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Influence of the structural framework on the origin of multiple fault patterns

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Abstract—We demonstrate that the general equation for three-dimensional strain by slip on orthorhombic faults can be rearranged to take a form that applies to two-dimensional strain due to slip on pre-existing planes of weakness. Therefore, either two-dimensional or three-dimensional strain may result from the same stress state. We deduce that the kinematic interaction between planes of weakness in a body is a fundamental factor to determine the type of strain produced by a stress state. Whether deformation occurs by forming new fractures or by slip on existing planes depends upon which requires a lower stress difference. The stress difference necessary to initiate slip along a plane is highly sensitive to variations in orientation, cohesion and depth. We propose a model for crustal deformation composed of an anisotropic body with existing planes of weakness that interact kinematically. The critical stress difference necessary to initiate sliding is that required by the interacting plane that needs the highest stress difference to slip. Because the stress difference will rise until it reaches a value that can cause slip on all interacting planes, once slip initiates it will occur simultaneously on all planes that require stress differences lower than the critical value. The anisotropic body model proposed here provides a mechanism for forming multiple fault sets and may pertain to the formation of low-angle normal faults.

INTRODUCTION

Faults are common in the crust. Usually, they occur in sets with different orientations. The number of fault sets that can be recognized in structurally complex zones depends on the detail of the field observations and the scale of work. More than two sets of faults as well as bimodal slip patterns have been observed in many areas (Reches 1978, Krantz 1989).

Analysis of fault sets is frequently based on the Coulomb–Navier failure criterion, which considers the crust as an isotropic medium. This simplified approach is valid in many cases. This criterion is limited, however, to two-dimensional brittle strain (plane strain), which is a special case of three-dimensional brittle strain (Krantz 1988). Coulomb–Navier theory predicts two sets of faults and a single slip pattern, so it cannot explain the origin of multiple fault patterns.

The theoretical principles of the faulting in three-dimensional strain were developed by Reches (1978, 1983). Reches' model assumes a medium that contains planes of weakness with random orientation and a sufficient number of individual planes in each orientation to consider the deformation as homogeneous. The model assumes further that slip occurs along the planes according to the Coulomb–Navier slip criterion; it predicts four sets of faults with orthorhombic symmetry and bimodal slip patterns. The Reches' theory is a good explanation for the four-sets patterns of faults observed in nature, but more complex three-dimensional brittle strain systems remain unexplored.

In recent years Huyghe & Mugnier (1992) analyzed the conditions for slip to occur along planes of weakness and Yin & Ranalli (1992) considered the problem in general stress systems with the principal stresses in any direction. Both analyses were based on the Coulomb–Navier slip criterion. The theoretical analysis presented here demonstrates that it is possible to rearrange the Reches' equation to take the form of the Yin & Ranalli's equation; therefore, any crustal brittle strain can be studied using the same equations. Also it shows that a single stress state can produce either two-dimensional or three-dimensional strain, leaving open the question of what controls the type of strain.

To explore a possible mechanism to produce multiple fault patterns and striae sets, this contribution analyzes the influence of the planes of weakness on the strain type produced by a stress state at shallow levels. The study emphasizes extensional tectonic conditions.

Field evidence shows that the type and geometry of the planes of weakness influence the deformational style (Jarrige 1992). For instance, stretched zones with pre-existing normal or thrust faults will accommodate the strain by reactivation of these structures (e.g. Allmendinger *et al.* 1987, Dewey 1988, Ivins *et al.* 1990, Huyghe & Mugnier 1992). We have applied the reactivation criterion to frameworks of planes of weakness under an extensional tectonic regime and found a possible origin for complex fault patterns and low angle normal faults.

THEORETICAL ANALYSIS OF BRITTLE STRAIN

The most general case of brittle deformation is represented by the tensor (Kostrov 1974, Reches 1978):

$$D_{ij} = \sum_{k=1}^{n} \gamma^k N_i^k S_j^k, \quad (1)$$

where γ^k is the simple shear produced by slip along the n^{k-th} plane, N_i^k the unit vector normal to the n^{k-th} plane and S_j^k the unit vector parallel to the shear component and tangent to the n^{k-th} plane.

The brittle deformation is accommodated by sliding along each plane. The planes may be formed by fracture or they could already exist in the material. In the first case, the Coulomb–Navier failure criterion is expressed by:

$$\tau = C + \mu\sigma_n \quad (2)$$

where τ is the shear stress and σ_n the normal stress on the potential plane of fracture, C is the cohesive strength, and μ is the coefficient of the internal friction of the material. A complete treatment of this equation is found as Coulomb's law in Jaeger (1979, pp. 163–165) or in Ranalli (1987, pp. 94–98). For existing planes, the Coulomb–Navier slip criterion is

$$\tau = C' + \mu'\sigma_n \quad (3)$$

where C' is the cohesion and μ' the friction, both on the plane of weakness.

