Origin and tectonic interpretation of multiple fault patterns

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Abstract

It is shown that in two-dimensional and three-dimensional deformation accommodated by fracture, the symmetry of the fault patterns is an intrinsic attribute because it reflects the symmetry of either stress or strain tensors. The deformation accommodated by sliding along pre-existing planes, when there is kinematic interaction between that planes, forms multiple fault pattern and multiple slickenline sets during a single deformation event. These fault patterns have no restrictions with respect to symmetry, number of fault sets or fault orientation.

The kinematic analysis developed here shows that an interacting system is formed by two cross cutting faults and three slickenlines. One slickenline must be parallel to the intersection line between the planes. Also, it is demonstrated that the slickenlines generally do not correspond to the shear stress solution on the planes. Thus, the interaction between planes does not satisfy the assumption of parallelism between shear stress and slip vector. We conclude that the inversion methods to calculate paleostress tensors can lead to erroneous interpretations in structurally complex zones with many pre-existing planes of weakness.

We propose four possibilities to form multiple fault patterns: (1) two or more events of faulting obeying Coulomb's law with a change of orientation of the principal stresses in each event; (2) reactivation of non-interacting planes according to the Bott (1959) model; (3) one three-dimensional strain event that obeys the "Slip Model"; this mechanism will form an orthorhombic four-fault pattern and two slickenline sets in a single strain event; and (4) one or more events obeying the interacting block model proposed here, with or without rotation of the principal stresses. We propose the last origin as the most common in continental regions.

Keywords: symmetry; tectonics; structural analysis; brittle deformation; faults

1. Introduction

In highly deformed zones, faults or other planes of weakness form groups with different orientations. Generally, older rocks contain more of these groups of planes because they record tectonic events that affected the rocks over geologic time. The number of fault sets recognized depends on the scale of work and on the meticulousness of the observations. Major fault sets are easy to recognize, but there are other sets comprised of smaller faults or consisting of a lesser number of faults. Considering all the fault sets

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in a zone, the fault pattern obtained is more complex than the pattern formed by major sets alone. A pattern with more than two sets of faults is referred to as a multiple fault pattern in the following discussion.

Commonly, multiple slickenline sets and multiple fault patterns found in nature are interpreted as the result of one or more tectonic phases of faulting (e.g., Donath, 1962; Armijo et al., 1982; Angelier, 1984; Gephart and Forsyth, 1984). This interpretation is based on the assumption that each tectonic phase produced a Coulomb fault system and a slickenline set. Consequently, each slickenline set can be inverted to obtain a paleostress tensor. Nevertheless, multiple fault patterns and multiple slickenline sets can be formed in a single phase of faulting as a consequence of the kinematics of interacting faults.

It is currently accepted that the origin of patterns with four sets of faults in orthorhombic symmetry can be produced by a single three-dimensional phase of deformation (Reches, 1978, 1983; Krantz, 1988, 1989). The origin of patterns with more than four sets of faults, or any pattern without orthorhombic symmetry have been explained by multiple events of deformation (e.g., Donath, 1962) or by reactivation of interacting planes of weakness (Nieto-Samaniego and Alaniz-Alvarez, 1995). In this paper we analyze geometric differences between patterns formed by fracturing and by sliding along pre-existing planes and demonstrate why many patterns do not lend themselves to an analysis using standard methods to calculate paleostress tensors.

2. Symmetry of fault patterns formed by fracture

Shear faulting in undeformed, homogeneous rock obeys the equation of the Coulomb criterion:

$$\tau = C + \mu \sigma_n$$  

(1)

where $\tau$ is the shear stress, $\sigma_n$ the normal stress, both on the potential plane of faulting, $C$ the cohesion and $\mu$ the coefficient of internal friction. According to this criterion, the rupture occurs on the plane having a high shear stress when it reaches the critical value expressed in Eq. (1). In a single rupture event two sets of conjugate faults are expected due to the symmetry of the stress tensor (Fig. 1a). The orientation of the faults in the general reference system is determined by the orientation of the stress tensor, and the acute angle $20^\circ$ between the conjugate faults is controlled by the coefficient of internal friction ($\mu$).

