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Incremental dilation of magma filled fractures: evidence from dykes on the Isle of Skye, Scotland

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Abstract

Localised swarms of narrow (10–120 mm) basaltic dykes occur at offsets and terminations of some larger basaltic dykes in Skye, Scotland. These narrow dykes cut and chill against each other and the larger dyke and its country rock. The narrow dykes can only be traced a short distance into the larger dyke before terminating. Some of these terminations show the central parts of both dykes merging as the chilled margins vanish, at other terminations the later dyke outcrop narrows progressively to a point. These all show that after initial dilation and some crystallisation of material in the dyke fissure there were additional (up to 11) increments of dilation. Increments were sufficiently spaced in time for preceding injections to have become solid. Time spans separating initial and later dilation may be sufficient for local crystallisation of dykes up to 3.2 m thick. Away from these terminations the dyke fissure remained an open void occupied by flowing magma during the successive increments of dilation. This paper demonstrates that fluid filled dyke fissures can vary in width with time, an observation consistent with the modern theoretical models of dyke emplacement that relate dyke width to magma input pressures and other magmatic parameters. Dyke offsets and terminations with late dilational increments are shown to provide a variety of other information on flow, crystallisation and sealing of dyke fissures. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

It is a relatively easy matter to determine the total dilation resulting from the emplacement of dykes and other sheet intrusions when both walls of the intrusion can be seen (Bussell, 1989). It is, however, more difficult to show whether dilation was a single event or occurred in stages. The literature is limited. Gudmundsson (1995), and references therein, shows that multiple rows of columnar jointing in Icelandic dykes represent successive dilation events in hot dyke rocks. This indicates incremental dilation in the feeder fissure system below. Hoek (1991) briefly describes secondary apophyses at dyke bridges that record bridge deformation and ongoing dilation.

Wall-parallel variations in composition and texture (Platten and Watterson, 1987; Platten, 1995) record the history of changing flow and crystallisation in a dyke fissure, but only provide a record of the final total dilation. Dykes such as these may have complex patterns of dilation but do not generally record direct evidence for it. Multiple dykes record repetitions of the sequence (1) fracture, (2) dilation and magma emplacement and (3) crystallisation. Each dilation event is associated with a new fracture at the site of observation. Where such dykes are petrographically similar they may be related to increments of dilation in a hidden, common feeder system, but direct demonstration of that relationship is impossible.

Recent theoretical treatments of dyke propagation and magma flow (Bruce and Huppert, 1990; Lister and Kerr, 1991) indicate that dyke fissure dilation is partly a function of magmatic driving pressures and is thus intrinsically likely to vary with time. These studies show that dykes are likely to have been subject to changing dilation but do not provide the evidence for a specific dyke observed in the field. Classical studies (Anderson, 1951; review

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in Pollard, 1987) related dyke emplacement primarily to the magma induced fracture of a rock mass subjected to differential stress. Recently Abelson and Agnon (1997) have shown that fracture during Mid Ocean Ridge spreading may be the result of magmatic driving pressure at some sites but the result of remote tectonic stress at other sites. The ability to record the dilation history of dyke fissures, distinguishing virtually instantaneous opening to full width from incremental growth of dilation over days or months, will ultimately assist in evaluating the relative roles of external differential stress and internal magmatic driving pressures in dyke fissure dilation.

This paper reports three sites from the Isle of Skye in Scotland where multiple dilation events can be shown to affect a single dyke fissure over a significant period of time, demonstrating incremental growth of the dyke fissure. These dykes are primarily dilational Mode I fractures but some mixed mode fracture may occur at strike changes and where en échelon dykes are developed. The Coire Lagan site illustrates the basic principles in a very well-exposed, simple and narrow dyke. The Uamh Tarscavaig site shows that the same phenomena occur associated with much thicker dykes and after much more crystallisation in the initial fissure. The Loch Brittle site demonstrates incremental dilation affecting a complexly zoned, thick dyke with a protracted history of flow. This site also demonstrates the different responses of fully and partly crystallised dyke material to later increments of dilation. These sites all occur at offsets, bridges and lateral terminations of dykes but only represent a small minority of observed offsets, etc, in the Skye dyke swarm. Most offsets and terminations are simple. In these, a single chilled surface coats bridge and horn walls and there is little record of the history of dilation (cf. Hoek, 1995).

A general account of the Skye centre is given by Emeleus (1991) and Speight et al. (1982), who provide general descriptions of the Skye basaltic dyke swarms. UK National Grid references are given for precise location of the examples cited.

