Pergamon

Journal of Structural Geology, Vol. 17, No. 11, pp. 1535 to 1542, 1995

0191-8141/95 $9.50+0.00

0191-8141(95)00063-1

Blunt-ended dyke segments

S. A. KATTENHORN* and M. K. WATKEYS

Department of Geology and Applied Geology, University of Natal (Durban), P.O. Box X10, Dalbridge, 4014, South Africa

(*Received* 21 *September* 1994; *accepted in revised form* 29 *April* 1995)

Abstract—Two examples of blunt-ended dykes from the Rooi Rand dyke swarm in South Africa are examined in order to determine the mechanism by which such features form. Although other interpretations of blunt-ended dykes have been proposed, evidence in the Rooi Rand examples suggests that dilation was transferred along a zone of shear at the dyke tip oriented at a high angle to the dyke plane. Microscopic analysis of samples from blunt-ended tip regions reveals cataclasis and mineral straining in the dyke walls in the zone of dyke linkage. The indication is that adjacent, blunt-ended, en échelon dyke segments dilate along a shear zone, producing cataclasis of the host rock. Both segments dilate in this manner and are blunt-ended prior to linkage. Horns may develop at the outer corners of the blunt tips so that, subsequent to linkage, the overall geometry resembles that predicted by the conventional model of bridge failure between overlapped en échelon dykes. However, permanently strained bridges predicted by that model are not necessary for the model described here. In addition, blunt-ended dykes that dilate along a cross-linking shear zone do not need to overlap in order to link together, in contrast to existing model predictions. Dilation adjacent to a blunt-ended dyke may also be accommodated by intrusion of magma into shear zone fractures that vary in orientation with respect to the main dyke. Near the dyke, the near-tip stress field overrides the remote stress field and generates magma-filled shear-related fractures at high angles to the dyke plane. With increasing distance from the dyke, the remote stress field becomes dominant and resultant shear-related fractures are oriented at successively lesser angles to the dyke plane.

INTRODUCTION

Blunt-ended dykes present theoretical problems. Elasticity theory approximates intrusions as being elliptical (Pollard 1973, Gudmundsson 1983a), although exceptions occur where gradients in internal magma pressure or regional stress exist (Pollard 1976), or where host rock ductility is variable along the length of an intrusion (Pollard & Muller 1976). Alternatively, deviations from the elliptical geometry approximation, as frequently occur in rock, may be produced through the interaction of the near-tip stress fields of overlapping en échelon intrusion segments. The interaction is related to the manner in which the adjacent intrusions are spatially arranged (Pollard 1973, Rogers & Bird 1987, Ransome 1991), but may also be affected by the remote differential stress (Olson & Pollard 1989, Thomas & Pollard 1993). For example, fractures oriented perpendicular to a regional tension and parallel to a regional compression (large remote differential stress) tend to exhibit straight propagation paths, rather than paths that converge, as occur under isotropic conditions (zero remote differential stress). Exceptions to the latter circumstance are possible however, under conditions of subcritical fracture growth or where the ratio of shear component to fracture opening is low, in which case surface roughness effects become significant (Renshaw & Pollard 1994a).

Numerous authors have documented the growth mechanisms of en échelon fractures, dykes and veins (e.g. Anderson 1951, Ramsay 1967, Hancock 1972, Nicholson & Pollard 1985, Thomas & Pollard 1993). Arrays of en échelon fractures and veins were classically assumed to be evidence of shear zones (Lajtai 1969, Hancock 1972, Rickard & Rixon 1983). More recently, however, some en échelon joints and intrusions have been interpreted as breakdown segments of a planar parent fracture that rotated out of the plane of the parent under mixed mode I–III loading (Pollard *et al.* 1982, Pollard & Aydin 1988). A third possibility, suggested by numerical simulations (Olson & Pollard 1989, 1991, Du & Aydin 1991) is that en échelon fractures develop under mode I conditions. This is supported by laboratory experiments on a brittle coating attached to an acrylic sheet under an applied tension (Renshaw & Pollard 1994b).

Nicholson & Pollard (1985) described two end-member scenarios for dilating en échelon fractures that are linked together (Fig. 1). Fractures with straight propagation paths link via failure of the bridge of host rock separating the overlapping segments (Fig. 1a), resulting in bent bridge formation. Overlapping fractures with curved propagation paths (Fig. 1b) form *T*-type intersections and result in rotated bridges of host rock. Where linkage occurs through failure of the intervening bridge between adjacent, overlapped segments (Fig. 1a), the segments may exhibit abrupt terminations, called steps (Nicholson & Pollard 1985, Pollard 1987) or offsets (Pollard *et al.* 1975, Bussel 1989) flanked by horns. Excluding the horns, such linked intrusions are essentially blunt-ended and these have been frequently documented (Noble 1952, Currie & Ferguson 1970, Pollard *et al.* 1975, Nicholson & Pollard 1985, Bussel 1989).

*Current address: Dept. of Geological & Environmental Sciences, Stanford University, Stanford, CA 94305, U.S.A.

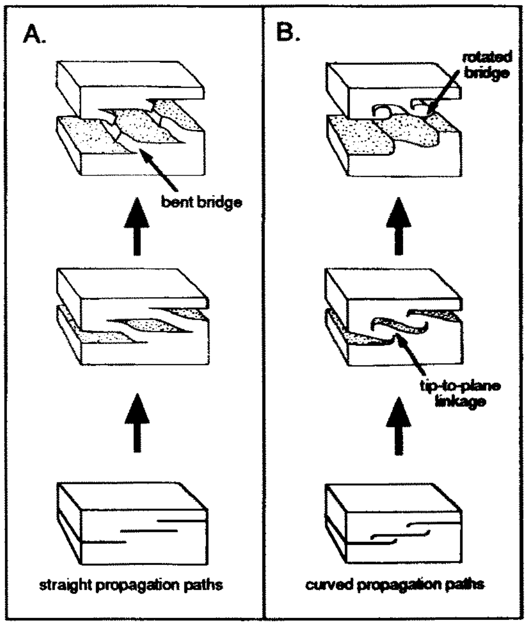

Fig. 1. End-member modes of en échelon dyke overlap and linkage (after Nicholson & Pollard 1985). (a) Dykes with straight propagation paths link via failure of the intervening bridge of host rock. (b) Linkage of curved propagation path dykes occurs when one dyke tip propagates into the near wall of the adjacent dyke.