On the other hand, a single event of three-dimensional brittle strain produces four sets of faults with...
orthorhombic symmetry (Reches, 1978; Krantz, 1988). The orientation of the fault pattern in the general reference system is defined by the orientation of the strain tensor. The angle $\alpha$ is formed by the intermediate axis and the intersection line formed by a fault plane and the intermediate-similar plane.
If the slip is small relative to the spacing between faults, $\alpha$ is determined by:

$$\tan^2 \alpha = \frac{A_{\text{int}}}{A_{\text{sim}}}$$  \hspace{1cm} (2)

where $A_{\text{int}}$ and $A_{\text{sim}}$ are the magnitudes of the strain in the axes that have the same “sign” (shortening or extension). The angle $2\theta'$, formed between the two faults of each pair, depends on the coefficient of internal friction ($\mu$), as in the Coulomb criterion. Evidently, the symmetry of the orthorhombic four-fault pattern reflects the shape of strain tensor.

We generalize that the symmetry is an intrinsic attribute of the fault patterns produced by fracture in two-dimensional or in three-dimensional strain. The reason is that newly-formed faults respond directly to the stress or strain tensors, which are defined as symmetric second order tensors.

3. Reactivation of pre-existing planes of weakness

Slip along pre-existing planes in a crustal block is well-known (e.g., Jaeger, 1979; Ivins et al., 1990). The stress difference needed to initiate the slip along pre-existing planes and the stress difference needed to fracture the material can be calculated using the equations (Yin and Ranalli, 1992):

$$\sigma_1 - \sigma_3 = \left\{ \mu' \rho gz (1 - \lambda) + C' \right\} \times \left\{ \left[ (N_1^2 + R^2 N_2^2) - (N_1^2 + R N_2^2) \right]^{1/2} + \frac{\mu' \left[ (M_1^2 + R M_2^2) - (N_1^2 + R N_2^2) \right]}{2} \right\}$$  \hspace{1cm} (3)

$$\sigma_1 - \sigma_3 = \frac{2 \mu' \rho gz (1 - \lambda) + 2 C}{\left( \mu^2 + 1 \right)^{1/2} - \mu + 2 \mu \left( M_1^2 + R M_2^2 \right)}$$  \hspace{1cm} (4)

to initiate the slip along a plane of weakness and:

to fracture the material. Where $\sigma_i$ are the principal stresses ($\sigma_1 > \sigma_3 > \sigma_2$), $C'$ is the cohesion and $\mu'$ the coefficient of friction, both on the plane of weakness. $C$ and $\mu$ are the cohesion and coefficient of internal friction of the intact rock. $\rho$ the mean density, $g$ the acceleration due to gravity, $z$ the depth, $\lambda$ the pore fluid factor (pore fluid pressure/overburden pressure), $R = (\sigma_2 - \sigma_3)/2(\sigma_1 - \sigma_3)$ (stress ratio), $N_i$ the components of the unit vector $\vec{N}$ normal to the plane of weakness, and $M_i$ the components of the vertical unit vector, both specified in a Cartesian frame ($X_1$, $X_2$, $X_3$) coinciding with the principal stress directions. Comparing values of stress difference in Eqs. (3) and (4) we know what mode is preferred to accommodate deformation: fracturing or slip on a pre-existing plane. Obviously, the one which needs less stress difference will be preferred.

The continental crust contains many planes of weakness, especially if the lower part is composed of old rocks. Many orientations of these planes are suitable to slide under numerous conditions of depth, density, cohesion, friction, fluid pressure and stress ratio (Yin and Ranalli, 1992; Nieto-Samaniego and Alaniz-Alvarez, 1995). Therefore, it is very possible that much of the brittle deformation in continental regions is accommodated by slip along pre-existing planes of weakness. Sliding will occur on those planes that need a smaller stress difference to slip than the one being applied, according to Eq. (3). In continental crust the planes of weakness very likely interact kinematically because superimposed tectonic events produced cross cutting relationships between pre-existing and newly-formed planes (Figs. 1c and 2). The condition of kinematic interaction becomes more probable as the number and the orientations of the planes increases.

