Variation in slip on intersecting normal faults: Implications for paleostress inversion

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Abstract. Numerical models based on linear elasticity theory predict asymmetric slip distribution with a steep slip gradient near the line of intersection of intersecting normal faults. They also predict a discrepancy between the direction of slip on the fault plane and the direction of resolved shear stress. Both variations in slip magnitude and direction are due to mechanical interaction between the faults with intersecting patterns. These interactions cause local perturbations of the shear stress field acting on the plane of the adjacent fault. Field observations from the Chimney Rock area of central Utah show that slickensides on normal faults cutting the Navajo Sandstone change rake away from the expected downdip direction as the intersection line with adjacent faults is approached. The sense and magnitude of this change in orientation are similar to those computed by using the numerical models. The good correspondence between field observations and theoretical results from this paper, not only provides insight into the mechanics of intersecting faults, but suggests that care is required when using standard inverse methods to compute paleostresses from slickenside data. The slickenside orientation near intersection lines will generally not be in the direction of the remote maximum shear stress as resolved on the fault plane. A parameter study of this change in orientation provides helpful results for evaluating field data prior to a paleostress analysis.

1. Introduction

Our understanding of the mechanics of normal faults can be improved considerably by analyzing the three dimensionality of fault geometry and the changes in fault slip distribution and direction along adjacent segments. Furthermore, field measurements of fault slip can provide a quantitative appraisal of the extent of fault segment interaction. Three-dimensional fault shape and slip variations are closely related to local stress/strain perturbations [Willemse et al., 1996]. Therefore knowledge of fault geometry, slip distributions, and orientation is required for understanding fault interaction, fault linkage, and the localization and style of secondary structures. In this work, attention is focused on the mechanics of intersecting normal faults and their slip distribution by combining field observations and three-dimensional numerical modeling.

Intersecting normal faults are observed at many scales in normal fault systems, both on maps and in cross sections, and such patterns are commonly imaged in seismic reflection data sets. Studies have documented slip distributions that exhibit multiple slip maxima near the intersection line connecting two faults [Walsh and Watterson, 1991; Childs et al., 1993; Mansfield and Cartwright, 1996; Nicol et al., 1996; Maerten et al., 1999]. These slip maxima are usually associated with zones of locally high slip gradients, often several times greater than typical slip gradients over the rest of the fault surface. These slip characteristics have been explained by mechanical interaction between the coeval linked faults [Willemse, 1996; Maerten et al., 1999]. Variations in fault slip directions or multiple slickenside orientations are observed along coplanar fault surfaces [Roberts, 1996; Dart, 1991] and, particularly, close to fault intersection lines [Krantz, 1988; Nieto-Samaniego and Alaniz-Alvarez, 1995]. These variations in slip direction are usually interpreted as the result of different successive tectonic events, if we postulate that slip vectors are expected to be parallel to the resolved shear stress. However, Cashman and Ellis [1994] observed and explained slip vectors of multiple orientations on a single fault surface by the interaction of crustal-scale faults in response to nearby earthquakes. Pollard et al. [1993] relate slip variations to the fault shape, the Earth's traction-free surface, and frictional anisotropy. Roberts [1996] suggests that slip vector variations observed at the terminations of normal fault segments are due to local variation in the strain patterns in these areas. Others explain the different slip directions along intersecting fault planes kinematically, assuming the faulted rock mass is a system of rigid blocks [Nieto-Samaniego and Alaniz-Alvarez, 1996].

The above studies demonstrate that the slip vector (both magnitude and direction) varies along the plane of intersecting faults, especially near geometrical irregularities such as intersection lines. Consequently, building upon previous research, this paper interprets and discusses the fault slip characteristics on intersecting faults via a threefold approach: (1) a theoretical analysis to understand the basic mechanics behind intersecting faults and slip characteristics, (2) a comparison with field data to evaluate the effectiveness of the theoretical models, and (3) a study of the implications...
for stress inversion methods to understand possible shortcomings for regions with complex intersecting fault patterns.

