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Quantification of true displacement using apparent displacement along an arbitrary line on a fault plane

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ABSTRACT

This paper introduces some approaches to determine the true displacement (S_t) using an apparent displacement (S_m) measured from an arbitrary line on a fault plane. The considered parameters are the pitch of slip lineation (γ), the pitch of a cutoff (β), the apparent displacement along the observation line (S_m), and the pitch of the observation line on the fault plane (φ). We analyzed the following cases. First, if the apparent displacement is taken as the true displacement, the degree of overestimation or underestimation of the true displacement can be calculated. The displacement cannot be obtained along the null line because the pitch of the observation line (φ) is equal to the pitch of the cutoff of the marker (β). Second, the total true displacement can be obtained not only along the slip direction but also along another particular line depending on the values of γ and β. Third, if the apparent displacements from two non-parallel markers can be measured, the slip direction can be estimated. We apply the methods to calculate the extensions due to the normal faults of San Miguelito in Mesa Central, Mexico. The results indicate that the largest fault strain reaches ca. 0.50 and the smallest fault strain is ca. 0.08. Also, the isolated faults show more regular strain profiles along the fault strikes than the faults with overlapping or intersecting geometries.

1. Introduction

The term “displacement” is an ambiguous word in geology (Tearpock and Bischke, 2003). According to Walsh and Watterson (1988), displacement refers to the displacement accumulated through the whole active period of the fault. This definition indicates that displacement is a total slip or total true displacement. Displacement also represents the variation in position of a marker displaced by the fault movement (Tearpock and Bischke, 2003). In the light of this concept, displacement is an apparent displacement. Previous work did not distinguish a true displacement from an apparent displacement (e.g. Dawers et al., 1993; Clark and Cox, 1996). In this paper, we use the term “true displacement” (S_t) by following Walsh and Watterson's definition. Therefore, the true strike displacement (S_{th}) refers to the component of S_t along the fault strike. True dip displacement (S_{td}) refers to the component of S_t along the fault dip (Fig. 1).

Three problems influence the obtainment of the true displacement. First, observed sections in outcrops may not be vertical at times, and the sample lines may not be perpendicular to the strikes of faults. Second, the beds are not horizontal or the strikes of the beds are not parallel to that of the fault. Third, faults are not absolute dip-slip or strike-slip faults. For all cases above, it is necessary to establish a quantitative relationship between the true displacement and apparent displacements.

Traditionally, the main parameters to determine the fault displacement are slickenside lineations and kinematic indicators on or near the fault (e.g. Billings, 1972; Suppe, 1985; Doblas et al., 1997a, b). Recently, there has been some work for quantitatively determining the fault true displacement (e.g. Rouby et al., 2000, Xu et al., 2004a; Xu et al., 2007). Billi (2003) analyzed the components of fault slip and separations generated by cleavage-controlled fault zone contraction, on the assumption that shortening occurs perpendicularly to solution cleavages. The methods by Xu et al. (2004a) are appropriate only for the faults on subsurface maps. The approaches by Xu et al. (2007) consider only data measured from cross-section perpendicular to the fault strike or from map view. These methods need more assumptions than the approaches that we introduce here.

In this paper we quantify the magnitude of true displacement and the direction of fault slip on faults. The approaches introduced here can be applied to data measured along arbitrary lines on the fault plane, which are more general than methods proposed by Xu et al. (2007).

This paper consists of two parts. The first part is to establish equations for obtaining the magnitude of true displacement, the direction of fault slip, or both, according to the available data. The second part gives an example of how to calculate the strain due to faulting. In most cases, the accurate strain is difficult to obtain if the

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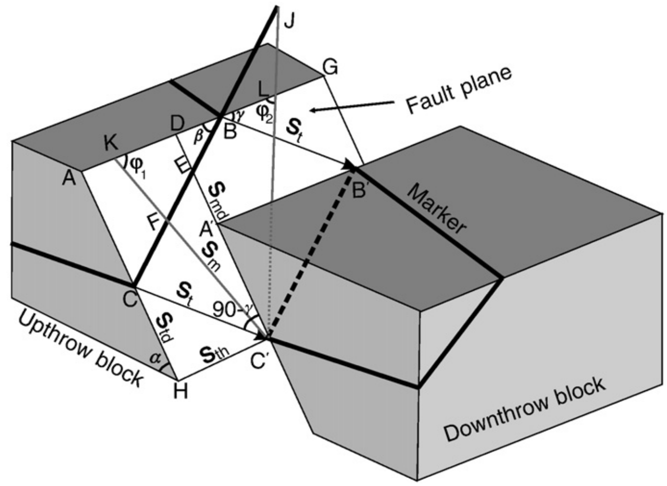

Fig. 1. Block diagram showing that the slickenside lineation and the marker cutoff have opposite directions. S_t = CC′ = true displacement, S_{th} = HC′ = true strike displacement, S_{td} = CH = true dip displacement, γ = pitch angle of true displacement, β = pitch angle of cutoff of the marker. KC′ and JC′ are two arbitrary lines along which the apparent displacements are measured. φ_1 and φ_2 are pitch angles of KC′ and JC′, respectively. Apparent displacement is FC′ for line KC′, whereas, LC′ for line JC′. Note that the apparent dip displacement (S_{md} = EC′) is not equal to S_{td}.

true fault slips are not known. The example in this paper provides an excellent application based on our methods.

