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The use of Stress Tensor Discriminator Faults in separating heterogeneous fault-slip data with best-fit stress inversion methods

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ABSTRACT

A widely accepted best-fit stress inversion method is applied on synthetic extensional heterogeneous fault-slip data generated by two driving Andersonian stress tensors having similar stress ratios, and σ_3 axes with different trends, in order to examine whether the misfit angle (MA) minimization criterion can be used for separating heterogeneous fault-slip data. The examination shows that the resolved best-fit stress tensors have σ_3 axes that tend to the bisector of the σ_3 axes of the driving stress tensors, and stress ratios smaller than those of the latter. Moreover, there is a tendency towards determining radial extension stress regimes, although such regimes are rare in the Earth's crust. More importantly, the best-fit stress inversion methods that use solely the MA minimization criterion cannot be used for the separation of heterogeneous fault-slip data, especially when the extensional driving stress tensors have stress ratios smaller than $R = 0.5$, i.e., as are the favored paleostresses in the Earth's crust. In contrast, the percentage of the Stress Tensor Discriminator Faults (STDF) can be a very useful discriminator tool for the establishment and comparison between two resolved stress tensors as the latter have been determined by a best-fit stress inversion method. Moreover, the existence of fault-slip data that can been considered as possible STDFs during the recording stage advocate for the heterogeneous origin of the fault-slip dataset.

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1. Introduction

Nowadays, half a century after the establishment of (a) the relationship between faults and stresses in the crust (Anderson, 1905, 1951), and (b) the Wallace-Bott slip criterion, i.e., the slip vector on a fault plane is parallel to the maximum shear stress of the driving stress on this fault plane (Wallace, 1951; Bott, 1959), studies dealing with the determination of the contemporary crustal stresses, and the paleostress analysis of a region have been easily accomplished, becoming one of the most favorable and interesting subjects.

Several algorithms, and consequently several stress inversion methods, have been proposed with the goal to define the best-fit stress tensor of a given fault-slip dataset by minimizing or maximizing some object function (whether explicitly or implicitly) (e.g., Carey and Brunier, 1974; Angelier and Goguel, 1979; Angelier, 1979, 1984, 1989; Etchecopar et al., 1981, Etchecopar and Mattauer, 1988; Hardcastle and Hills, 1991; among others). Although Bott (1959) showed that oblique-slip can be generated on preexisting planes with a vertical principal stress direction, and thus did not require principal stress direction rotated away from Anderson's (1905) positions, most of the stress inversion methods resolve stress tensors without such restriction. The Misfit Angle (MA) between the observed fault slickenlines and the slip preferences (SP), i.e., the direction of the maximum shears on the fault planes, as induced by the Wallace-Bott criterion, is the most widely used minimization criterion in the best-fit stress inversion methods (Célérier et al., 2012). In general, if the MA of each activated fault is less than 20° (e.g., Angelier, 1979; Etchecopar et al., 1981; Bellier and Zoback, 1995; Tranos, 2009), then the resolved stress tensors are considered quite successful, whereas several applications use the Mean Misfit Angle (MMA), instead of the MA of each fault-slip datum. In stress inversion methods, the fault-slip data include only the orientations of fault planes and associated slip directions and therefore they do not provide information on shear stress magnitudes. Because of this, stress inversion methods instead of calculating the complete stress tensor which consists of six independent quantities, they calculate the reduced tensor (Angelier, 1989, 1994) which is considered homogeneous for the size of the faults, and it is

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composed of three variables specifying the orientation of the principal stress axes and a fourth variable, often called the stress ratio, that expresses the ratio of the differences between pairs of principal stress magnitudes. As a result, the orientations of the three principal stress axes ($\sigma_1, \sigma_2, \sigma_3$) and the stress ellipsoid shape ratio $R = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ with $0 \leq R \leq 1$ (Etchecopar et al., 1981; Delvaux and Sperner, 2003) are actually elaborated. The solution of any stress inversion in case of homogeneous fault-slip data is direct, quick, and mathematically robust, and it needs at least four differently oriented striated fault planes (Etchecopar et al., 1981). In contrast, in paleostress analysis where the fault-slip dataset is heterogeneous (mixed or polyphase), including fault-slip data driven by different stress tensors, there are several key problems, apart from possible measurement errors (Shan et al., 2006), that make the separation of the dataset to homogeneous subgroups driven by different paleostress tensors, and therefore the paleostress analysis, a puzzling issue. The concept of the paleostress tensor refers to the 'mean' or 'averaged' tensor that represents the regional stress regime over several thousand or even several millions years (the duration of a tectonic event) and over the rock volume investigated (Lacombe, 2012). Such key problems are related to: (a) the size of the heterogeneous fault-slip dataset, (b) the diversity of the fault-slip data in type, orientation and number among the possible homogeneous subgroups, (c) the choice of a criterion or criteria used for the separation of the dataset into homogeneous subgroups, e.g., the chosen MA minimization criterion, (d) the mechanical compatibility among the fault-slip data included into the homogeneous subgroups.

