = S_f = P = 0$, are investigated so that the effect of fault shape can be determined independently. The geometric complexity of the model fault is varied to see the effects on slip and opening. This is accomplished by scaling the y -coordinates, while fixing the corresponding x -coordinates to produce more or less roughness. The normalized slip and opening distributions for a planar fault and non-planar faults with half the measured roughness in the y -direction, the measured roughness, and twice the measured roughness are shown in Figure 9; values normalized by the maximum resultant slip for the planar fault, D_s^* . These distributions illustrate two key observations previously mentioned in studies of slip along non-planar faults (for

example, Dieterich and Smith, 2009; Griffith et al., 2010; Marshall and Morris, 2012; Ritz and Pollard, 2012): non-planar faults have lesser magnitudes of mean slip than idealized planar faults, and do not have the symmetrical, elliptical, distributions that are predicted for planar faults with uniform stress drop (Pollard and Segall, 1987).

The slip change between experiments of a planar and non-planar fault, with all other parameters held equal, is calculated as:

$$\text{slip change} = \left[\left(\overline{D_s}/L \right)_{\text{non-planar}} - \left(\overline{D_s}/L \right)_{\text{planar}} \right] / \left(\overline{D_s}/L \right)_{\text{non-planar}} \times 100 \quad (2)$$

where the overbar indicates the mean slip. The definition in equation (2) is similar to the slip deficit defined by Griffith et al. (2010), but takes into account the total length of the fault, L , calculated by summing all element lengths. Positive slip change values indicate that the mean slip on the non-planar fault is greater than the planar fault, while the opposite is true for negative values. The slip change increases slightly with fault shape complexity. For the smoothed, measured, and exaggerated non-planar fault shapes shown in Figure 9, the slip changes are -0.34% , -0.98% , and -2.46% , respectively. The decrease in slip change is caused by decreased local slip along sections of the fault that open. The slip is most perturbed along the releasing bends of the non-planar fault traces; Figure 9a shows that slip locally decreases in these areas. For frictionless faults, opening is a significant component of the slip surface deformation along releasing bends, and opening locally limits the amount of slip.

Figure 9b shows that slip on non-planar faults induce several sections of opening, generally with larger apertures of opening along the longest releasing bends, consistent with the measured apertures presented in Figures 4 and 7. As expected, the planar fault does not open. More complex fault shapes induce greater magnitudes of opening. The greatest opening apertures are an order of magnitude less than the maximum slip of the non-planar faults. Figure

9c highlights the opening results from the model geometries along one releasing bend; both the aperture and length of sections of opening increase with geometric complexity. More geometrically complex faults have fewer, but longer areas of opening along the fault.

5.2 Sensitivity tests with frictional properties and fluid pressure

Here the influence of three poorly constrained parameters on the mechanical behavior of the non-planar model fault are discussed: the coefficient of friction, frictional strength, and fluid pressure. In this section, fault openings are traction-free unless a non-zero fluid pressure is designated. Fluid pressure is $\sigma_{nn}^{open} = -P$ along open elements, and the coefficient of friction and frictional strength are eliminated to reflect a shear-traction-free boundary condition. The broad influence of the coefficients of friction $0 \leq \mu \leq 1$, frictional strengths $0 \leq S_f \leq 50$ MPa, and fluid pressures $0 \leq P \leq 100$ MPa on the mechanical behavior of the discretized non-planar fault B are investigated in this section. While the influence of any one parameter is tested, the other two are set to zero.

Figure 10 presents normalized slip and opening distributions for faults with varying coefficients of friction, frictional strengths, and fluid pressures in sections of opening. Each profile is normalized by the greatest magnitude for the planar simulation with $\mu = S_f = P = 0$. The slip distributions and magnitudes are most sensitive to changes within the range of tested coefficient of friction, with greater departures from an elliptical slip distribution (Figure 11a). For the non-planar fault with $\mu = 1$, no slip occurs along the model fault, resulting in a -100% slip change relative to the planar fault under the same conditions.

