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Homogeneous stress hypothesis and actual fault slip: a distinct element analysis

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Abstract—The different inverse methods used in slip data analysis depend on the general validity of the mechanical model adopted by Carey and Brunier, and others. The mechanical scheme is based on the Wallace–Bott relationship assuming a faulted rock mass as a system of rigid blocks interacting mechanically without friction. Until now the validity of this conceptual model was supported by internally consistent results obtained by applying numerical inversion techniques to fault slip data. This paper presents the first results of a numerical modelling investigation of this simple mechanical model by a direct approach to the problem. The numerical method used here is a three-dimensional Distinct Element Method which is suitable to study discontinuous media. First, by modelling the behaviour of one fault, we propose an extrinsic verification of the Wallace–Bott relation in three dimensions and considering rock linear elasticity and friction effects on faults. According to the small discrepancy obtained (i.e. the deviation between the modelling results and the theoretical results), we conclude that the assumptions of the basic model are justified in the range of stress values that we study. Second, using a two-fault model, the effects of overlap in stress perturbations around the faults results in particular fault slip interactions. The existence of such phenomena invalidates, in a generally minor way taking into account practical uncertainties, the assumption of fault slip independence in the basic model. Finally, we discuss limits to inverse methodologies and the necessity for interactions between data collection, interpretation of these data and the ability of the basic model to be used in microtectonic analyses.

INTRODUCTION

DURING the last 20 years, several numerical methods have been developed in order to solve the inverse problem in which a mean reduced stress tensor is determined by using fault slip data sets. The inverse problem was first formulated and solved by Carey & Brunier (1974) using the Wallace–Bott assumption (Wallace 1951, Bott 1959). In the original theoretical model, the behaviour of a discontinuous (faulted or fractured) rock mass was assumed to consist of body movements of rigid blocks, assuming small displacement and rotation. Friction on faults was not considered at this early stage because observation of striated faults or fractures implies that slip had actually occurred.

Up to now, several numerical methods have been used to analyse sets of fault slip data, but since all refer to the mechanical model defined by Carey & Brunier (1974), all are similar from a physical point of view. Attempts to introduce more realistic conditions have been done in terms of friction-failure criteria and lithostatic–hydrostatic pressure in several ways (Sassi 1985, Reches 1987, Sassi & Carey-Gailhardis 1987, Angelier 1989).

Using numerical methods, numerous studies have been performed to characterize palaeostress fields. None of these studies suggested that deviations between theoretical and actual stresses may be statistically significant in sites where numerous faults were measured. This explains in part why there has been no explicit verification by brittle deformation modelling of how a fractured rock mass actually behaves when discontinuities interact.

However, there is a difference between the actual shear on a fault plane and the shear computed on the same plane according to the Wallace–Bott model. This difference has never been examined by any means, experimental or numerical. In fact, few attempts to investigate theoretically the validity of this basic mechanical model of deformation, which is an extreme simplification of the problem, were done because practical results showed that these deviations always remain statistically small as most users pointed out. Considering the difficulty of such a problem (the analytical solution cannot be derived easily) and its dependence on many parameters, numerical modelling is the best approach that can be used. Several existing numerical methods could be envisaged to solve this problem (e.g. based on finite element or finite difference scheme). In the present paper, the Distinct Element Code developed by P. A. Cundall (Cundall 1988) has been employed because the method is well adapted to study rock masses as discontinuous media with brittle behaviour.

We have modelled the directions of displacements on (a) one and (b) several fault planes and compared our results with the theoretical solution given by the Wallace–Bott relation. The purpose of this study is to highlight possible discrepancies between the conceptual model adopted by Carey & Brunier (1974) and a more realistic representation of the behaviour of a faulted rock mass. Thus, we discuss the principles and application of modelling as they relate to the previously defined scientific objectives. The patterns of surface displacements obtained on one and several fault planes resulting from triaxial loading have been calculated. These results validate in a quantitative way the application of the Carey & Brunier's mechanical assumptions.

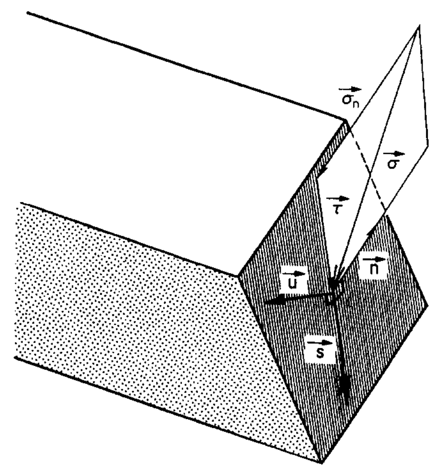

Fig. 1. Fault plane and stress state: the Wallace–Bott relationship for fault slip data analysis. Stress on the fault plane (σ) includes two components, the normal stress (σ_n) and the shear stress (τ); the slip direction 's' (lineations on fault plane) is assumed to be parallel with the shear stress direction (τ) with the same sense. **n**, vector of unit length normal to fault plane; **s**, vector of striae on the fault plane; **u**, **n** $\wedge$ **s**.

FAULT ANALYSIS IN TECTONIC STUDIES

In brittle deformation, any procedure of mechanical or kinematic analysis is based on a conceptual model of mechanical behaviour. The simplified scheme discussed by Wallace (1951) and Bott (1959) resulted in the first successful attempt to formulate the inverse problem (Carey & Brunier 1974).

Inverse procedures in brittle tectonics

According to Carey & Brunier (1974), a site of microtectonic measurements could be regarded as a fractured rock mass containing planes of discontinuities with variable orientations and distribution. The total deformation at the site is the summation of finite small displacements by slip on the planes of discontinuity. Moreover, the behaviour of the fractured rock mass is described by the following hypothesis: considering the properties of block materials and faults, each block has a rigid behaviour and friction is not taken into account. Implicitly, the faults are planar and have infinite dimensions. Considering the kinematic laws, displacements on different faults are small and independent. A single homogeneous tectonic stress field is considered responsible for the displacement on faults. Following Bott (1959), the basic assumption to relate stress and slip is: "the direction of a striae on a fault represents the direction of the tangential stress applied to this plane" (Fig. 1).