2. Calculations of the true displacement

In order to define the pitch angles, the following conventions are used.

(a) The angle of pitch is in the range from 0° to 90°. Starting from the strike line, the angle is measured in a sense which is down the dip of the plane. This is used in conjunction with conventions b and c.
(b) Direction of pitch is the direction of the strike from which the angle of pitch is measured.
(c) Opposite direction of pitch refers to the direction of strike which is opposite to the strike from which the angle of pitch is measured.

For calculation, four parameters should be known: the pitch of slip lineation (γ), the pitch of a cutoff (β) of a marker (bed, vein, etc.), the pitch of an observation line (φ), the apparent displacement along the observation line (S_m). To calculate the magnitude of true displacement, the following cases can be considered (Table 1).

(1) Case of slickenside lineation with opposite pitch direction to that of marker traces on the fault. There are two sub-cases: (a) the observation line has the same pitch direction as the slickenside lineation; (b) the observation line has the opposite pitch direction to the slickenside lineation.
(2) Case of slickenside lineation with the same pitch direction as marker trace on the fault. Two sub-cases are considered: (a) the observation line has the same pitch direction as the slickenside lineation; (b) the observation line has the opposite pitch direction to the slickenside lineation. Two further situations should be included: sub-cases where $\beta > \gamma$ and where $\beta < \gamma$.

There are some principles for determining whether a slickenside lineation and a marker trace or an observation line on the fault has the same or opposite pitch direction (Xu et al., 2007). Sometimes, the pitch of intersection line of a bed with a fault plane could not be directly obtained. This problem can be resolved using the equations (Eqs. A1 to A18) established by Xu et al. (2007). For example, if a fault with an angle of α intersects a marker with an arbitrary marker with an angle of θ, the pitch angle of the cutoff (β) will be $\beta = \arctan\left(\frac{\sin\mu\tan\alpha\tan\theta}{\sin\alpha(\tan\theta\cos\mu - \tan\alpha)}\right)$, where μ is the acute intersection angle of the fault strike with the marker strike.

2.1. Case of slickenside lineation with opposite pitch direction to marker trace on the fault

For this situation, we should consider two sub-cases (Table 1) according to the pitch direction of an observation line on the fault plane (Fig. 1). The first sub-case is that the observation line has the same pitch direction as the slickenside lineation. Let the pitch angle of the line be φ_1. In Fig. 1, for the triangle CC′E, we can obtain

$$\begin{aligned} &\angle CEC' = 90-\beta, \\ &\angle CC'E = 90-\gamma, \\ &\text{then } \angle C'CE = \beta + \gamma, \end{aligned} \tag{1}$$

where $\angle$ indicates angle.

For the triangle FCC′, FC′ = S_m, CC′ = S_t, because $\angle$FC′E = $90-\varphi_1$, $\angle$CC′E = $90-\gamma$, therefore we can infer that $\angle$CC′F = $\angle$CC′E − $\angle$FC′E = $\varphi_1-\gamma$, $\angle$CFC′ = $180-(\varphi_1+\beta)$. By using the Law of Sines of triangle, the following equation can be established

$$S_t = \frac{S_m \sin(180-(\varphi_1+\beta))}{\sin(\gamma+\beta)} = \frac{S_m \sin(\varphi_1+\beta)}{\sin(\gamma+\beta)} \tag{2}$$

The condition $S_m = S_t$ holds for $\sin(\varphi_1+\beta) = \sin(\gamma+\beta)$ and $\sin[180-(\varphi_1+\beta)] = \sin(\gamma+\beta)$ reflecting periodicity of trigonometric function; then, we obtain

$$\varphi_1 = \gamma \tag{3}$$

and

$$\varphi_1 = 180-\gamma-2\beta \tag{4}$$

Eqs. (3) and (4) indicate that if $\varphi_1 = \gamma$, or $\varphi_1 = 180-\gamma-2\beta$, the measured displacement is equal to the true displacement. For the given values of β and γ (marker and slickenside pitches), the true displacement can be obtained along two lines of observation. One of them is not the slickenside direction. A special case is $\beta+\gamma = 90°$, in that case S_m and S_t are equal to each other for only one value of φ_1. For example, curve 4 in Fig. 2a has two intersection points with true displacement (S_t). At point a, φ_1 is equal to 40°, and at point b, φ_1 is equal to 80°.

From Eq. (2), given two of the three angles β, γ, and φ_1, the relationship between S_m and the third angle can be calculated (Fig. 2). It can be seen that the value of S_m (apparent displacement along the observation line) could be larger, equal, or smaller than the total true displacement. From Fig. 2a, we can see that there are two curve tendencies between S_m and φ_1. For small value of φ_1, the value of S_m has a negative relationship with the value of φ_1, whereas for large value of

Table 1
Cases for calculation of true fault displacement

Case 1: slickenside lineation with pitch direction opposite to that of marker traces	Case 2: slickenside lineation with the same pitch direction as that of marker traces	
Case 1a: the observation line with the same pitch direction as the slickenside lineation.	Case 2a: the observation line with the same pitch direction as that of the slickenside lineation.	Case 2b: the observation line with the opposite pitch direction to that of the slickenside lineation.
Case 1b: the observation line with the opposite pitch direction to that of the slickenside lineation.	Case 2a-a: $\beta > \gamma$ Case 2a-b: $\beta < \gamma$	Case 2b-a: $\beta > \gamma$ Case 2b-b: $\beta < \gamma$