2. Theoretical Models

Perturbed three-dimensional fault slip distributions, caused by the interaction between intersecting faults, were investigated with the computer program Poly3D [Thomas, 1993]. This is a three-dimensional boundary element program based on the displacement discontinuity method and the governing equations of linear elasticity theory [Crouch and Starfield, 1983; Becker, 1992]. One of the main advantages of this method, compared with finite element methods, is that only the "boundary" surfaces themselves are discretized by polygonal elements, instead of discretizing the surrounding material. The polygonal elements are particularly well suited to model complex surfaces such as a curving fault with irregular tip line.

In the following set of experiments, combinations of traction and displacement boundary conditions (i.e., Burger's vector), associated with some far-field loading or strain, are prescribed for each element to compute the slip on faults and the elastic deformation of the surrounding material. When modeling faults, the displacement component normal to the element plane is prescribed to be zero, to avoid opening or interpenetration of the fault walls. The two in-plane shear tractions on each element can be prescribed as a boundary condition either directly on the element centers or by remotely applied stresses. In this mode, mechanical interaction between neighboring structures is taken into account. The behavior of the linear elastic and isotropic solid used in the following models is characterized by two elastic constants, Poisson's ratio and the shear modulus. I took a value of 0.25 for Poisson's ratio and 15,000 MPa for the shear modulus, which are representative of many rocks [Clark, 1966].

Elastic models are used because they are computationally simple and adequately explain the slip perturbations observed on interacting normal faults [Pollard and Segall, 1987; Bürgmann et al., 1994; Willemsen, 1997; Maerten et al., 1999]. Faults are idealized as three-dimensional surfaces of displacement discontinuity in a homogeneous, isotropic, linear elastic material. This provides a first-order understanding of how faults accommodate slip, concentrate stresses, and interact. The same motivation is followed in choosing elliptical tip lines in the theoretical models: a simpler geometry allows a better understanding of the results. Perhaps of greatest importance is the fact that the solutions to the linear elastic and isotropic solid used in the following models is characterized by two elastic constants, Poisson's ratio and the shear modulus. One took a value of 0.25 for Poisson's ratio and 15,000 MPa for the shear modulus, which are representative of many rocks [Clark, 1966].

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2.1. Model Configuration

The model configuration (Figure 1) consists of two normal faults dipping 60°. Fault A has an elliptical tip line with an aspect ratio of 2, defined by the ratio of the horizontal length over the fault dip dimension that has a unit value. The aspect ratio of 2 is approximately equal to the average aspect ratio observed in some normal fault data sets that vary between 1.25 and 3 [Rippon, 1985; Barnett et al., 1987; Walsh and Watterson, 1989; Nicol et al., 1996]. Fault B has the same tip line shape, but it is truncated by fault A. The faults are linked together along their center to form an intersecting fault array. The angle α is the angle between the strike of the faults. The big open arrows represent the direction of applied vertical compressive stress (σzz = -1 MPa), and the dashed lines are the observation lines of Figure 9 and Figure 12.

Figure 1. Model configuration of the theoretical models consisting of two normal faults dipping 60°. Fault A has an elliptical tip line with an aspect ratio of 2 so that half the length (1 unit) is the fault dip parallel dimension. Fault B has the same elliptical shape, but it is truncated by fault A. The faults are linked together along their center to form an intersecting fault array. The angle α is the angle between the strike of the faults. The big open arrows represent the direction of applied vertical compressive stress (σzz = -1 MPa), and the dashed lines are the observation lines of Figure 9 and Figure 12.

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The model material corresponds to a homogeneous whole elastic space. This is representative of natural faults that are buried deeply in relation to their in-plane dimensions; so the free surface has insignificant effects. The models are loaded with a remote homogeneous compression in the global z coordinate direction, σzz = -1 MPa, in order to produce the same tractions on the two fault surfaces. In the absence of slip on the faults, this produces a uniform extension in the x and y directions and shortening in the z direction [Jeager and Cook, 1979]:

\[
\varepsilon_{xx} = \varepsilon_{yy} = -\frac{\sigma_{zz}}{E}, \quad \varepsilon_{zz} = \frac{\sigma_{zz}}{E},
\]

where εxx and εyy are the in-plane strains, εzz is the out-of-plane strain, and σzz is the remote stress.
where $E$ is Young’s modulus and $\nu$ is Poisson’s ratio. I use the conventions employed in engineering mechanics, e.g., the principal stresses are arranged such that $\sigma_1 > \sigma_2 > \sigma_3$ with tension positive.