Several methods of palaeostress reconstruction using fault slip data sets have been developed and improved by many authors. They may consist of graphic determinations (Anderson 1951, Arthaud 1969, Angelier & Mechler 1977, Vergely *et al.* 1987) or involve numerical inverse techniques (Carey & Brunier 1974, Carey 1976, Etchecopar *et al.* 1981, Angelier 1983, 1984, Gephart & Forsyth 1984, Michael 1984, Reches 1987). These methods have been applied to several scales of structural problems such as in the European platform (Letouzey & Trémolières 1980, Letouzey 1986, Bergerat 1987).

The common aim of these methods is to characterize the average reduced stress tensor that could explain the slip directions observed on faults in a tectonic site. The reduced stress tensor is defined by the orientation of the principal stress vectors σ_1, σ_2 and σ_3, and by their relative magnitudes given by commonly adopted stress ratios such as $R = (\sigma_2 - \sigma_1)/(\sigma_3 - \sigma_1)$ with $\sigma_3 > \sigma_2 > \sigma_1$ (tension positive) or $\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ with $\sigma_1 > \sigma_2 > \sigma_3$ (compression positive). Note that $R = 1 - \Phi$. Note also that a different definition of R was given by Etchecopar *et al.* (1981); using that definition, R and Φ are equivalent. A more complete discussion of stress ratio definitions can be found in Angelier (1989). In this paper, we shall adopt the ratio $(\sigma_2 - \sigma_1)/(\sigma_3 - \sigma_1)$ with $\sigma_3 > \sigma_2 > \sigma_1$, tension positive, and name it R.

The analysis of fault slip data is in general both self-consistent and coherent in terms of compatibility with other stress data such as palaeostress directions inferred from stylolites and tension gash measurements (Arthaud & Mattauer 1969), joints (e.g. Bouroz 1990) or analysis of calcite tectonic twins (e.g. Lacombe *et al.* 1990). Consequently, until now, the consistency between these different kinds of data brought an implicit validation to the basic mechanical scheme. These consistencies should be considered 'internal'. An independent check is still needed, which is the aim of this paper.

Direct procedures in brittle tectonics

Wallace and Bott proposed an explicit relationship between stresses and slip. Holding the orientations of the stress principal directions constant, there is a specific relationship between the stress ratio (R) and the direction and sense of the shear on a given fault plane (with the assumptions listed above). Furthermore, an analysis of these variations with R (Sassi 1985, Vergely *et al.* 1987) showed that the theoretical striae (orientation and sense of slip of the maximum shear stress) for different stress states (e.g. $R = 0.5$ and $R = 0.75$, respectively, for the examples of extensional and strike-slip stress systems) obeys certain geometrical rules, such as the systematic clustering of the slip directions for particular set of planes (Fig. 2).

The modelling objects

We previously emphasized the internal consistency of the inverse methods in fault slip analysis. These methods are concerned with small slips in the absence of rotation. Others have derived methods that apply to the case of polyphase tectonics (Angelier & Manoussis 1980, Etchecopar *et al.* 1981, Armijo *et al.* 1982, Angelier 1984). Here this aspect of the problem is not included, and our discussion is limited to single phase tectonism with synchronous fault slips.

In order to obtain a mechanical scheme with an extrinsic validation procedure, we have undertaken numerical modelling using the Distinct Element Method. This provides the opportunity to check the hypothesis of Carey & Brunier's (1974) model. The objectives of this work include:

(1) the modelling of fault slips in order to estimate the validity of Wallace–Bott relations and to characterize the displacement field on fault.

(2) the interactions between two or several faults either with variable distances between them or with intersections. How different will be the displacement field on each fault? In other words, is the assumption of independent slip valid in all cases? If this assumption is not valid, can the effects of such interactions be estimated?

We describe first three-dimensional modelling of a single fault with finite geometrical extent. This first step will also constitute a test of the Distinct Element Method accuracy for such problems. Second, we examined a two-fault model to estimate the degree of independence for several faults. In this study, the influence of rheological parameters such as friction is considered and the intact material follows an elastic isotropic behaviour.

MODELLING METHODOLOGY

The results of a numerical modelling scheme must fit the variety and the quality of the data effectively available. Starfield & Cundall (1988) have discussed the methodology of using numerical methods in geomechanics, and they infer that a modelling process must include: first, modelling investigations to define fundamental parameters of the system for more complex cases; second, the basic notion that computer solves problems with the same quality as the quality of the data the user enters in it.

The Distinct Element Method

The Distinct Element Method ('DEM') is a numerical method in geomechanics that enables one to simulate the mechanical response of systems composed of discrete blocks. Detailed description of the numerical schemes have already been published by many authors (Cundall 1971, 1988, Hart *et al.* 1988, Harper & Last 1990). The description of the TRIDEC computer program used in this study is beyond the scope of this paper. The DEM is based on a time marching integration scheme using central finite difference. It is an explicit method in which the equations of dynamics (e.g. Newton's second law for rigid block motion) are integrated over time. With the DEM, a rock mass consists of a system of discrete blocks in mechanical interaction at their boundaries (Fig. 3). Blocks may behave as deform-