Using the Coulomb–Navier criteria, Yin & Ranalli (1992) deduced equations that give the critical stress difference $(\sigma_1 - \sigma_3)$ necessary to fracture the isotropic material or to cause slip on planes of weakness as a function of C or C', μ or μ', depth and the orientation of principal stresses. Using the notation presented here, the equations are:

$$(\sigma_1 - \sigma_3) = \frac{2\mu\rho g z(1-\lambda) + 2C}{(\mu^2+1)^{1/2} - \mu + 2\mu(M_1^2 + RM_2^2)} \quad (4)$$

for an isotropic medium and

$$(\sigma_1 - \sigma_3) = \frac{\mu'\rho g z(1-\lambda) + C'}{[(N_1^2 + R^2N_2^2) - (N_1^2 + RN_2^2)^2]^{1/2} + \mu'[(M_1^2 + RM_2^2) - (N_1^2 + RN_2^2)]} \quad (5)$$

to initiate slip along a plane of weakness. ρ is the mean density of rocks, g the gravity acceleration, z the depth, λ the pore fluid factor (pore fluid pressure/overburden pressure), $R = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ (stress ratio), N_i the unit vector normal to the plane of weakness, and M_i the unit vector perpendicular to horizontal plane. The geometrical relationships of the unit vectors are shown in Fig. 1. Comparing the stress difference necessary to fracture the rock with the stress difference necessary to cause slip along the planes of weakness, it is possible to predict which of the two possibilities will occur.

In order to explain three-dimensional brittle strain, Reches (1978, 1983) developed the 'slip model', which assumes that the principal directions of strain and stress coincide, and that the strain is accommodated by simple shear along slip planes of faults. In Reches' model, the preferred faults have an orthorhombic symmetry with respect to the principal strain directions because only the

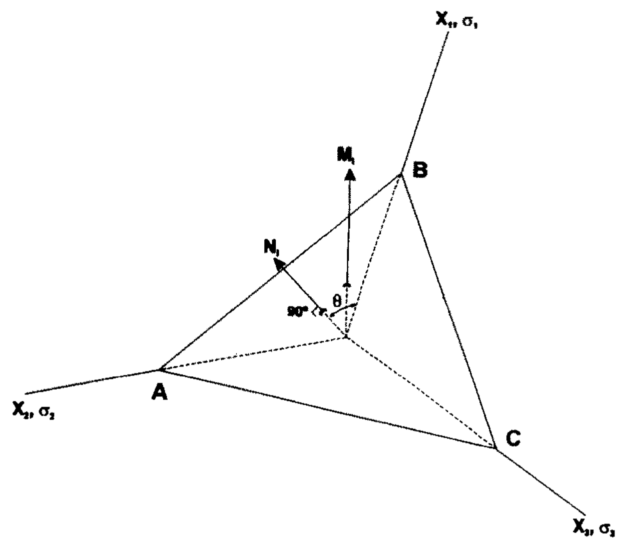

Fig. 1. Diagram showing the geometrical relationships of unit vector N_i, which is perpendicular to the plane ABC, the vertical unit vector M_i, the reference axes X_i, and principal stresses. The reference axes and principal stresses coincide. θ is the angle between σ_1 and N_i.

non-rotational deformation is considered. The preferred faults minimize both the stress difference and the work dissipation necessary to initiate the slip. The equations used to predict the stress difference are (Reches 1983, equations 13a & b):

$$(\sigma_1 - \sigma_3)[N_1S_1(1 + RK) - \mu'(N_1^2 + RN_2^2)] = C' + \mu'\sigma_3 \quad (6a)$$

$$(\sigma_1 - \sigma_3)(1 + RK) = \bar{w}. \quad (6b)$$

The strain ratio is $K = e_2/e_1$, where e_i are the principal strains and therefore e_2 and e_1 the principal intermediate and maximum compressive strain; $\bar{w} = 4w/e_1$, where w is the work dissipation per unit volume in the fault set along which the slip occurs (see Reches 1983, appendix 1). Equation (6a) is the Coulomb–Navier slip criterion rearranged in terms of the principal stresses σ_1 and σ_3, the stress and strain ratios, the slip unit vector and the unit vector normal to one of the four sets of faults predicted by Reches (1978, Appendix 2) to accommodate the three-dimensional non-rotational strain.