### 2.2. Computed Slip Characteristics

Figure 2a shows the contours of the computed dip slip over the two modeled faults. Fault slip is normalized to the maximum slip that would occur if fault A were isolated, that is, for the base case ($\alpha = 180^\circ$). The slip on faults is perturbed by their interaction and therefore diverges from idealized elliptical distributions [Sih, 1975; Rippon, 1985; Tada et al., 1985; Watterson, 1986; Barnett et al., 1987]. Fault A has two distinct slip maxima on either side of the intersection line. On the footwall side of fault B, the maximum dip slip on fault A is reduced to about 80% of the base case maximum, whereas on the hanging wall side, it is increased to about 120%. In addition, mechanical interaction leads to an asymmetric slip distribution and a greater slip gradient near the intersection line. Fault B has a single asymmetric slip maximum that is about 80% of the base case.

Figure 2b shows the contours of the normalized strike slip over the two modeled faults. On fault A, two 10% contours, with opposite signs, are adjacent to and on either side of the intersection line. Fault B has up to 20% strike slip, which is greater than that on fault A. In order to visualize the variations in the computed slip in three dimensions, the dip-slip and strike-slip components have been combined and plotted as a slip vector map over the entire fault surfaces (see Figure 2c). The slip vector is not generally parallel to the resolved shear stress on the faults [Bott, 1959]. Fault A shows opposite variations in slip directions on both sides of the fault.

**Figure 2.** Computed slip distributions for the theoretical model. Contoured three-dimensional distribution of normalized (a) dip slip and (b) strike slip along the two dipping faults (case $\alpha = 90^\circ$). The contour value of 1 indicates the maximum that would occur on a single isolated fault. Large arrows show the sense of slip on the hanging wall of the faults. (c) Slip vectors (combination of dip-slip and strike-slip components) displayed on a map of the fault planes. (d) Contoured three-dimensional distribution of slip vector; $90^\circ$ represents pure dip slip.
On the hanging wall side of fault B, the slip vectors on fault A tend to be parallel to the inclined intersection line. Slip vectors on fault B also tend to parallel the intersection line. However, on the footwall side of fault B, the slip vectors on fault A tend to be perpendicular to the intersection line. The perturbation of slip vectors is larger and more important near fault intersection. This is best shown in Figure 2d, which represents the contours of the slip vector in degrees (or computed striation rakes). The graphs show that there is an oblique slip up to -70º of striation rake near the intersection on fault B, compared with the expected 90º with no interaction.

2.3. Fault Mechanical Interaction

The model results just described can be explained in terms of the perturbation of the stress components acting on the fault surfaces due to fault interaction [Bürgmann et al., 1994; Willemse et al., 1996; Willemse, 1997; Maerten et al., 1999]. Here I looked at how the faults interact by modifying the local shear stress field on their neighbor. The perturbation of normal stress is not considered. This condition should be considered a first approximation that will nonetheless capture some of the principal effects of mechanical interaction [Willemse et al., 1996; Maerten, 1999]. The general idea is that where the stress perturbation from slip on one fault produces shear stress on its neighbor, it will tend to enhance or decrease slip, depending on the sign of the shear stress, and it will produce oblique slip if the shear stress is not directed down-dip.

Figure 3 illustrates both the down-dip and horizontal shear stresses on fault A caused by dip slip on fault B. The shear stresses \( \sigma_{x}(fA) \) and \( \sigma_{y}(fA) \) caused by motion of fault B alone are contoured on an observation plane that coincides with fault A (Figures 3a and 3c). The maximum shear stress perturbation is concentrated at the intersection line and has opposite signs on either side for the two shear stress components.

