



Stress, strain and fault patterns

Ángel Francisco Nieto-Samaniego

Universidad Nacional Autónoma de México, Universidad de Ciencias de la Tierra, Apartado Postal 1-742, Santiago de Querétaro, Querétaro, 76001, Mexico

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Abstract

If faulting is treated as a stress-controlled phenomenon, the generation of a single fault set, or two sets in conjugate arrangement are inevitably predicted implying plane strain. Alternatively, considering faulting as a strain-controlled process, multiple-set patterns can be predicted. The analysis of multiple-set patterns requires identifying the type of fault pattern from four possibilities: Coulomb, isolated, orthorhombic and complex fault patterns.

There are techniques that permit a unique solution of strain tensor for Coulomb and orthorhombic fault patterns. For isolated fault patterns, the principal paleostress directions could be used to approximate the principal strain directions. In this case, we need to assume a homogeneous stress field, independence between faults, and parallelism between shear stress and slip vector on the sliding plane.

For complex fault patterns, it is not possible to uniquely determine the total strain tensor without knowledge of all the slip planes. Furthermore, inverting fault-slip data to determine the stress tensor is not correct because the assumptions of the inversion methods are not satisfied. Only a rough approximation is possible assuming that strain produced by major faults represents the total strain tensor. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Field geologists working in faulted areas commonly deal with the reconstruction of the faulting history and the determination of principal strains. Until now, the different methods used are based on several assumptions, which are transgressed if there are multiple fault patterns (i.e. more than two interacting sets of faults).

Where complex fault patterns occur, the recognition of phases of faulting has been invoked as a tool to reconstruct the faulting history (e.g. Angelier, 1994). Paleostress analysis using fault-slip data requires, assuming a homogenous stress field, parallelism between shear and slip vectors on a fault plane and independence between faults.

To calculate tectonic strain, the interest is focused on estimating the principal strains. A common method consists of constructing structural sections to measure

displacements fault-by-fault along the ‘transport direction’, which is assumed to be orthogonal to the trend of major faults. This methodology is based on the assumption that strain along the trend of major faults is negligible and therefore the obtained strain is on a principal plane. In order to include the displacements of faults that are too small to be measured, extrapolation has been proposed assuming a power-law relation between number of faults and displacement (e.g. Walsh et al., 1991; Marrett and Allmendinger, 1992).

Fault patterns composed by more than two fault sets have been recognized widely (e.g. Reches, 1978; Johnson, 1995). Orthorhombic four-fault patterns violate the plane strain assumption because they are formed under three-dimensional strain (Oertel, 1965). In rocks containing planes of weakness, several planes could slip during a single phase of faulting. In this case, the assumptions of plane strain, homogeneous stress field and independence of faults are not necessarily satisfied (Nieto-Samaniego and Alaniz-Alvarez, 1997). These characteristics imply that multiple fault

E-mail address: afns@servidor.unam.mx (Á.F. Nieto-Samaniego)