Equation (6a) is not applicable directly to field cases because it does not include the lithostatic stress in the crust. However, it is possible to introduce the lithostatic pressure and make it valid in non-Andersonian stress systems (with the principal stresses having any orientation). Following the Yin & Ranalli (1992) derivation of equations (4) and (5), the effective vertical stress applied on a horizontal plane is

$$\sigma_1 = \rho g z(1 - \lambda). \quad (7)$$

The normal stress on the horizontal plane can be also expressed as

$$\sigma_n = \sigma_1 M_1^2 + \sigma_2 M_2^2 + \sigma_3 M_3^2 \quad (8)$$

where σ_1, σ_2, and σ_3 are the principal stresses. Introducing equation (7) and the stress ratio into (8), solving for

σ_3, substituting it into equation (6a), and rearranging we get:

$$(\sigma_1 - \sigma_3) = \frac{\mu'\rho gz(1-\lambda) + C'}{N_1S_1(1+RK) + \mu'[(M_1^2 + RM_2^2) - (N_1^2 + RN_2^2)]}. \quad (9)$$

Equation (9) is equation (6a) for a general non-Andersonian stress system rewritten in terms of depth z and pore fluid factor λ. This equation is identical to (5) if

$$N_1S_1(1+RK) = [(N_1^2 + R^2N_2^2) - (N_1^2 + RN_2^2)^2]^{1/2}. \quad (10)$$

To demonstrate that equation (10) holds, we use equation (11) from Yin & Ranalli (1992):

$$\frac{\tau}{(\sigma_1 - \sigma_3)} = [(N_1^2 + R^2N_2^2) - (N_1^2 + RN_2^2)^2]^{1/2}. \quad (11)$$

Introducing equation (11) into equation (10) we obtain

$$N_1S_1(1+RK) = \frac{\tau}{(\sigma_1 - \sigma_3)}. \quad (12)$$

If equation (12) is correct, then equation (10) must hold. The equation for the shear stress on a plane with any orientation written in terms of the principal stresses is:

$$\tau = \sigma_i N_i S_i. \quad (13)$$

Introducing the stress and strain ratios R and K and the no-volume change condition $e_1 + e_2 + e_3 = 0$, rewritten using $e_1 = N_1S_1$, $e_2 = N_2S_2$, and $e_3 = N_3S_3$, we obtain:

$$\tau = \sigma_1N_1S_1 - \sigma_3N_1S_1 + (\sigma_1 - \sigma_3)KRN_1S_1. \quad (14)$$

Rearranging, we get equation (12), thus demonstrating that equations (5) and (9) are equivalent.

This analysis shows that the equation of the 'slip model' of Reches (1983) is the same equation obtained by Yin & Ranalli (1992) for the activation of planes of weakness criterion. Therefore, 'slip model' represents a particular, non-rotational case of a more general deformation model by slip along planes of weakness.

Applying progressively differential stresses to a body containing planes of weakness which are not interacting, the stress difference cannot be increased indefinitely because it is released during sliding on the plane that needs the least stress difference to move. To increase the stress difference, it is necessary to hinder movement either by resistance to the lateral growth of faults or by interactions between planes of weakness. With interactions between planes, the stress difference can be increased, and it must rise to the value needed by the interacting plane that needs the highest stress difference to slip. When this critical value is reached, slip will occur on those planes that need a stress difference equal to or less than the applied stress difference.

The total strain produced could be either two-dimensional or three-dimensional, depending upon the number and the orientation of the sets of planes on which displacement occurred. Each set will consist of many parallel planes of weakness. When slip occurs on one or two sets, the strain is two-dimensional, whereas when slip occurs on three or more sets the strain is three-dimensional (Reches 1978). Thus, the type of strain is not controlled by the stress state but it is determined by the number of planes available in the crustal block (pre-existing or formed by fracturing), along which displacement occurs to accommodate the deformation. The equations that describe the brittle strain are (1), (4) and (5). In equation (1), n refers to the number of sets that need a value of stress difference equal or less than the applied.

IDENTIFYING DOMAINS OF FRACTURE FORMATION OR SLIP REACTIVATION

In order to understand the deformation of rock with existing planes of weakness, we determine which planes are prone to experience slip under specific crustal conditions. In particular, we analyze whether slip occurs on existing planes of weakness or on newly formed fractures. The assumptions of the following analysis are: (i) a crustal block is deformed only in a brittle manner, without volume change; (ii) fault planes cut the block completely; (iii) displacement magnitude is constant at every point along each individual fault plane.