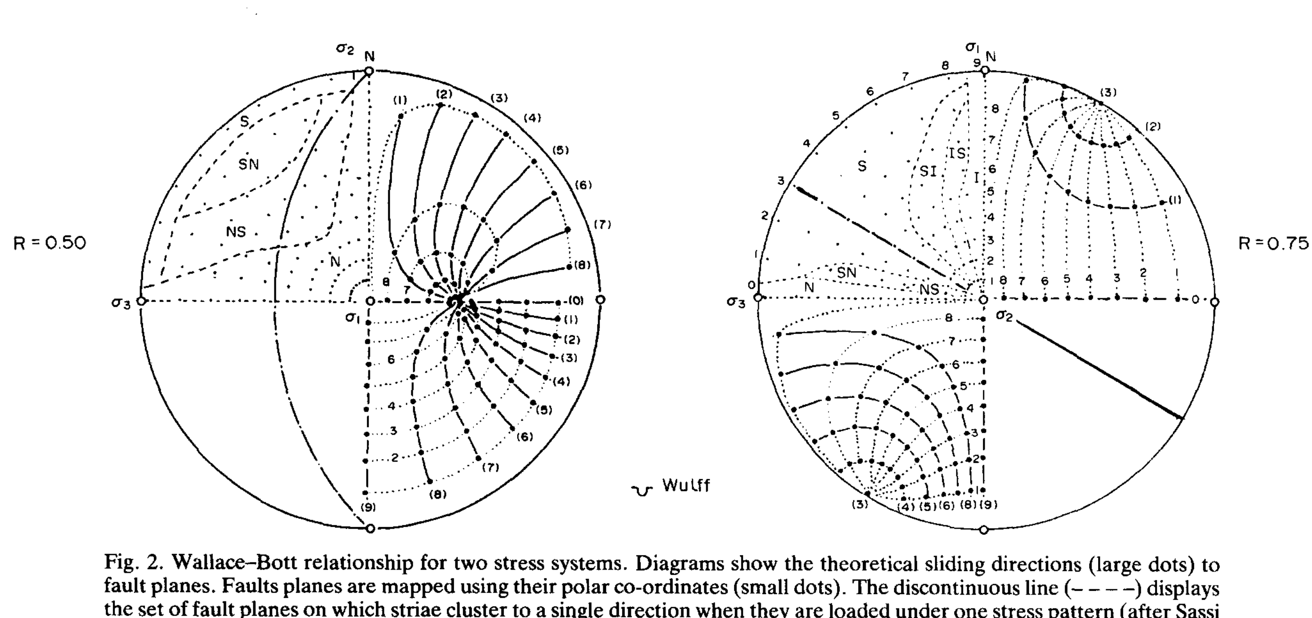

Fig. 2. Wallace–Bott relationship for two stress systems. Diagrams show the theoretical sliding directions (large dots) to fault planes. Faults planes are mapped using their polar co-ordinates (small dots). The discontinuous line (– – – –) displays the set of fault planes on which striae cluster to a single direction when they are loaded under one stress pattern (after Sassi 1985). (a) E–W extensional stress system with $R = 0.5$; (b) strike-slip stress system with $R = 0.75$.

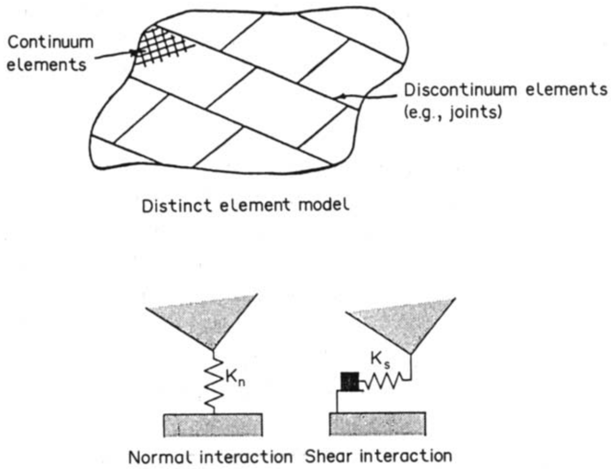

Fig. 3. Basic scheme of the Distinct Element Method. (a) Nature of distinct element model; (b) mechanical representation of interfaces in the Distinct Element Method (after Cundall *et al.* 1987).

able elastic bodies. Block interactions are computed assuming finite stiffness at contact points along the interface between blocks. The contact forces applied to rigid blocks or discrete particles (in the case of deformable blocks, a finite difference grid with mass points at vertices of tetrahedra) are given by the elastic response at contact points (stiffnesses both in normal and tangential direction are defined as properties of the contacts) which are evaluated after each integration cycle over the time step. Opening or shear displacement (sliding) along block interfaces occurs when the normal and the shear forces (or stresses) meet conditions for tensile or shear failure, respectively. The shear strength is defined by a Mohr–Coulomb failure criterion, which requires definition of the angle of sliding friction and a cohesion as joint properties.

Modelling methodology

With any numerical method of geomechanics, modelling requires the definition of the problem geometry, then the definition of the material properties (parameters and rheological behaviour) and finally the *in situ* and boundary conditions. In this study, a number of fault block models have been constructed. Our first type of models consists of a single faulted block, i.e. a medium in which one has defined one plane of discontinuity (a joint with frictional resistance to slip). Our second and third model types are blocks with two faults that intersect or not. Figure 4 shows an example of a one fault-block model, with different perspective views. In this figure, the mesh inside the blocks is made up by tetrahedra. Some blocks have been hidden to display the internal structure of blocks at the location of the surface of failure.

Table 1 gives the elastic parameters of the continuum as well as the interface properties. The fault (surface of potential failure) follows a Mohr–Coulomb failure criterion for sliding friction. The blocks are glued together everywhere except along a square planar area that will be the slip surface. Therefore the faults in these series of models have finite dimensions, and we expect some distortions in the displacement field near the fault boundary. Our purpose is to determine the displacement induced on fault surface in the case of a well-defined far-field stress system. Different fault geometries have been considered, corresponding to our knowledge of their theoretical behaviour when they are submitted to a particular average stress tensor (Fig. 2). Stress fields are presented in Table 2.

The problem solved is the following. First, blocks are pre-stressed according to a given stress state defined in Table 2; at this stage the response is purely elastic and