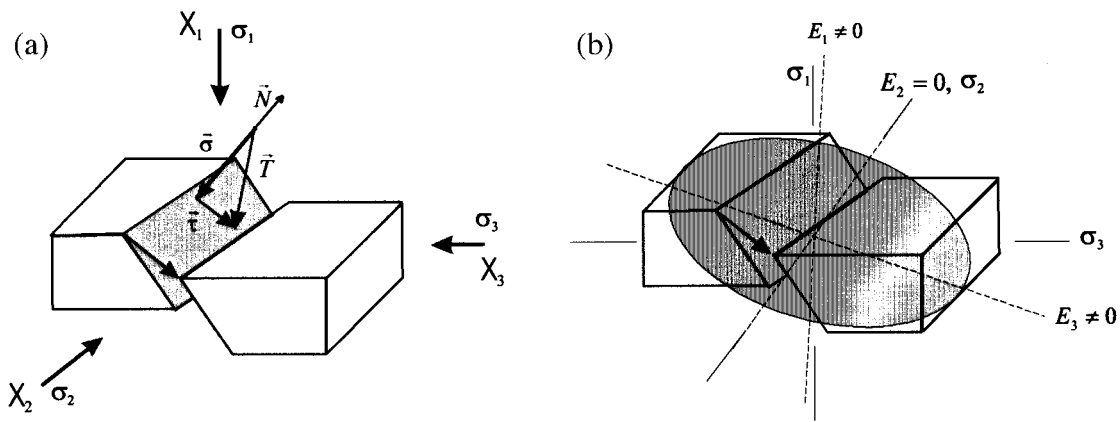


Fig. 1. A single fault sliding under a stress field. (a) Geometrical relationships among stresses on a sliding plane. \vec{N} is a unit vector normal to the plane, \vec{T} the stress vector on the plane solved from stress tensor, $\bar{\sigma}$ the normal stress and $\bar{\tau}$ the shear stress, and $\sigma_1, \sigma_2, \sigma_3$ are the principal stresses. In this case, it is assumed that fault plane slides parallel to shear stress. (b) The fault produces two-dimensional strain ($E_2 = 0$) with a rotational component.

patterns do not permit calculation of valid total strain or paleostress tensors.

In order to show why the multiple fault patterns cannot be analyzed adequately by standard methods, a brief revision of the principal theories of faulting is presented. In a practical way, the problem stated here could be divided into two parts, both addressed in this paper: the first one is determining the cases for which the assumptions mentioned above are satisfied, and the second is how we can obtain a sufficiently good estimation of strains if the assumptions are not satisfied.

2. Stress and predicted number of fault sets

2.1. Fracture mechanics theory

Fracture mechanics theory has been used to model the growth of a fault. The perturbations of a compressive stress field due to the presence of cracks have been modeled using stress intensity analysis. Near the tips of mode II and III cracks the stress field is tensile and

the fractures show a curved shape becoming perpendicular to the minimum compressive stress σ_3 (e.g. Segall and Pollard, 1980; Nemat-Nasser and Horii, 1982). Under a uniaxial compression, one set of mode I cracks is predicted. Under triaxial compression, the mode I cracks show a finite growth (Brace and Bombolakis, 1963; Nemat-Nasser and Horii, 1982) and the coalescence of cracks culminates forming a fracture parallel to the plane of shearing predicted by Coulomb's law. The growth of faults by linkage of nearing segments is supported by the stress distribution, which predicts the generation of secondary fractures. Fracture mechanics theory focuses on the stress or energy needed to increase the crack length, implying that only one fracture or a few closely spaced fractures linked during growth can be modeled.

2.2. Shear stress theory

This theory assumes that the maximum shear stress in a body produces the rupture. Due to the symmetry of the stress tensor, it is deduced that there are two

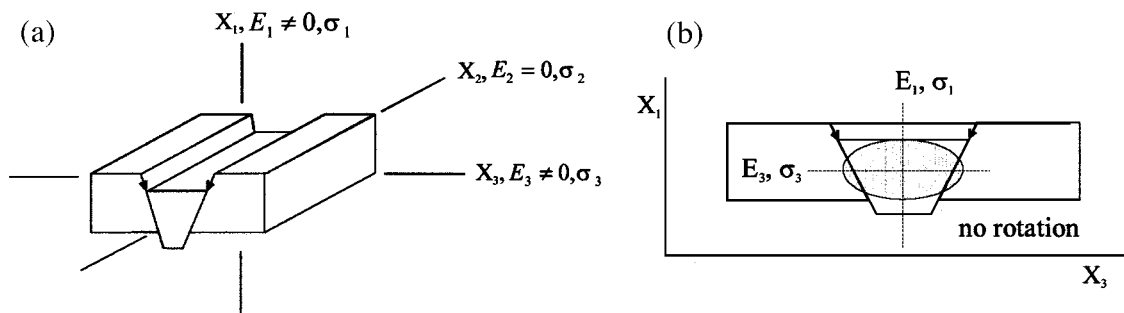


Fig. 2. Two faults in conjugate symmetry produce two-dimensional non-rotational strain. In (a) it is shown there is no deformation in one principal direction ($E_2 = 0$) and in (b) that there is no rotation.