The mode of strain that occurs, i.e. whether slip occurs on existing planes of weakness or on newly formed fractures, depends upon which requires the lower stress difference. In order to evaluate the relative magnitudes of stress difference required for deformation by either mode, we use the parameter F,

$$F = (\sigma_1 - \sigma_3)_{(4)} - (\sigma_1 - \sigma_3)_{(5)} \quad (15)$$

where the subscripts (4) and (5) indicate the value of the stress difference fixed by equations (4) and (5) respectively. If $F < 0$, the material will fracture. If $F > 0$, displacement takes place along pre-existing planes of weakness.

We explore the variations in F for a range of situations by solving equation (15) numerically. We examine different cases with σ_1 vertical by plotting F against positive values of N_1 and N_2, which portray the effects of changing orientation of planes of weakness (Figs. 2 and 3). In each case, we identified the $F = 0$ contour using the inverse distance interpolation method. We call areas where $F < 0$ and fracturing occurs 'fracturing domains' and areas where $F > 0$ and reactivation of existing planes of weakness occurs 'slip domains'.

Figures 2 and 3 can be used to determine whether slip will occur on a particular plane of weakness or whether the material will fracture. Taking the appropriate graph, if the point with coordinates (N_1, N_2), which denote the orientation of the plane, plots in a domain where $F > 0$, then slip on the existing plane of weakness requires lower differential stress and will occur. If that point plots in a domain where $F < 0$, formation of a new fracture requires lower differential stress, and it will occur. In addition, Figs. 2 and 3 can be used to predict the range of orientations for which reactivation is preferred to the formation of new fractures. As an example, Fig. 4(a) represents low cohesion planes with 'typical' friction