Some terms used in this account need definition. 'Dyke' is used to describe the observed, fully solidified structure whilst 'dyke fissure' refers to a magma filled void. Dykes with no preserved record of dilation history are called 'unitary dykes'. Groups of dykes with touching or nearly touching contacts that show chilled and/or cross-cutting relations are termed 'multiple dykes'. Dyke terminations showing multiple, internal chilled margins are called 'multiple terminations'. The first recorded event at any site is called the 'initial dyke' or 'initial dyke fissure' for rock or magma filled conditions, respectively.

2. Observations and preliminary interpretation

2.1. Coire Lagan site

A thin (0.5 m maximum thickness) basaltic dyke trending 170° intrudes coarse gabbros between NG 4437.2088 and NG 4437.2083 on the lip of Coire Lagan in the Cuillin Hills. The dyke dips 60° towards the pluton centre and belongs to Harker (1904) tangential set of dykes. The main part of the dyke shows a well-developed, dark chilled margin and simple wall parallel structures (marginal aphyric zones; a central, sparsely porphyritic zone; inwards coarsening matrix grain size) that are continuous around small offsets in the dyke. Most of these offsets are less than the dyke thickness and thus do not interrupt dyke continuity in

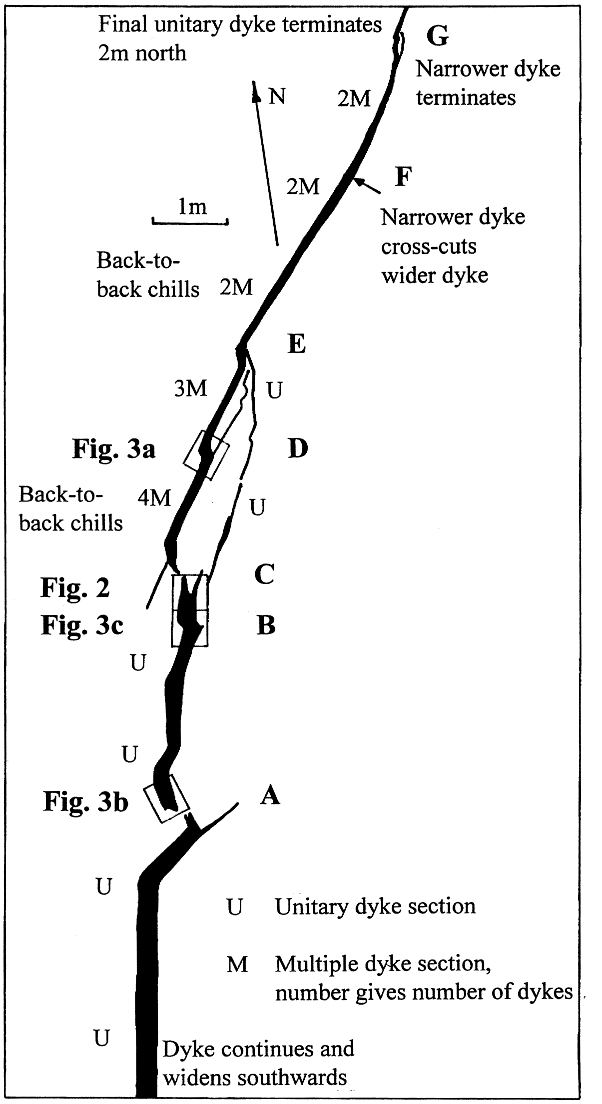

Fig. 1. Plan view of dyke in Coire Lagan showing the change from unitary dyke to multiple dyke complex. Localities A–G are described in the text and some illustrated in Figs. 2 and 3.

outcrop. Some offsets of the dyke are sited on pre-dyke fracture sets. Phenocrysts are small, plagioclase tablets 1–2 mm long and brown and altered ferromagnesian mineral and as prisms with maximum dimensions 1 × 2 mm.

At its northern end the dyke becomes irregular with larger offsets that result in partial loss of continuity in plan view as the dyke thins northwards (A–C in Fig. 1). These localities record evidence (Figs. 2 and 3) of multiple dilation. As its termination is approached the dyke splits into several narrower dykes, some of which show cross-cutting relationships (C–G in Fig. 1, details Figs. 2 and 3a). This constitutes a lateral passage from a unitary dyke to a multiple dyke. The local sections of dyke in this area deviate from the gross dyke trend and consequently most show oblique dilation vectors. These show mixed mode conditions and indicate a substantial component of vertical propagation in the fracture system (Pollard et al., 1982; Abelson and Agnon, 1997).