Figure 10b, d, and f presents the opening distributions for model faults with a range of frictional properties and fluid pressures. The occurrence and extent of opening is more sensitive to changes within the range of tested coefficients of friction than frictional strength and fluid

pressure. The slip change metric (2) inspires another metric to describe the change in opening between two non-planar model results:

$$\text{opening change} = \left[\left(\overline{D_n} \right)_{test} - \left(\overline{D_n} \right)_{base} \right] / \left(\overline{D_n} \right)_{base} \times 100 \quad (3)$$

where *base* denotes the mean normal displacement discontinuity from a numerical experiment with $\mu = S_f = P = 0$ and *test* denotes the result from an experiment testing one of those three parameters. A base case non-planar fault is used instead of a planar fault because planar faults do not open. The percentage of opening change for the coefficient of friction, frictional strength, and fluid pressure is shown in Figure 11b. Unsurprisingly, the mean opening decreases along the fault with an increase in either frictional property, and opening increases with an increase in fluid pressure. Less intuitive results are discussed below.

6 Discussion

Figure 8 not only illustrates that the aperture and infill material vary along a single fault, but also that the deformation of the fault infill varies along its strike. Along releasing bends the quartz infill shows undulose extinction, subgrain formation and recrystallization, and grain bulging (Figure 8a and c). Large, euhedral grains of epidote are observed along the fault surfaces, but also ribbons of smaller, pulverized grains. In contrast, Figure 8b shows mylonitized quartz infill and host rock between the restraining bend fracture surfaces; darker ribbons are smeared biotite, although most of the mylonitized material is quartz and feldspar. These observations, and similar observations from within in the study area, suggest that deformation of the initial joint infill material varies along geometrically complex faults. Restraining bends display mylonite fabrics within the quartz infill, with more progressed grain size refinement than observed in releasing bends.

Although the joints may have had non-uniform apertures, previous numerical mechanical modeling by Ritz and Pollard (2012) suggests that slip can lead to a systematic pattern of discontinuous lenses of opening along releasing bends of simplified sinusoidal non-planar faults. Fault widths in the Bear Creek valley are generally greater than joint widths, according to Segall and Pollard (1983b), and continued opening during slip may contribute to this disparity, so that releasing bends systematically exhibit greater apertures than restraining bends. Figure 8 shows that, although restraining bends (8b) and releasing bends (8a and c) both may have apparent apertures, fault thickness is attributed to a zone of ductile deformation along restraining bends and releasing bends have greater apertures due to fault surface separation and subsequent mineralization.

Changes in the size of sections of opening depend on position, length, and aperture distribution (for example, Figure 9c). The total apparent apertures observed in outcrop along the fault B are an order of magnitude greater than those of the model. Internal fluid pressure is one mechanism that can cause greater apertures, although the numerical results show that adding fluid pressure to open sections does not increase the apertures tenfold. The opening calculated with the numerical model is similar, however, to both the distribution and width of the epidote infill observed along the fault in outcrop and thin section, although the total aperture along the fault is attributable to multiple slip events.

Geometric barriers impede slip along a non-planar fault. Griffith et al. (2010) found that the effect of elevated normal stress along these geometric barriers, or restraining bends, may be at least partially counteracted by opening along releasing bends, or temperature-related weakening mechanisms such as the formation of pseudotachylyte during seismic slip. Mylonite formation also may be a mechanism that accommodates strain preferentially on restraining

bends. Figure 12 shows the variation in normal and shear stress magnitude before deformation, which are the remote stresses resolved along the initial fault shape. Before deformation, normal and shear stresses are elevated on restraining bends of the fault and reduced on releasing bends, relative to a planar fault. The range in magnitude for the normal stress resolved along the length of the non-planar fault is approximately 200 MPa, while the range in resolved shear stress is approximately 50 MPa.

For the numerical results, varying the magnitudes of frictional strength or fluid pressure have little influence on slip distributions, but varying the coefficient of friction within the tested range can produce slip distributions that diverge greatly from elliptical (Figure 10a). The non-linear trend in slip change for the coefficient of friction (Figure 11a) also reflects this variation in slip distributions and magnitudes. Figure 10a illustrates that local maxima in the slip distribution switch from restraining bends to releasing bends as the coefficient of friction increases. This is likely due to the increase of the physical resistance to slip that the addition of frictional properties present to the restraining bends, which already host greater normal stress due to their orientation with respect to the remote stress state. With non-zero frictional properties, opening is more prevalent along releasing bends (Figure 10b), reducing the resistance to slip that those elements would otherwise provide. Opening along releasing bends has the opposite effect for non-planar faults with lesser frictional properties, due to greater separation of the fault surfaces inhibiting the slip deformation. For example, the base case non-planar fault with no frictional properties or fluid pressure has locally reduced slip along the releasing bends (darkest gray line in Figure 10a) but with increased coefficients of friction the slip is locally increased along releasing bends.