Figures 3b and 3d show contours of the dip slip and strike slip on fault A caused only by the perturbed shear stress field due to fault B. A positive shear stress \( +\sigma_{x}(fA) \) induces a normal slip, and a negative shear stress \( -\sigma_{x}(fA) \) induces a reverse slip on fault A. The dip slip on fault A is in the normal sense on the hanging wall side of fault B and in the reverse sense on the footwall side. These results show a direct correlation between the perturbed shear stress field and the dip-slip distribution (Figure 2a). A positive shear stress induces a normal sense of slip; so the normal slip is increased on that part of fault A. Where the perturbed shear stress induces a reverse sense of slip, the slip is decreased. Similarly, a positive shear stress \( +\sigma_{y}(fA) \) induces a left-lateral slip and a negative shear stress \( -\sigma_{y}(fA) \) induces a right-lateral slip on fault A. The shear stress inducing strike slip combined with the shear stress inducing dip-slip can

![Figure 3. Relationship between shear stress perturbation and slip variations for the theoretical model on fault A. (a, b) Computed distribution of the fault parallel shear stresses \( \sigma_{x}(fA) \) and \( \sigma_{y}(fA) \) caused by motion of fault B alone and contoured on an observation plane that coincides with fault A. Dashed contours are negative shear stress. (c, d) Contour of dip slip and strike slip distribution on a passive fault A caused by perturbed shear stress field due to slip on fault B. A positive shear stress \( +\sigma_{x}(fA) \) induces a normal slip, and a negative shear stress \( -\sigma_{x}(fA) \) induces a reverse slip on fault A. A positive shear stress \( +\sigma_{y}(fA) \) induces a left-lateral slip, and a negative shear stress \( -\sigma_{y}(fA) \) induces a right slip on fault A. Large arrows show the sense of induced slip on the hanging wall of the fault.](image-url)
explain the oblique slip observed in the theoretical model results of Figure 2c.

Figures 4a and 4c illustrate the same mechanism to explain the oblique slip observed on Fault B. They show contours of the perturbed shear stresses \( \sigma_{zx}(B) \) and \( \sigma_{zy}(B) \) caused by slip of fault A only, on an observation plane that coincides with fault B. These affect the dip-slip and strike-slip components on fault B. There is a direct correspondence between the shear stress components and the slip components, as shown in Figures 4b and 4d.

3. Field Observations and Models

The numerical experiments described above have been compared with published data on slip distributions [Maerten et al., 1999]. However, the value of most published slip distributions is limited, as the papers rarely contain information on both the slip distribution and the striation rake. Therefore a field investigation was initiated to evaluate how the model results might compare to natural faults. The goal was to use quantitative field observations on slip distribution and orientation to test the fault mechanical interaction theory for intersecting normal faults [Maerten et al., 1999]. A field area located at Chimney Rock, Utah, has been chosen because it is located in a simple geologic setting and the Chimney Rock fault array is well exposed.

3.1. Geological Setting

The Chimney Rock fault array is located in central Utah (Figure 5 inset) in the northern portion of the San Rafael Swell. The San Rafael Swell is a major Laramide uplift [Kelley, 1955; Dickinson and Snyder, 1978; Davis, 1978], approximated as a broad, north plunging dome-like anticline [Baker, 1935]. The Chimney Rock fault array occupies the gently flexed strata near the crest of the anticline (see Figure 5). Most of the faults at Chimney Rock are exposed as fault line scarps and crop out in a region of about 25 km². Many of the faults can be traced from tip to tip or from tip to intersection with other faults (see Figure 6). Both the larger normal faults, with up to 38 m of dip slip, and the smaller faults intersect each other to form a systematic pattern with orthorhombic symmetry. The system is comprised of four dominant sets: a first pair striking west-northwest with one set dipping to the northeast and the other to the southeast and a second pair striking east-northeast with one set dipping northwest and the other dipping to the southeast. Field evidences show that the faults are not synsedimentary faults and that 1 to 2 km of overlaying sediments were present during the development of the fault array.

The 15 largest faults, traceable along strike for 1 to 6 km, displace the Jurassic Navajo Sandstone, a well-sorted, highly porous aeolian sandstone, and the overlying Carmel...
by The faults of the Chimney Rock array were first mapped to tightly constrain the fault offsets and fault block study area and thus provide the marker horizons that are used presents beddings that are laterally continuous over the entire and mudstone. The basal section of the Carmel Formation, a Middle Jurassic thin-bedded limestone, siltstone, is 300 m. Modified from Triassic Chinle Formation (sea level datum). Contour interval of the San Rafael Swell, central Utah. The faults (heavy lines) are drawn on top of the structure contours of the top of the Upper Triassic Chinle Formation (level datum). Contour interval is 300 m. Modified from Baker [1935].

