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A simple method for the determination of the dilation direction of intrusive sheets

M. A. Bussell

School of Earth Sciences, Thames Polytechnic, Walburgh House, Bigland Street, London E1 2NG, U.K.

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Abstract—It is shown that the occurrence of offsets of various orientations along the contacts of an intrusive sheet permits the rapid establishment of the net dilation direction for the sheet. The application of the method to some dykes on Arran shows that oblique opening of a fissure was sometimes accompanied by a vertical component of opening. The technique provides a tool for the analysis of patterns of crustal displacement associated with dyke intrusion.

INTRODUCTION

In many field studies dykes are frequently presumed to have been emplaced by dilation in a horizontal direction perpendicular to the trend of the dyke. When evidence of oblique dilation is observed, a common implicit assumption is that the shear component is dominantly horizontal. Under favourable circumstances simple geometric techniques permit the rapid establishment of the net dilation direction: the finite direction of opening of the dyke fissure. The techniques used involve an adaptation of standard fault solution methods (see, for example, Badgley 1959, pp. 174–178).

If pre-existing structures in the host rocks possess various orientations they may be used to monitor displacements caused by the emplacement of a dyke. Kuenen (1937) hinted that such a method might permit the establishment of the amount of central uplift within the cone sheet complex of Ardnamurchan. Footwall and hangingwall intersections may be established for these pre-existing structures (FW and HW in Fig. 1). From these the orientation of the net dilation direction may be found by considering a vertical section containing FW and HW. The trend is simply the azimuth of FW–HW while the plunge may be obtained from the vertical section (A–B in Fig. 1) containing FW and HW. The problem with this solution is that there may have been movement along the fractures exploited by the dyke prior to dyke emplacement: the net dilation determined in this way may therefore be incorrect.

DISPLACED OFFSETS

Field observations of well-exposed dykes show that matching pairs of angular offsets of opposed contacts are very common. Currie & Ferguson (1970) described offsets from the margins of dykes, while similar structures were figured by Farmin (1941) from the walls of veins. Currie & Ferguson considered that lateral emplacement of magma along dilatant en échelon cracks was responsible for the formation of matching offsets. Nicholson & Pollard (1985) have also described the steps in dyke contacts that form by dilation and linkage of en échelon cracks during dyke emplacement. Pollard *et al.* (1975) considered that magma flow is parallel to the edges of these steps. Pollard *et al.* (1975) have discussed the stress conditions that accompany such fractures.

The present paper is concerned with dyke contacts that have formed by dilation along fractures of varying orientations and their use to establish the net dilation direction for a dyke. One condition only must be met for the method to work: that the intrusion is emplaced by dilation along fractures, the walls of which are preserved as intrusive contacts during the emplacement process. Offsets that are of no value in the determination of dilation direction may originate in a number of ways:

(i) plastic deformation of dyke and host rocks produces pinch-and-swell structures and boudins that may

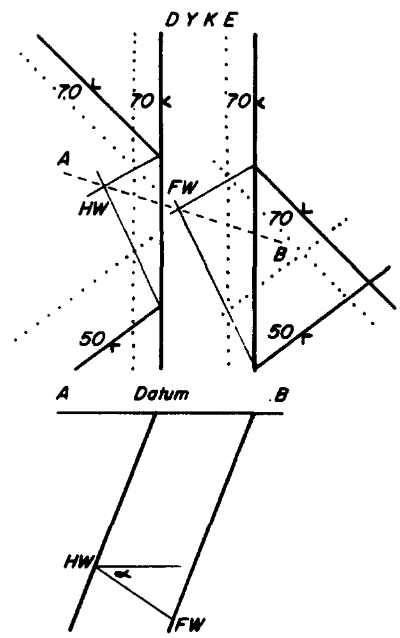


Fig. 1. Plan and cross-section (along dashed line A–B) of dyke that has cut and displaced two inclined planar structures. Dotted lines are structure contours at a constant depth, thin lines are lines of intersection between dyke wall and inclined planar structures. HW and FW are hangingwall and footwall piercing points.