These localities will be considered in three groups: (1) the change from a predominantly unitary dyke to a multiple dyke at locality C; (2) the multiple dyke section, localities C–G; (3) offsets in the predominantly unitary dyke section at localities A and B. The features in groups 1 and 2 give the most compelling evidence for incremental dilation whilst the features in group 3 show some of the more complex structures that may result from incremental dilation.

2.1.1. The junction between the predominantly unitary dyke and the multiple dyke sections at locality C

The clearest evidence for incremental dilation is seen at location C and illustrated in Fig. 2. Here three discrete, narrow (10–60 mm), late dykes in the country rock (ND1, 2 and 3 in Fig. 2b) can be traced south into the initial dyke material, which they penetrate for 0.1–0.2 m. These dykes each have well-developed dark, very-fine-grained chilled margins against the country rock and the initial dyke rock (Fig. 2a). The grain size in these cannot be resolved. Traced south, the chilled margins of ND2 do not converge and meet but remain separate. Eventually the very-fine-grained chilled margins end and the porphyritic core of ND2 merges with the porphyritic core of the unitary dyke. There is no detected textural change in the core groundmass at this point. Internal, wall-parallel textural boundaries, marked by an abrupt inwards decrease in grain size

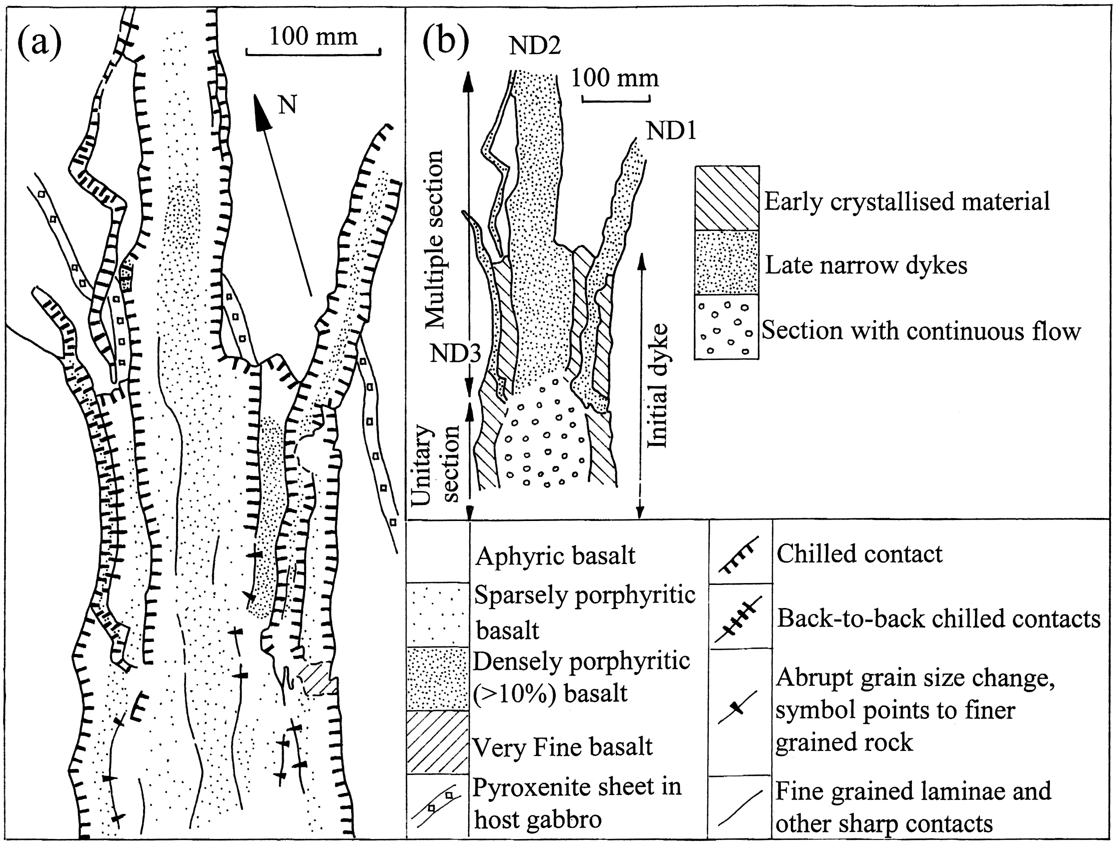

Fig. 2. (a) Line drawing of locality C from Fig. 1 showing three narrow dykes dilating the initial termination of the Coire Lagan main dyke and extending the fissure laterally. (b) An interpretation of the structure shown in Fig. 2(a).

followed by a gradual inwards coarsening, occur within the adjacent unitary dyke section. The outer pair of these lies just outside the line of strike of the very fine chilled margins to ND2 and may be linked to ND2. The dyke ND1 is not open to the unitary dyke centre but ends in a complex chilled mass. The dyke ND3 cuts the outer margin of the early crystallised dyke material but details of its termination within the initial dyke material are uncertain. The three narrow dykes do not show mutual intersections so their relative ages are unknown.