Within the tested ranges of fluid pressure, increased P along sections of opening allow the non-planar faults to have greater mean slips than the fluid-free base case non-planar fault, but not the planar faults with comparable parameters. This is likely due to the increased number of elements with zero shear traction, as a longer length of fault opens due to the fluid pressure pushing the fault surfaces apart within those sections of opening. Figure 11b shows that greater mean opening apertures are produced for greater fluid pressures.

The impact of either frictional property on the shear stress along the fault depends on the value of the normal stress. If the two terms $-\mu\sigma_m$ and S_f are equivalent, they have the same influence on the shear stress, which ultimately drives slip. The larger of the two terms is therefore more important to the mechanical behavior of the fault in general. Figure 13 shows the parameter space for the range of frictional properties investigated, with lines indicating that the two terms equally contribute to the magnitude of the shear stress. To the left of each line, the frictional strength term will be greater than the product of the coefficient of friction and normal stress. To the right of each line, the opposite is true, and the coefficient of friction is more influential. Uniform μ and S_f are assigned for an entire fault in this model, which can be mapped as a point in Figure 13. However, Figure 12 demonstrates that the resolved normal stress along the model fault is non-uniform. A range of normal stresses along the fault corresponds to a vertical range in Figure 13, so both frictional properties may have an influence along different sections of non-planar fault. According to Figures 12 and 13, the frictional strength is more likely to have a greater influence than the coefficient of friction on releasing bends, while the coefficient of friction will likely be the dominant frictional property on restraining bends. Remote stress states at shallower depths or with lesser principal stress differences would result in

lesser magnitudes of resolved normal stress along the model fault, which would expand the parameter space for which the frictional strength term is more influential.

The numerical technique used in this study can also be employed to predict off-fault damage along non-planar faults; stress magnitudes constrain the spatial distribution, stress orientations constrain the orientation, and the sign of the stress constrains the style of damage. Griffith et al. (2010) found that microcrack density along a strand of the Gole Larghe fault zone in the Adamello batholith, southern Italian Alps, varies systematically with fault shape and is associated with the static stresses rather than transient stresses due to dynamic processes. Greater microcrack densities were measured along releasing bends of the Italian fault than the restraining bends. These observations warrant further investigation on the relationship between fault shape and off-fault damage, in igneous and other rock types. Other studies have shown that fluid flow and mineralization also can occur outside the main fault, often controlled by inelastic deformation (Micklethwaite and Cox, 2004; Micklethwaite and Cox, 2006; Sheldon and Micklethwaite, 2007). The numerical technique used in this study cannot account for inelastic deformation of the host rock and does not include secondary structures, so predictions about mineralization outside of the faults are not made here.

7 Conclusions

Fault traces mapped in the Sierra Nevada exhibit geometric complexities that significantly contribute to their mechanical behavior. The field observations provide model geometries and parameter constraints used to investigate the effect of fault shape, frictional properties, and the presence of fluid pressure in sections of opening along a small left-lateral fault. Opening only occurs along faults with non-planar geometries, not along planar faults with non-uniform frictional properties. Fault shape therefore is the first order control on the spatial

distribution of fluid along faults. Although opening is greater on releasing bends, sections of opening on restraining bends demonstrate that using more objective terms to describe the fault shape is appropriate. For suggested terminology see Ritz and Pollard (2012), who introduce the objective terms stoss and lee. Sections of opening channelize fluid flow, as evidenced by mineralized openings and alteration haloes in the field area. The discontinuous sections of opening calculated with the elastic model have apertures less than a few millimeters, similar in aperture and distribution to the epidote infill observed in outcrop and thin section. However, the distribution of total apparent opening measured from outcrop photos and calculated from the modeling are also similar (Figure 7 compared to Figures 9 and 10). Additionally, increased compression along restraining bends due to fault non-planarity may cause mylonitization of the earlier fault infill along those sections. Mylonites were observed along restraining bends of the small left-lateral faults but not along releasing bends, despite similar infill thicknesses and slip, suggesting that fault shape is an important factor in the style of infill deformation within faults in the study area.