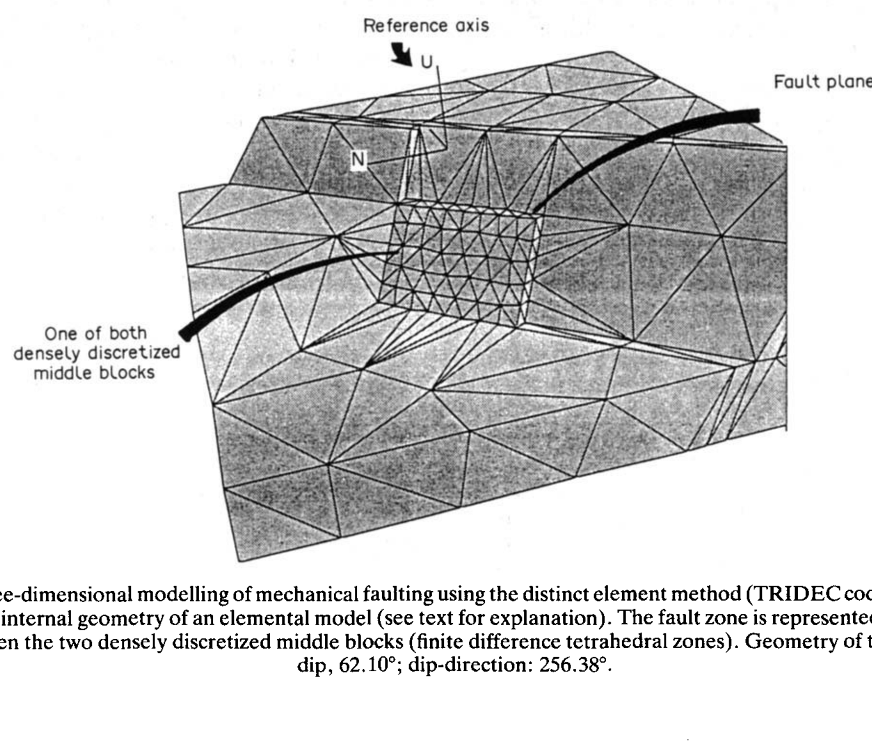

Fig. 4. Three-dimensional modelling of mechanical faulting using the distinct element method (TRIDEC code). Perspective view of the internal geometry of an elemental model (see text for explanation). The fault zone is represented by the contact area between the two densely discretized middle blocks (finite difference tetrahedral zones). Geometry of the model view: dip, 62.10°; dip-direction: 256.38°.

Table 1. Numerical values of the mechanical and rheological parameters adopted in the different models

Parameter	Block material properties	Joint material properties without sliding	Joint material properties with sliding
Density	2500 kg m^{-3}	—	—
Young's modulus, E	60×10^9 Pa	—	—
Poisson ratio, ν	0.25	—	—
Normal stiffness	200×10^9	200×10^9	
Shear stiffness	200×10^9	200×10^9	
Friction coefficient, μ ($\mu = \tau\gamma\phi$, where ϕ: friction angle)	—	100	0.1

the fault is given an infinite strength to sliding. Second, the friction coefficient of fault is set to the standard value in Table 1; the stored elastic energy in the whole body is then partly released by shear failure on the fault planes when they can be reactivated.

MODELLING DISPLACEMENT–STRESS RELATIONSHIP: SLIP DUE TO ANDERSONIAN STRESS STATE

An example of model geometry is shown in Fig. 5(a). It consists of a fault that dips 60° towards the direction 140° submitted to an E–W extensional stress pattern with a stress ratio $R = 0.5$. Note that 'dips' and 'dip directions' are defined in a reference system with one vertical principal stress axis (Andersonian stress state). The result for this case is shown in stereographic projections (Fig. 5b), where it is compared to the theoretical shear stress vector of Wallace–Bott. In order to visualize the variations in the computed shear stress vectors, the computed slips are also displayed on a map of the fault plane (Fig. 5c); each vector is normalized to the magnitude of the maximum vector. Others cases have been considered, some results are mentioned in Table 3. All the results must be examined knowing that an angular difference smaller than about 5° between two slip directions is not significant, such directions should be considered as similar.

Our initial runs were made with a low frictional coefficient of 0.1. We then repeated our runs with severe frictional parameters. However, as expected, only the magnitude of the displacement is modified and not the direction of the vectors. According to these results, we conclude in the case of a finite single fault in a medium of finite dimensions:

(1) finite and infinite dimension analyses yield very consistent results. This leads us to disregard the scale problems for other examples provided that we keep the different parameters we previously defined within a same scale order;

(2) considering slip directions on fault, the model of an independent crack presented herein is consistent with the basic assumptions of Bott. Consequently, our results support the validity for the mechanical model and hence the theoretical basis of the inverse procedures for fault slip data sets analysis. This suggests that the fundamental assumption of the Wallace–Bott relationship, parallelism between shear stress and observed striae, can be used in the numerical inversion techniques;

(3) variation of displacement vectors on fault plane is not significantly perturbed when friction coefficient is changed in a reasonable range of values. We conclude that this frictional parameter does not affect the orientation of slip in the range of stress magnitudes and for the range of friction parameters we observe, although it has an obvious influence on slip magnitude. Considering the magnitude of the displacements on a fault plane (Fig. 5c), some variations occur between the boundary zones and the central zone of the active slip plane. The elliptic distribution of slip displacement magnitudes is due to the finite dimension conditions.

Small variations in slip directions close to the boundaries of the active plane apparently reflect the contrast between elastic behaviour inside the blocks and frictional behaviour along the fault. We observed that the displacements reach their largest values in the centre of the sliding area.

The elastic behaviour of the blocks induces a gradient in the fault displacement. Considering the stress field properties computed through our model, and according to Xiaohan (1983) and Phan Trong Trinh (1989) who carried out finite element modelling on similar problems, we observe stress concentration around the zero displacement boundary of the fault. As the agreement between models and theory is good (Fig. 5b), the stress pattern which induces slip is the regional stress pattern. Stress perturbations close to the fault represent an adaptation of the local stresses to the deformation induced by global stresses. It ensures that stress field homogeneity is an arbitrary notion; its degree of applicability depends on the scaling factor.

These results are products of numerical modelling of information computed for discontinuous rock mass ele-

Table 2. Geometries and shape ratios of the boundaries stress conditions adopted in the different models

Principal stress axes	Azimuth (°)	Inclination (°)	Shape ratio ϕ and stress state nature
σ_1	—	90	
σ_2	000	00	$\phi = 0.5$ and E–W extensional stress state
σ_3	090	00	
σ_1	000	00	
σ_2	—	90	$\phi = 0.25$ and strike-slip stress state
σ_3	090	00	