Formation, a Middle Jurassic thin-bedded limestone, siltstone, and mudstone. The basal section of the Carmel Formation presents beddings that are laterally continuous over the entire study area and thus provide the marker horizons that are used to tightly constrain the fault offsets and fault block deformation.

The faults of the Chimney Rock array were first mapped by Gilluly [1929] as part of his regional mapping and analysis of the San Rafael Swell. In 1986 Krantz, [1986] completed a detailed mapping of the faults. He used the orthorhombic nature of the fault system and the characteristics of the faults (e.g., direction of fault pole and fault spacing) to predict, with the odd-axis model, the principal paleostrain orientations and ratios [Krantz, 1988, 1989]. Cowie and Shipton [1998] and Shipton [1999] analyzed the slip profile along one of the main faults and relate the linear slip gradients at the fault tips to a positive stress feedback between sequential slip increments.

3.2. Field Mapping and Data Analysis

The ProXL System™, made by Trimble Navigation, was used to collect the data in the field. The ProXL is a portable Global Positioning System (GPS) that uses differential corrections to achieve submeter precision. The data capture strategy consisted of walking along the main faults and along a resistant limestone layer of the Carmel formation, which crops out almost everywhere along the edges of the gullies. A line feature, recording the Universal Transverse Mercator (UTM) coordinates and elevation every 5 s was used to map the layer while walking. When exposed, the contact between the Navajo and Carmel was also mapped, as well as other significant stratigraphic markers within the Carmel Formation. Mapping of the major faults was done by using point features to collect the location of measured fault strike, dip angle, dip direction, striation rake, approximated fault offset and other fault-related information. Where the fault zones were complex with overlapping segments or when striations were not visible, a line feature was used to record the geometry of the fault traces.

The data were analyzed by using GOCAD, a threedimensional surface interpolator developed at the National School of Geology, Nancy, France [Mallet, 1992]. First, the fault surfaces were constructed in three dimensions, including constraints provided by the measured strikes and dips. Because data on the geometry of the faults were limited to only a few tens of meters of the stratigraphic section, their vertical extent was approximated and their shape idealized for the purpose of modeling. Then the three-dimensional surface of the mapped limestone layer was created by interpolating between the data points (Figure 6). Precise stratigraphic logs of the lower Carmel Formation, measured in the field throughout the area, were used to extrapolate the elevation of the limestone layer where it did not crop out. The strike and dip of the layer measured in the field also were used to constrain the surface interpolation. Slip distributions along each fault were calculated by using the elevation separation between the hanging wall and the footwall cutoffs and the local dip of the fault plane.

Figures 7 and 8 represent the dip-slip distribution and the striation rakes measured along six of the major faults that show four kinds of fault intersection. The striation rakes reported on the graphs are only the significant ones measured in the field. For instance, the measured rakes have been weighted by a criterion, which is a fault surface quality factor that depends on the area of exposed surface exhibiting slickensides. When the area was more than 1 m², the quality was set to good, whereas a medium quality was for areas between 0.5 m² and 1 m², and a poor quality was for areas of less than 0.5 m². It can be seen that for the four intersecting faults, North fault, La Sal fault, Short fault, and Little fault, the maximum slip does not occur at the intersection, but rather away from the intersection line. The striations along the intersecting faults show a systematic variation of the rake, ranging from 90° plus or minus 20° to 30° close to the intersection lines, to almost pure dip slip (i.e., 90°) away from the intersection (see Figures 7b and 7c, and Figures 8b and 8c). In principle, the rake can vary from 0° to 180°. In the field it was measured by following the right-hand rule, which, when staying on the hanging wall and facing the normal fault plane, gives a positive rake measured on the right-hand side and a negative rake measured on the left-hand side. A rake of 90° represents a pure dip slip, and a rake of 0° represents pure strike slip.