Geometric irregularities along non-planar faults generally lead to lesser mean slips relative to idealized planar faults under the same conditions. The addition of fluid pressure enlarges sections of opening, while the two frictional properties decrease mean opening. Increased opening, chemical alteration, and precipitation of new minerals due to the presence of fluid may change the rheological properties of the host rock and strength of the fault surfaces. The coefficient of friction strongly influences both the magnitude and distribution of opening and slip, whereas the frictional strength has little effect on distributions of opening and slip. The spatial distribution and size of sections of opening along a non-planar fault are most sensitive to fault shape, the coefficient of friction, and fluid pressure. Variation in stresses along non-planar

faults highlights the importance of achieving a better understanding of how fault shape influences deformation, both along and alongside of the fault surfaces, and complicates the effect of frictional properties. Furthermore, geometric irregularities occur along fractures at many scales and the slip and opening behavior of each irregularity will constructively or destructively interfere with the next. While this study focused on meter-scale natural faults, the model results may be applicable to larger structures with dominantly elastic host rock. For faults at the kilometer-scale and greater, for example, gravity becomes significant and the modeling technique used here may not be applicable.

Appendix A

This implementation of a two-dimensional displacement discontinuity method (DDM) (Crouch 1976; Crouch and Starfield, 1983) in combination with a complementarity solver is similar to that of Ritz et al. (2012), with two main departures: it includes a more efficient implementation of the complementarity solver PATH (Dirkse and Ferris, 1995; Ferris and Munson, 1999), and the addition of an normal stress, σ_{nn}^{open} , which only acts on open elements along the fractures. The additional normal stress can be used as a proxy for fluid pressure, among other physical processes, and is included through an iterative scheme. This allows for tracking the effect that fluid pressure within sections of opening has on the mechanical deformation of the entire structure.

Quasi-static numerical experiments are conducted on cracks, which act as models for vertical fractures. Cracks are discretized into linear segments called boundary elements of constant displacement discontinuity, while the surrounding rock is assumed to be a homogeneous, isotropic, linear elastic material (Figure A1). Certain constraints or conditions can be specified for any or all boundary elements, and boundary conditions define the other relevant

parameters. The solution, the shear and normal displacement discontinuities and the shear and normal stresses for each element, are found by summing the effects of each boundary element on the others. The stresses are only specified at the element midpoints; therefore, the DDM solution will match prescribed traction conditions only at the midpoints of the elements. Tension is positive in this sign convention, which follows Crouch and Starfield (1983).

Changing the number of boundary elements will change the shape of the model fault. Increasing the number of elements will produce a more accurate solution. As an example, every other boundary element from an initial discretization of 1,200 was eliminated to smooth the eastern fault from profile B (Figure 3), and Figure A2 shows that the percent change in the maximum aperture, D_n^* , and maximum slip, D_s^* , for several smoothed versions of the original fault shape. The percent change decreases rapidly as the discretization of the natural fault becomes more precise. The percentage change of D_n^* and D_s^* from 600 to 1,200 boundary elements are less than one percent each. Stress fields in the elastic material are calculated with the displacement discontinuities, so the precision of D_n and D_s correlates with the precision of the resulting stress field as well as the opening and slip distributions.

The stresses σ_{nn} and σ_{ns} at the midpoint of each element $i = 1$ to N are related to the uniform displacement discontinuities D_n and D_s for the same element and all others, denoted by $j = 1$ to N (Crouch and Starfield, 1983, p. 88):

$$\left. \begin{aligned} \sigma_{ns}^i &= A_{sn}^{ij} D_n^j + A_{ss}^{ij} D_s^j \\ \sigma_{nn}^i &= A_{nn}^{ij} D_n^j + A_{ns}^{ij} D_s^j \end{aligned} \right\} \text{ for } i, j = 1 \text{ to } N \quad (4)$$

where A_{nn}^{ij} , A_{ns}^{ij} , A_{sn}^{ij} , and A_{ss}^{ij} are influence coefficients from the original DDM formulation (Crouch and Starfield, 1983, p. 93).