These narrow dykes post-date local crystallisation of magma in the local termination of the initial dyke fissure, but predate crystallisation of magma in the core of the main unitary part of the fissure, hence the open-ended chilled margins in ND2. The structure of the initial dyke termination can be reconstructed by removing the dilation of the three later dykes. This gives an initial dyke with a total thickness of 60 mm, composed of a densely porphyritic axial zone that is 20 mm thick with sparsely porphyritic outer zones and external chilled margins. The axial porphyritic zone in this remnant is not continuous with the later axial porphyritic zone of the unitary dyke. The axial porphyritic zone in the early crystallised material is conspicuously more densely porphyritic than that in the ND2 or the unitary section. The dilation that is unequivocally shown by the country rock is repeated in the dilation of the

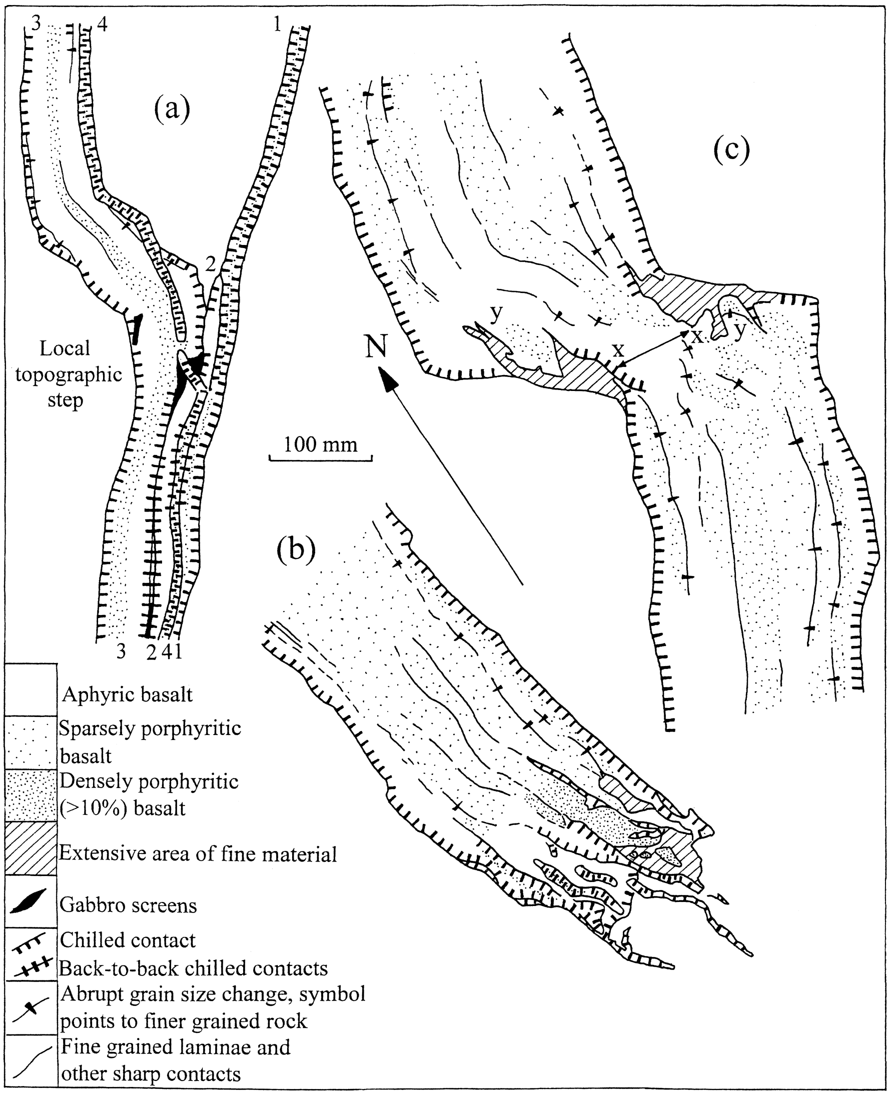

Fig. 3. Detailed plans of parts of the Coire Lagan dyke. (a) Multiple dykes at locality D on Fig. 1 showing how back-to-back chills become cross-cutting and allow intrusion sequences to be established. The full numbered sequence shown uses additional data from south of the figured area. (b) Narrow dykes intruding main dyke at locality A on Fig. 1. (c) The offset at locality B on Fig. 1 showing the effects of later dilation on the plug of chilled magma bridging the narrower section of dyke. Matching points separated by the later through-going dilational fracture are shown as x–x. Tips of an earlier dilational fissure that failed to break through the plug are shown as y.

early crystallised basalt, showing both new tip propagation and increments of dilation. The whole structure is termed a multiple dyke termination.