Along the intersected Blueberry and Glass faults, both the slip distribution and the rake distribution show abrupt variations near major fault intersections. The Blueberry fault (Figure 8a) clearly displays striation rakes that switch direction where crossing the intersection with both the La Sal fault and the Little fault. Away from the intersections and toward the lateral tips of the faults, the significant rakes tend to be approximately 90°. Along the Glass fault (Figure 7a), the rake distribution is not so clear because of the many intersections with other major and minor faults (see Figure 6).
However, a switch in sign appears at the crossing of the North fault and the Short fault.

3.3. Comparison With Numerical Models

A set of numerical models have been undertaken in order to qualitatively understand the slip and striation rake variations measured in the field. The four types of observed intersections have been analyzed by using the boundary conditions, remote loading, and elastic constants from section 2 (theoretical models). No effort has been made to reproduce the exact geometry of the faults. The angle $\alpha$ (see Figure 1) has been modified as well as the orientation of the faults in order to ideally recreate the four types of intersections (see Figure 9).

Figure 9 shows the computed slip variations (magnitude in gray and direction in black) on the faults along a horizontal line through their center (see Figure 1) for the different configurations. In addition to the correspondence between slip gradients and rake observed in the model results of Figure 9 and the field measurements shown in Figures 7 and 8, other significant characteristics can be compared. For instance, the greatest values of oblique slip (i.e., up to 60° rake) as observed along the North fault and Short fault close to their intersections with the Glass fault are also found in the model results (i.e., up to 40° rake). The two rake anomalies observed along the North fault at about 1 km from the intersection might be explained by the interaction with collinear fault segments or with the NW-SE striking secondary fault found to the north (see Figure 6). Along the Glass fault and between the intersections with the North fault and the Short fault, the measured striation rakes tend to be, on average, negative. This is clearly observed for the slip vectors computed in Figures 9a

Figure 6. Detail of the fault pattern of the Chimney Rock area with the structure contour map of the mapped limestone layer of the Jurassic Carmel Formation. Coordinates are UTM (zone 12 north), elevations are in meters above mean sea level, and contour interval is 10 m. Solid fault lines are faults dipping to the north, and dashed fault lines are faults dipping to the south.
developed [Krantz, 1986]. The units comprise the Navajo Sandstone, the Kayenta Formation, and the Wingate Sandstone. This large competent unit of approximately 320 m is bounded by the less competent Carmel Formation (above) and Chinle Formation (below). A total of 400 m was chosen for the vertical dimension of the faults in order to take into account the portion of the faults dying out into the less competent units, as observed in the field. The elastic constants are the same as those in the previous models. The faults were loaded with a three-dimensional strain defined by

\[
\varepsilon_{\text{vertical}} = -0.07 \\
\varepsilon_{\text{east/west}} = 0.035 \\
\varepsilon_{\text{north/south}} = 0.035.
\]

**Figure 7.** Measured dip-slip distribution (squares) and measured striation rake (diamonds) along (a) the Glass fault, (b) the North fault, and (c) the Short fault. (d) Fault traces in plan view. Dashed lines are areas of no data. See Figure 6 for location of these faults. Dashed vertical lines are the position of fault intersections. Question marks show the end of field measurements but not the fault tip.

and 9b, where the values stay negative on fault A (i.e., the Glass fault) and do not reach pure dip slip even close to the fault tip.

A second model has been designed to quantitatively compare the observed slip and the computed slip. This model simulates the southern area of the fault array (i.e., the Blueberry, La Sal, and Little faults) and honors both the fault trace geometries as well as the fault dips (see Figure 10). However, the vertical dimensions have been inferred from the competent units of the stratigraphic column of the area that might correspond to a mechanical unit in which the faults

**Figure 8.** Measured dip-slip distribution (squares) and measured striation rake (diamonds) along (a) the Blueberry fault, (b) the La Sal fault, and (c) the Little fault. (d) Fault traces in plan view. Dashed lines are areas of no data. See Figure 6 for location of these faults. Dashed vertical lines are the position of fault intersections. Question marks show the end of field measurements but not the fault tip.
Figure 9. Computed slip distribution and slip vector along fault A and fault B for four different fault intersection patterns studied at Chimney Rock. The left-hand side column shows the model configurations and the right-hand side columns are the model results sampled on a horizontal line through the fault center (see Figure 1). Gray curves are dip-slip distribution, and black curves are slip direction distribution.