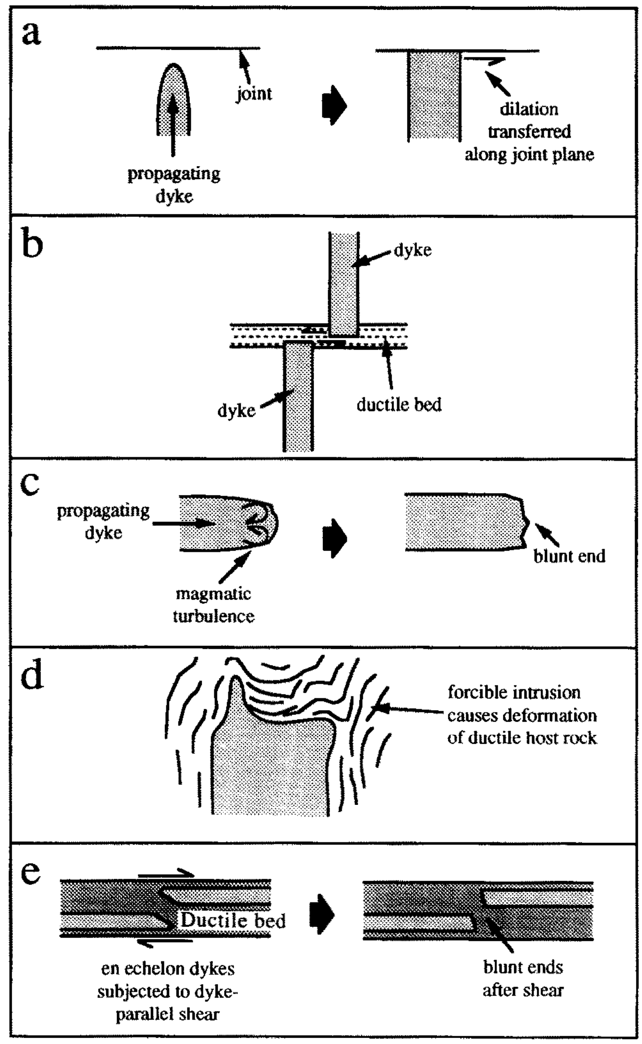

Fig. 2. Postulated conditions that may lead to the formation of blunt-ended dyke segments. (a) Dilation transferred along either a pre-existing joint at a high angle to the dyke plane, or (b) a pre-existing rock inhomogeneity (e.g. bedding or cleavage) at a high angle to the dyke plane. (c) Magmatic erosion at the dyke tip. (d) Forcible intrusion of magma causing ductile deformation of the host rock. (e) Dyke-parallel shear rotation of the host rock during intrusion.

In some cases, however, blunt-ended dykes exist where there is no overlap of adjacent segments, or where linkage of adjacent segments has not occurred, as seen in a two-dimensional outcrop. Such dykes have abrupt terminations, frequently almost perpendicular to the dyke length. Numerous mechanisms may be advocated to account for such dyke geometries (Fig. 2), such as dilation transferred along pre-existing joints (Fig. 2a, Baer & Beyth 1990, Stephenson 1990), contacts, or rock fabric (Fig. 2b, Gudmundsson 1983b, Baer & Reches 1987, Walker 1987) at high angles to the dyke plane; internal magmatic erosion (Fig. 2c, Platten & Watterson 1987) at the end of a sharp dyke; forcible intrusion via deformation of the host rock (Fig. 2d, Noble 1952); or shear displacement of the host rock parallel to the dyke length during dyke emplacement (Fig. 2e).

This paper presents the findings of an investigation of dykes at the Rooi Rand dyke swarm in South Africa (Fig. 3). The results indicate that blunt-ended dykes can result from the breakdown of a parent dyke into individual en échelon segments that remain parallel to the plane of the parent dyke. Dilation induces a stress concentration between adjacent segments, resulting in a zone of cataclasis of the host rock associated with opening transferred along a shear zone linking the segments. The individual segments may eventually re-link along the shear zone as converging points in each segment meet, forming abrupt steps along the resultant dyke at high angles to the dyke length. Such blunt-ended dykes may thus form as a result of dyke segmentation under mode I conditions, followed by linkage of adjacent segments, rather than being the result of linkage of overlapping en échelon dyke segments that form under mixed mode I–III conditions at the leading edge of a parent dyke.

Blunt-ended dykes with no apparent adjacent segment may also show the effect of dilation being transferred along a shear zone that extends away from the dyke into the adjacent host rock. An example is described in which dyke material has intruded fractures within the zone of shear.