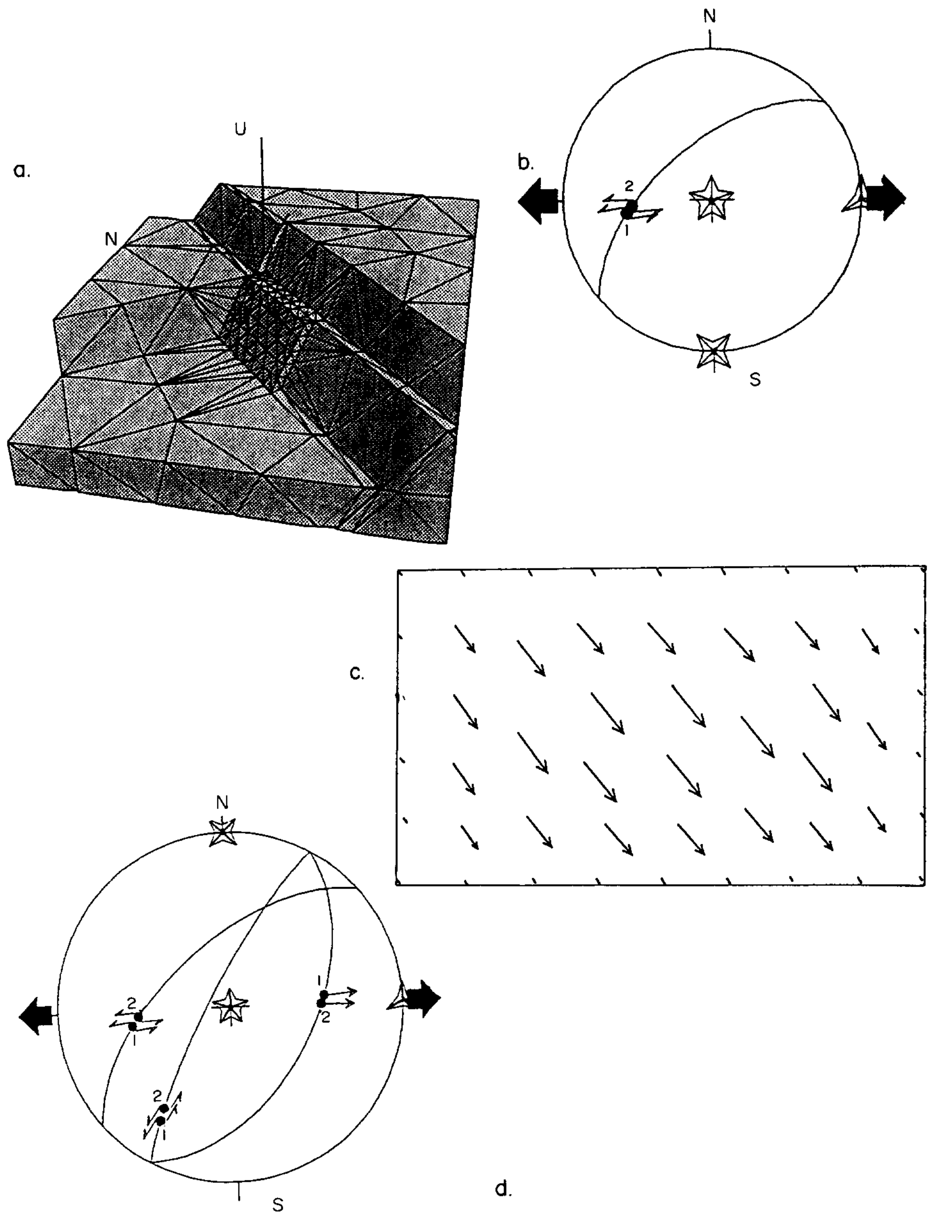

Fig. 5. Modelling of the displacement–stress relationship. (a) Sectional view of the model: fault plane (with small elements) corresponds to the common area of both parallelepipeds in the middle of the model; a N050 60NW fault as a case example. (b) Stereographic plot with stress tensor, Wallace–Bott model (MWB) slip (2) and Distinct Element Model (MED) slip (1) on the fault plane. (c) Slip distribution on the fault plane. (d) Same as (a), but shows other calculations given in Table 2. Stress plots: σ_1; σ_2; σ_3.

Table 3. Results of the displacement–stress relationship modelling. Slip directions on fault planes in models, MED-1, are compared with slip directions inferred from MWB application. (a) Extensional stress state conditions (presented in Fig. 5); (b) strike-slip stress conditions (see Table 2 for numerical values of stress state)

Model reference	Geometry of fault plane	Wallace–Bott slip direction on the fault plane: MWB (2)	Modelling slip direction on the fault plane: MED-1 (1)	Difference: MWB − MED-1	Maximum value of shear displacement on the fault plane
(a)					
Tens 14	N050 60NW	56W	51W	5	1.66×10^{-3}
Tens 15	N030 80NW	32W	25W	7	1.16×10^{-3}
Tens 16	N030 50NW	70W	66W	4	2.35×10^{-3}
(b)					
Dec 15	N030 90	0	0	0	1.37×10^{-3}
Dec 16	N030 40NW	0	5W	5	1.28×10^{-3}
Dec 17	N010 30NW	48W	43W	5	6.28×10^{-4}
Dec 18	N010 80NW	12W	8W	4	6.57×10^{-4}

ments. This is quite different from the basic mechanical model that we check, in which the mechanical behaviour of the rock mass is considered homogeneous although discontinuities are present. Considering this major difference, the deviation observed between computed Distinct Element Model and Bott's model is remarkably small. This comparison provides the first explicit demonstration of Bott's model consistency. As pointed out before, previous demonstrations were empirical. Moreover these results constitute an interactive test to check the accuracy of the method we use in resolving such problem.

MECHANICAL AND KINEMATIC INTERACTION BETWEEN FAULTS

We also analysed the possibility of significant changes in fault slip as a result of local stress perturbations for a pair of faults. This analysis allows verification of the slip independence hypothesis adopted by Carey & Brunier (1974), in the case of a simple system with two synchronous fault slips.

Modelling scheme modifications

The procedure for the two-fault model is similar to the previous analysis in terms of active area size. The size of the faults has been chosen such as to avoid any edge effects. The location of the second fault is always symmetrical to the first one, with respect to the geometric centre of the model. An extensional stress pattern is simulated (Table 2), whose characteristics are the same as those for the one-fault case. The material mechanical properties of this model are also the same as those in the one-fault model. The orientation of the faults are: (1) N030 50SE and N050 60NW; and (2) N030 50NW and N030 80SE. Many other patterns have been used, but these are not described herein because they led us to the same conclusions.

For each pair of faults, two cases will be considered: (1) the active area of the two faults do not intersect in the model; and (2) these active areas intersect, and the intersection line contains the centre of the model. In cases where faults intersect, each plane has been divided by their common line into two smaller fault elements.

