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y-gRaph: An OpenOffice application to reconstruct paleostress fields from striated faults

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ABSTRACT

y-gRaph, a user-friendly spreadsheet for reconstructing paleostress fields by means of the *y–R* diagram is presented. The *y–R* diagram is based on Bott's equation and translates the parameters of the stress ellipsoid to a *XY* plot representing the maximum horizontal stress orientation (σ_y) and the stress ratio (R), compatible with a given set of striated faults. In cases where several stress tensors fit the dataset, *y-R* diagram aids in visualizing unrealistic solutions or changes in the stress field with time. Furthermore, the spreadsheet allows to rotate planes and lines, thus simplifying the work with tilted fault populations. Histograms and rose diagrams showing the strike of faults and the trend of striae complement the *y-gRaph* main output. The application was built using Apache OpenOffice software and supports a variety of input data formats: (i) strike, dip and dip direction (SDD), (ii) azimuth and dip (AD) according to the “Right-hand rule”, and (iii) dip and dip direction (DD).

1. Introduction

Stress analysis methods based on brittle structures started to develop in the late sixties and early seventies with the works presented by Arthaud (1969), Arthaud and Choukroune (1972) and Mattauer (1973). During the following decades, additional techniques were developed (Angelier, 1984, 1994; Fry, 1992; Ramsay and Lisle, 2000; Yamaji, 2000; Célérier and Séranne, 2001; Yamaji et al., 2006; Zalohar and Vrabec, 2007; Célérier et al., 2012) and some of them were based on Bott's (1959) equation. This equation relates the shear stress component on the fault plane (striation) to the reduced stress tensor (expressed by the orientation of the three principal axes $\sigma_1 > \sigma_2 > \sigma_3$, and the ratio between these axes, which defines the stress regime, Angelier, 1994). Casas-Sainz et al. (1990) reviewed some of the different methods in the literature and concluded that one of the most reliable procedure to calculate paleostress axes from faults with striae is the synergic use of (i) a kinematical approach (e.g. Right Dihedra; Angelier and Mechler, 1977) as a first approximation to the solution, (ii) Bott's based graphical approach (e.g. *y–R* diagram; Simón-Gómez, 1986; FSA; Célérier, 1998) in order to graphically establish a more accurate estimation as well as to display the spectrum of reduced stress tensors compatible with the fault population and (iii) an iterative numerical approach based on Bott's equation (e.g. Etchecopar's method, Etchecopar et al., 1981, FSA; Célérier, 1998) to explore the results suggested by the previous methods and to obtain more precisely defined tensors. This procedure has been used by many authors (e.g., Casas-Sainz and Simón-Gómez, 1992, 1996; Arlegui-Crespo and Simón-Gómez, 1998; Liesa and Simón, 2009, among others). However, the lack of a user-friendly software to perform the *y–R* diagram hindered its widespread use within the scientific community.

The *y–R* diagram is a particularly useful tool when a variety of stress fields are recorded within a region: this method displays the spectrum of possible solutions and thereby allows the identification of faults related to different stress fields. In addition, it serves to properly track the intermediate stages of the paleostress analysis. In this paper we present a user-friendly application (*y-gRaph*) that displays the *y–R* diagram associated to a given population of striated.

2. Theoretical background

Under a specific stress regime, reactivation of pre-existing fault planes is frequently favored compared to formation of new fault

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planes. This is especially observed in complex settings, where the measured sets of faults may not be consistent with Anderson's theory of faulting. That fact can hinder the interpretation of the stress regime under which the faults were formed. However, by gathering measurements from a population of these reactivated planes/discontinuities (fault plane strike and striae with sense of movement), the orientation of the maximum shear stress acting on a plane can be mathematically inferred from Bott's equation (1) (Bott, 1959; Célérier et al., 2012):

$$\tan\ \theta = [n/(lm)][m^2 - (1-n^2)R] \tag{1}$$

where the stress ratio is $R = (\sigma_z - \sigma_x)/(\sigma_y - \sigma_x)$;

l, m, n are the direction cosines of the plane referred to the stress axes (σ_x, σ_y, σ_z) system and θ is the striation (resolved shear stress) rake on the fault plane. σ_z, σ_y and σ_x are the principal stress axes (eigenvectors of the stress matrix, (2)) in the *xyz* coordinate system, whose base vectors can be normalized according to the deviatoric stress tensor.

Based on a modified version of Bott's Equation (2) and considering that one of the main stress axes is vertical (σ_z), Simón-Gómez (1986) proposed the y–R diagram as a method to show the relation between two parameters: (i) y, the possible azimuth of σ_y, and (ii) R, the stress ratio of the deviatoric stress tensor:

$$R = \sin^2\lambda - [(\tan\ \theta\ \sin\ 2\lambda)/2\ \cos\ \phi] \tag{2}$$

where λ is the angle between y and the azimuth (α) of the fault, therefore $\lambda = \alpha \pm y$ (it is added or subtracted according to the sense of movement: dextral or sinistral, respectively), ϕ is the fault dip and θ is the striation rake on the fault (Fig. 1). For each fault, there is a 90° interval in which σ_y is compatible with the measured movement of the fault. The azimuth of the strike is one of the endpoints of this interval: the start point if the strike-slip component of the fault is dextral, and the end point if this component is sinistral. Therefore, there are values of y–R (equal values of R correspond to $y+180$). Those values, once plotted in the y–R diagram, draw a curve per each fault measured in the set.