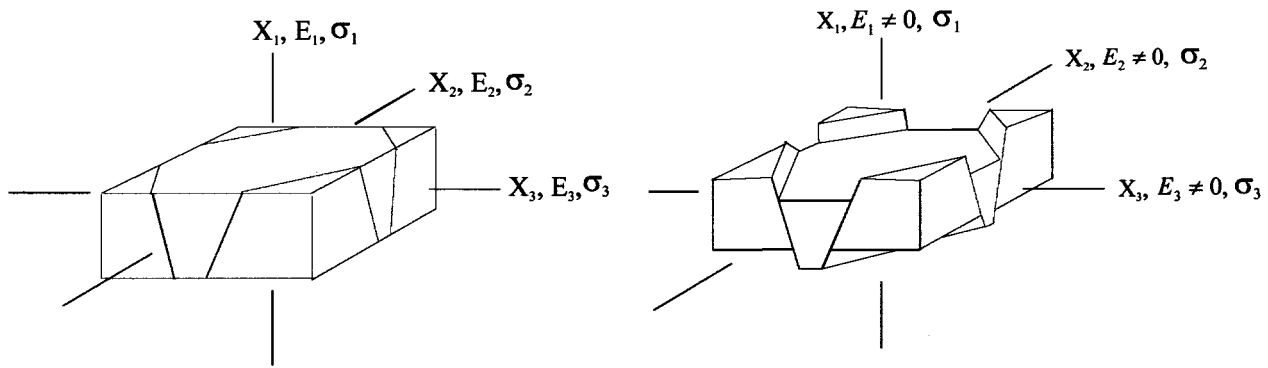


Fig. 3. Four faults in orthorhombic symmetry produce three-dimensional non-rotational strain.

planes of maximum shear stress, which contain the intermediate principal stress σ_2 and form an angle of 90° (e.g. Ramsay, 1967; Jaeger and Cook, 1969). The analysis of shear stress geometry developed by Wallace (1951) followed by the work of Bott (1959), established the mechanics of oblique faulting (Fig. 1). The first complete theory of faulting was proposed by Anderson (1951) based on the Coulomb law. The essence of Anderson's scheme is that no shear stress can exist on the surface of the earth and consequently, one of the principal stresses must be vertical. Under compression a conjugated shear fault is predicted, with the maximum principal stress (σ_1) bisecting the angle formed by the faults (Fig. 2). The angle bisected by σ_1 is determined by the coefficient of internal friction according to $\theta = 45^\circ - \frac{1}{2} \tan^{-1} \mu$, where μ is the coefficient of internal friction and θ the angle between σ_1 and the fault plane (Jaeger and Cook, 1969). The formation of normal, thrust or strike-slip faults depends on which principal stress is vertical. Anderson's theory is a powerful tool in the study of faulted regions and explains broadly the structural style observed in many zones. Nevertheless, it is restricted to regions where plane strain took place, supporting the common interpretation that strain along the strike of normal or thrust faults is negligible. In consequence, it is clear that it does not address synchronous multiple-fault sets.

2.3. Dilatancy-based theory

Another way to find the preferred fault orientations in a three-dimensional stress analysis was developed by Johnson (1995). He used the 'virtual work' concept and deduced the equation

$$\bar{W} = 2V|\bar{\epsilon}_s|(\sigma_n d + |\tau|), \tag{1}$$

where V is the volume of the deformed body, σ_n the normal stress, \bar{W} the virtual work and $\bar{\epsilon}_s$ the virtual shear strain along the fault; d is the coefficient of dila-

tancy defined as $d = \bar{\epsilon}_n/2|\bar{\epsilon}_s|$ and $\bar{\epsilon}_n$ is the virtual normal strain. Eq. (1) shows that virtual work is proportional to the magnitude of the virtual shear strain. Using Eq. (1) rearranged as a function of the strike (ω) and dip (β) of one preferred plane of shearing and maximizing the work done by applying the condition $\partial W/\partial \omega = \partial W/\partial \beta = 0$, Johnson (1995) found the orientations of the preferred planes of shearing

$$\beta = 45^\circ - \frac{1}{2} \tan^{-1} d, \text{ and } \omega = 0. \tag{2}$$

Due to the zero value obtained for ω and the symmetry of the stress tensor, a conjugate fault pattern is expected.

The main point emerging from the theories outlined above is that, for the general case $\sigma_1 > \sigma_2 > \sigma_3 > 0$, faulting analyzed as a stress-controlled phenomenon inevitably leads to the prediction of two sets of faults in conjugate geometry reflecting the symmetry of the stress tensor.