If a plane is not interacting with another, the stress difference needed to initiate sliding is obtained from Eq. (3), which is the Coulomb equation for sliding along a preexisting plane in terms of the stresses and plane orientations, depth, stress ratio and rock parameters. Using only the shear and normal stresses as variables the equation is:

$$\tau = C' + \mu' \sigma_i$$  \hspace{1cm} (5)

where $C'$ is the cohesion and $\mu'$ is the coefficient of friction, both on the plane of weakness. If a plane is interacting with another and considering opening does not occur, the movement of the fault-bounded block produces two slip vectors, one of them parallel to the intersection of the planes (Fig. 2a). These slickenlines are independent of the maximum shear
stress on the planes, they are determined for kinematic restrictions. The unit vector along the intersection is obtained from:

\[ 1.2 \mathbf{I} = 1\mathbf{N} \times 2\mathbf{N} \]  

(6)

where the left superscripts indicate the plane, \( A \) is a scalar, \( 1.2 \mathbf{I} \) is the unit vector along the intersection of planes 1 and 2, \( 1\mathbf{N} \) and \( 2\mathbf{N} \) the unit vectors perpendicular to the planes 1 and 2, respectively, and \( \times \) indicates the cross product.

From Cauchy's formula (e.g., Ranalli, 1987) we know that:

\[ \mathbf{T} = (\sigma_1 \mathbf{N}_1, \sigma_2 \mathbf{N}_2, \sigma_3 \mathbf{N}_3) \]  

(7)

where \( \mathbf{T} \) is the stress vector on a plane and \( \sigma_i \) the principal stresses. The maximum shear stress vector on the \( k \) plane (\( \tau_{\text{max}}^k \)) is obtained if \( \mathbf{T} \) is known:

\[ k\tau_{\text{max}}^k = (\mathbf{T} \times \mathbf{N}) \times \mathbf{N} \]  

(8)

where \( k \) indicates the plane. The magnitude of the shear stress on the plane \( k \) and parallel to the intersection direction is:

\[ k\tau_{\text{int}} = k\tau_{\text{max}}, 1.2 I_1 + k\tau_{\text{max}}, 1.2 I_2 + k\tau_{\text{max}}, 1.2 I_3 \]  

(9)

To initiate sliding along the intersection direction, it is required that \( k\tau_{\text{int}} \) satisfy the Coulomb condition (5), so we define:

\[ k\tau_{\text{int}} = C + \mu \sigma_n \]  

(10)

Fig. 3 shows this criterion in Mohr space.

In more complex scheme many slickenlines are formed (Fig. 2b and c), the expected number is:

\[ \text{( # of slickenlines)} = 2(\# \text{ intersection lines}) + 1 \]  

(11)

Each interaction system is formed by two planes, one intersection line and three slickenlines. For instance, the interacting pair formed by the faults 1 and 2 in Fig. 2 shows a cross cutting relationship with intersection vector \( 1.2 \mathbf{I} \). There will be kinematic interaction only if the stress difference needed to initiate the slip on plane 2 is higher than on plane 1. The implication of this condition is that plane 1 cannot move alone. When stress difference is sufficiently high to produce slip on plane 2, it is also enough to initiate slip on plane 1 permitting the movement of the blocks A and C in Fig. 2. Three slickenline sets are formed, they are represented by the unit vectors \( nS_n \), where the left subscript \( n \) indicates the slickenline. The first set (\( 1S_1 \)) is parallel to the intersection vector (\( 1.2 \mathbf{I} \)) and the shear stress needed is calculated in Eq. (10). The second set is defined by:

\[ 2S_2 = 1S_1 + 3S \]  

(12)

The shear stress is determined by the equation:

\[ k\tau_{(2S)} = (k\tau_{\text{max}})(1S_2) + (k\tau_{\text{max}})(2S_2) + (k\tau_{\text{max}})(3S_2) \]  

(13)

which is equivalent to Eq. (9) for \( 2S \) direction, and the magnitude to initiate the slip is calculated using the Coulomb condition. The third set (\( 3S \)) is a function of another interaction system if it exists.
Otherwise, $\bar{\tau} = \sqrt{2\tau_{\text{max}}^2}$, which is the tensor solution on the plane 2.

Kinematic interaction permits the stress difference to be raised until it reaches the value required for slip along the interacting plane that needs the highest stress difference to slip, or that is necessary to fracture the material. Thus, when the critical value is reached, the deformation will be accommodated by simultaneous sliding along those planes that need less stress difference to initiate the slip (Nieto-Samaniego and Alaniz-Alvarez, 1995). In elastic bodies, before the critical value is reached, slip may have occurred in some points on the fault planes far from the intersections, in which case there are no kinematic restrictions imposed by other faults. It is clear that the kinematic interaction only acts when the slip occurs near the intersections with other planes. However, a model which assumes rigid blocks (Fig. 2) is valid for faulting which occurred in the geologic past because the accumulated slip is considered and it includes the movement along the intersections.