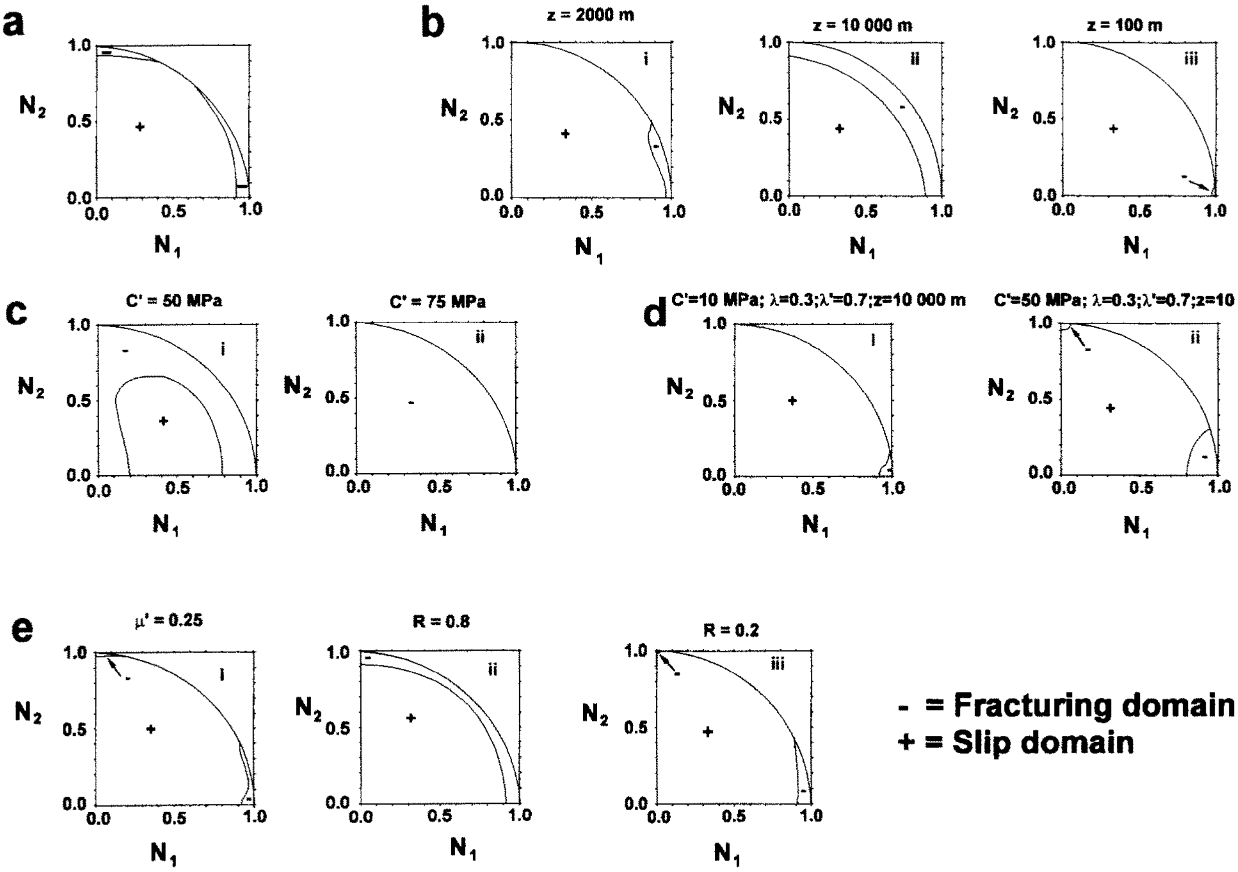

Fig. 2. Diagrams showing relative magnitudes of the parameter F, defined by equation (15), plotted as a function of N_1 and N_2, the direction cosines for existing planes of weakness. Stress principal directions and reference axes coincide. $\rho = 2650$ kg m^{-3}, and $g = 9.8$ m s^{-2}. σ_1 is vertical, so $M_1 = 1$ and $M_2 = 0$. In each diagram, $F = 0$ contours separate slip domains, where slip on existing planes of weakness is favored ($F > 0$), from fracturing domains, where formation of new fractures is favored ($F < 0$). In (a), which we use as a reference state for comparison with other diagrams, $z = 5$ km, $\mu = 0.75, \mu' = 0.50$, $C = 75$ MPa, $C' = 10$ MPa, $R = 0.5$, and $\lambda = \lambda' = 0$. New values of variables are shown directly on other diagrams.

factor and without pore fluid pressure, at the surface and in an extensional regime. The fracture of the material is preferred only when the planes are subhorizontal, because the fracture domain covers only $N_1 > 0.97$ values. Knowing a plane's inclination relative to one of the stress principal directions, we can determine the range of orientations for which formation of new fractures is preferred. Consider the family of planes inclined 13° to the horizontal, which are tangent to a vertical cone with an opening angle of 77°. With σ_1 vertical, $N_1 = \cos 13° = 0.9744$ (Fig. 4a). For any plane $N_1^2 + N_2^2 + N_3^2 = 1$, so N_2 could conceivably vary between 0 and 0.22. For a plane inclined 13° to the horizontal to fall within a fracturing domain, however, N_2 can vary only between 0 and 0.05 (Fig. 4a), indicating that fracturing is preferred to slip on an existing plane of weakness inclined 13° to the horizontal only if the strike of that plane forms an angle <13° to σ_2 (Figs. 4b & c). Similar analyses can be made for different combinations of factors in equations (4) and (5) to simulate different crustal conditions. Diagrams presented in Figs. 2 and 3 are equivalent to triangular diagrams of Yin & Ranalli (1992).

We use Fig. 2(a), which represents shallow crustal level conditions without pore fluid pressures and with low cohesion on existing planes of weakness, as a reference state for assessing the sensitivity of F to changing conditions. The position of the $F = 0$ contour is relatively insensitive to moderate variations in μ' and R [Figs. 2e(i)–(iii)], whereas variations in z *and* C' cause dramatic changes in the position of the $F = 0$ contour (Figs. 2b & c). Therefore, we consider depth and cohesion to be critical factors to predict in order to determine whether strain will be accommodated by slip on existing planes of weakness or by formation of new fractures. In Fig. 2(d) we have given the pore fluid factors distinct values for isotropic and anisotropic media, λ and λ' respectively, to simulate the situation in which anomalous pore fluid pressure is present on faults, as was described by Huge & Mugnier (1992).

For cases where σ_3 is positive (compressive) and σ_1 is vertical, we observe the following general tendencies in the behavior of parameter F. First, preexisting low cohesion planes of weakness oriented nearly parallel to the σ_3 direction (peripheral area in the quadrant) are unsuitable to slip [Figs. 2a, b(i)–(ii), c & e]. Second, at shallow levels ($z < 5$ km), fracture is preferred when $N_2 \approx 0$ and $N_1 > 0.92$ (planes with dips <23° and subparallel to σ_2 direction) [Figs. 2a, b(i),(iii) & e]. Therefore, we deduce that under Andersonian conditions in an extensional regime, the planes of weakness with strikes near the σ_2 direction and dip >23° are prone to accommodate the deformation by slip. Third, at shallow levels, when