Despite the fact that several semi-automatic and automatic methods have been suggested for the separation of heterogeneous fault-slip data (e.g., Nemcok and Lisle, 1995; Fry, 1999; Yamaji, 2000; Shan et al., 2003, 2004; Tranos, 2015), best-fit stress inversion methods have also been used to determine paleostress tensors from such data. The process is iterative (sometimes in combination with several proposed strategies such as the Monte Carlo research method (Etchecopar et al., 1981) or Gauss method (Zalohar and Vrabec, 2007)), and is repeated until no physically meaningful stress tensor can be calculated from the remaining data. However, Yamaji et al. (2006) and Sato and Yamaji (2006) indicated that the object function used in the best-fit stress inversion methods can have multiple peaks when dealing with heterogeneous fault-slip data, and therefore they might be problematic in such cases. In other words, although the tensors explaining the greatest number of fault-slip data are taken to be favored candidates for the real paleostresses, might be mixed ones explaining fault-slip data driven by completely different stress regimes.

Unfortunately, the best-fit stress inversion methods could not have any anterior constraint about the orientation of the stress axes or the stress ratio in order to check the compatibility among the input fault-slip data; a fact that functions as a drawback when the fault-slip data are heterogeneous, as pointed by Nemcok and Lisle (1995) who stated that "If data collected from areas which have been subjected to multiple stress events are analyzed using standard techniques for stress analysis, the obtained results are likely to be of doubtful value, giving at best a calculated stress configuration which is some sort of compromise between the different real stress tensors represented in the data."

On the other hand, the Slip Preference Analysis (SPA) showed that Andersonian stress regimes (either extensional or compressional) with similar orientation, but different stress ratios, activate faults with different SPs and these faults outline different slip preference activation regions in the TR diagrams (Tranos, 2012, 2013, 2015), i.e., a condition of stress ratio compatibility. Based on this condition, Tranos (2015) has proposed a new separation and stress inversion method for heterogeneous fault-slip data, the TR method (TRM) that takes into account the stress ratio compatibility as a prior constraint, if an Andersonian stress tensor is considered. Besides, as afore-mentioned, oblique-slips can be generated on preexisting planes with a vertical principal stress direction, without any requirement of the principal stress directions rotating away from Anderson (1905) positions.

The fact that paleostress tensors as defined by the stress inversion methods are not complete, but reduced stress tensors presents problems (a) for the calculation of an average paleostress state, and (b) when different reduced tensors are to be compared (Orife and Lisle, 2003). The same authors argue that a comparison of two tensors should not be based purely on their directional attributes, but must instead be based upon all six components of the respective tensors; a preferred approach which, however, is prevented by the incomplete nature of the stress tensors. As they pointed out, some workers, in order to obtain a description of the average stress for a region, have resorted to separately averaging the individual principal stress directions, even though the mean axes so calculated do not possess the orthogonality property for principal directions (Lisle, 1989). Others have calculated variants of the arithmetic average of the stress ratios for different sites or methods (e.g. Hardcastle, 1989; Bellier et al., 1997; Orife et al., 2002). Because of this, Orife and Lisle (2003) suggested methods which involve constructing, for each stress result, a normalized stress tensor composed of the four components determined from the stress inversion of fault data and supplemented by nominal values for the other two unknown components, so that tensor differences and tensor averages can be calculated from these normalized stress tensors. Similar methods have been proposed afterwards by Sato and Yamaji (2006).

Nonetheless, these methods are more mathematical than geological, and focus on the stress tensors themselves. On the contrary, from a geological point of view concerning the fault activity in the crust, it seems more interesting defining the degree to which two reduced stress tensors (as determined by stress inversion methods) are similar or not by taking into account not their components, but the number or percentage of the different fault-slip data of a given fault-slip dataset that have been activated by these two stress tensors. Considering this, a new term, the Stress Tensor Discriminator Fault (STDF) has been recently introduced, and used as a tool to discriminate two stress tensors, A and B, as the latter might be resolved from a heterogeneous fault-slip dataset (Tranos, 2015). The STDFs are the fault-slip data from a given fault-slip dataset that activate from either tensor A, or tensor B (with specific MA, e.g., MA $\leq 20°$), but not from both of them. With the STDFs the comparison between the two stress tensors is not based on their components, but it is based on the percentage of those fault-slip data that cannot be activated by both stress tensors under comparison. In this way, the main goal of the comparison between the reduced stress tensors is not the tensors themselves, but the activated fault-slip data from which they have been elaborated.

In this paper, by using synthetic fault-slip data and the percentage of the STDFs, it is examined whether two extensional Andersonian stress tensors can be fairly distinguished or not only by the use of the MA minimization criterion, when they differ in the trend of σ_3 axis, but have similar stress ratios. This examination, gives rise to a better understanding of whether and why the best-fit stress inversion methods fail to define the correct stress tensors in the case of heterogeneous extensional fault-slip data. It also shows which fault-slip data can be considered as possible STDFs in a recorded fault-slip dataset, and should such fault-slip data be recognized in a recorded fault-slip dataset, these might advocate for the heterogeneous origin of this dataset prior to the application of any stress inversion method.

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