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The estimation of fault slip from map data: The separation-pitch diagram

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ABSTRACT

Although an essential feature of faults is that they produce a relative movement of two blocks, the total or net slip is known only for a very small percentage of faults. This note proposes a diagram for the graphical determination of net slip from the strike separation of markers recorded on geological maps, with or without knowledge of the net slip direction. The strike separation of one marker allows the drawing of a solutions line on the diagram, depicting the range of slip vectors compatible with the measured separation. The net slip vector can be obtained by either the intersection of two or more solutions lines, or from a single solutions line if the direction of slip is independently known. The diagram gives a visual appreciation of the effects of data uncertainty on the estimate of net slip, and is a useful device for the representation of the kinematic characteristics of a collection of faults. The use of the diagram is illustrated with examples from the South Wales Coalfield and the Moine Thrust zone.

1. Introduction

By definition, faults during their history accumulate a total relative displacement of the two walls. This is known as the net slip, a vectorial quantity specifying the amount and direction of cumulative movement. Net slip is a fundamental kinematic attribute used for fault classification (e.g. dip-slip, strike–slip, etc.) that allows the fault to be interpreted in a regional tectonic context and in terms of palaeostresses (Angelier, 1984; Ramsay and Lisle, 2000). Remote-sensing analyses of fault sets are limited to orientation, requiring that fault kinematic datasets be defined by outcrop-based field studies (e.g., Wilson et al., 2010).

The measurement of slip requires the identification of a pair of mutually displaced points within the fault surface, one in each fault block, that were coincident prior to movement. These so-called piercing points could be provided by some small object fortuitously dissected by the fault, but generally they are defined by some linear feature (e.g., the hinge line of a fold) being cut and offset by the fault plane (e.g. Huerta and Rodgers, 1996). Two non-parallel planar features that intersect (e.g., marker beds with differing dips, veins, and sheet intrusions), can also form a linear feature that can be matched across the fault. It is, however, common that the lack of piercing points prevents the determination of the net slip vector for a given fault.

Most faults are recognized on maps or cross-sections by planar markers that are shifted along the fault trace. The offset of the planar marker observed on such two-dimensional views is termed the separation. For at least a century, geologists have been aware that the separation is generally not equal to the slip magnitude (Leith, 1914; Peach et al., 1907; Ransome et al., 1910). The amount of separation depends on the net slip but is also a function of the orientations of the net slip vector, the displaced marker, and the plane of observation. Therefore, unless the net slip orientation is known, it is not possible to calculate the net slip vector from the amount of separation of a single planar marker (Crowell, 1959; Hill, 1959). In fact, most of the so-called displacement estimates used in studies of fault kinematics are *separations* rather than *slips*. This calculation of slip requires the separation of two planar markers of known strike and dip, or one planar marker combined with the slip vector orientation (see Ragan, 2009, p.177; Ree and Kwon, 2005). The necessary geometrical constructions are well known (e.g., Billings, 1954). Graphical methods using structure contours are given by Roberts (1982) and Lisle (2004) whilst methods using the stereographic projection are described by Badgly (1959), Ramsay and Huber (1987, p.53), and Lisle and Leyshon (2004, p.56). Yamada and Sakacuchi (1995) and Xu et al. (2007) present computer programs for calculating slip from separation. In this short note we present a simple alternative graphical method that illustrates how separation data measured from a planar geological feature constrain the net slip of a fault, and visually conveys the effects of data uncertainty on the robustness of the net slip estimate.

2. The proposed method for calculating the net slip

Many fault geometry problems can be solved by constructing a cross-section in the fault plane (Groshong, 1999) which allows a direct comparison of geometries in both walls of the fault. For example, Allan (1989) suggested the construction of fault-plane sections for the analysis of hydrocarbon traps because they display the juxtaposition

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of permeable and impermeable rock units across the fault. In a similar manner, fault juxtaposition diagrams are used by Knipe (1997) to estimate the sealing of a fault and by Bistacchi et al. (2010) to discuss the effect of wall-rock heterogeneity on damage zone thickness and evolution.

Another use of fault-plane sections is in the calculation of net slip from displaced planar markers (Billings, 1954; Crowell, 1959). This involves constructing the position and orientation of the footwall and hangingwall cut-off lines for more than one marker plane in the cross-section coinciding with the fault plane. The required markers need to have different orientations so that their respective cut-off lines are non-parallel. Such variably-dipping contacts arise in the context of angular unconformities, pre-fault folding, cross-cutting faults and intrusive relationships.

For each block of the fault, the point of intersection of the pair of cut-off lines on the cross-section defines a piercing point. The distance between the piercing points for the hanging and footwalls is the calculated net slip (Fig. 1A). The details of this method are explained in a number of text books (e.g. Badgley, 1960; Lisle and Leyshon, 2004; Ragan, 2009). The procedure proposed here is similar in concept, but instead of a fault-plane section it uses a graph in which lines are drawn according to the pitches (rakes) in the fault plane of the cut-off lines and their strike separation (Fig 1B). The modification consists of defining the graph's origin at the piercing point on the far wall which is treated as a fixed point, and constructing the equivalent piercing point on the observer's wall.