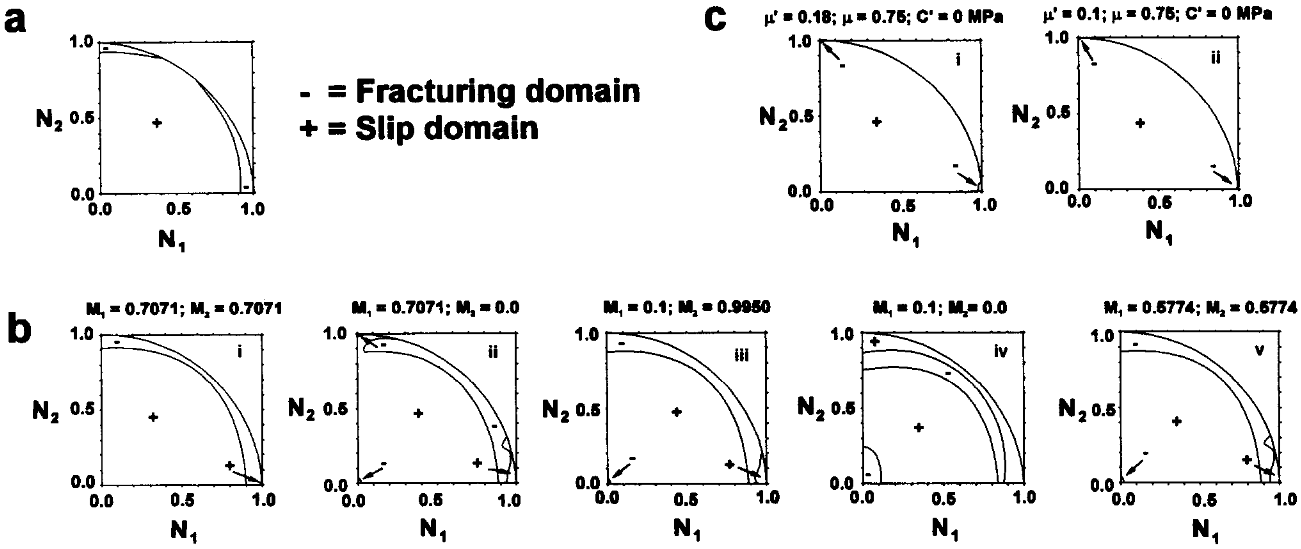

Fig. 3. Additional diagrams showing the relative magnitude of F as a function of N_1 and N_2. (a), the reference diagram, is identical to Fig. 2(a). New values of variables are shown directly on other diagrams.