The choice of the fault geometry and the remote loading are not discussed in the present paper but will be considered elsewhere (L. Maerten, manuscript in preparation), where the orthorhombic fault pattern, the three-dimensional strain, and the fault vertical dimension are evaluated with regard to the slip model theory developed by Reches [1983].

The profiles of the distribution of both the computed dip slip and the computed striation rake along the modeled faults are shown in Figure 11. The profiles have been sampled on horizontal lines (dashed lines of Figure 10) at 50 m from the upper tip of the faults, because field evidence suggests that slip decreases upward from the outcrop locations; so the faults may terminate in the overlying Carmel Formation. In the models presented here, based on linear elasticity theory, the uniform fault shear strength and uniform remote stress result in large slip gradients near the tip line, and the faults do not propagate in response to these applied stresses. Furthermore, inelastic deformation as well as cohesive zones are not taken into account. Such considerations are very important for analysis of near-tip slip and secondary deformation but are of little consequence for the distribution of slip over the majority of the fault [Willemse et al., 1996]. Therefore no attempt is made to correct the slip distribution in the model fault tip region, and I focus attention on deviation from symmetrical slip characteristics at the fault intersections.

Despite the somewhat simplified configuration of the model, the computed slip is similar in form and magnitude to the observed slip distributions (Figure 8), especially close to the intersection where I focus attention. The greatest dip slip on the modeled Blueberry fault (Figure 11a) is at the center between the two intersections with the La Sal fault and the Little fault. The dip slip decreases with distance from the intersection lines. The computed slip direction or striation rake switches sign at the intersection and approaches 90° towards the fault tips. The maximum dip slip along the modeled La Sal and the Little faults (Figures 11b and 11c) is not adjacent to the intersection with the Blueberry fault but away from the intersection as observed in Figures 8b and 8c. The slip direction varies from 90° to approximately -85° when approaching the intersections.

4. Implication for Stress Inversion Methods

Over the last 30 years, several graphical and numerical methods [Arthaud, 1969; Carey, 1979; Etchecopar et al., 1981, Etchecopar and Mattauer, 1988; Angelier, 1983, 1989; Gephart and Forsyth, 1984; Reches, 1987] have been developed to infer the components of a regional stress tensor from populations of faults containing slickensides. They are all based on the inverse problem first formulated and solved...
Figure 11. Computed dip-slip distribution (squares) and computed striation rake (diamonds) along (a) the Blueberry fault, (b) the La Sal fault, and (c) the Little fault. (d) Fault traces in plan view. See Figure 10 for model configuration. Dashed vertical lines are the position of fault intersections.

4.1. Effect of the Angle Between the Strike of the Intersecting Faults

For the first set of analyses, the same model configuration as described in Figure 1 has been used to evaluate the effect of the angle between the strike of the intersecting fault on the collinearity between the slip vector and resolved maximum shear stress. In the simulations the faults have an aspect ratio of 2, and \( \alpha \) varies from 30º to 180º with steps of 30º. The case \( \alpha = 180º \) is treated as a single planar elliptical fault, which is used as a reference or base case. Figure 12 shows plots of the variation of the discrepancy angle \( \gamma \), defined by the angular difference between the direction of maximum resolved shear stress and direction of slip, along a horizontal line at midheight of the faults for various angles \( \alpha \). They show that the greatest discrepancy occurs when \( \alpha = 30º \) especially along the intersecting fault B where \( \gamma \) reaches -50º close to the fault intersection. Along fault A, on the hanging wall side of fault B, the discrepancy angle \( \gamma \) increases as angle \( \alpha \) decreases. For \( \alpha = 30º \), the value of \( \gamma \) stays above 10º even far away from the fault intersection. Figure 13 is a contour representation of the discrepancy angle \( \gamma \), for three configurations corresponding to \( \alpha \) equal to 30º, 90º, and 150º. It shows how \( \gamma \) varies spatially over the entire fault surface. It appears that, as a general rule, the discrepancy is the greatest adjacent to the intersection line and toward the bottom of the faults.