3. Strain and predicted number of fault sets

An alternative way of studying faulting is from a kinematic point of view. In this case, there is no consideration of the cause of strain and the boundary conditions are defined by the strain field. This approach is based on the work developed by Taylor (1938), Oertel (1965) and Reches (1978). Using a local Cartesian frame with an axis normal to the fault plane, a fault contains two shear systems. Each shear system is composed of the fault plane and a shear vector parallel to one axis on the fault plane. The total deformation could be represented by the tensor (Kostrov, 1974; Reches, 1978)

$$D_{ij} = \sum_n a_{ik} a_{jl} a_{kl}^n, \tag{3}$$

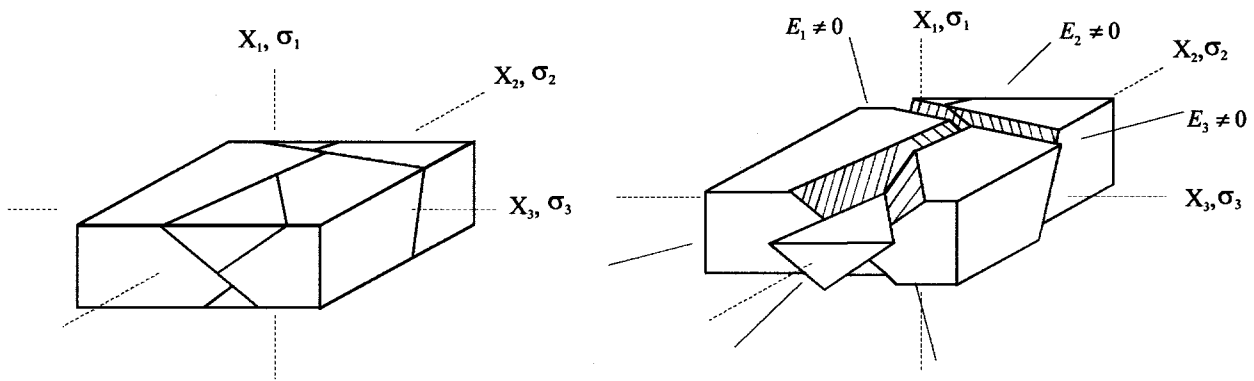


Fig. 4. Sliding along three or more preexisting interacting planes can produce, in the more general case, three-dimensional rotational strain. Slickenlines show different orientations non-parallel to the shear stresses on the planes (Nieto-Samaniego and Alaniz-Alvarez, 1997). Note that the stress tensor symmetry is not reflected in the final configuration of the fault pattern.

where D_{ij} is the general deformation tensor, a_{ik} and a_{jl} the direction cosines between the local and general reference frame and d_{kl} the local tensor of deformation produced by the n th shear system.

According to Eq. (3) any deformation field imposed by the boundary conditions can be accommodated by a combination of faults. The restrictions of the model come from mechanical considerations such as minimizing shear during deformation (e.g. Reches, 1978) and from geometrical relationships of preexisting faults (Nieto-Samaniego and Alaniz-Alvarez, 1997).

Assuming homogeneous bodies and that preferred planes of sliding are those that minimize the total shear (Reches, 1978) or maximize the work done (Johnson, 1995), the formation of a four-fault pattern in bi-conjugate geometry is predicted (Fig. 3). Complex fault patterns are predicted by considering preexisting planes of weakness prone to sliding before fracture occurs (Fig. 4). If there is kinematic interaction between planes, the assumption of fault independence is not satisfied (Nieto-Samaniego and Alaniz-Alvarez, 1997). Complex fault patterns have no restrictions with respect to the number of fault sets or to their symmetry.

Reactivation is commonly observed in nature, owing to the presence of preexisting planes of weakness such as faults, foliations, contacts, bedding, etc. Sliding along faults weakened during the faulting process is much easier. A major weakened fault in an advanced stage of growth slides under many stress fields, including those unfavorably oriented (e.g. Alaniz-Alvarez et al., 1998).