Modelling specific results

The modelling results are presented in Figs. 6 and 7 for the first pair of faults (stereographic projections and map of slip vectors in the fault plane as before), and in Table 4 for both cases. Comparison between Figs. 5 and 6 or 7 and between Tables 3 and 4 enables one to compare computed results of the single fault 'MED-1' and two fault models 'MED-2'. These figures and tables also include the theoretical results obtained with the Bott's simple model 'MWB'.

Let us examine the case of the N050 60NW and N030 50SE fault planes shown in Figs. 6 and 7. The first model presents a rock volume crossed by two faults that do not intersect. The slip directions are very homogeneous (Fig. 6c), that is no significant variation occurs within the range of acceptable errors defined before. The average slip vectors are also similar to the one-fault model result, and they also fit Bott's theoretical model within the range of acceptable errors.

Let us consider now the example of Fig. 7, where the two fault planes intersect at the centre of their respective slip areas. We first observe that slip vectors are now heterogeneous in direction on the individual fault planes (Fig. 7c). In other words, variations in slip directions occur within a given fault active area. As a consequence, local conformity with the Bott's model may be poor, i.e. only within 30° in some locations in the fault plane. The N030 50SE plane (plane B) displays variations in slip directions as large as 23° (Table 4). Notably, variations occur in a rather continuous way and the largest variations occur close to the boundaries of the active slip area. Moreover, slip directions which widely differ from the mean value are scarce.

In contrast, the N050 60NW fault plane of the same model (plane A) displays a double set of variations in slip directions on both sides of the fault intersection (Fig. 7c). The perturbations of shear stress or displacement vectors are larger and more important near the fault intersection. We point out that there is a striking contrast in fault behaviour. One of the two fault planes, that is the N050 60NW plane, undergoes more perturbations and larger ones, whereas the other fault shows little slip dispersion. We conclude that in the first case (Fig. 6) the slip displacements on the two faults may be considered stable and independent whereas in the second case, significant slip deviation occurs due to fault slip interactions. The distribution of slip deviations between the two planes is quite asymmetrical. One fault remains more stable in terms of slip direction vector than the other one.

As a consequence of this second experiment, the hypothesis of independent slip displacements which is the one of the most important bases of Carey & Brunier's (1974) theoretical model, needs particular comments as follows:

(1) when fault planes do not intersect, and when their distance is beyond the effect of stress perturbation, slips on each fault occur in directions and magnitudes very similar to those independently determined based on the single fault case. They are also similar to the results directly computed by applying the Wallace–Bott simple model. In this case, the independence hypothesis is verified;

(2) where fault planes intersect (or are close to each other), slip directions may exhibit significant variations within a fault plane. However, the average slip vector remains similar to that predicted by the Wallace–Bott model and to that obtained with the single fault modelling experiment. Where active planes do not intersect but are not located far away, continuous variation in directions commonly occur throughout each plane.

Such continuous variations are also present in the case of intersecting fault planes, provided that one considers the two portions of fault surface on both side of intersection line instead of the whole surface. In other words, discontinuous change occurs along this line. This discontinuity and its vicinity correspond to the largest variations: this line may be considered as an actual failure in slip mechanics. Note, however, that there is always a region, generally around the central segment of this intersection line, where change in slip vectors of both sides occurs continuously (Figs. 6c and 7c). In this particular region, the slip is parallel to the average slip direction of the total active fault area and consequently can be considered representative with respect to the Wallace–Bott model. Summarizing, in cases of fault intersection, two gradients of slip vector reorientation are present; the first one corresponds to the gradient in each portion of fault induced by the difference of behaviour between the boundaries and the centre of the fault. The other gradient occurs along the intersection line, and it is actually induced by kinematic interactions between fault movements.

DISCUSSION

First, our single fault experiments allow for the first time extrinsic justification of the assumptions of the Wallace–Bott mechanical scheme with a three-dimensional DEM study.

Second, the perturbations that we have observed provide evidence for the existence of kinematic interactions between different fault planes in a single rock volume subjected to a single tectonic stress pattern and at one time. The distance between the planes on which such interactions are induced depends upon whether the zones of local stress concentration near the faults overlap (previous subsection). Where different faults are present in a single rock volume, kinematic interactions may occur. For the pairs of fault slips that we have studied, we observe that in both cases (Fig. 7 and Table 4) one plane is always more affected by those perturbations that the other. It allows us to define a criterion about preferential fault planes' geometry with respect to the homogeneity of slip on them. For a given stress