ROOI RAND DYKE SWARM

The Rooi Rand dyke swarm, in the southern Lebombo region of southern Africa (Fig. 3), consists of basaltic (dolerite) dykes. It extends a distance of approximately 200 km from the Hlazane River, KwaZulu–Natal, in the south, to central Swaziland in the north, and has been described by numerous authors (e.g. Bristow 1976, Armstrong 1978, Saggerson *et al.*

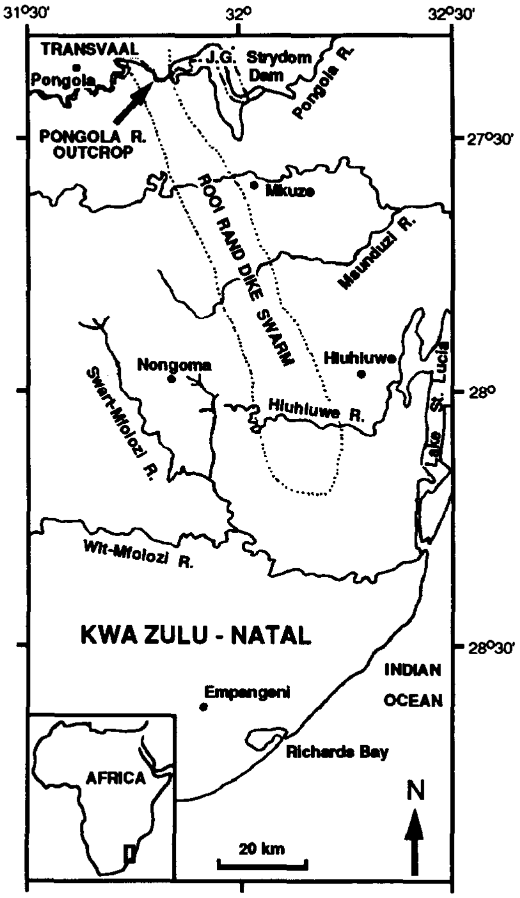

Fig. 3. Location of the Rooi Rand dyke swarm in southern Africa. The outcrop position along the Pongola River is indicated.

1983, Armstrong *et al.* 1984, Duncan *et al.* 1990). Many dykes were intruded 188, ±5 million years ago (K–Ar date; Cleverley 1977), resulting in both single and composite intrusions (the latter referring to dykes that intruded through the centres of older dykes). The dyke swarm has an approximately N–S trend, dips steeply to the west at 65–75°, and reaches a maximum width of about 20 km (Armstrong *et al.* 1984). The swarm is the manifestation of an estimated 40% regional crustal extension (Saggerson *et al.* 1983). Its dolerite composition resembles enriched MORB produced by decompression melting due to lithospheric thinning associated with mantle plumes (Duncan *et al.* 1990) and/or early attempted fragmentation of eastern Gondwana during the Jurassic.

Ten episodes of dyke intrusion have been postulated on the basis of field relationships (Watkeys *et al.* unpublished mapping), petrography and geochemistry (Meth 1991). The dykes range in width from 25 m to mm-scale dykelets (Armstrong *et al.* 1984). At this locality they intrude the Karoo Supergroup, isolating selvages of Permo–Triassic shales and early Jurassic dolerite sills. Many of the thinner dykes exhibit en échelon geometries and abrupt offsets, with linkage of adjacent segments frequently in accordance with Nicholson & Pollard's (1985) model (Fig. 1). Some older dykes contain cooling joints at right angles to the dyke margins. Where younger dykes are intruded along the centres of older dykes, these cooling joints have often been intruded by younger dyke magma and dilated by as much as a few centimetres.

EN ECHELON DYKE DEVELOPMENT

At the Pongola River outcrop (Fig. 3), a 3.5 cm thick vertical dyke within the dyke swarm is composed of a number of linked en échelon segments. A portion of the outcrop was removed and sawn into rock slabs cut perpendicular to the dyke, along the horizontal plane. In addition, each slab was cut along numerous planes oriented perpendicular to both the dyke plane and the horizontal plane (Fig. 4a). This facilitated the construction of a three-dimensional representation of the dyke (Fig. 4b), showing the nature of zones of offset and linkage. For the sake of clarity, the slabs are shown (Fig. 4b) so that the top surface of each slab is visible. In reality, each upper surface joins directly onto the lower surface of the overlying slab in the sequence. Where steps are oblique to the propagation direction within the dyke plane, offsets in the horizontal plane (Fig. 4b) are accompanied by visible offsets in the vertical plane, but offset segments are parallel to the plane of the parent dyke.

The blunt-ended nature of the adjacent dyke segments is apparent in Fig. 4(b). Lower down, where the

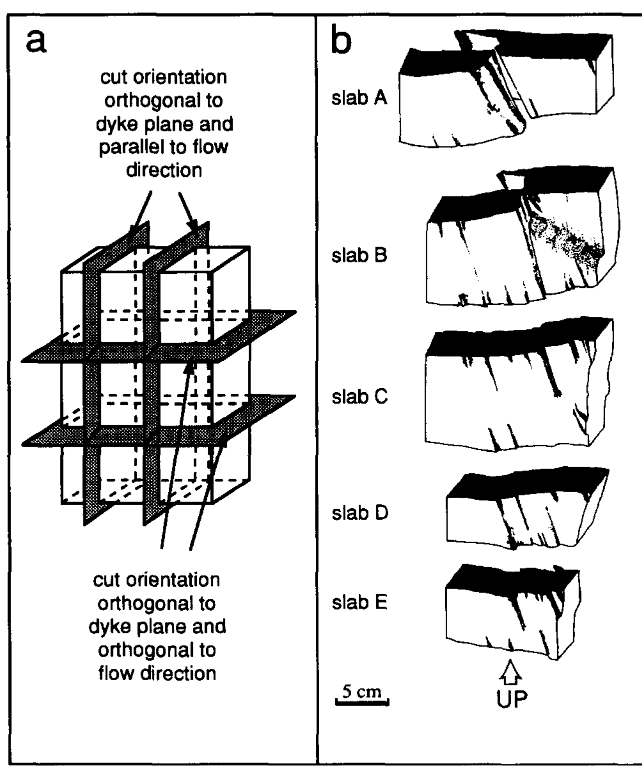

Fig. 4. Three-dimensional representation of dyke intrusion at the Pongola River outcrop, with host rock omitted. (a) A sample of the dyke was cut into rock slabs to allow the determination of the three-dimensional dyke geometry. (b) A single dyke divided into two en échelon segments in the propagation direction. The segments dilated as blunt-ended dykes, with a horn projecting away from the outer edge of one dyke segment.