The DDM does not include frictional contact properties because interpenetration is allowed, preventing contact between the two crack surfaces. A complementarity algorithm adds a mathematical optimization scheme to correct the initial DDM solution and enforce contact boundary conditions along the cracks, such as stick-slip behavior. Since the behavior of each boundary element is not known a priori, the complementarity solver utilizes the basic relationships between sticking, slipping, and opening to correct the DDM solution. The following conditions, written in terms of the element-local stress and displacement discontinuity components, are true for every element:

1) $D_n \leq 0$, where the equality implies that the surfaces are in contact and the inequality implies opening;

2) $\sigma_{nn} D_n = 0$, because $D_n = 0$ if the surfaces are in contact and $\sigma_{nn} = 0$ if no fluid is present;

3) $|\sigma_{ns}| \leq -\mu\sigma_{nn} + S_f$, where the equality implies sliding and the inequality implies sticking (Figure A2); and

4) $\sigma_{ns} D_s \leq 0$, since a positive shear stress on the crack surface drives a negative shear displacement discontinuity, and vice versa (Figure A3).

Frictional strength S_f is the resistance to slip without a normal stress. Condition 1 prevents interpenetration. The additional σ_{nn}^{open} along elements that open is included in a later step; therefore, condition 2 is written for normal-traction-free sections of opening along the fault.

Conditions 3 and 4 suggest that if the element slips sinistrally, then

$$D_s > 0 \text{ and } \sigma_{ns} = \mu\sigma_{nn} - S_f \quad (5)$$

and if the element slips dextrally, then

$$D_s < 0 \text{ and } \sigma_{ns} = -\mu\sigma_{nn} + S_f \quad (6)$$

498 The mixed complementarity problem describing the four conditions above is combined
 499 with the following six relationships:

$$500 \quad \sigma_{ns}^i = \sigma_{ns}^{\infty j} + A_{sn}^{ij} D_n^j + A_{ss}^{ij} D_s^j \quad (7)$$

501 which is made orthogonal ($\perp$) to the free variable σ_{ns}^i , along with

$$502 \quad \sigma_{nn}^i = \sigma_{nn}^{\infty j} + A_{sn}^{ij} D_n^j + A_{ss}^{ij} D_s^j \perp D_n^i \text{ free} \quad (8)$$

$$503 \quad D_s^i = D_s^R - D_s^L \perp D_n^i \text{ free} \quad (9)$$

504 where D_s^R and D_s^L are the non-negative components of right- and left-lateral slip for each
 505 element, respectively (Figure A4), and also

$$506 \quad D_n^i \leq 0 \perp \sigma_{nn}^i \leq 0 \quad (10)$$

$$507 \quad 0 \leq \sigma_{ns}^i - \sigma_{nn}^i \mu + S_f \perp D_s^R \geq 0 \quad (11)$$

$$508 \quad 0 \leq -\sigma_{ns}^i - \sigma_{nn}^i \mu + S_f \perp D_s^L \geq 0 \quad (12)$$

509 Expressions on the left of relationships (7)-(12) are assembled into the left-hand side of the
 510 complementarity equation $f(Z) = MZ + Q$, while the expressions on the right of relationships
 511 (7)-(12) are assembled into the vector Z :

$$512 \quad \begin{bmatrix} \sigma_{ns}^i - \sigma_{ns}^{\infty j} - A_{sn}^{ij} D_n^j - A_{ss}^{ij} D_s^j \\ \sigma_{nn}^i - \sigma_{nn}^{\infty j} - A_{sn}^{ij} D_n^j - A_{ss}^{ij} D_s^j \\ D_s^i - D_s^R + D_s^L \\ D_n^i \\ \sigma_{ns}^i - \sigma_{nn}^i \mu + S_f \\ -\sigma_{ns}^i - \sigma_{nn}^i \mu + S_f \end{bmatrix} = \begin{bmatrix} I & -A_{sn}^{ij} D_n^i & -A_{ss}^{ij} D_s^i & 0 & 0 & 0 \\ 0 & -A_{nn}^{ij} D_n^i & -A_{ns}^{ij} D_s^i & I & 0 & 0 \\ 0 & 0 & I & 0 & -I & I \\ 0 & I & 0 & 0 & 0 & 0 \\ I & 0 & 0 & -\mu I & 0 & 0 \\ -I & 0 & 0 & -\mu I & 0 & 0 \end{bmatrix} \begin{bmatrix} \sigma_{ns}^i \\ D_n^i \\ D_s^i \\ \sigma_{nn}^i \\ D_s^R \\ D_s^L \end{bmatrix} + \begin{bmatrix} -\sigma_{ns}^{\infty j} \\ -\sigma_{nn}^{\infty j} \\ 0 \\ 0 \\ S_f \\ S_f \end{bmatrix} \quad (13)$$