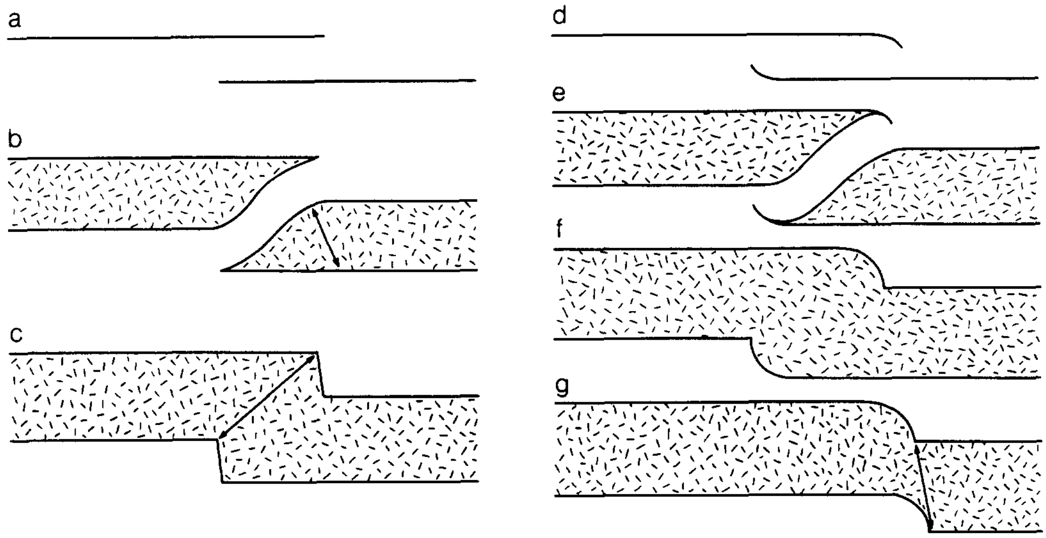


Fig. 2. (a–c) Diagram showing the sequence of emplacement of magma by dilation of dilatant en échelon fractures (after Nicholson & Pollard 1985). The arrows in (b) show the true dilation direction but in (c) they show the apparent dilation direction after bridge removal. (d–f) Diagrams showing the sequence of emplacement of magma by dilation of en échelon fractures with curving tips. In (f), linkage of two tips and removal of the bridge gives a superficial and false sense of dilation but the geometry of the offsets on opposite dyke walls does not match. (g) Shows how linkage by one fracture may prevent the removal of the bridge. The matching geometry of offsets permits the true strike of a dilation plane to be recognized.

appear similar to offsets (Roddick & Armstrong 1959, Nicholson 1985);

(ii) faulting may produce apparent offsets that may be mistaken for primary offsets in poorly exposed ground;

(iii) stoping of angular blocks from the walls of the dyke will produce offsets.

The first two cases are relatively trivial and pose no real problems, but the difficulties raised by stoping are more serious. Offsets resulting from random stoping may not match systematically on opposed dyke walls and are of no value in dilation determination. Dykes with offsets that have formed by the dilation and linkage of en échelon cracks in particular may be subject to breakage and removal of bridge material (Nicholson & Pollard 1985, Rodgers & Bird 1987, fig. 5). The result is an apparently matching pair of offsets that gives an entirely misleading indication of the dilation direction (compare Figs. 2b and c). However, if the bridge remains intact then Nicholson & Pollard show that the dilation direction may be determined directly by reconstructing the original position of the bridge prior to rotation (Fig. 2b). Bridges may also form by the dilation and linkage of curved en échelon fractures but the stoping of bridge material is easily recognized in this case since it results in a mismatch of angular and curved offset morphologies on opposed dyke walls (Fig. 2d–f). If such fractures are linked by only one of the curving crack tips then no bridge is formed and the matching morphology of the offsets, one composed of a concave inwards curve and the other convex inwards, is completely unambiguous (Fig. 2g).

Care must therefore be taken to distinguish between offsets which are of no value in establishing dilation geometry and those due entirely to the injection of magma along host rock fractures of different orientations. Offsets that have resulted from, or have been modified by, stoping are likely to be the most difficult to recognize and methods of minimizing such problems are suggested below.

Sheets with one offset

Dilation along fractures that are oblique to the principal fracture followed by the dyke results in the formation of an offset plane. The intersection of the offset plane with the main dyke wall will result in the formation of two offset edges (Fig. 3). A change of orientation of the dyke wall from one planar orientation to a different orientation will result in one offset edge along the intersection of the planes. Offset edges formed in this way will match with congruent edges of similar orientation on the opposite wall of the intrusive sheet and so may be used to constrain the net dilation direction.

If one matching pair of offset edges is available then the plane containing the dilation direction may be found. It is preferable that the plunge and trend of offset edges are measured directly. If this is not possible then strikes and dips of the contacts can be measured and the matching offset edges may be found on both sides of the dyke (AB and DC in Fig. 4a) either by construction or by stereographic projection. If the dilation has been non-

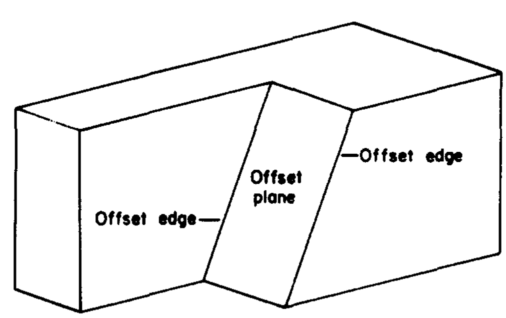


Fig. 3. Sketch showing the intersection of a dyke wall with an offset plane to form an offset edge.