2.1.2. The multiple dyke segment, localities C–G

The section between C and E in Fig. 1 shows five narrow, subparallel dykes forming the northwards continuation of the dyke system. Locally (Figs. 1 and 3a) these narrow dykes are in contact with each other and show back-to-back chilled margins. This gives miniature three- and four-component multiple dyke systems. Each narrow dyke shows chilled margins and a sparsely porphyritic core, and is petrographically similar to the unitary dyke south of location C. Cross-cutting relations (Fig. 3a) allow a local time sequence to be established. This shows that the narrow dykes represent discrete dilation events and are not the result of synchronous magma injection into a pre-existing zone of shattered country rock. Two of these narrow dykes continue to locality G (Fig. 1) where one terminates. They show back-to-back chilled margins through most of the section but cross at locality F (Fig. 1), showing that the narrower dyke was the later dyke. Since the multiple dyke systems here can be shown to be a lateral continuation of the petrographically similar unitary dyke (localities A–B, Fig. 1) they can be used to determine that four, and possibly five, dilation events were involved in the opening of the unitary dyke fissure.

2.1.3. Offsets of the predominantly unitary dyke section, localities A and B

The offset at locality A (Fig. 1) shows narrow basalt dykes within early crystallised basalt adjacent to the bridge (Fig. 3b). Traced north towards the local unitary dyke section, these narrow dykes terminate within 0.1 m, either dying out with the late fissure remaining open to the unitary dyke, or converging to close the late fissure before reaching the unitary dyke section. One late dyke extends into the bridge. At least four narrow dykes are present cutting the initial dyke here, similar to the number of dilation events recorded to the north.

The offset at locality B (Fig. 1) shows the dyke as a continuous, but locally narrowed, body (Fig. 3c). The porphyritic zones of the unitary dyke section are not continuous through the offset. Two large patches of chilled material are preserved on the inwards facing corners of the offset. Assuming that the dilation vector is approximately horizontal, closing the dyke by 60–75 mm brings these into contact (x–x in Fig. 3c) to form a plug closing the offset. There are also some very narrow dyke-like forms within the chilled masses suggesting that these may also involve multiple dilation. Two conspicuous re-entrants in the margins of the two chilled masses (y in Fig. 3c) occur in matching positions on the east and west sides of the offset. These have central porphyritic and marginal aphyric basalts. The former is not however continuous with the central porphyritic basalt of the adjacent unitary dyke sections. These re-entrants mark the en échelon, overlapping tips of dilated fractures that partly penetrated the plug of chilled material but did not link up. There are thus two later dilation events recorded at this site, the first producing the 'y' fractures, which did not completely disrupt the bridge of chilled material whilst the second late dilation event (x–x) was large enough to re-establish fissure continuity across the offset. The magma filling the latest fissure chilled against the earlier chilled materials. The axial porphyritic magmas from the unitary dyke fissure did not however penetrate the reopened neck of the offset, suggesting flow parallel to the steeply plunging offset.

2.1.4. Summary of the initial and later dilations at the Coire Lagan site

The narrow dykes cutting the initial dyke materials thus represent increments of dilation. The sum of the