The y–R method assumes that one of the principal axes is vertical, which is, under brittle conditions, a common tendency in nature (Lisle et al., 2006; Liesa and Simón, 2009); this simplification is the basis of the method since it allows stress states to be represented by the y–R values compatible with each fault, defining a curve on a 2D diagram. The "knots" where the curves intersect show a preliminary range of possible solutions for the azimuth of σ_y (y) and R under which the faults could have moved. However, due to this simplification (one of the stress axes is vertical), it is essential to couple y–R diagram to other 3D methods since, even though it is expected that one of the stress axes was vertical during the slipping time, faults may have been tilted after their formation. A complementary method to deal with tilted fault systems is also included in *y*-g*R*aph.

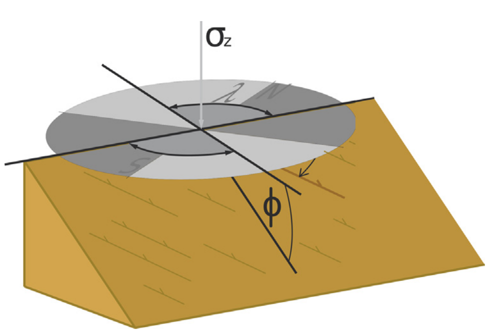

Fig. 1. Defining parameters of the converted Bott's equation. σ_z, vertical principal stress direction; σ_y, maximum horizontal principal stress direction; λ, angle between azimuth and σ_y; θ, rake; Φ, plunge. The possible range of directions of the maximum horizontal stress axis σ_y (90° from the azimuth of the fault counted clockwise or counter-clockwise depending on whether the fault is dextral or sinistral respectively) is represented by the dashed line included in the horizontal plane (note that the depicted fault is sinistral).

3. Spreadsheet description

y-g*R*aph is written as a spreadsheet template using the free software suite Apache OpenOffice. This spreadsheet consists of nine worksheets (Fig. 2):

- *Instructions* worksheet.
- The *Input data* block is divided into three different worksheets (SDD, AD and DD). Their differences only involve data input format according to the user's preferences.
- In the "*Graph*" worksheet the y–R diagram corresponding to the fault population is generated.
- "*Extras*" worksheet contains graphics (rose diagram and histogram) representing the strike of faults and trend of striae in order to assist in the interpretation.
- "*y–R calculation*" worksheet includes the automatic calculations which generate the y–R diagram.
- "*Fault rotation*" worksheet performs automatic computations to define the coordinates of fault vectors in a rotated reference system (i.e., faults are rotated according to its bedding orientation).

3.1. Data input

Three formats of fault data entry can be used (strike, dip and dip direction; azimuth and dip; dip and dip direction). Each one can be found in a different worksheet labeled as "SDD", "AD" and "DD", respectively. Striae data may be introduced as the rake of the line on the measured plane or as trend and plunge. More precise specifications about data entry format are available in the Introduction worksheet and in User´s guide.

Data entry section (A–J columns in SDD, A–I AD and DD worksheets) receives the raw data from the user. The "NEW" button in the "Input data" worksheets must be used if the user wants to clean the input cells. This button has an associated macro that deletes all the values in the data entry section, restoring the section to default.

"Data revision" section is available in all the "Input data" worksheets (L–S columns in "SDD", K–Q in "AD" and "DD" worksheets). In this section, an "IF" function evaluates the consistency of the data, eventually displaying a "review" label if data incompatibility is found.

The single goal of the "Automatic Computation" section (AE–AS columns in "SDD", AB–AP in "AD", AC–AQ in "DD" worksheets) is to standardize the introduced data. The standard data format is established as azimuth (0–2π rad) and dip (0–π/2 rad) for fault planes and rake (0–π rad measured from the azimuth on the fault plane) and movement sense (in horizontal component D or S) for striae (rakes of 90° are considered by the application as 89.9999). If the striae orientations have a trend/plunge format, this section converts these data, by vector calculation (3), to standard rake format (AE–AJ columns in "ADD" worksheet.):

$$\cos\ \theta = (a_1 * b_1 + a_2 * b_2 + a_3 * b_3)/[\sqrt{(a_1^2 + a_2^2 + a_3{}^2)} * \sqrt{(b_1^2 + b_2^2 + b_3^2)}] \tag{3}$$

where a_1, a_2, a_3 are the vector components of the azimuth in the Cartesian reference system (x, y, z in North, East and vertical directions, respectively; a_3 is always 0) and b_1, b_2, b_3 are the vector components of the striae.

In any case, the rake is modified to the standard format (rake measured from the azimuth) by means of an "IF" function which