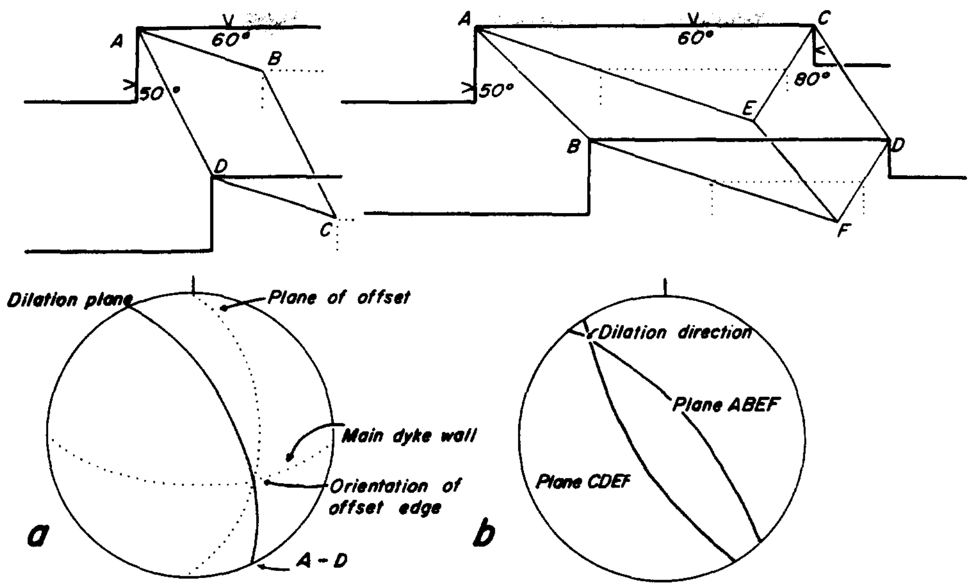


Fig. 4. (a) Plan of dyke with a pair of matching offsets; dotted lines are structure contours at a constant depth. ABCD is the dilation plane which has been found on the stereonet. (b) Plan of dyke with two pairs of matching offsets; dotted lines are structure contours at a constant depth. CDEF and ABEF are dilation planes which intersect along the dilation direction EF that has been found on the stereonet.

rotational these edges will have the same orientation on both sides of the dyke. The azimuth of the horizontal line which joins these two intersections (AD in Fig. 4a) is measured in the field and the dilation direction must lie in the plane containing the matching offset edges and this azimuth (ABCD in Fig. 4a). The dip of this dilation plane is easily obtained from the stereonet. A great circle is found which contains AB and AD and this great circle must contain the net dilation direction (Fig. 4a).

The example of Fig. 4(a) makes the important point that, in the absence of other information, the net dilation direction could lie anywhere in plane ABCD. Prior to dyke intrusion D could have been concurrent with B and DB could represent the net dilation direction. The plan view gives the impression of sinistral dilation but the dilation could have been achieved by movement of the hangingwall up and to the west with respect to the footwall.

The main value of the technique applied to one offset is that a limit may be set on acceptable net dilation directions. For example, any dilation direction that has been determined from the displacement of pre-existing structures in the wall rocks may be checked for consistency with the dilation plane determined by the single offset method. Contradictions between valid dilation information provided by contrasting sources, such as from wall rock structures and from a single dilation plane determination, may lead to further insights into the history of movement along a dyke trace.

Sheets with two offsets

Although the determination of a dilation plane is of value, it is clear that the occurrence of contrasting offset edge orientations on the dyke wall permits the determination of unique offset corners (Fig. 5). The offset corners may have no physical reality: they may have been removed by stoping. Nevertheless, if the converging offset planes forming the corners have formed by dilation along fractures without stoping, the concept of the offset corner can be used to resolve the dilation direction. Just as offset planes and edges will match on opposed walls of a dyke, matching offset corners can also be found. The line connecting a pair of matching offset corners across the width of a dyke will define the dilation direction for the dyke. It is most important that the offset planes are not separated from one another by other structures that could have contributed to the displacement pattern: for example a later cross-cutting dyke or a secondary branch of the same dyke. If this is not the case then the dilation direction determined will be entirely the result of dyke emplacement.

A plane of dilation is found for each matching pair of offset edges as described previously (planes ABEF and CDEF in Fig. 4b). The unique dilation direction is then defined by the intersection of these two dilation planes (EF in Fig. 4b). It must be emphasized that this is a finite dilation direction that must represent the accumulation

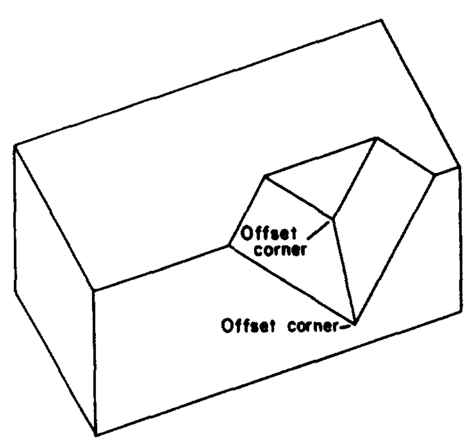


Fig. 5. Diagram showing the geometry of a dyke wall with two offsets that intersect to form offset corners.

of many (unknown) dilations that took place during the initial injection of the magma and over the period of magma flow prior to the final consolidation of the dyke.

Practical considerations

The usefulness of the technique depends on a number of factors. The size of the angle between the dilation planes is important: too narrow an angle could result in a large error in the estimated dilation direction. Reliance solely on such offset geometries should be avoided. As noted previously, the method will produce errors if the offset geometry has been modified by stoping. Because of this problem the angle between planes forming matching offset edges must be the same on both sides of the dyke. This will exclude offsets produced by stoping along fractures that are not parallel to offset fractures, but will not exclude the collection of data from offsets modified by stoping along parallel fractures on both sides of the dyke. In the case of curving offsets, stoping is clearly recognizable since removal of the intervening bridge produces a mismatch of angular and curved offset edges on opposed walls of the dyke (compare Figs. 2f and g). As a general principle it seems most unlikely that matching offset edges defined by an axis of curvature rather than a sharply defined linear intersection of two planes could result from stoping. Such offset edges provide secure data. Further, edges defined by the intersection of long smooth planar dyke walls are unlikely to have been significantly modified by stoping. Dilation planes found using these types of edges will similarly provide sound data. Other offset edges result from the dilation of overlapping planar rather than curved fractures (Figs. 2a–c) but it should be observed that when these fractures have overlaps that are short relative to their separation, bridges will be small and the contribution of any stoping to the apparent dilation consequently less significant. Dilation determinations that are seriously in error due to stoping should be recognizable if multiple determinations of dilation planes for each dyke are made. Ideally, as many dilation planes as possible should be determined. Poles to these dilation planes may then be plotted and, providing that the scatter is not too large, the dilation direction is the pole to the great circle that most closely fits the distribution of poles to dilation planes. The method is directly comparable to that used in paleomagnetism studies (Halls 1976, Bailey & Halls 1984) and in the determination of fold axes.