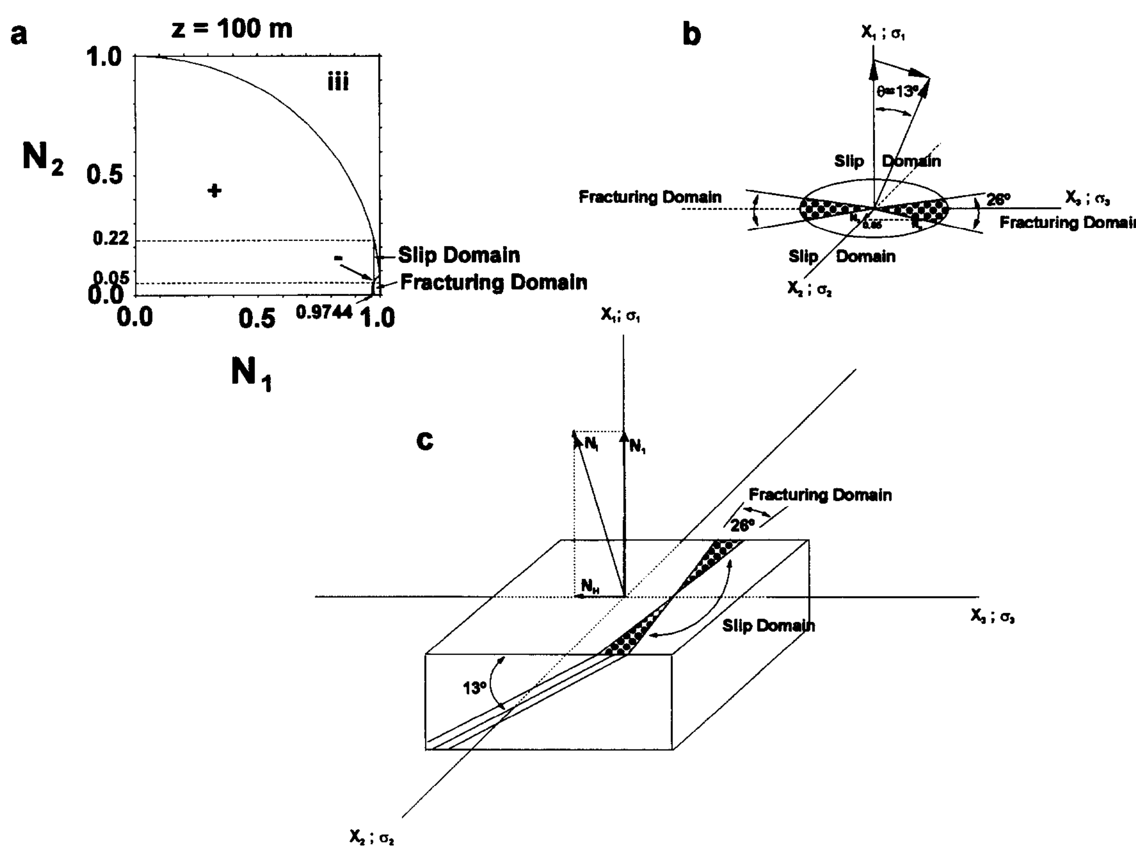

Fig. 4. Application of Figs. 2 and 3. (a) Diagram identical to Fig. 2[b(iii)], with $z = 0.1$ km, vertical σ_1 and $F = 0$ contour separating slip and fracturing domains. For planes dipping 13°, where $N_1 = 0.9744$, $F < 0$ only if $N_2 < 0.05$. (b) Plot of the stress principal directions (and reference axes). With vertical σ_1, a horizontal circle represents all orientations of existing planes of weakness by possible combinations of N_2 and N_3. The dotted areas show N_2 values of planes with 13° dips whose strikes fall within the fracturing domain. (c) Diagram representing the range of orientations of existing planes that fall within the slip and fracturing domains.

$\mu' < 0.25\,\mu$ (anomalously low friction on the planes of weakness) slip occurs along cohesionless planes dipping >10° (Fig. 3c), which agrees with the Ivins *et al.* (1990) and Huge & Mugnier (1992) argument for reactivation of low angle faults in extensional regimes. In all cases the angle of reactivation diminishes as z decreases; for instance at the surface (z = 100 m), reactivating angle is 14° ($N_1 = 0.97$) for the reference conditions [Fig. 2b(iii)]. Finally, when C' is close to C and z is increased as well, the size of the fracturing domain increases, indicating fracture of the material instead of slip, for many plane orientations (Figs. 2b & c). On subhorizon-

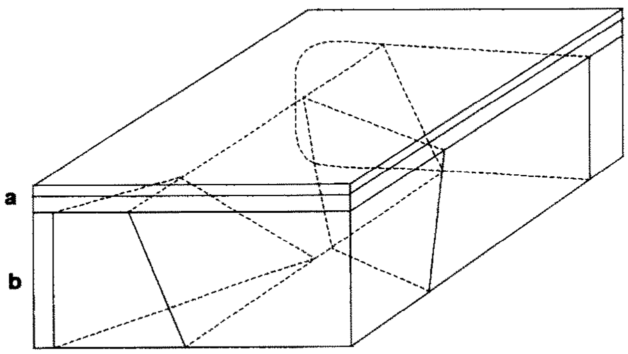

Fig. 5. Diagrammatic block showing interacting planes of weakness. The upper part (a) is a horizontal layered sequence and the lower part (b) a complex structural interacting pattern defined by non-crossing planes of weakness.

tal ($N_1 > 0.95$) and subvertical ($N_1 < 0.05$) planes of weakness, slip occurs if the stress directions are rotated adequately, as it is shown by the positive values of F parameter in Fig. 3(b).

ANISOTROPIC BODY MODEL IN CRUSTAL STRAIN

According to our analysis, at shallow levels, planes of weakness that dip more than 23° are prone to sliding under most conditions, and the deformation is likely to occur by slip on existing planes of weakness. To produce multiple striae directions, multiple fault patterns, or three-dimensional strain, slip on three or more planes is necessary. We argue that kinematic interactions between existing planes of weakness are needed to allow the stress difference to rise until it reaches a value sufficiently high to move several planes.

The strain of a crustal block is determined by either the crustal block or the surrounding matter, depending upon which has the higher stiffness. When surrounding matter stiffness is higher than block stiffness, the strain applied on the block faces determines whether deformation will be two-dimensional or three-dimensional according to Reches' model. On the other hand, when surrounding matter stiffness is equal to or less than the block stiffness, strain will be determined by existing planes of weakness because surrounding matter cannot hinder the movement of the block's faces. In this case, interacting planes of weakness are the fundamental factor which determines whether deformation will be two-dimensional or three-dimensional, and if a multiple fault pattern will be formed.