513 where I is an $n \times n$ identity matrix and 0 is an array of zeros. Vectors σ_{ns}^∞ and σ_{nm}^∞ are lists of
 514 the resolved remote stresses acting on each element, calculated in the DDM formulation.

515 Complementarity constraints require that, for each component in the $6N \times 1$ arrays Z
 516 and $f(Z)$, either the component in Z or the corresponding component in the non-linear
 517 function $f(Z)$ is an equality, and the product of the two components is zero. For example, since
 518 the relationships to the left of the orthogonal disjunction symbol $\perp$ in (7)-(9) above are
 519 equalities, the three variables to the right are free: σ_{ns} , $-D_n$, and D_s . Free variables are
 520 boundless, and can therefore range from negative to positive infinity. Bounds (l for lower and u
 521 for upper) on variables in other subarrays of Z_{sub}^i and $f(Z_{sub}^i)$ determine the meaning of $\perp$:

$$522 \text{ if } \begin{cases} Z_{sub}^i \geq 0 & Z_{sub}^i \geq 0 \perp f(Z_{sub}^i) \geq 0 & Z_c^i \times f(Z_{sub}^i) = 0 \\ Z_{sub}^i \leq u & \text{then } Z_{sub}^i \leq u \perp f(Z_{sub}^i) \leq 0 \text{ and } (u - Z_{sub}^i) \times f(Z_{sub}^i) = 0 \\ l \leq Z_{sub}^i & l \leq Z_{sub}^i \perp f(Z_{sub}^i) \geq 0 & (Z_{sub}^i - l) \times f(Z_{sub}^i) = 0 \end{cases} \quad (14)$$

523 The subscript in Z_{sub}^i denotes the targeted relationship from sets (7) to (9), while the overscript
 524 denotes the range of boundary elements. The lower bounds on the variables in Z , which are
 525 consistent for all boundary elements $i = 1$ to N are

$$526 \quad l = [-\infty \quad -\infty \quad -\infty \quad -\infty \quad 0 \quad 0]^T \quad (15)$$

$$527 \text{ and upper bounds on } Z \text{ are } u = [\infty \quad \infty \quad \infty \quad 0 \quad \infty \quad \infty]^T \quad (16)$$

528 where each component in (15) and (16) is an $i \times 1$ array. The bounds on the variables in Z are
 529 thus: $-\infty \leq \sigma_{ns}^i \leq \infty$, $-\infty \leq D_n^i \leq \infty$, $-\infty \leq D_s^i \leq \infty$, $-\infty \leq \sigma_{nm}^i \leq 0$, $0 \leq D_s^R \leq \infty$, $0 \leq D_s^L \leq \infty$. Tensile
 530 normal stresses along the elements are not permitted, and the variables D_s^R and D_s^L are positive.

531 The first solution using the complementarity algorithm is found with the above
 532 implementation, and open elements can be identified from this initial solution. In order to include
 533 the additional internal normal stress σ_{nn}^{open} along elements that open, one set of bounds is altered
 534 before resolving the problem. Only for these open elements, both the lower and upper bounds of
 535 σ_{nn} are set to the user-determined value of σ_{nn}^{open} in order to force the normal stress on that
 536 element to be $\sigma_{nn} = \sigma_{nn}^{open}$. When this variable is doubly-bounded (there is both an upper and
 537 lower bound) one of the following four cases is true:

$$538 \quad l \leq Z_{sub}^i \leq u \quad \perp \quad \left\{ \begin{array}{ll} l < Z_{sub}^i < u & f(Z_{sub}^i) = 0 \\ Z_{sub}^i = u & f(Z_{sub}^i) \leq 0 \\ Z_{sub}^i = l & f(Z_{sub}^i) \geq 0 \\ l = Z_{sub}^i = u & f(Z_{sub}^i) = \text{free} \end{array} \right. \quad (17)$$

539 For this application, the bounds on σ_{nn} are changed to $l = \sigma_{nn} = u \quad \perp \quad D_n \text{ free}$, and $l = u = \sigma_{nn}^{open}$.
 540 The new solution will not include σ_{nn}^{open} along elements that open due to the mechanical effect of
 541 σ_{nn}^{open} along the previously opened elements. Therefore, new bounds must be set and the solution
 542 iteratively solved until no new elements open.