A fundamental implication is that, considering the boundary conditions set by the deformation field, the number of faults that accommodate the deformation is highly dependent on the number and orientation of preexisting planes of weakness. This dependence prevents the calculation of a unique solution of the total

strain tensor because not all the faults are known. Moreover, the kinematic interactions do not permit inverting fault-slip data to determine a paleostress tensor (Fig. 4).

4. How to analyse fault patterns for strain estimation?

To determine the strains in faulted zones, we start recognizing the type of fault pattern observed from four existing possibilities (Nieto-Samaniego and Alaniz-Alvarez, 1997):

Case 1. Coulomb patterns consist of two sets of faults in conjugate arrangement, produce two-dimensional non-rotational strain (Fig. 2).

Case 2. Isolated-fault patterns are formed by one or more preexisting planes, reactivated according to the model of Bott (1959). These patterns can produce two- or three-dimensional rotational strain. It can be recognized because there are no slickenlines parallel to fault intersections (Fig. 1).

Case 3. Orthorhombic four-fault patterns are formed by four sets of faults with orthorhombic symmetry forming rhombic arrangements in map view. These patterns produce three-dimensional non-rotational strain, and obey the slip model of Reches (1978) (Fig. 3).

Case 4. Complex fault patterns have no restrictions in either, the number of fault sets or symmetry; they produce two-dimensional or three-dimensional, rotational or non-rotational strain and obey the interacting block model proposed by Nieto-Samaniego and Alaniz-Alvarez (1997). This pattern can be recognized because there are slickenlines parallel to the fault intersections (Fig. 4).

For Cases 1 and 3 above, it is possible to determine the principal strain orientations using the technique

proposed by Krantz (1988). In Case 2, the transport direction can be roughly approximated by the horizontal maximum and minimum stresses in some cases. Horizontal principal stresses can be obtained using fault-slip inversion methods (e.g. Angelier, 1994), but careful analysis is needed.

In Case 4, the asymmetry and the rotational components of strain preclude determining the direction of principal horizontal strains using the strike of faults. Also, the slip vectors are not necessarily the solution of the far-field stress on the plane. Thus, it is not possible to calculate a paleostress tensor. The directions of principal strains can be determined by sampling all the faults and summing local deformations as indicated by Eq. (3). But, of course, this approach is unrealistic. The assumption that most of the strain is accommodated by sliding along major faults remains the better approximation. An estimation of the direction of maximum horizontal strain could be obtained from the displacements in major faults, preferentially obtained from displacement of stratigraphic units. In some cases, the orientation of principal elongations could be inferred from regional tectonics and the magnitudes by indirect methods such as some section balancing models (e.g. Groshong, 1994) or by crustal thickness data. In the case of complex fault patterns, this information leads to the possibility of analyzing the fault system starting from strain boundary conditions and calculating the kinematics of measured faults. The weak point in this proposed scheme is the lack of a kinematic model that permits determination of the orientation of slip vectors considering the reactivation of preexisting planes, the generation of new faults and the interactions among them. Thus, only a rough approximation can be obtained.

If a reasonable approximation of principal strain directions is obtained, the strain accommodated by minor faults remains an unsolved problem. Probably the strain calculated using major faults will be an underestimation because minor faults could accommodate much of the deformation (e.g. Marrett and Allmendinger, 1992).

The interpretation of minor faults is a major problem. They cannot be mapped because either direct observation is not possible, or it requires field work at a larger scale, including in some cases spanning several orders of magnitude of size. The most promising way to get high confidence extrapolations comes from fractal analysis. The more complete description of a fracture pattern as well as the length–displacement distribution in a fault population is a fractal (e.g. King, 1983; Hang and Turcotte, 1990).

In a fault–displacement population, the number of faults and the magnitude of displacements follows a power-law distribution (e.g. Scholtz and Cowie, 1990; Walsh et al., 1991). In a crustal block, the increment

in length produced by all minor faults can be obtained by extrapolating the power-law distribution of the measured faults (Marrett and Allmendinger, 1992). The amount of strain accommodated by unseen faults depends on the number of faults measured (major faults) and the fractal dimension.