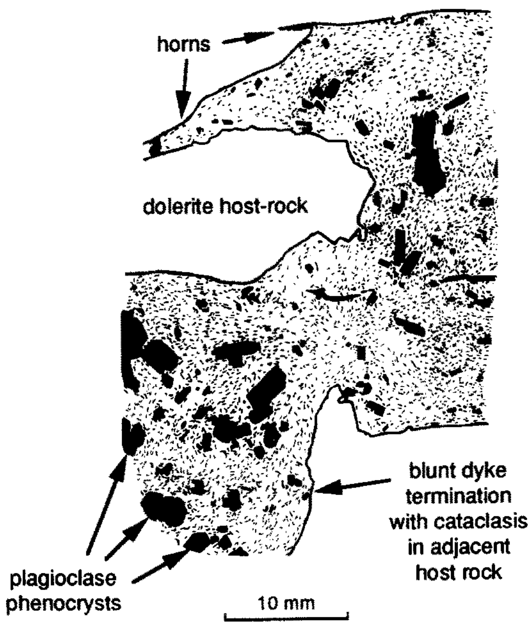

Fig. 5. Dyke morphology in the zone of linkage of the blunt-ended, en échelon dyke segments shown in Fig. 4, slab B. Orientations of acicular microphenocrysts and tabular phenocrysts of plagioclase are shown. As a result of size constraints of the thin section, one margin of one dyke segment is not visible.

adjacent segments are linked, sharp offsets occur despite no overlap of the segments (slab C, Fig. 4b). Higher up (slabs A and B, Fig. 4b) the blunt-ended segments are not linked, and one of the segments exhibits a horn on the outer edge. The horn is not present lower down (lower part of slab B, Fig. 4b), where the amount of offset is noticeably smaller than higher up, thus it increases in length along the propagation direction. The lower edge of the horn plunges at 26° at the lowest level, but reaches a stable configuration higher up, where it plunges at 80°. This latter orientation parallels the calculated flow direction in the dyke, determined using a three-dimensional statistical digital analysis of chill-zone phenocrysts along the frozen dyke margins. Similarly, the grain of the dyke walls (Fig. 4b), produced by steeply plunging minor steps, also parallels the flow direction.

Within slab B of the dyke (Fig. 4b), the zone of linkage of the blunt-ended segments was examined in thin section (Fig. 5). The host rock was examined in the vicinity of the linkage to locate evidence indicating the dilation mechanism. The occurrence under the microscope of a zone of cataclasis of the dolerite host rock in the region between the offset dyke segments, and along the edges of the blunt-ended terminations, suggests that dilation may have been facilitated by a miniature shear zone that linked the underlapping segments at a high angle to the dyke plane. Dilation of the dyke segments was transferred along this shear zone, resulting in cataclasis of the host rock. The chloritization of pyroxene and sericitization of plagioclase characteristic of this zone may be an indication that chemical effects associated with magmatic fluids weakened the host rock in the region of stress concentration between the adjacent segments.

A reconstruction of the dilation history, as seen in a two-dimensional plan view of the dyke, is presented in Fig. 6. Microscopic features that were connected prior to dilation, such as zones of cataclasis and fracturing, were reconnected during conjectural increments of dyke closure. The shear zone (right-lateral in the plane of Fig. 6) did not propagate beyond the outer edges of each dyke segment. This resulted in a significant amount of strain being imparted to the dolerite host rock on the outer edges of the dyke segments, along a zone parallel to an in-plane projection of the shear zone. Strain effects in plagioclase crystals include bent, elongate grains, grain annealing, mechanical twin formation (e.g. Tullis 1975) and the development of subunits within strained crystals, similar to an effect described for strained pyroxene crystals (Saggerson & Logan 1988). Pyroxene crystals exhibit undulatory extinction in cross-polarized light, and are more commonly chloritized in the strained zone. Numerous, closely spaced dyke-parallel fractures immediately adjacent to both dyke margins (Fig. 6), exhibit microscopic amounts of shear.

MULTIPLE OFFSHOOTS

A second blunt-ended dyke at the Pongola River site (Fig. 3) provides additional evidence of dilation along a zone of shear (Fig. 7). In this two-dimensional example, an adjacent dyke segment is not visible at the outcrop. The 31 cm thick dyke exhibits a rectangular termination with a 4.5 cm wide horn extending from the western edge (Fig. 7a). In addition, a number of thin (1–2 cm) offshoots extend away from the eastern edge of the blunt termination, essentially perpendicular to the plane of the dyke, but oriented at successively smaller angles to the dyke plane further away from the dyke. Dilation of the dyke was transferred along a left-lateral shear zone (with respect to the plane of Fig. 7). The zone of shear does not involve displacement along a discrete fault plane, but rather a zone of numerous progressively dilated fractures, comparable to en échelon veins in a zone of ongoing shear (Cloos 1955, Ramsay 1980, Fig. 7b) or extensional shear fractures (Engelder 1987). The cumulative dilation of the intruded shear fractures (simplified as $d_1 + d_2 + d_3$ in Fig. 7c), measured perpendicular to the plane of the main dyke, constitutes a dilation, D, in the region adjacent to the main dyke. This cumulative dilation of numerous dykelets may account for the lack of an adjacent dyke segment. The amount of opening, $i = 4.5$ cm, in the main dyke associated with the horn projecting from one of the blunt end corners (Figs. 7a & c) is interpreted as the initial amount of elastic dilation prior to shearing orthogonal to the dyke termination and formation of the multiple offshoots.