The anisotropic body model

The model considers some planes of weakness kinematically interacting in a crustal block. Slip along one plane does not occur without slip along other planes or without fracture of the material (Fig. 5). Thus, to initiate slip, a sufficiently high stress difference is required to produce slip along the interacting plane that needs the highest stress difference (or the sufficient stress to fracture the material). Once slip initiates it will occur simultaneously on all planes that require stress differences lower than the critical value.

Complex fault patterns and low angle normal faults

It is difficult to produce displacement on subhorizontal planes when the reasonable values for the cohesion and coefficient of friction are used. Subhorizontal planes are not favorably oriented to slip if σ_3 is positive, as is shown in Fig. 2. Nevertheless, without a vertical principal stress (non-Andersonian stresses), slip along these planes may occur instead of rock fracturing (Figs 3b & d). Another possibility suggested by Ivins *et al.* (1990) is that cohesionless planes of weakness, where $\mu' \leq 0.25\mu$, may slip as is shown in Fig. 3(c). This explanation requires uncommon crustal conditions. Sibson (1985) suggested $\sigma_3 < 0$ as another explanation for normal slip on subhorizontal planes.

On the other hand, stretched regions with fault patterns consisting of more than two sets cannot be explained by the Coulomb–Navier failure criterion. Since these patterns suggest three-dimensional strain, the slip model of Reches (1983) is a possible explanation (Krantz 1989). Multiple deformation events with rotation of the stress directions (Donath 1962) is another possibility.

Although low angle normal faults and complex fault patterns are commonly observed in the field, there is not a complete explanation of their origin. The anisotropic body model presented here gives a possible formation mechanism assuming a continental crust environment.

Consider a continental block composed of two parts. The lower part is an old, strongly anisotropic mass of rocks with numerous, differently-oriented planes of weakness which are the product of the many tectonic events that have affected the rocks. It is unlikely that all planes of weakness cut the block completely. More likely, the planes are interacting. The upper part consists of younger sedimentary or volcanic successions with subhorizontal planes of weakness. The contact between lower and upper parts may be either a stratigraphic or tectonic contact. Examples of these continental blocks are orogenic and cratonic zones like the Basin and Range province (e.g. Stewart 1978) or the Sierra Madre Occidental province in Mexico (e.g. Ortega-Gutiérrez *et al.* 1992).

Commonly these continental zones are affected by tensional tectonics (e.g. Dewey 1988), during which their behavior is very complex. In the lower part there is a potential three-dimensional strain by slip along existing planes of weakness, because the slip along planes with moderate to high dips is preferred over fracture. In the upper part there is a potential two-dimensional strain by fracturing the rock, due to the difficulty to produce slip along horizontal planes of weakness.

Three-dimensional strain in the lower part cannot occur without fracturing the upper part, because this requires lower differential stress than slip on the subhorizontal contact separating them. On the other hand, when the stress difference is sufficiently large to fracture rocks in the upper part, strain compatibility precludes two-dimensional strain in the upper part. There are two possible outcomes:

(1) Differential stresses could rise to the value needed to initiate slip along the subhorizontal upper part/lower part boundary, thereby forming a detachment fault and enabling the upper and lower parts to deform independently.
(2) Three or more fault sets could form in the upper part without the formation of a detachment, leading to compatible strain in the upper and lower parts.

The possibility that demands the least stress difference will be preferred.

This model provides a simple mechanism for explaining the formation of complex fault patterns observed in continental stretched zones and provides an alternative origin for low-angle normal faults.

CONCLUSIONS

Our analysis shows that the same stress state may lead to two-dimensional or three-dimensional deformation in a medium containing planes of weakness. Whether deformation leads to slip on existing planes or to the formation of new fractures depends on both the fundamental physical characteristics of the intact rock and on the orientation of the planes of weakness. Our analysis shows that depth and cohesion are critical parameters in permitting slip on planes of weakness. Slip is facilitated when N_1 <0.92 (dip >23°), $C' \approx 0$, and z <5 km, and especially when $\mu' \leq 0.25\mu$. When the stress system is rotated, sliding can take place on vertical and horizontal planes of weakness.

In order to explain the origin of complex fault patterns observed in continental stretched zones, we proposed an anisotropic body model, which consist of a block with interacting planes of weakness. Due to the interaction condition, we argue that the critical stress difference to initiate sliding is that which is required by the interacting plane needing the higher stress difference to slip (or that which is necessary to fracture the material). Semi-simultaneous slip will occur along all the planes that require less stress difference than the critical value, and the strain mode will be determined by the number of planes with displacement. The model also gives an alternative explanation for low-angle normal faults.

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