5. Conclusions

Faulting produced by fracture is restricted to plane strain if it is considered a stress-controlled process. In this way, a single set of faults, or conjugate sets of faults is predicted. Faulting as a strain-controlled process permits analysis of three-dimensional strain forming four-sets of faults in orthorhombic symmetry. To develop a fault pattern without restrictions in the number of fault-sets or symmetry it is necessary to consider in addition to rupture, the slip along preexisting planes of weakness.

It is essential to identify the type of mapped fault pattern to analyze it adequately. If the pattern is a Coulomb or orthorhombic pattern the use of the odd-axis model (Krantz, 1988) is useful to calculate the directions of horizontal maximum strains. For isolated fault patterns, horizontal maximum strains can be approximated in some cases using paleostress calculations. In complex fault patterns, it is not yet possible to calculate the horizontal maximum strains or paleostress tensor from fault data.

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References

- Alaniz-Alvarez, S.A., Nieto-Samaniego, A.F., Tolson, G., 1998. A graphical technique to predict slip along a preexisting plane of weakness. *Engineering Geology* 49, 53–60.
- Anderson, E.M., 1951. *The Dynamics of Faulting*, 2nd ed. Oliver & Boyd, Edinburgh.
- Angelier, J., 1994. Fault slip analysis and paleostress reconstruction. In: Hancock, P.L. (Ed.), *Continental Deformation*. Pergamon Press, Oxford, pp. 53–100.
- Bott, M.H.P., 1959. The mechanics of oblique slip faulting. *Geological Magazine* 96, 109–117.
- Brace, W.F., Bombolakis, E.G., 1963. A note on brittle crack growth in compression. *Journal of Geophysical Research* 68, 3709–3713.
- Groshong, R.H., 1994. Area balance, depth of detachment, and strain in extension. *Tectonics* 13, 1488–1497.

- Hang, J., Turcotte, D.L., 1990. Evidence for chaotic fault interactions in the seismicity of the San Andreas fault and Nakai trough. *Nature* 348, 234–236.
- Jaeger, J.C., Cook, N.G.W., 1969. *Fundamentals of Rock Mechanics*. Methuen, London.
- Johnson, A.M., 1995. Orientations of faults determined by premonitory shear zones. *Tectonophysics* 247, 161–238.
- King, G., 1983. The accommodation of large strains in the upper lithosphere of Earth and other solids by self-similar fault systems: geometrical origin of b-value. *Pure and Applied Geophysics* 121, 761–815.
- Kostrov, B.V., 1974. Seismic moment and energy of earthquakes, and seismic flow of rock. *Izvestiya of the Academy of Sciences USSR Physics of Solid Earth* 1, 23–44.
- Krantz, R.W., 1988. Multiple fault sets and three-dimensional strain: theory and application. *Journal of Structural Geology* 10, 225–237.
- Marrett, R., Allmendinger, R.W., 1992. Amount of extension on “small” faults: An example from the Viking graben. *Geology* 20, 47–50.
- Nemat-Nasser, S., Horii, H., 1982. Compression-induced nonplanar crack extension with application to splitting, exfoliation and rockburst. *Journal of Geophysical Research* 87, 6805–6821.
- Nieto-Samaniego, A.F., Alaniz-Alvarez, S.A., 1997. Origin and tectonic interpretation of multiple fault patterns. *Tectonophysics* 270, 197–206.
- Oertel, G., 1965. The mechanism of faulting in clay experiments. *Tectonophysics* 2, 343–393.
- Ramsay, J.G., 1967. *Folding and Fracturing of Rocks*. McGraw-Hill, New York.
- Reches, Z., 1978. Analysis of faulting in three-dimensional strain field. *Tectonophysics* 47, 109–129.
- Scholtz, C.H., Cowie, P.A., 1990. Determination of total strain from faulting using slip measurements. *Nature* 346, 837–839.
- Segall, P., Pollard, D.D., 1980. Mechanics of discontinuous faults. *Journal of Geophysical Research* 85, 4337–4350.
- Taylor, G.I., 1938. Plastic strain in metals. *Journal of the Institute of Metals* 62, 307–328.
- Wallace, R.E., 1951. Geometry of shearing stress and relation to faulting. *Journal of Geology* 59, 118–130.
- Walsh, J., Watterson, J., Yielding, G., 1991. The importance of small-scale faulting in regional extension. *Nature* 351, 391–393.