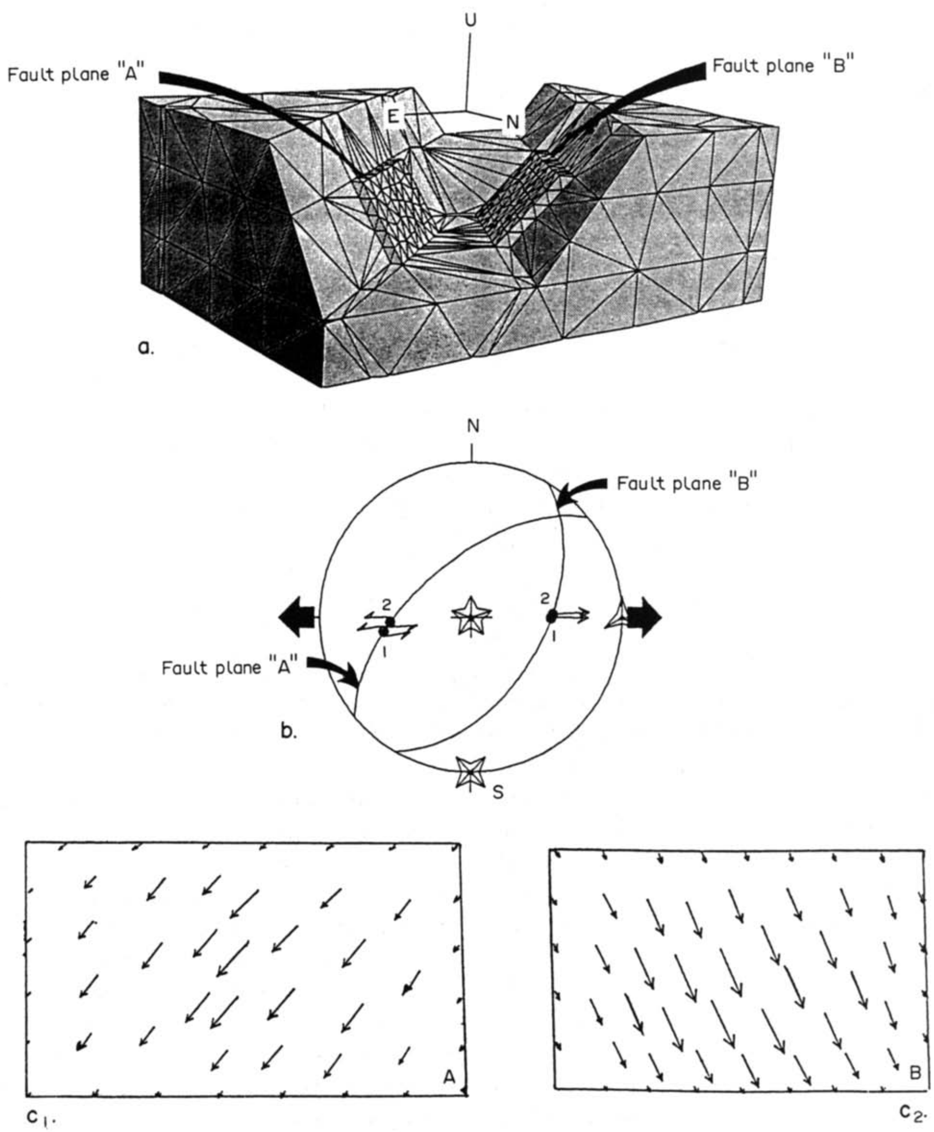

Fig. 6. A two-fault model without fault intersection: N050 60NW and N030 50SE fault planes as a case example. (a) Sectional view of the model; (A) N050 60NW fault plane; (B) N030 50SE fault plane. (b) Stereographic plot with stress tensor, MWB slip (2) and MED slip (1) on the fault planes. (c) Slip distribution on the N050 60NW fault plane. (c) Slip distribution on the N030 50SE fault plane.

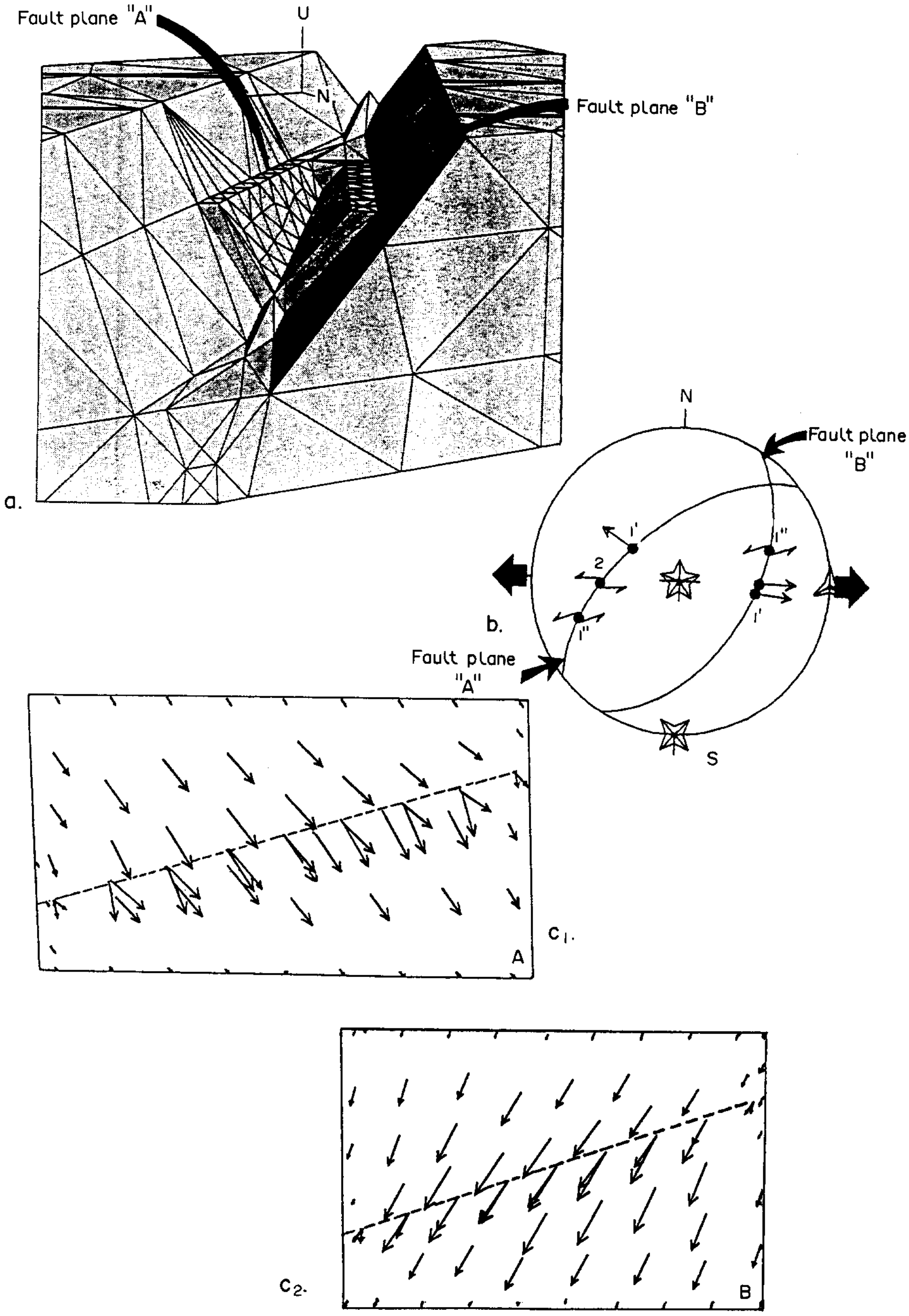

Fig. 7. Model of mechanical and kinematic interaction between intersecting faults, with N050 60NW and N030 50SE fault planes as a case example. (a) Sectional view of the model; (A) N050 60NW fault plane; (B) N030 50SE fault plane. (b) Stereographic plot with stress tensor, MWB slip (2), MED slip and its variation on each fault plane (1′−1″). (c_1) Slip distribution on the N050 60NW fault plane. (c_2) Slip distribution on the N030 50SE fault plane.

pattern, the 'master' fault (more stable than the other) is the fault which has the best orientation with respect to the stress axis and the failure criterion, in other words the plane which is easier to be reactivated. For example, under the stress regime of Fig. 7, a N030 50SE fault plane is more stable than a N050 60NW one because the difference between the geometrical pattern and the stress pattern on the latter is more significant than for the former.