543 With or without including fluid pressure, the shear traction along elements that open
 544 needs to be reset to $\mu = S_f = 0$, since fluid only exerts a normal pressure and the openings are
 545 shear-traction-free. This adjustment is done within the same iterative loop as the implementation
 546 of the fluid pressure, and may trigger additional iterations to reach equilibrium.

547 Under the current bounds, with $\sigma_{nn}^{open} < 0$, the additional internal normal stress along the
 548 crack can be used as a proxy for several processes, including the presence of fluid, dilational
 549 gouge, or magma. Similarly, if $\sigma_{nn}^{open} > 0$, the additional normal tensile stress along the crack can

550 be used as a proxy for a "fault pump" scenario (Sibson et al., 1975), or to force the fault closed.
 551 A list of N values of σ_{nn}^{open} is specified as an input parameter, but any single value is only called
 552 if the corresponding element opens (if $D_n < 0$). Non-uniform values of σ_{nn}^{open} are possible, but a
 553 physical rationale would be needed to support the differences in magnitude and/or sign between
 554 the elements.

555 This arrangement allows one to model, for example, the physical process of fluid flow
 556 entering open spaces along a fracture or fault. The fluid pressure P would force the open
 557 elements to remain open and change the normal pressure acting on the fracture walls along the
 558 sections of opening to a new value, $\sigma_{nn}^{open} = P$. Resolving the reduced mixed complementarity
 559 problem may determine that new elements open due to the fluid pressure acting on previously
 560 opened elements; if so, the normal stress along the newly opened elements also will be set to
 561 $\sigma_{nn}^{open} = P$ and the shear stresses to $\sigma_{ns} = 0$, and the calculations repeated until no new elements
 562 open. Although no time steps are considered here, one can record the effect of the proxy
 563 parameter σ_{nn}^{open} on the evolution of a section of opening.

564 One major advantage of using a DDM is that only discretization of the crack is required,
 565 whereas other popular methods require discretization of the surrounding material. Additionally,
 566 several optional steps are taken to increase the computational efficiency of PATH. The solution
 567 for the stresses at the center of each element are initialized as the resolved remote stresses for
 568 each element in the Z array for the complementarity solver. The resolved remote stresses are
 569 already calculated within the DDM formulation, so no further calculations are needed. If
 570 subsequent iterations are needed, the previous solution for Z is the starting point. Another step
 571 taken to increase efficiency is to scale the D_n and D_s parameters and the components D_s^R and

D_s^L that are used in the complementarity solver and then rescale the solution for these parameters and components. This is helpful because the values of the stresses and displacements differ by several orders of magnitude. The smaller displacements are scaled when implementing relationships (7) and (8) (see code). Another advantage of this method over the method described in (Ritz et al., 2012) is that the inverse of the influence coefficients is not found before utilizing the complementarity solver, since that calculation is handled within the complementarity solver. Lastly, the stress slack variables utilized in (Ritz et al., 2012) are no longer needed.

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Figure Captions

Figure 1. Bear Creek study area in the central Sierra Nevada, California. Left is a topographic map, from the National Atlas of the United States (<http://nationalatlas.gov>). Right is a geologic map, based on work by Lockwood and Lydon (1975), with photomosaic localities of Figure 2 identified.

Figure 2. Mapped photomosaics from the Bear Creek valley (see Figure 1 for locations). Dashed photomosaic boundary shows extent of photographs, first orthorectified and then stitched together. LHF is the Lower Hilgard Meadows Fault from Griffith et al. (2009). Figure 8 shows photomicrographs from fault B at the marked core locations.

Figure 3. Definition of a) releasing and restraining bends along a simplified fault shape, with lenticular sections of opening along the releasing bend, and b) rhombochasm formation through four time steps between either two initially distinct faults (left) or two sections of slip along an earlier filled fault (right).