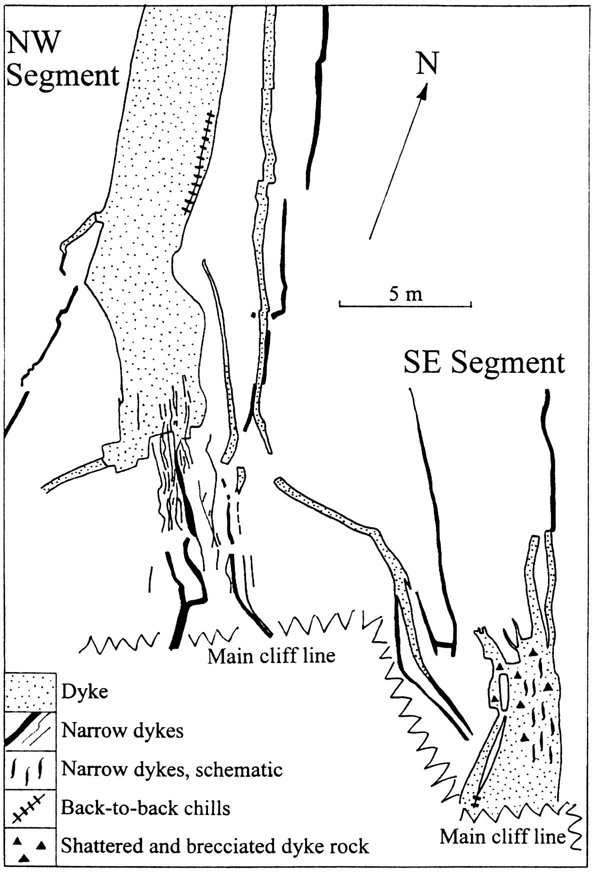

Fig. 4. Plan view of the Uamh Tarscavaig site showing offset of main dyke, linking narrow dykes in the bridge and the position of the later narrow dykes in the NW and SE terminations of the initial dyke.

thickness of screens of basalt between the late narrow dykes records the initial dilation. The sum of the late narrow dyke thicknesses gives the sum of the late dilation events. This gives 60 mm initial dilation with 120 mm later dilation added to give local total dilation of 180 mm in Fig. 2. Similar proportions of dilational increments are shown in Fig. 3(c) where the last 60–75 mm dilation (x–x) matches the dilation of ND2 in Fig. 2. The initial dilation is thus only 33% of the final dilation, post initial magma injection dilation exceeding the dilation caused by initial arrival of magma. Cross-cutting relationships in some of the narrow dykes suggest that at least four dilation events occurred, the initial dilation and three subsequent events. If none of the narrow dykes are synchronous then the number of events is raised to five. The largest of the later dilational increments can be correlated with the development of sharp, wall-parallel, textural internal junctions in some of the adjacent unitary dyke sections.

2.2. The Uamh Tarscavaig site

A feldsparphyric dolerite dyke from the main Skye dyke swarm is described from near Uamh Tarscavaig (NG 5835.1105) on the northwest coast of Sleat. This 3.6-m-thick dyke shows an offset of 15 m with well-developed multiple terminations to each of the offset segments (Fig. 4).

2.2.1. Dilational events in the local termination of the NW segment

The NW segment is cut at its termination by at least nine narrow (30–70-mm-thick) dykes of fine-grained, feldsparphyric basalt with cumulative dilation of 0.44 m. These narrow dykes strike parallel to the host dyke. They cut the last 2 m of the initial dyke termination and also extend out into the local country rock. Chilled margins are developed against both dolerite and external host rock in all but one of these dykes. Six of the narrow dykes were seen to taper and pinch out northwestwards within the dolerite. Three of the narrow dykes showed cross-cutting relationships, indicating that these fractures were not synchronous.

2.2.2. Dilation events in the SE segment

The SE segment of the initial dyke shows massive dolerite and local areas of fractured and brecciated dolerite that are all cut by at least seven narrow (10–120-mm-thick) dykes of feldsparphyric basalt with a cumulative dilation varying from 0.29 to 0.4 m. These are clearly absent from the main dolerite to the SE and the country rock to the NW. The intruded zone is some 3 m long and occurs between 0.6 and 1.8 m in from the SW contact of the host initial dolerite. Four of the narrow dykes can be seen to taper and terminate southeastwards within the dolerite. These terminations showed thoroughly chilled rocks. The narrow dykes all post-date the fracturing and brecciation event and can be divided into two groups: group 1 pre-dating cementation of the breccia material and group 2 post-dating cementation of the breccia material.

The group 1 dykes are narrow (mostly 10 mm, locally reaching 60 mm), irregular and traceable only very short distances (0.1–0.2 m). Their irregularities (Fig. 5) are on the same scale as the clast size in the brecciated material and wedge like apophyses can be seen to extend between clasts in the fractured host. Very short 10 × 20 mm bodies of very fine basalt occur in spaces between clasts adjacent to the continuous dykes. All chill directly onto the clast surfaces. These relations are similar to some described from intrusions into uncemented breccia pipes by Platten and Money (1987) and indicate dilational opening of uncemented, coarse fragmental materials.