A multiple fault pattern formed by sliding on three or more non-parallel planes of weakness is not necessarily symmetric. It reflects the geometric relationships between reactivated planes instead of the symmetry of the stress or the strain tensor (Fig. 1c). The continental crust contains planes of weakness that can determine the strained state if the stiffness of the surrounding matter is equal to or less than the stiffness of the strained block (Nieto-Samaniego and Alaniz-Alvarez, 1995). The fault pattern produced in this way has no restrictions with regards to symmetry, number of fault sets, or fault orientations.

Considering a crustal block deformed in brittle form, without volume change and containing many planes of weakness, four types of fault patterns can be formed:

1. Two-fault pattern. This pattern is a Coulomb fault system, it produces two-dimensional strain and obeys Eq. (1). It is a requirement that boundary conditions do not allow strain in one principal direction. Therefore, the stiffness of the surrounding matter must be greater than that of the block itself, at least in the non-deformed principal direction.

2. Isolated-faults pattern. It consists in reactivation of one or more isolated preexisting planes under the influence of a reoriented stress system according to the model of Bott (1959). This pattern requires not kinematic interaction between faults, this condition is less probable as the number of faults increase.

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Fig. 3. Three-dimensional Mohr circle for failure in isotropic rock and failure along a plane of weakness. Circles concentric with the circle with diameter $\sigma_1 - \sigma_3$ represent stress states on planes with fixed $N_1$; circles concentric with the circle with diameter $\sigma_2 - \sigma_3$ represent stress states on planes with fixed $N_i$. (a) The upper envelope displays the condition for failure in isotropic rock, and the lower envelope the condition for sliding along preexisting plane of weakness. Stars represent planes forming an interacting system similar to the one showed in Fig. 2 and 4. There is kinematic interaction because the stress difference needed to place plane 2 on the region of unstable states of stress is higher than to place the plane 1. The stress ratio, pore fluid pressure and depth are considered fixed. Although plane 1 is in the unstable region, the sliding is hindered by the plane 2. Diamond 1 represents a hypothetical plane on which the resolved shear stress equals the shear stress along the intersection direction $\tau_{\text{int}}$. Diamond 2 represents another hypothetical plane on which the resolved shear stress equals the shear stress $\tau_{\text{int}}(\sigma_1, \sigma_3)$ along the direction fixed by $\bar{\tau} = \sqrt{2\tau_{\text{max}}^2}$. (b) Increasing the stress difference $\sigma_3 - \sigma_1$, plane 2 reaches the envelope for sliding. However, sliding does not occur because the geometric relations force to slide along the directions given by the diamonds, which are in the stable region (Eqs. (9) and (12) and Fig. 2). (c) Simultaneous displacement occurs along the three planes when diamond 2 reaches the sliding envelope. Rupture does not occur because the failure envelope is never reached.
(3) Orthorhombic four-fault pattern. This pattern produces three-dimensional strain and obeys the Slip Model of Reches (1978). It is a requirement that boundary conditions determine the strain in two principal directions. Therefore, the stiffness of the surrounding matter must be higher than that of the block, at least in two principal directions.

(4) Complex fault pattern. This pattern produces either two-dimensional or three-dimensional strain and obeys the interacting block model described in this paper. For this pattern to form, pre-existing planes of weakness determine the strain tensor and the stiffness of the surrounding matter must be equal to or less than the stiffness of the block.

4. Implications for fault slip analysis

Much effort has been expended to determine the stress tensor from fault planes and slickenline data (Armijo et al., 1982; Angelier, 1984, 1989; Gephart and Forsyth, 1984; Michael, 1984; Gauthier and Angelier, 1985; Reches, 1987; Marrett and Allmendinger, 1990; Fleischmann and Nemcok, 1991; Yin and Ranalli, 1993). Slickenlines are kinematic indicators (slip vector), whereas the stress tensor is a dynamic entity. Thus, to use slickenlines in stress calculations it is necessary to assume that the maximum shear stress vector is parallel to the slickenline on the fault plane. Furthermore, the methods to calculate the stress tensor assume that slickenlines are produced by the general stress tensor, implying that faults do not interact and that no perturbations in the stress field are produce by fault slip.