DISCUSSION

En échelon dykes and fractures have previously been interpreted as a breakdown fringe at the leading edge of a parent feature that propagated within a rotating stress

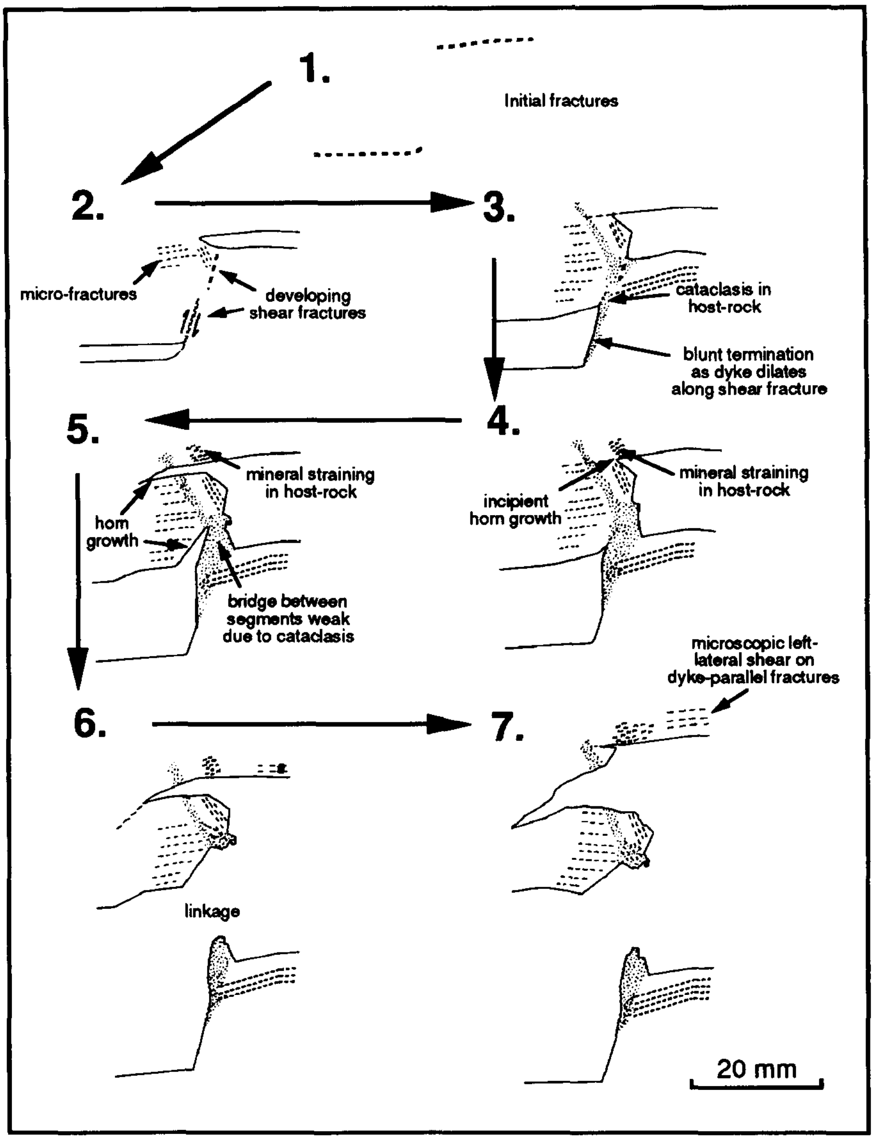

Fig. 6. Reconstruction of the dilation history of the blunt-ended, en échelon dyke segments in the zone of linkage shown in Fig. 5, as seen in two dimensions. Zones of cataclasis and shear fracturing are shown. Dilation along shear fractures oriented at high angles to the dyke plane resulted in blunt-ended dyke segments. Mineral straining occurred in the outer walls of the dyke segments adjacent to the zone of linkage. The actual timing of horn development during the dilation sequence is unknown and only conjectural in the reconstruction.

field (Pollard *et al.* 1975, Delaney & Pollard 1981, Pollard *et al.* 1982), or as having localized along a pre-existing zone of weakness oriented oblique to the then current orientation of σ_3 (Gudmundsson 1987). Numerical and laboratory experiments, however, have shown that en échelon fractures can form under a mode I remote tension (e.g. Olson & Pollard 1991, Renshaw & Pollard 1994b). The Rooi Rand dyke swarm is a physical manifestation of a failed rifting event and provides a good field approximation of conditions of remote tension that produced mode I features. In this region, therefore, the en échelon dyke segments formed under mode I opening conditions orthogonal to the maximum regional extension. The en échelon dyke segments shown in Fig. 4 were the result of dilation of out-of-parent-crack-plane fractures as the magma migrated towards the Earth's surface. In this example, intrusion proceeded via the splitting of an older, crystallized dyke along its centre, with intrusion occurring along a new set of mode I en échelon brittle fractures, producing chill zones in later magmas that facilitate recognition of the younger dyke phases. Intrusion thus proceeded via a repetitive splitting and re-linking action as the magma propagated upwards through the en échelon fractures along the centre of the older dyke. Conceivably, this could occur numerous times during propagation of dykes towards the Earth's surface.

Blunt-ended dykes which are not apparent correlatives of the Nicholson & Pollard (1985) model are frequently observed in the field, either linked or unlinked (i.e. Noble 1952, Currie & Ferguson 1970, Pollard *et al.* 1975, Bussel 1989, Baer & Beyth 1990, Figs. 4 and 7). The geometries of such dykes deviate from the elliptical profiles expected in elasticity theory (Pollard 1973), yet little attempt has been made to demonstrate the mechanism by which dykes form blunt