The second group (20–120 mm thick) have relatively planar contacts that take no account of the pattern of

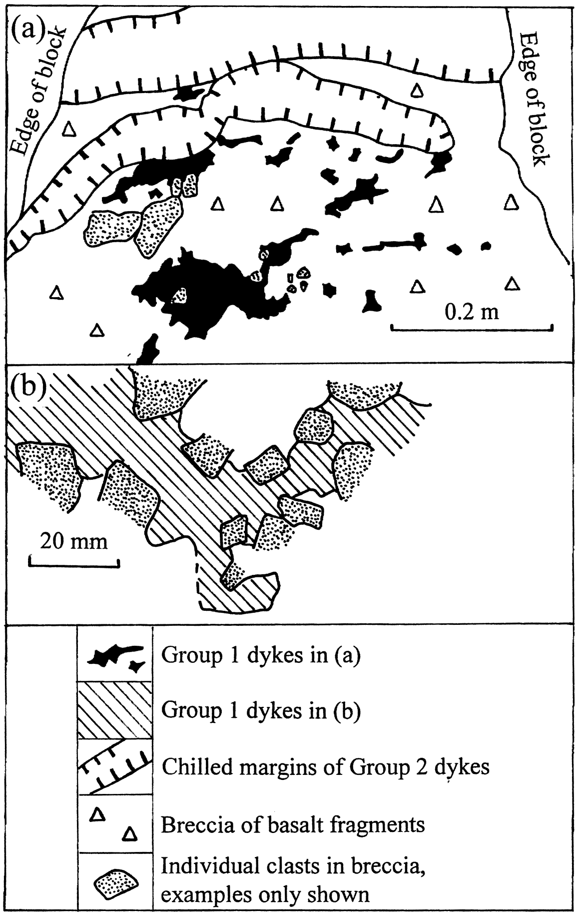

Fig. 5. Drawing of a fallen block from the SE segment of the Uamh Tarscavaig dyke showing type 1 and type 2 narrow dykes cutting the brecciated main dyke. (a) General features and (b) detailed relationships between type 1 dykes and clasts in the breccia.

fracture in the host (Figs. 5a and 6). These represent fracture after cementation of the host material. These dykes also extend into intact dolerite, cutting both the sparsely and more densely porphyritic facies of the zoned initial dyke. Oblique cross-cutting relationships are seen between the narrow dykes (Fig. 6) that both allow dilational opening to be demonstrated and show that there were at least three late dilation events, each separated for enough time for the preceding narrow dyke to become solid. There are up to seven dykes of this type so it may be inferred that they represent that number of fracture and dilation events cutting the initial dolerite. The maximum cumulative thickness of the narrow dykes recorded was 0.4 m representing 11% of the total 3.6 m dilation.

2.2.3. *Summary of recorded dilation history at Uamh Tarscavaig*

The overall time sequence in the SE segment is thus (1) 3.2 m of dilation allowing emplacement of the initial dyke, (2) crystallisation of dolerite, filling the entire 3.2 m thickness of the local termination, (3) local fracturing of chilled and crystallised dyke material, (4) emplacement of group 1 narrow dykes, number of events unknown, but involving some additional dilation, (5) cementation of fractured material, (6) dilational emplacement of group 2 narrow dykes, recording at least three and possibly seven dilation events, each dyke solidifying before the next was emplaced. This resulted in an additional net dilation of 0.4 m, approximately 11% of the total dilation. The simpler NW segment shows evidence of nine dilation events after the dilation of the initial dyke fissure and the local crystallisation of a plug of dolerite at the dyke termination. All these dilation events are recorded by narrow dykes that are spatially related to the main dyke offset and are therefore inferred to be related genetically. As they have very limited lateral extent, do not open laterally into the dolerite and have steeply plunging small offsets they are inferred to have both propagated, and been fed with magma, from below.

2.3. *Loch Brittle site*

A zoned olivine rich amygdaloidal dolerite dyke with a complex history trends 152° across the south shore of Loch Brittle (NG 4131.1933) and shows a local lateral termination southwards. In the north it is a unitary 5.5–4.5 m dyke (traverses 1 and 2, Fig. 7) with outer amygdaloidal zones and an amygdale-free, finer-grained central zone. The outer amygdaloidal zones show wall-parallel layering of amygdaloidal and non-amygdaloidal rock and changes in dolerite grain size. No internal strongly chilled contacts can be seen associated with these textural boundaries though some surfaces show abrupt inwards decreases in grain size (from 1–2 to < 1 mm) followed by a gradual inwards increase in grain size. These zones and internal layering thicken southwards and eventually amygdaloidal dolerite occupies the entire dyke thickness between traverses 2 and 3. This kind of pattern is interpreted by Platten and Watterson (1987) as evidence of many episodes of flow within the dyke fissure. The non-amygdaloidal fine-grained central dolerite terminates abruptly southwards, the tip forming a steeply plunging half cylinder (Fig. 8). This body was the last magma to flow in the dyke fissure, occupying the residual void left after crystallisation of the amygdaloidal basalt on the walls and termination. The boundary represents a temporary rock–magma interface and no significant additional dilation is required to accommodate the non-amygdaloidal dolerite.

