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Slip preference on pre-existing faults: a guide tool for the separation of heterogeneous fault-slip data in extensional stress regimes

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ABSTRACT

Synthetic fault-slip data have been considered in the present paper, in order to examine through a simple graphical manner the validity and use of the widely mentioned and applied criteria such as the slip preference, slip tendency, kinematic (P and T) axes, transport orientation and strain compatibility. The examination and description concern extensional stress regimes whose greatest principal stress axis (σ_1) always remains in vertical position as in Andersonian stress states. In particular, radial extension (RE), radial–pure extension (RE–PE), pure extension (PE), pure extension–transtension (PE–TRN) and transtension (TRN) are examined with the aid of the Win-Tensor stress inversion software. In all of these extensional stress regimes only extensional faults can be activated. The lower dip angle of the reactivated faults is about 40° assuming that the coefficient of friction is no smaller than 0.6. The increase of the stress ratio and/or the fault dip angle up to 70° results in the increase of the slip deviation from the normal activation. Based on the present examination of the slip preference and slip tendency in different extensional stress regimes, a new simple and practical method is proposed herein in order to separate originally heterogeneous fault-slip data into homogeneous fault groups, by which different extensional stress regimes could be determined. The application of the method on the already published fault-slip data of Lemnos Island supports its validity since over 90% the resulted fault groups and stress regimes coincide to the already published ones.

1. Introduction

The classic work of Anderson (1905, 1951) as a first attempt to relate fault geometry and kinematics with Earth's stresses, demonstrated three main types of stress states: (a) extension with conjugate normal faults, (b) strike-slip with conjugate strike-slip faults and (c) compression with conjugate reverse faults. In all these stress states one of the principal stress axes always remains in vertical position and the angle between the greatest principal stress axis (σ_1) and the fault plane equals 30°.

However, after Wallace (1951) who showed that the maximum resolved shear stress (magnitude and orientation) on any surface varies continuously with the orientation of the surface in a stress field, and as a function of the relative magnitudes of the principal stresses, and Bott (1959) who stated explicitly that: "the maximum shearing stress within a . . . plane of fracture . . . may lie in every possible direction for a variable stress system of given orientation . . .", the problem of finding the driving stress regime from the fault-slip data became very complex.

In addition, the introduction of transpression or transtension regimes (Harland, 1971) associated with boundary controlled deformation (Dewey et al., 1998) and the possible resulted strain or slip partitioning on the kinematics of the faults in these regimes question the traditional approaches in deformation zones which follow Anderson (1951) in considering stress to be the main deformation control, particularly in the brittle crust.

Despite the above-mentioned obstacles, Carey and Brunier (1974) firstly addressed this vexing problem with the basic hypothesis, based on the Wallace–Bott criterion (Bott, 1959; Wallace, 1951), i.e., that although the fault planes studied may be of arbitrary orientation, the striae or slickenline accurately indicates the direction of the maximum shear stress. They proposed an algorithm by which the stress inversion from fault-slip data was possible. Since then, numerous methods using fault-slip data or focal mechanisms of earthquakes have been proposed with various approaches (Angelier, 1979, 1984, 1994; Armijo et al., 1982; Carey, 1979; Carey-Gailhardis and Mercier, 1992; Etchecopar et al., 1981; Fry, 1992, 1999; Gephart and Forsyth, 1984; Michael, 1984; Reches, 1987; Yamaji, 2000; Yin and Ranalli, 1993). The majority of these methods assume that the sampled faults slipped independently, but in a homogeneous stress field. These faults should activate with a specific slip preference (SP), i.e. to indicate slickenlines which are in the direction of the maximum shear as imposed by the Wallace–Bott criterion under the different driving stress regimes.

Furthermore, several of these stress inversion methods could work in reverse order, i.e., to define from a certain stress tensor the slip preference on specific fault planes. Nevertheless, very few

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approaches have dealt with the presentation of the slip preference itself. In particular, apart from the effort of Vergely et al. (1987) and the detailed theoretical approach of Célérier (1995) only generalized tangent-lineation diagrams with P and T axes (Twiss and Unruh, 1998) and theoretically predicted patterns of slip directions (Lisle and Srivastava, 2004) have been published, with the latter authors simply mentioning that with progressive increase in the value of stress ratio, R, (where $R=\sigma_2-\sigma_3/\sigma_1-\sigma_3$) from 0.1 to 0.9, the maxima representing lineations with greatest slip tendencies shift from the vicinity to the σ_1 axis toward the σ_3 axis in the $\sigma_1\sigma_3$-plane. More precisely, Célérier (1995), through a detailed theoretical approach, predicted the slip orientations of the differently oriented faults that can reactivate in extensional, wrench and compressional stress regimes. He also defined a geometrical method in a manner similar to Breddin's graph in order to infer the tectonic regime from a fault-slip data set. However, in this procedure he did not take into account the slip tendency for any of these faults, since the latter does not influence their slip orientations.