Other problems may arise in the application of the method if there is significant vertical dilation and the orientation of an offset plane changes with height. This feature may sometimes be observed on well-exposed dykes in which the dyke rock has been removed by erosion to expose the morphology of the walls in three dimensions (see Pollard *et al.* 1975, fig. 14B). When this change in offset orientation can be observed and matched on both walls of such dykes then it can be turned to advantage since direct identification of an offset corner and field measurement of the dilation direction is possible. This is the case in one of the examples described below.

EXAMPLES OF DILATION DETERMINATIONS

Permo-Triassic sedimentary rocks on the Isle of Arran, Scotland, are cut by a number of Tertiary basic dykes on well-exposed wave-cut platforms. Examples from these shoreline exposures at Cleiteadh, west of Kildonan, and between Corrie and Brodick provide illustrations of dilation determination (Fig. 6).

Dyke dilation in southern Arran

Examples from west of Kildonan and Cleiteadh in southern Arran are shown in Figs. 7 and 8. Figure 7(a) shows three pairs of matching offsets. Two of these are matching concave- and convex-inwards surfaces while the third results from the intersection of planar dyke walls of different orientations. Following the previous discussion, a high degree of confidence can be assigned to the three resulting dilation planes. These dilation planes are consistent with a dilation vector that plunges at 3° towards 072°. An adjacent dyke (Fig. 7b) provides closely comparable results, while an aggregation of dilation planes for the Kildonan area can all be satisfied by the same dilation direction (Fig. 7c). West of Cleiteadh a ruptured bridge has been preserved close to matching offset fractures on opposed walls of the dyke (Fig. 8). The shape of the northern end of the bridge

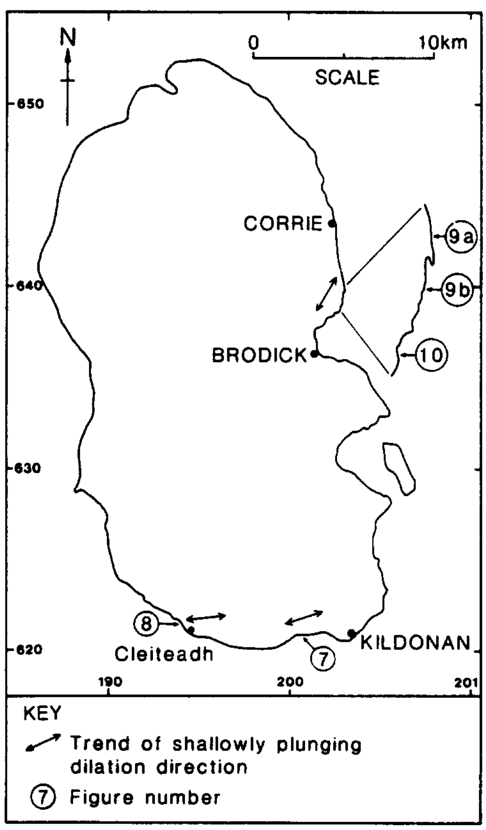


Fig. 6. Map of Arran, Scotland, showing the locations of Figs. 7–10 together with dilation directions found for those areas.