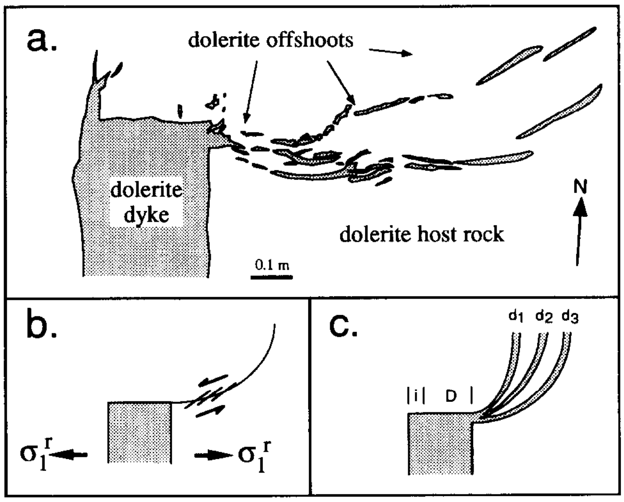

Fig. 7. (a) Multiple offshoots of dilated shear-related fractures adjacent to a blunt-ended dyke along the Pongola River outcrop (plan view). The magma flow direction is out of the plane of the figure. (b) The proposed zone of left-lateral shear curves gradually into parallelism with the dyke plane with increasing distance from the dyke. (c) In this schematic representation, cumulative dilation of the shear fractures is D ($= d_1 + d_2 + d_3$). In this way, dilation of the main dyke is accommodated in the adjacent host rock. Additional dilation in the dyke, i, is the initial elastic dilation of the dyke prior to development of a shear zone into the adjacent host rock essentially orthogonal to the dyke plane.

terminations prior to linkage with adjacent dyke segments. Following Pollard & Holzhausen (1979)'s account of stress intensity factor history as crack tips approach a free surface, Baer & Beyth (1990) suggested that blunt-ended dykes reflect an instantaneous decrease in the stress intensity factor at the tip of a dyke as it reaches a freely slipping interface, such as a joint. Stress intensity factor reduction at dyke tips may also be caused by ductile flow near the tip (DeGraff & Aydin 1993), resulting in tip blunting and a decreased propensity for dyke propagation.

However, at the Pongola River outcrop, microscopic evidence in the region of adjacent blunt-ended dyke segments, and a reconstruction of the dilation history (Fig. 6) in accordance with observed offsets of microscopic dyke margin features such as zones of cataclasis and fracturing, suggests that dilation occurred along a shear fracture linking the two dyke segments. This allowed the formation of the blunt terminations. The zone of shear does not continue beyond the dyke margins, discounting the possibility that dilation occurred via shear along a pre-existing joint plane. A cross-linking shear fracture may initially develop as two separate fractures propagating away from each dyke tip that would tend to approach each other and link (e.g. Du & Aydin 1993). The Nicholson & Pollard (1985) model predicts permanently strained bent bridges (Fig. 1a), with strains ranging from zero at the bridge centre (as seen in a cross-sectional view) to maxima at the two surfaces, and a similar distribution from the midsection to either end of the bridge. The strains occur as longitudinal extension along the convex surfaces and contraction along the concave surfaces. In contrast, blunt-ended en échelon dykes that dilate along cross-linking shear fractures produce no permanently strained bridges; deformation occurs along a zone of shear, and as strained minerals and minute slip surfaces in adjacent host rock. The overall shear effect may have application to step formation in twist-hackle fringes of joints (Pollard & Aydin 1988, Engelder *et al.* 1993). The steps between planar en échelon joint segments are frequently orthogonal to the segments and do not appear to result from modification of the growth paths of the individual joint segments.

Under static conditions of extension, the en échelon fractures would be expected to either interact and curve towards each other (under conditions of zero to intermediate, or negative, remote differential stress) (Nicholson & Pollard 1985, Olson & Pollard 1989), or propagate along straight paths (under conditions of large remote differential stress). An increased driving pressure would be required for continued growth (Olson & Pollard 1989) and eventual linkage would likely result from bridge failure (Nicholson & Pollard 1985, Fig. 1a). The large remote differential stress that might be expected to be associated with a dyke swarm (rift) setting would promote straight fracture paths. This may explain the lack of curved intersection type dykes (Fig. 1b) in the Rooi Rand outcrop. Where the dyke separation to length ratio is not too small (as seen in the plane perpendicular to the flow direction), linked en échelon dykes exhibit geometries similar to Fig. 1(a). However, adjacent, closely spaced en échelon dykes have difficulty overlapping, and the high shear strain in the region between the dyke terminations produced by near-tip stress interaction (e.g. Olson & Pollard 1991) may favour the development of a cross-linking shear zone, facilitated by high magma pressures in slightly underlapped dyke segments, and occurring at a high angle to the dyke plane. For example, Du & Aydin (1991) document a maximization of the stress intensity factor for narrow spacing of en échelon fractures at an angle of 80° to the fracture plane, where the tip spacing to fracture length ratio is low (~1). Linking fractures may also be initiated between, and at high angles to, pre-existing, overlapping en échelon fractures if the pre-existing fractures are subject to an applied shear, having the same sense as the sense of overlap (e.g. left-lateral, left-stepping) (Cruikshank & Aydin 1994). However, the Pongola River outcrop of the Rooi Rand dyke swarm exhibits no evidence of dyke-parallel shear, and dykes can be sequentially undilated orthogonal to the dyke plane.

In the case of the blunt-ended dyke exhibiting multiple offshoots of intruded fractures (Fig. 7), no adjacent dyke segment is observed, yet dilation was transferred along a zone of shear. The shear zone initiates approximately orthogonal to the dyke end, then curves, becoming oblique to the dyke further away (Fig. 7b). In this two-dimensional perspective, fractures growing away from the dyke are predicted to have followed a path that was orthogonal to the maximum circumferential stress (Erdogan & Sih 1963). This effect has been described for kink fractures growing away from a larger fracture

(Thomas & Pollard 1993). Closer to the dyke, a near-tip shear–stress concentration (Savin 1961) dominates the shear zone behaviour, but further away the remote stress field is dominant, inducing dilating offshoots to develop preferentially perpendicular to the direction of regional extension (i.e. parallel to the dyke), and causing some of the longer offshoots closer to the dyke to be gently curved.

A number of reasons may be postulated to explain the dilation of the dyke in Fig. 7(a) along a shear zone. An adjacent dyke segment may actually exist beyond the boundaries of the outcrop, possibly in the unobserved third dimension. Alternatively, dyke growth may have been hindered due to a stress shielding effect between concurrently emplaced adjacent, longer dykes, similar to the effect between overlapping fractures (e.g. Segall & Pollard 1983, DeGraff & Aydin 1987, Olson 1991). High magma pressures may also have served to promote dilation along shears at high angles to the dyke plane, perhaps in a zone of host rock inhomogeneity.