The steps in the procedure are:

1) From the map, record along the trace of a single fault the amount and sense of the strike separation, S, of two or more displaced planar markers (A, B, C, etc.). Sinistral sense is assigned a positive value; dextral is negative. For example in Fig. 2A. $S_A = -10$ m, $S_B = 8$ m.
2) For each marker plane, determine the pitch, π, of the cut-off line in the plane of the fault by plotting stereographically the great circle of the fault plane, and the great circle of the marker plane. For example in Fig. 2B, $\pi_A = 34°$.
3) Select a direction on the map perpendicular to the fault's strike as the chosen viewing direction.
4) On the graph, locate the point on the horizontal axis corresponding to the known strike separation (Fig. 2C). Draw a line through this point which is tilted at the angle of pitch with a correct sense considering the viewing direction. Incidentally, the intercept on the vertical axis gives the dip separation with positive values corresponding to the up-throw of the near block.
5) The line drawn in (4) is called here the *solutions line* because a vector drawn from the origin of the graph to any point on this line represents a possible solution for the net slip of the fault. This vector, which points away from the origin, represents the direction and magnitude of net slip of the near block relative to an assumed stationary far block (Fig. 2C). A single displaced planar marker thus constrains the slip direction to a range of 180° (Hill, 1959), and the magnitude of slip cannot be less that the cut-off separation (i.e., the separation measured in the fault perpendicular to the cut-off lines; Fig 2C). If the direction of the net slip is known from kinematic information derived from field indicators (e.g., slickenlines) the vector can be drawn in the known direction and the amount of slip determined from its intersection with the solutions line from a single displaced marker.
6) If a slip direction is not known *a priori*, a unique determination of the net slip vector is obtained by plotting the solutions line for a second marker in the above manner (Fig. 2D). The point of intersection of the two solutions lines defines the head of the slip vector describing the relative movement of the near block.

3. Examples

3.1. South Wales

A prominent set of steeply-dipping faults cut the South Wales coalfield. These faults strike N–S in the west of the coalfield and NW–SE in the east. They are classified as cross-faults in relation to the limbs of the east–west trending South Wales syncline (Owen and Weaver, 1983; Trotter, 1947) indicating that at least in part they post-date the main Variscan folding. Published slip estimates for the cross-faults are rare, though magnitudes of throws (the horizontal component of the dip separation) deduced from coal seam offsets are sometimes quoted (e.g. Cole et al., 1991; Owen and Weaver, 1983).

Data on the cross-faults were collected from the geological map of the Ammanford District (Geological Survey of Great Britain). The area lies on the north limb of the South Wales syncline and the faults dissect Devonian rocks in the north and Upper Carboniferous (Coal Measures) rocks in the south. Overall, the rocks dip southwards at decreasing angles towards the axial trace of the syncline in the south. The straight outcrops of the faults suggest they have steep dips.

The data, consisting of strike separations and angles of dip, were collected from at least two displaced geological contacts per fault. By assuming a vertical dip of the faults, separation-pitch diagrams could be plotted for 11 faults. Fig. 3A–C shows examples for three faults, and Fig. 3D shows a compilation of the results.

The results (Table 1) show that the faults have net slips in the range 73–428 m. They are oblique slip faults, i.e. they have both

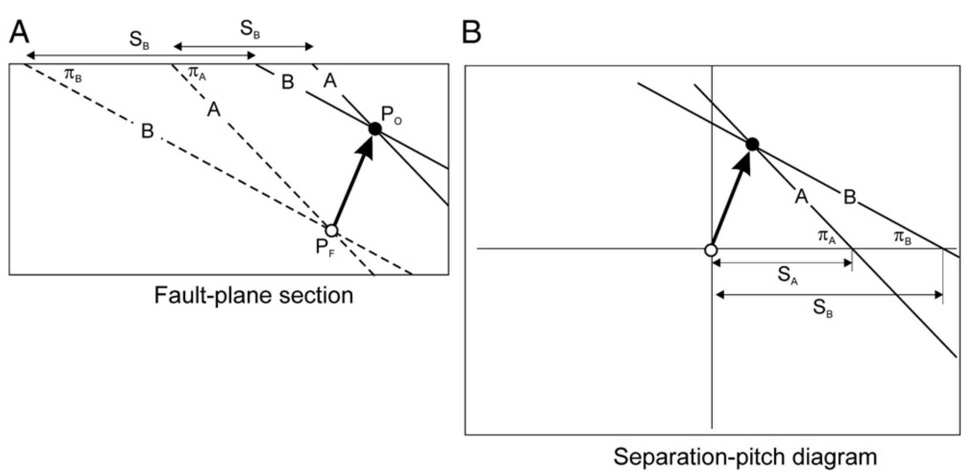

Fig. 1. A, fault-plane section with markers A and B intersecting to give piercing points P_O, P_F in the observer's fault wall and far fault wall respectively; B, separation-pitch diagram with slip vector relative to a stationary far wall of the fault.