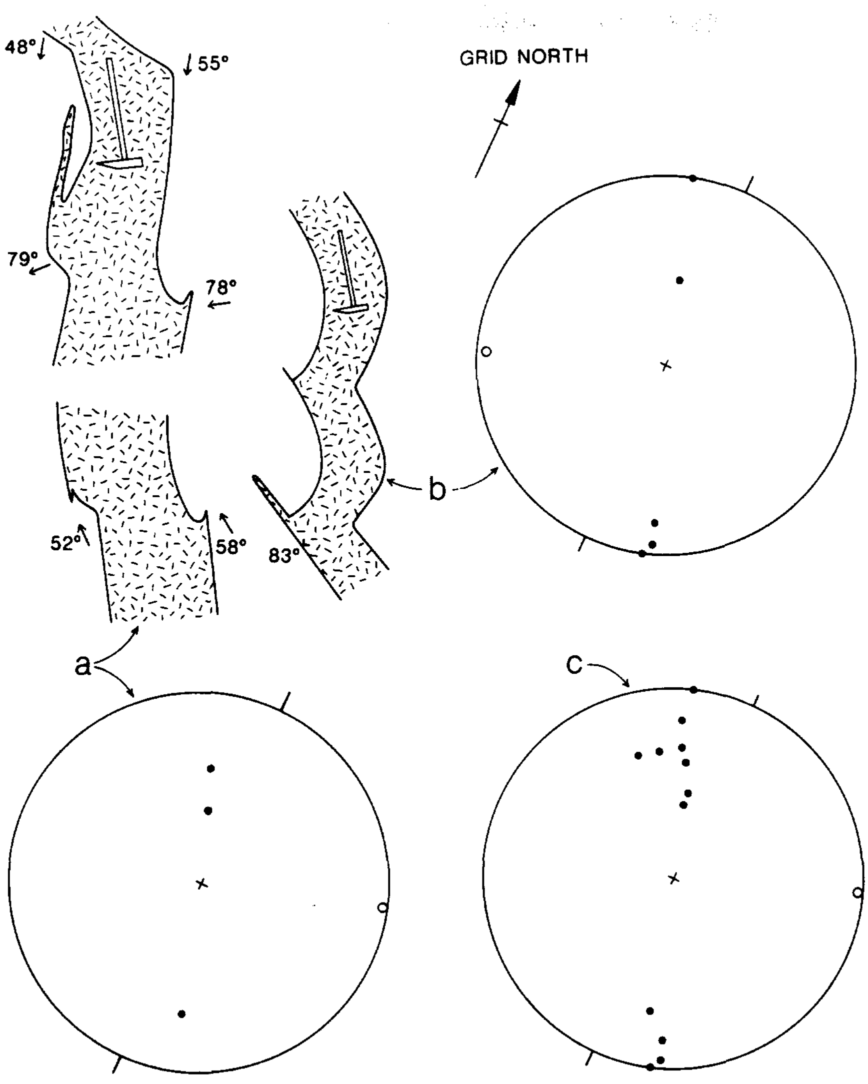


Fig. 7. Sketch maps of dykes near Kildonan (located in Fig. 6). Plunges of offset edges that depart significantly from the vertical are shown. On the stereonets dilation plane poles are solid circles, open circles are deduced dilation directions. Stereonet (a) shows data for the dyke indicated. Stereonet (b) shows data for the dyke indicated together with data collected from the same dyke along strike from the sketch. Stereonet (c) shows all the data for the Kildonan area.

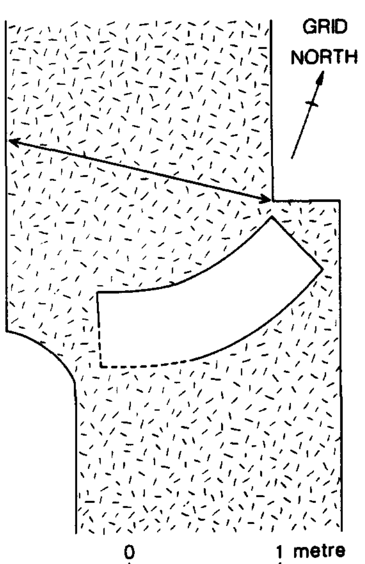


Fig. 8. Sketch of dyke near Cleiteadh (located in Fig. 6) illustrating the stoping of bridge material. Broken lines indicate uncertainty. The arrow indicates the dilation direction assuming minimal stoping from the southern end of the bridge.

matches closely the offset in the eastern wall of the dyke, but because of poor exposure, the shape of the southern termination of the bridge is less clear: it is possible that some material may have been stoped, either from the bridge or from the offset in the west wall of the dyke. Restoration of the slab of rock forming the bridge to its probable position prior to dilation and rotation permits the horizontal component of dilation to be determined in the same way as for the dyke of Fig. 2(b). Restoration shows that the dyke dilated along a bearing of 084°. If significant stoping took place then this azimuth would be larger.

Dykes in eastern Arran

A number of fractures affect the Permian dune sandstones between Brodick and Corrie. Some aspects of these fractures have been described recently by Woodcock & Underhill (1987) and Underhill & Woodcock (1987). Careful examination of field relationships shows that a general chronology of fractures exists