In the case of a two-fault system, fault slip will follow the Bott's relationship in any situation except where stress perturbations associated with faults overlap. Our models indicate that when faults interact, the average slip vector is close to the theoretical value (computed using the Wallace–Bott simple model). The mean slip direction, generally located in the center of the active fault area, is the best fit of the tangential stress applied to this fault. Also, it represents the best value on the active slip area from which to compute tectonic palaeostresses with inverse methods. Considering that data are more consistent with the theoretical slip direction according to the Wallace–Bott model near the central zone of a fault plane than near its extremities, we should consider in theory a larger number of data in this area to get good numerical results. As it is difficult in reality (except perhaps in quarries or mines) to visualize the different parts of a fault plane in three dimensions, we may consider that an analysis based on numerous data helps

Table 4. Results of the fault interaction modelling. Average slip directions on fault planes in models, MED-2, are compared with slip direction on one-fault models, MED-1, and with slip directions infered from MWB application. The variability of slip directions in these two-faults cases has been displayed

Geometry of fault planes	Wallace–Bott slip direction on the fault plane: MWB	Modelling slip direction in the one-fault model: MED-1	Average slip direction in the two-fault model: MED-2	Gap of variability in modellized slip directions	Difference: MWB − MED-2
		Without fault plane intersection			
N050 60NW	56W	51W	50W	0	6
×					
N030 50SE	70E	66E	68E	0	2
N030 50NW	70W	66W	66W	0	4
×					
N030 80SE	32E	25E	35E	(20, 35) − 15	3
		With fault plane intersection			
N050 60NW	56W	51W	50W	(34, 81) − 47	(0, 18)
×					
N030 50SE	70E	66E	58E	(52, 75) − 23	(0, 25)
N030 50NW	70W	66W	70W	(60, 84) − 24	(0, 14)
×					
N030 50SE	32E	25E	30E	(20, 66) − 46	(0, 34)

to limit the influence of eventual disturbed slip vectors in the inverse procedure.

This modelling did not take into account deformation mechanisms as pressure solution (Mercier personal communication, 1990). This kind of slow deformation mechanism would probably reduce the importance of interactions effects and consequently increase in this case the consistency of Carey & Brunier's (1974) mechanical scheme even in complexly faulted tectonic locations. In this case, we could draw inferences from field data. For example, there exists some evidence of pressure solution striae (e.g. in Navacelle, South France) but the geometrical relationships between those planes and their sliding vectors have not been analysed in detail. In a completely opposite situation, where fast deformation occurs as for the seismic case example, the results of the present study remain valid considering the DEM characteristics. So, interaction effects are not only dependent on fault geometries but also probably depend on the deformation velocity.

In microtectonic studies, stress states inferred from analyses of fault slip data sets are representative at a scale greater than the typical size of the faults (e.g. Mattauer & Mercier 1980). In other words, the use of Carey & Brunier's (1974) model requires that the medium in which measurements have been collected is seen as homogeneous. Therefore it is better not to mix measurements made on large faults (regional scale) with small-scale fault data for example taken in a quarry (metric to decametric scale).

In practice, the collected data are usually good since the accuracy of measurements is usually within 5°. However, it is not rare to observe variations in the direction of the striae for planes of almost identical orientations, even in areas of single phase tectonics. Such elements in a collection of fault data set may induce some difficulties, such as large apparent discrepancies, in the computed palaeostress states using inverse methods. It is always a puzzling problem for the geologist to identify possible errors in the measurements (i.e. wrong data) with variations that could be related to the actual behaviour of the fractured rock mass.

Here, we have shown that the Wallace–Bott relationship seems validated for rather realistic computer modelling of the mechanical behaviour of such medium. It has been shown that variations in the direction of the displacement vectors can be related to interaction effects between active fault planes closely spaced or intersecting each other. However, the mean value of the pitch on such fault planes is centred on the Wallace–Bott theoretical value. According to these results of modelling, it is recommended to increase the number of measurements as much as possible in the search of a better statistical evaluation of the regional stress state. Following this line, it may seem important to perform numerical inversion of the data set directly in the field, in order to interactively go back to geological observations when necessary.

CONCLUSION

In this paper, we presented and examined the preliminary results by numerical investigation of the Wallace–Bott and Carey–Brunier key assumptions, which provide the basis for all palaeostress tensor determinations using fault slip data and focal mechanisms of earthquakes. We aimed at reconstructing a more realistic model taking into account stress variations with a fractured rock mass, using a three-dimensional Distinct Element numerical method. The main results of this preliminary analysis are as follows. First, we demonstrate that in most practical cases, Wallace–Bott's assumptions are valid as a first approximation. This is confirmed especially where fault spacings are large enough to prevent mechanical interactions. Second, where fault spacings are smaller or faults intersect, which results in significant mechanical and kinematic interactions, our first results suggest that large deviations of shear relative to a given homogeneous far-field stress remain rare. As a result, the simplified model remains valid as a first approximation, provided that data sets are large and include several fault orientations.

We thus confirm, based on a consistent mechanical approach carried out by numerical means, the reliability of fault slip studies which developed following Carey & Brunier's analysis of rigid discontinuous rock mass behaviour. Previously, this reliability was simply suggested by the consistency of the results obtained using these methods. We point out the importance of collecting numerous data, in order to statistically attenuate the local disturbances that would result from mechanical and kinematic interactions between fault slips. We conclude that in a multi-fractured elastic medium loaded under a global stress state, mechanical interactions may influence block movement to a degree which depends on the geometry and the size of faults. Following our preliminary two-fault models, a more systematic exploration of these geometrical effects will be undertaken in order to seek for generalization of the current conclusions of this study.

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