Figure 4. Two sections of fault from the study area with lenticular openings on releasing bends and alteration haloes surrounding the sections of opening. Each fault is shown with a photograph, map, and aperture distribution, where the aperture is measured perpendicular to the general fault trend along the x -axis. In the maps, fault surfaces and infill are shown in black, and alteration haloes are gray. Each aperture distribution comprises over 500 measurements, with errors of ± 0.1 mm.

Figure 5. a) Two rhombochasms mapped along a fault: b) photograph of rhombochasm between two fault segments, c) photograph of rhombochasms within fault infill. 1-4 show photomicrographs of thin sections taken from core samples in plane polarized light. Transect 1-3 shows alteration (cloudiness) decreasing away from fault, while 4 shows more alteration on the southern side of the fault than the northern.

Figure 6. Extensional steps along several fault segments: photomosaic (top) and map (bottom). Secondary cracks concentrate hydrothermal fluid alteration in the steps, which alters the host rock (gray) and mineralizes the openings (black).

Figure 7. Total apparent aperture, measured in the y -direction, along the eastern fault in profile B, Figure 2. Apertures have measurement errors of ± 0.5 mm.

Figure 8. Thin section photomicrographs in plane light from three areas along the eastern fault in profile B, Figure 2. Releasing bends (a) and (c) have quartz infill (translucent) with epidote rims (dark green) and cut through highly altered host rock (cloudy feldspar and light green chlorite). Restraining bend (b) has mylonitized quartz infill and host rock, but little to no epidote or alteration. Photomicrographs are rotated so that the fault surface is approximately horizontal.

739 Figure 9. a) Slip and b) opening distributions for model faults of varying shape. The adjusted y' -
740 coordinates for the planar fault are $y' = y \times 0 = 0$, while the other shapes are half and twice that
741 measured along fault B. Fault shapes shown for reference between the plots. c) Enlargement of
742 section of opening distribution in (b). In these numerical experiments, $\mu = S_f = P = 0$.

743 Figure 10. The influence of the coefficient of friction (a and b), frictional strength (c and d), and
744 fluid pressure (e and f) on slip (top graphs) and opening (lower graphs) distributions. Each
745 distribution is normalized by the maximum slip for the planar case with $\mu = S_f = P = 0$.

746 Figure 11. a) Slip change, equation (2), and b) opening change, equation (3), for a range of
747 frictional properties and fluid pressures.

748 Figure 12. Resolved normal (gray) and shear (black) remote stresses for each element along the
749 model fault (solid lines) before deformation. Uniform stresses along planar faults with an
750 identical remote stress loading are provided as dashed lines for reference.

751 Figure 13. Relationships between the coefficient of friction and the frictional, strength
752 normalized by normal stress, where each line indicates the parameter space for which these two
753 terms have equal influence on the magnitude of shear stress.

754 Figure A1. Schematic problem setup for displacement discontinuity boundary element model. a)
755 Two-dimensional linearly elastic material contains a crack which deforms due to a remote stress
756 loading (positive stresses shown). b) Crack is discretized into N linear boundary elements, each
757 with a local orientation given by normal and shear unit vectors (n , s). C) Each element has a
758 resultant uniform normal and shear displacement discontinuity and representative normal and
759 shear stress at the center.

760 Figure A2. Percentage change in the greatest magnitude normal and shear displacement
761 discontinuity along the fault, each normalized by the total fault length L , which is the sum of all
762 N element lengths. With a sufficient number of elements, the solution changes insignificantly.

763 Figure A3: Failure surfaces in relation to representative normal and shear stresses at center of
764 boundary element. Given sufficient positive shear stress, the element will slip with a sinistral
765 sense of shear, and given sufficient negative shear stress, the element will slip with a dextral
766 sense of shear.

767 Figure A4: Decomposed shear displacement discontinuity along an element: see equation (9).

Fig1

Fig2

Fig3

Fig4

Fig5

Fig6

Fig7

Fig8

Fig10

Fig11

a)

b)

Fig12

Fig13

FigA1

a)

b)

c)

FigA2

FigA3

a) dextral slip, $D_s^L = 0$

b) sinistral slip, $D_s^R = 0$

c) stick, $D_s^R = 0$, $D_s^L = 0$