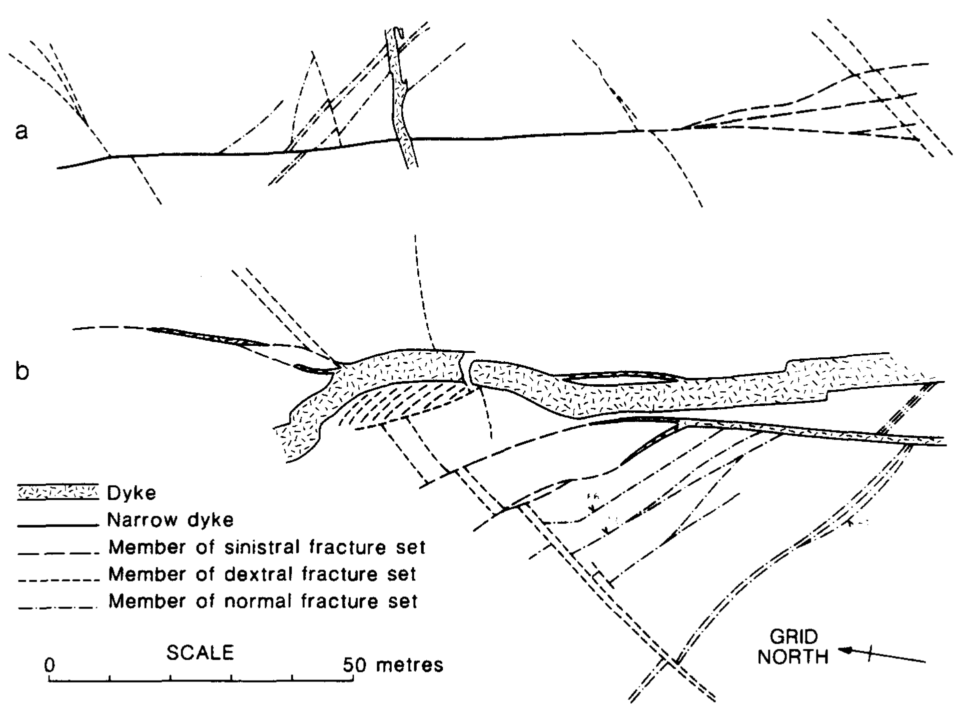
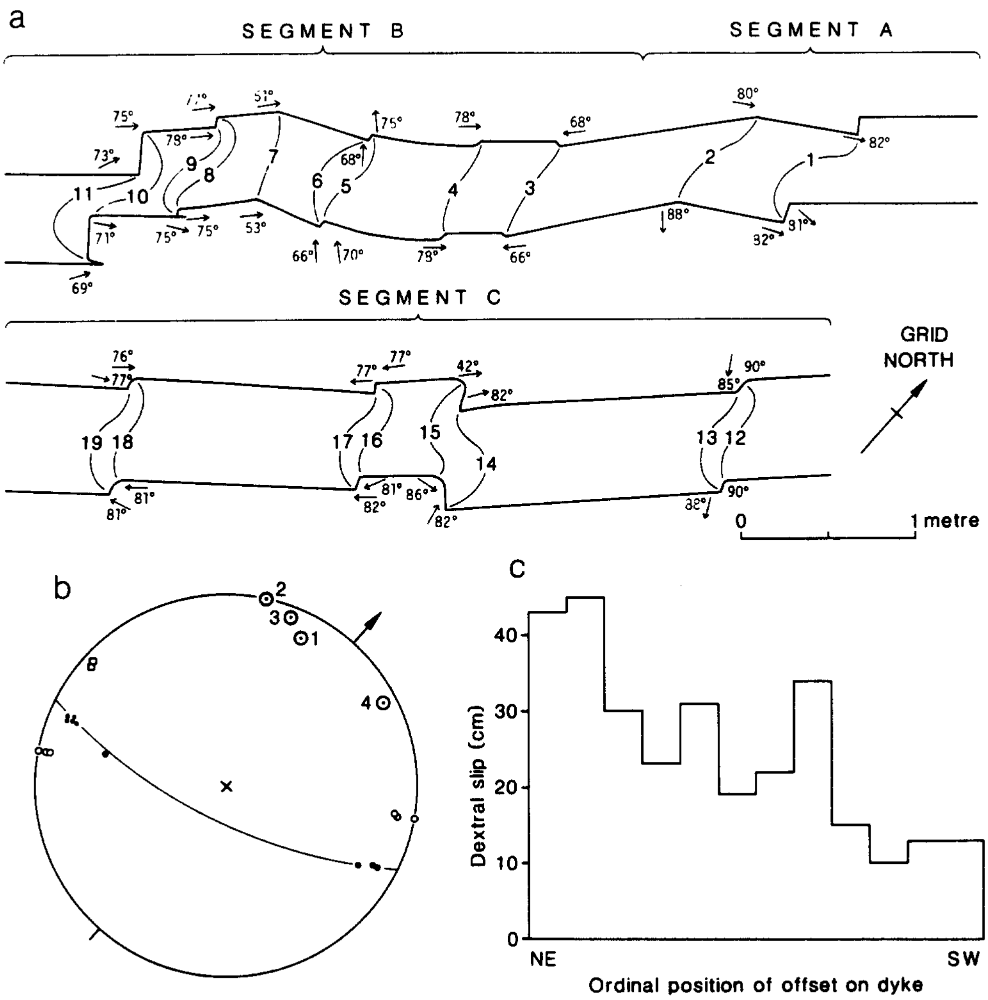


Fig. 9. (a) Narrow dyke emplaced by sinistral dilation (located in Fig. 6). (b) Dykes emplaced by dilation during sinistral movement of fractures (located in Fig. 6). Note the displacements of earlier fractures and the preservation of rotated bridge material.

in these localities (Fig. 9). Earliest were NW–SE-trending normal faults which may dip either to the northeast or southwest. These are cut by NE-trending dextral and oblique-slip faults. Both sets of fractures are cut by a number of N-trending dykes and associated fractures across which they show left-lateral separation. Splay fracture patterns extend beyond the terminations of these dykes as sinistral shears (Figs. 9a & b). These fractures may either be baked or possess thin selvedges of basalt. One of the dykes forms two en échelon segments separated by a bridge that remains unruptured (Fig. 9b). The bridge has been rotated sinistrally during the opening of the dyke fissures: bedding of the dyke wallrocks strikes at 303° and dips 27° to the southwest, but in the bridge it has been twisted anticlockwise to strike at 263°, with a dip of 41° towards the south. Because of the continuity of the bridge there seems to be little scope for relative vertical movement of the walls. The original position of the bridge before the rotation that accompanied dilation may easily be estimated and the horizontal dilation vector is found to trend towards 035°. This dilation vector also satisfies the geometry of a displaced earlier fault and so no prior displacement along the line of the dyke has taken place. The fracture chronology, the geometry of the bridged dyke and the clear relationship between the sinistral fractures and the basic dykes leave little doubt that the dykes were emplaced along the N-trending fractures during active wrenching.