CONCLUSIONS

Blunt-ended dykes deviate from the predicted geometries of elasticity theory. Slip along pre-existing planes of weakness oriented at high angles to the dyke plane, such as joints, faults and bedding planes, may accommodate dilation and produce blunt ends. However, where such planes of weakness are absent, an alternative solution is required. Observations of the dykes in the Rooi Rand dyke swarm indicate that blunt-ended dykes may form as a result of dilation along a shear fracture at a high angle to the dyke plane linking adjacent en échelon dykes. This may occur while the adjacent dyke segments are slightly underlapping. The shear fracture accommodating the opening is constrained to the region between the dyke segments. In cases where a blunt-ended dyke has no adjacent segment, opening may still be transferred along a shear zone propagating away from the dyke end, and dilation in the host rock adjacent to the dyke be accommodated by the intrusion of magma into numerous fractures (offshoots) within the zone of shear. Close to the dyke tip, the local stress field dominates and offshoots form at a high angle to the dyke plane, whereas away from the blunt-tip region the remote stress field dominates and the offshoots curve towards parallelism with the dyke.

Acknowledgements—This research was funded by the University of Natal Research Fund and the Foundation for Research and Development. The authors benefited from discussions with Deanna Meth, and also express gratitude to those in the 1990 Honours class who assisted in the initial mapping of the Pongola River outcrop. Suggestions that were provided on an earlier version of this work by Agust Gudmundsson and an anonymous reviewer helped improve the manuscript, and are greatly appreciated.

REFERENCES

Anderson, E. M. 1951. *The Dynamics of Faulting and Dyke Formation with Application to Britain*. Oliver and Boyd, Edinburgh, U.K.

Armstrong, R. A. 1978. A geological and geochemical appraisal of the Rooi Rand. Unpublished M.Sc. thesis, University of Natal, Durban, South Africa.

Armstrong, R. A., Bristow, J. W. & Cox, K. G. 1984. The Rooi Rand dyke swarm, Southern Lebombo. *Spec. Publ. geol. Soc. S. Afr.* **13**, 77–86.

Baer, G. & Beyth, M. 1990. A mechanism of dyke segmentation in fractured host rock. In: *Mafic Dykes and Emplacement Mechanisms* (edited by Parker, A. J., Rickwood, P. C. & Tucker, D. H.). Balkema, Rotterdam, pp. 3–11.

Baer, G. & Reches, Z. 1987. Flow patterns of magma in dikes, Makhtesh Ramon, Israel. *Geology* **15**, 569–572.

Bristow, J. W. 1976. The geology and geochemistry of the Southern Lebombo. Unpublished M.Sc. thesis, University of Natal, Durban, South Africa.

Bussel, M. A. 1989. A simple method for the determination of the dilation direction of intrusive sheets. *J. Struct. Geol.* **11**, 679–687.

Cleverley, R. W. 1977. The structural and magmatic evolution of the Lebombo monocline, southern Africa, with particular reference to Swaziland. Unpublished Ph.D. thesis, Oxford University, U.K.

Cloos, E. 1955. Experimental analysis of fracture patterns. *Bull. geol. Soc. Am.* **66**, 241–258.

Cruikshank, K. M. & Aydin, A. 1994. Role of fracture localization in arch formation, Arches National Park, Utah. *Bull. geol. Soc. Am.* **106**, 879–891.

Currie, K. L. & Ferguson, J. 1970. The mechanism of intrusion of lamprophyre dikes indicated by 'offsetting' of dikes. *Tectonophysics* **9**, 525–535.

DeGraff, J. M. & Aydin, A. 1987. Surface morphology of columnar joints and its significance to mechanics and direction of joint growth. *Bull. geol. Soc. Am.* **99**, 605–617.

DeGraff, J. M. & Aydin, A. 1993. Effect of thermal regime on growth increment and spacing of contraction joints in basaltic lava. *J. geophys. Res.* **98**, 6411–6430.

Delaney, P. T. & Pollard, D. D. 1981. Deformation of host rocks and flow of magma during growth of minette dykes and breccia-bearing intrusions near Ship Rock, New Mexico. *Prof. Pap. U.S. geol. Surv.* **1202**.

Du, Y. & Aydin, A. 1991. Interaction of multiple cracks and formation of échelon crack arrays. *Int. J. Num. Analyt. Meth. Geomech.* **15**, 205–218.

Du, Y. & Aydin, A. 1993. The maximum distortional strain energy density criterion for shear fracture propagation with applications to the growth paths of en échelon faults. *Geophys. Res. Lett.* **20**, 1091–1094.

Duncan, A. R., Armstrong, R. A., Erlank, A. J., Marsh, J. S. & Watkins, R. T. 1990. MORB-related dolerites associated with the final phases of Karoo flood basalt volcanism in southern Africa. In: *Mafic Dykes and Emplacement Mechanisms* (edited by Parker, A. J., Rickwood, P. C. & Tucker, D. H.). Balkema, Rotterdam, pp. 119–129.

Engelder, T. 1987. Joints and shear fractures in rock. In: *Fracture Mechanics of Rock* (edited by Atkinson, B. K.). Academic Press, London, pp. 27–69.

Engelder, T., Fischer, M. P. & Gross, M. R. 1993. Geological aspects of fracture mechanics. *Geol. Soc. Am.* Short Course Notes, Ann. Meeting, Boston, U.S.A.

Erdogan, F. & Sih, G. C. 1963. On the crack extension in plates under plane loading and transverse shear. *Trans. ASME, J. Basic Engng* **85**, 519–527.

Gudmundsson, A. 1983a. Stress estimates from the length/width ratios of fractures. *J. Struct. Geol.* **5**, 623–626.