Another critical issue is that, in the case of heterogeneous fault-slip data, i.e. fault-slip data that have been originated from more than one stress tensor, different approaches are needed to be developed in order to separate them into homogeneous fault-slip data subgroups. In general, the methods to analyze and separate stress tensors from heterogeneous fault-slip data can be roughly grouped into three essential procedures: manual procedures, semiautomatic procedures that minimize a parameter, and automatic procedures based on attributes of faults (see Liesa and Lisle, 2004). The manual procedures are based on graphical representations of the results, which are used to differentiate stress tensors. Some of the graphical procedures are based on the seismic P and T axes (McKenzie, 1969) or kinematic contraction (P) and extension (T) axes (Marrett and Allmendinger, 1990), the method of Arthaud (1969), the Right Dihedra (Angelier and Mechler, 1977) and Right Trihedra (Lisle, 1987) methods. These methods allow the recognition that data are heterogeneous, but do not allow the component tensors to be identified. Other scientists tried to face the problem using a hard division (Hardcastle and Hills, 1991; Nemcok and Lisle, 1995; Fry, 1999) or soft-division procedures (Shan et al., 2003). However, the solution to the problem is still to be found, since only the “dynamic attributes” (Nemcok and Lisle, 1995) are taken into account, but not geological parameters, i.e. relative chronological order among the different fault-slip data, and kinematic or strain compatibility (Marrett and Allmendinger, 1990). As a result, in the presence of heterogeneous fault-slip data, it is difficult to interpret stress estimated through applying the conventional inversion method (Nemcok and Lisle, 1995).

For this reason, many scientists dealing with heterogeneous fault-slip data prefer to separate the fault-slip data manually based on field cross-cutting and overprinting criteria (Angelier, 1994; Sippel et al., 2009; Sperner et al., 1993; Tranos, 2009, 2011). Then, they independently apply a stress inversion method on each separated fault group in order to define the different stress regimes. On this procedure, the P and T kinematic axes, although they do not provide an accurate measure of the orientation of the local principal stresses (McKenzie, 1969), have been widely used as a guide in the definition of the position of the stress axes (Marrett and Allmendinger, 1990), since generally these axes have been considered respectively to be parallel to the greatest and least principal stress axes causing the slip event (e.g., Raleigh et al., 1972).

It is worth mentioning that although the central goal of the stress inversion methods is to resolve the stress tensor that leads to the activation of the pre-existed faults in a region, the method itself verifies the ‘dynamic compatibility’ among the faults, i.e., what faults are capable of activating simultaneously under the specific resolved stress tensor. Therefore, on the application of the stress inversion methods to homogeneous fault-slip data, or even more, to heterogeneous fault-slip data, the most widely considered parameter is the Misfit Angle (MA), i.e., the angle between the real slickenline observed on the activated fault and the theoretical slip vector or the maximum shear as imposed by the Wallace–Bott criterion. In other words, it indicates the slip deviation (SD) from the slip preference of the fault activated in the different stress regimes. In most applications, the resolved stress tensors are considered quite successful if the MA of each activated fault is less than 20° (Tranos, 2009 and references therein).

Concerning the reactivation of the faults, Byerlee (1978) has shown that nearly all rocks share the same frictional properties with a failure criterion which may be adequately approximated by Amonton's Law:

$$\tau = \mu\sigma¢_n = \mu(\sigma_n - P) \tag{1}$$

where τ and σ_n are, respectively, the shear and normal stresses to the plane, P is the fluid pressure, and μ is the coefficient of friction. Morris et al. (1996) referred to the critical parameter, slip tendency (T_s), which is defined as the ratio of shear stress to normal stress on that surface: $T_s=\mu=\tau/\sigma'_n$. In the part of the crust that is subjected to a fixed orientation of a stress field, the frictional reactivation of the different oriented faults is mainly dependent on the fluid pressure, the differential stress, $\sigma_1-\sigma_3$, the sliding friction coefficient, μ, and the stress shape ratio $R=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$ (Collettini and Trippetta, 2007). Therefore, T_s that depends solely on the stress field (stress tensor) and the orientation of the surface is very useful for the fault instability and earthquake prediction (Morris et al., 1996) and this parameter is also considered in the present analysis.

According to Anderson–Byerlee frictional fault reactivation theory, in an extensional regime characterized by vertical trajectories of σ_1, the normal faults possess friction μ in the range of 0.6–0.85 (Byerlee, 1978). Thus, it predicts that it is easier to form a new optimally oriented fault (dip about 60°) instead of reactivating an existing one dipping less than 30° (Collettini and Sibson, 2001; Sibson, 1985).

The present paper addresses extensional stress states with a vertical principal direction; stress states that are also referred to as ‘Andersonian’ in recognition of the pioneering work of Anderson (1905). In particular, synthetic fault-slip data are calculated for various extensional stress regimes with the intension to examine and describe through a simple graphical manner the slip preference and slip tendency of the differently oriented faults in each stress regime. Furthermore, kinematic parameters such as the kinematic axes (P and T), strain compatibility and transport orientation are also examined if they could be used as indexes in finding the stress regimes and consequently as guides for the separation of the heterogeneous fault-slip data to homogeneous subgroups. More importantly, although Célérier (1995) and Célérier and Séranne (2001) suggested a method, based on the slip preference, to define the admissible stress ratio from the sampled fault-slip data, herein, a different and simple method is proposed. This method analyzes heterogeneous fault-slip data, with the advantage of subdividing them in different homogeneous subgroups and thus better defining their driving stress regimes, by taking into account that one of the principal stress axis remains in vertical position.

2. Methodology

In order to achieve the present analysis, a series of synthetic fault planes that have the same strike and dip direction, but dip at different angles from 10° to 80° in increments of 10° (Fig. 1a), has been considered to be activated as normal faults in various extensional stress regimes in which the principal stress axes are fixed to lie in horizontal and vertical planes (Figs. 2–6); a condition that is favored in the Andersonian stress states and it is generally considered to be the case in the Earth's crust (see Zoback and Zoback, 1980a,b). In this examination, the fault dip angle of 45° (Fig. 1a) is also taken into