Another dyke trends towards the NE in the same area. This dyke (Fig. 10) is of particular interest for the large number of offsets that it possesses and for the fact that the upper part of the dyke has been eroded away cleanly, leaving the sandstone walls and their offset surfaces very well exposed. A number of features of offset geometry suggests that the offsets have probably suffered little modification by stoping. With the exception of edge 15, there is a close similarity between the orientations of matching offset edges on opposite sides of the dyke. The two offsets between edges 10–11 and 14–15 are relatively large but in all other cases the length of the offset planes are very short compared to the width of the dyke. Edges 2 and 7 result from the acute intersection of large planar dyke walls with contrasting orientations while edges 3, 4 and 12–15, are composed partially or entirely of matching curved offsets. Following the previous discussion, it is concluded that nearly all the offsets provide data which may be used with a high degree of confidence to determine dilation planes.

Because of the three-dimensional exposure it has been possible directly to identify matching offset corners on both walls of the dyke in segment B between offset edges 8 and 9 (Fig. 10a). Such is the good fit of matching three-dimensional offset corners observed here that there is little doubt that the net dilation vector plunges at 6° towards 339° (grid) for this segment of the dyke, giving a dextral, north-side-down sense of dilation. Consistent with this, the distance separating the downward convergent offset edges 3 and 4 (Fig. 10a) is greater on the north side of the dyke than on the south side. The same is true for edges 6 and 7. Because most of the displaced offsets along the length of the dyke are not vertical, the dextral component of their displacement must be estimated after taking the vertical component of dilation into account (Fig. 10c). Two main points are evident: firstly offsets at the northeastern end of the dyke show the greatest dextral displacement and those from the south-



⊙1 Best fit dilation direction for segment B
⊙2 Best fit dilation direction for segment C
⊙3 Dilation direction by direct observation for segment B
⊙4 Dilation direction from piercing point data
▫ Pole of dilation plane, segment A
• Pole of dilation plane, segment B
∘ Pole of dilation plane, segment C

Fig. 10. (a) Dyke with numbered offset edges (located in Fig. 6). Plunges of offset edges are shown. (b) Stereonet showing dilation plane poles and dilation directions for the dyke. (c) Diagram showing variation in the dextral component of slip along the length of the dyke.

western end have the least; secondly offsets within any one segment (A, B or C in Figs. 10a & c), show broadly similar components of dextral displacement that contrast strongly with those within the adjacent segment.

Poles to dilation planes determined for offsets from segment B are shown in Fig. 10(b), where they provide a very good fit to a great circle. The pole to this great circle is the deduced dilation direction for the data from segment B and it lies very close to the directly measured dilation direction referred to above. The data for segment B therefore are internally consistent.

Dilation planes in segments A and C are inconsistent with the dilation geometry of segment B (Fig. 10b). It may be observed on the map and the stereoplot that the dilation plane data for segment A can only be satisfied by a greater degree of dextral displacement during dilation while those of segment C require a dilation with a much smaller shear component (Figs. 10a & c). The nature of the fit of opposed walls of the dyke within each of the segments A, B and C makes it very unlikely that stoping has contributed significantly to these contradictory offset patterns, but an explanation related to the emplacement process may be proposed.

A piercing point solution for pre-existing cross-fractures displaced by the dyke gives a dilation direction plunging at a shallow angle towards 021° (Fig. 10b). The dextral component of this displacement is approximately 1 m and the vertical component approximately 15 cm. This implies that some dextral movement along the line of the dyke took place before dyke emplacement. Maximum dextral offset separation of 0.44 m is observed in segment A, and separation decreases to values of about 0.15 m in segment C. These observations can be reconciled by a model in which magma was injected from the northeast towards the southwest along a developing dextral fracture zone (Fig. 11). Some movement on this

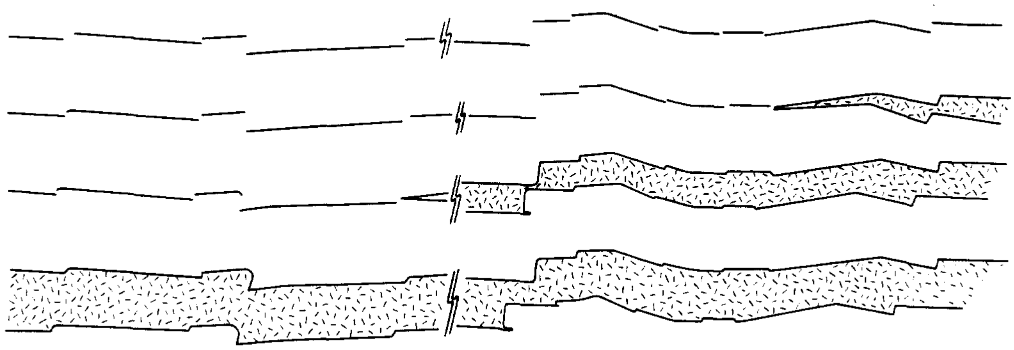


Fig. 11. Diagram showing a possible time sequence for the emplacement of the dyke shown in Fig. 10; the double line shows a break in the map. (a) Shows an initial stage of en échelon fractures that developed at the start of dextral shearing. These were linked to form offsets (b & c) during the injection of magma. These offsets were progressively displaced as magma advanced along the fractures (c & d). Although there is an apparent lateral migraton of magma, it is possible that the pattern developed by initial vertical injection of magma in stage (b), followed by further sequential vertical injection in stage (c) and finally stage (d).