4.2 Effect of Fault Aspect Ratio

The second set of analyses consisted of evaluating the effect of the fault aspect ratio. In the simulations the angle \( \alpha \) between the strike of the two faults is kept constant and equal to 90º. The aspect ratio of the faults, before truncation of fault B, was set to 1, 2, 3, 4, 5, and 10, so that the horizontal axis gets longer in comparison with the downdip axis as the aspect ratio increases. Figure 14 provides plots of the variation of the discrepancy angle \( \gamma \), along a horizontal line at midheight of the faults for the various aspect ratios. The horizontal axis of the plots is the normalized strike dimension of the faults. The plots show that, as the aspect ratio of the faults increases, the lateral dimension of the mechanical interaction is reduced and, consequently, that the zone of large discrepancy angle \( \gamma \), concentrated along the fault intersection, decreases.

In the analysis I have shown that slip directions on faults can be strongly influenced by local factors such as mechanical interaction, especially in zones adjacent to fault intersections where the interaction is the greatest. In these zones, the assumption of parallelism between maximum resolved shear stress and slip vector used in inverse methods is not satisfied. If one considers that \( \pm 5º \) is the angle of precision of many field measurements and stress inversion analyses [e.g., Gephart and Forsyth, 1984], the following rule can be drawn from the above simulation in order to reduce the effects of the discrepancies when using stress inversion techniques. If the fault geometry in known or assumed, between the direction of slip and the direction of maximum resolved shear stress. This was done by designing a set of numerical experiments that consider factors such as the angle between the strikes of the faults and the aspect ratio of the faults. This study builds upon the evaluation done by Dupin et al. [1993] and Pollard et al. [1993] and provides a more complete evaluation of the inversion techniques for complex but realistic arrays of natural faults.
collected fault slip data in the area adjacent to fault intersections should be removed prior to inversion. The size of the restricted area is a function of the angle between the strikes of the faults, the vertical dimension of the faults, and the vertical location of the measured data.

For instance, if the strike angle between two intersecting faults is 30° and the outcropping slickensides are located at midheight, the fault slip data collected within a zone that has a lateral dimension equal to the vertical size of the fault should be removed from paleostress inversion procedure. Because of mechanical interaction, this zone may have $\gamma > 10^\circ$, and thus data from this part of the fault should be avoided.

5. Conclusions

The distribution of slip magnitude and the slip direction have been documented and analyzed on fault surfaces that intersect. The theoretical analysis suggests that elastic
deformation and mechanical interaction between faults produce deviation from both the symmetric slip distribution and the expected constant slip vector on an individual fault surface in response to a homogeneous remote stress field. The models show that significant slip gradients away from fault tip lines and asymmetric slip distributions, commonly observed on intersecting faults, can be due to mechanical interaction. Similarly, the variation of slip direction over a single fault surface, especially near fault intersections, can also be ascribed to fault interaction. This mechanical interaction is attributed, at least in part, to elastic deformation that modifies the local shear stress acting on one fault as induced by slip on the other fault.

Detailed quantitative field observations of intersecting normal faults at Chimney Rock, central Utah, show slip gradients and asymmetric slip distributions along intersecting normal faults cutting the Navajo Sandstone and Carmel Formation. The rake of the measured striations varies along the fault especially as the intersection line with adjacent faults is approached. The characteristics of the variation in fault slip distribution and slip direction are similar to those computed by using the idealized numerical models. When more realistic fault geometry and boundary conditions are used, the magnitude and sense of the computed slip distributions and computed slip directions, respectively, are comparable to the ones observed.

The analysis also suggests that the basic assumptions of stress inversion techniques, which assume parallelism between maximum resolved shear stress and the slip vector for a homogeneous remote stress field, are not strictly valid. Indeed, the simple examples used here, based on a consistent mechanical approach and supported by field observations, illustrate the concept that slip direction and resolved shear stress are not parallel in the vicinity of fault intersections and that the slip direction can deviate up to 50° from the direction of resolved shear stress. Factors such as the strike of the faults and their vertical dimension, if known, can be used to estimate the area adjacent to fault intersections where fault slip data should not be used in stress inversion analyses.

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