Gudmundsson, A. 1983b. Form and dimensions of dykes in Eastern Iceland. *Tectonophysics* **95**, 295–307.

Gudmundsson, A. 1987. Tectonics of the Thingvellir fissure swarm, SW Iceland. *J. Struct. Geol.* **9**, 61–69.

Hancock, P. L. 1972. The analysis of en échelon veins. *Geol. Mag.* **109**, 269–276.

Lajtai, E. Z. 1969. Mechanics of second order faults and tension gashes. *Bull. geol. Soc. Am.* **80**, 2253–2272.

Meth, D. 1991. The Rooi Rand dyke swarm: classification and intra/inter-dyke geochemical relationships. Unpublished B.Sc. (Hons) thesis, University of Natal, Durban, South Africa.

Nicholson, R. & Pollard, D. D. 1985. Dilation and linkage of echelon cracks. *J. Struct. Geol.* **7**, 583–590.

Noble, J. A. 1952. Evaluation of criteria for the forcible intrusion of magma. *J. Geol.* **60**, 34–57.

Olson, J. E. 1991. Fracture mechanics analysis of joints and veins. Unpublished Ph.D. thesis, Stanford University.

Olson, J. & Pollard, D. D. 1989. Inferring paleostresses from natural fracture patterns: a new method. *Geology* **17**, 345–348.

Olson, J. E. & Pollard, D. D. 1991. The initiation and growth of en échelon veins. *J. Struct. Geol.* **13**, 595–608.

Platten, I. M. and Watterson, J. 1987. Magma flow and crystallization in dyke fissures. In: Mafic dyke swarms (edited by Halls, H. C. & Fahrig, W. F.). *Spec. Pap. geol. Ass. Canada* **34**, 65–73.

Pollard, D. D. 1973. Derivation and evaluation of a mechanical model for sheet intrusions. *Tectonophysics* **19**, 233–269.

Pollard, D. D. 1976. On the form and stability of open hydraulic fractures in the Earth's crust. *Geophys. Res. Lett.* **3**, 513–516.

Pollard, D. D. 1987. Elementary fracture mechanics applied to the structural interpretation of dykes. In: Mafic dyke swarms (edited by Halls, H. C. & Fahrig, W. F.). *Spec. Pap. geol. Ass. Canada* **34**, 5–24.

Pollard, D. D. & Aydin, A. 1988. Progress in understanding jointing over the past century. *Bull. geol. Soc. Am.* **100**, 1181–1204.

Pollard, D. D. & Holzhausen, G. 1979. On the mechanical interactions between a fluid-filled fracture and the Earth's surface. *Tectonophysics* **53**, 27–57.

Pollard, D. D. & Muller, O. H. 1976. The effect of gradients in regional stress and magma pressure on the form of sheet intrusions in cross section. *J. geophys. Res.* **81**, 975–984.

Pollard, D. D., Muller, O. H. & Dockstader, D. R. 1975. The form and growth of fingered sheet intrusions. *Bull. geol. Soc. Am.* **86**, 351–363.

Pollard, D. D., Segall, P. & Delaney, P. T. 1982. Formation and interpretation of dilatant echelon cracks. *Bull. geol. Soc. Am.* **93**, 1291–1303.

Ramsay, J. G. 1967. *Folding and Fracturing of Rocks*. McGraw-Hill, New York.

Ramsay, J. G. 1980. Shear zone geometry: a review. *J. Struct. Geol.* **2**, 83–99.

Ransome, I. G. D. 1991. The geochemistry, kinematics and geodynamics of the Gannakouriep dyke swarm. Unpublished M.Sc. thesis, Department of Geochemistry, University of Cape Town, South Africa.

Renshaw, C. E. & Pollard, D. D. 1994a. Are large differential stresses required for straight fracture propagation paths? *J. Struct. Geol.* **16**, 817–822.

Renshaw, C. E. & Pollard, D. D. 1994b. Numerical simulation of fracture set formation: a fracture mechanics model consistent with experimental observations. *J. geophys. Res.* **99**, 9359–9372.

Rickard, M. J. & Rixon, L. K. 1983. Stress configurations in conjugate quartz-vein arrays. *J. Struct. Geol.* **5**, 573–578.

Rogers, R. D. & Bird, D. K. 1987. Fracture propagation associated with dyke emplacement at the Skaergaard intrusion, East Greenland. *J. Struct. Geol.* **9**, 71–86.

Saggerson, E. P., Bristow, J. W. & Armstrong, R. A. 1983. The Rooi Rand dyke swarm. *S. Afr. J. Sci.* **79**, 365–369.

Saggerson, E. P. & Logan, C. T. 1988. Deformation and chemistry of calcic pyroxenes in granophyric gabbro. *S. Afr. J. Geol.* **91**, 439–449.

Savin, G. N. 1961. *Stress Concentration Around Holes*. Pergamon Press, London.

Segall, P. & Pollard, D. D. 1983. Joint formation in granitic rock of the Sierra Nevada. *Bull. geol. Soc. Am.* **94**, 563–575.

Stephenson, P. J. 1990. Some aspects of dyke emplacement and characteristics in the Townsville-Ingham district, North Queensland, Australia. In: *Mafic Dykes and Emplacement Mechanisms* (edited by Parker, A. J., Rickwood, P. C. & Tucker, D. H.). Balkema, Rotterdam, pp. 421–430.

Thomas, A. L. & Pollard, D. D. 1993. The geometry of échelon fractures in rock: implications from laboratory and numerical experiments. *J. Struct. Geol.* **15**, 323–334.

Tullis, J. 1975. Deformation of feldspars. In: *Reviews in Mineralogy, Volume 2: Feldspar Mineralogy* (edited by Ribbe, P. H.). Mineralogical Society of America, Chelsea.

Walker, G. P. L. 1987. The dike complex of Koolau Volcano, Oahu: internal structure of a Hawaiian rift zone. *Prof. Pap. U.S. Geol. Surv.* **1350**, Book 2, 991–963.