array of fractures must have taken place before the arrival of magma at the site. Because of the postulated earliest injection of magma in the northeast, the offsets associated with segment A have undergone the greatest dextral transport. This is because they have accumulated displacements throughout the entire history of local magma injection. As the magma proceeded further to the southwest, displacements of offsets record progressively smaller amounts of dextral shear associated with dyke dilation (Fig. 11). The dilation direction most completely representative of the geometry of offset displacement during dyke injection is therefore that of segment A, which has a northerly orientation. The strong possibility remains that even this represents an incomplete record of events. The dextral slip on the fracture system that apparently predated dyke injection may have accompanied yet earlier emplacement of magma along the unexposed portion of the dyke lying to the northeast of segment A. This interpretation therefore takes the net dilation given by the piercing point solution of displaced pre-existing cross fractures as that most closely approximating the net dilation vector (Fig. 10b).

Finally, it may be noted that, in the examples of Figs. 9 and 10, dykes of contrasting trend were emplaced during episodes of shearing that were accompanied by dilation. NNW-trending dykes were emplaced by sinistral dilation along 035° and the NE-trending dyke was emplaced by dextral dilation along 021°. A general NNE dilation direction is consistent with all three examples figured (Fig. 6).

DISCUSSION

Dyke propagation direction

The data presented have a bearing on the general question of dyke propagation direction. A common view is that dyke propagation is principally in the direction of offset edges: an array of precursory finger-shaped bodies of magma form individual segments that extend ahead of the main advancing sheet intrusion (Pollard *et al.* 1975). Similarly, studies in the classic area of Spanish Peaks show that numerous magmatic flow indicators are aligned parallel to the edges of dyke segments. These segments dilated during initial emplacement and then acted as magma conduits carrying the magma upwards and outwards away from the magma focus (Smith 1987). In contrast Currie & Ferguson (1970) proposed that dykes studied by them extended laterally by magma injection at a high angle to steep dyke offsets. Sigurdsson (1987) presents a well-documented case for lateral dyke propagation and magma flow over distances of 70 km in Iceland. Increasing evidence for lateral dyke propagation and impressive large-scale lateral magma flow in Precambrian dykes has been summarized by Halls (1988). In the example of Fig. 10, a significant lateral component for dyke propagation is consistent with the data. Magma spread from the northeast along dilatant en échelon factures. Adjacent members of the set linked via the curved termination of one member of an overlapping pair (as in Fig. 2g) or by breakage of bridge material by a single fracture without stoping.

The vertical component of this propagation direction is unknown but it may be anticipated that a variety of propagation directions may develop during the emplacement of a dyke into an active strike-slip fracture zone. Indeed, the contrasting views on dyke propagation are not incompatible: vertical and lateral dyke propagation may take place at the same time along different parts of the same developing dyke fissure. For example, where magma is penetrating vertically from a uniform depth, and at a constant rate, along en échelon fractures then fracture linkage and offset formation might occur simultaneously at the same crustal level. Any subsequent strike-slip displacements of fissure walls before dyke consolidation would produce roughly constant strike-separation of matching offsets. By contrast, where magma has penetrated by vertical injection along en échelon fissures with a significant lateral gradient of injection rate then at any one structural level there will be an apparent lateral migration of magma. Similarly, offsets will be progressively younger in the direction of apparent magma migration and a gradient in their lateral displacement might be set up: the oldest offset undergoing the greatest displacement as seems to be the case for the dyke of Fig. 10. From this it follows that the location of a zone of greatest offset displacement may lead to the location of that sector of a dyke first penetrated by rising magma.

Regional dyke swarms

The geometry of dykes has often been used to establish the nature of large-scale patterns of crustal dilation associated with dyke swarms. Such studies are limited where dyke orientations are taken from regional maps and limitations may be compounded if only the horizontal component of opening perpendicular to the strike is considered. The techniques described here permit the correct three-dimensional determination of dilation direction for dykes to be made and the maximum amount of information from the primary field evidence to be extracted. The observations presented above show that plunging dilation directions may be recognized. Dykes of different trend at the same location may share closely similar dilation directions: they must have been emplaced under the same conditions of regional strain, perhaps during the same tectonic episode. Similarly, it is possible that dykes of the same trend may possess contrasting dilation directions if emplaced under different conditions of regional strain.

Models of stress systems for dyke emplacement are often based on the assumption that dykes have been emplaced along true extensional fractures with no shear component (Odé 1957, Moore & Shanti 1973); Vann (1978) based a model for the stress regime on Arran on this assumption. While such studies provide helpful and stimulating attempts to model the stress trajectories associated with sheet intrusion, they are limited by their lack of reference to the dilation geometry that may be obtained from field study of the dykes. Consideration of the examples from Arran shows that shallowly-plunging dilation directions predominate. In northeast Arran these shallowly-plunging dilations trend between 021° and 035° while on the south coast they vary from 072° in the east to 084° in the west (Fig. 6). It may be suggested speculatively that this forms part of a concentric pattern of dilation trajectories centred on northwest Arran.

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