In recent years the homogeneous stress field hypothesis has been tested by Dupin et al. (1993) and Pollard et al. (1993). They demonstrated that there are deviations between the maximum shear stress calculated from the far field stress tensor and the maximum shear stress calculated from the local stress tensor. These deviations, produced by changes in fault parameters or by perturbations in the stress field, are $< 20^\circ$, and more commonly $< 10^\circ$ considering a single fault (Pollard et al., 1993). Deviations due to stress field perturbations produced by the interaction between pre-existing planes vary up to $40^\circ$ when the density of planes is high (Pollard et al., 1993).

In this study, it is demonstrated that kinematic interaction also produces large deviations between the direction of the maximum shear stress and the slickenline. Each pair of interacting faults may produce three slip directions independently of the stress tensor solution on each plane. Then, other slickenlines will be formed in addition to the slickenline parallel to the maximum shear stress formed on one plane of the group (Fig. 2c and Fig. 4). The number of slickenlines depends of how many pairs of faults were reactivated according to Eq. (11).

Multiple slickenline sets on a single fault that belongs to a multiple fault pattern were documented by Cashman and Ellis (1994). In order to explain the origin of multiple slickenline sets, they used the boundary-element method to demonstrate that displacements on surrounding faults can produce slip vectors with the orientations observed on the fault studied. So, multiple slickenline sets on a single fault can be formed by multiple events of displacement on surrounding faults under a single regional stress tensor. This model considers the elastic response within the blocks whereas the kinematic interaction outlined above considers the movements of rigid blocks. Both models (elastic and rigid blocks) focus on different components of the complex deformation process occurring within a body which contains planes of weakness. The main deduction is that the interaction between pre-existing planes can produce multiple slickenline sets under a single regional stress field.

It is clear that the assumptions of a homogeneous stress field, dynamic and kinematic independence between faults, and parallelism between maximum shear stress and slickenline are not satisfied when there are interacting planes of weakness. In nature, these planes are faults or other geological structures such as fractures, stratification, unconformities, contacts, joints or foliation. It is very unlikely that multiple fault patterns and multiple slickenline sets developed in continental blocks containing such planes were formed by simple superposition of faulting phases that can be separated by inversion methods. The reason is that the assumptions of these methods are not satisfied if there is kinematic and dynamic interaction. We propose that complex fault and slickenlines patterns are formed by one or more events of strain by sliding along interacting planes. Each event produced several groups of faults and
slickenlines that do not necessarily correspond to the regional stress tensor but rather to kinematic interactions and local stress field perturbations. Thus, inversion methods cannot be applied in such a case.

5. Conclusions

Four possibilities exist to produce multiple fault patterns: (1) two or more phases of faulting with rotation of the principal stresses that obey Coulomb's law; (2) reactivation of non-interacting faults according to the Bott (1959) model; (3) a three-dimensional strain phase obeying the Slip Model (Reches, 1978) which produces an orthorhombic four-fault pattern; and (4) one or more phases of deformation with or without rotation of the principal stresses obeying the interacting block model. We propose the last origin as the most common because the continental crust contains many planes of weakness that are likely to interact during deformation.

Fault patterns formed by fracturing of rocks have symmetry as a fundamental attribute, reflecting the symmetry of the stress and the strain tensors (cases 1 and 3 above). Due to kinematic interaction, a fault pattern formed during a single deformation event of sliding on pre-existing planes has no restrictions regarding symmetry, number of slickenlines sets, number of faults, nor orientation of the faults (case 4 above). Thus, the symmetry of a fault pattern can be used to infer the mechanism of its formation. Qualitatively, simple and symmetric arrangements of faults may reflect the symmetry of the causative stress, but as the number of phases of faulting increase lower symmetry is expected. A quantitative analysis of the symmetry in fault patterns is under investigation.

Multiple fault patterns are complex deformation systems that have dynamic and kinematic interaction...
between pre-existing planes. This interaction does not satisfy the assumptions of the slickenline inversion methods to calculate paleostress tensors. Only patterns formed by two conjugate faults can be unambiguously dealt with using standard inversion methods to calculate paleostress tensors. In areas where inversion methods show two or more events of deformation (i.e. two or more paleostress tensors), it is necessary to evaluate whether the region has interacting planes of weakness that existed at the beginning of the deformation event. If that is the case, a reevaluation of the interpretations in the light of the model proposed in this paper is required.

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