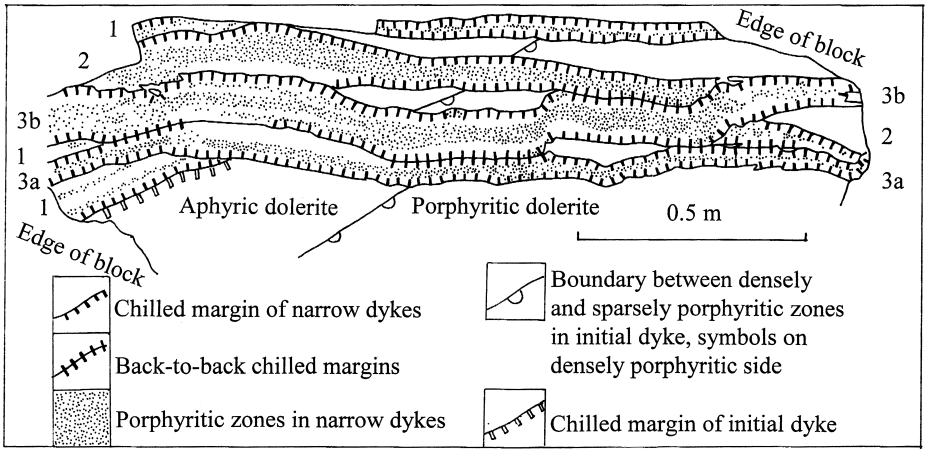

Fig. 6. Detail of a fallen block of multiple type 2 narrow dykes cutting the SE segment of the main Uamh Tarscavaig dyke. This shows time relations and evidence of dilation for the type 2 dykes and their relation to the marginal aphyric zone and central porphyritic zones of the main dyke. The type 2 dykes are emplaced in numerical order, relative time relations of dykes 3a and 3b are indeterminate, but both post-date dyke 2.

Traced southwards (traverses 3–5, Fig. 7) the dyke becomes multiple with internal chilled contacts that locally cut textural layering and leucodolerite micropegmatite and zeolite segregation veins in the earlier amydaloidal dolerite. The number of dilation events recorded as affecting earlier dyke material increases from traverse 3 to traverse 5, with most new fractures being generated near the mid-line of the pre-existing crystalline dyke material. The final traverse (No. 6) shows a local swarm of 11 narrow dykes lying on the line of strike of the unitary section. Some are separated by country rock screens but others are in contact, showing back-to-back and cross-cutting chilled margins. This sequence shows how a progressively more complete record of dilation events is preserved as the multiple dyke termination is traced away from the 4.5–5.5-m-thick unitary dyke section. The main part of this record is preserved in the 10-m-long plug of crystalline dolerite formed earlier at the termination of the initial dyke (traverses 3–5).

The site also shows some evidence of the deformation of partly crystalline dolerite near the temporary termination of the magma filled part of the fissure. The swarm of small (10–50-mm-thick) leucodolerite micropegmatite and zeolite veins trending parallel to the dyke walls converge sharply as they are traced north towards the end of the axial non-amygdaloidal dolerite in the unitary dyke section (Fig. 8 and traverses 3 to 2 in Fig. 7). They adopt a sub-radial pattern around the tip of the non-amygdaloidal dolerite and die out towards it (Fig. 8). These veins represent a small cumulative dilation of 82 mm that is associated with the largely non-dilational emplacement of the 1.2–2.6-m-thick central non-amygdaloidal dolerite. The vein fill is considered to be an exudate from a partly crystallised host amygdaloidal dolerite.

3. Discussion

3.1. Incremental dilation of dyke fissures

3.1.1. At local dyke terminations and large scale offsets

The evidence presented here shows that incremental dilation of dyke fissures can occur over a sufficient span of time for some of the early emplaced dyke material to have crystallised. This is most readily seen at large scale dyke offsets (Uamh Tarscavaig), where local dyke continuity is lost, and near dyke terminations (Coire Lagan). The local narrowing of the original fissures, more extensive local (four or more in place of two) cooling surfaces, possible flux of cooling water in fractures not occupied by magma, and the probability that these regions have slower flowing

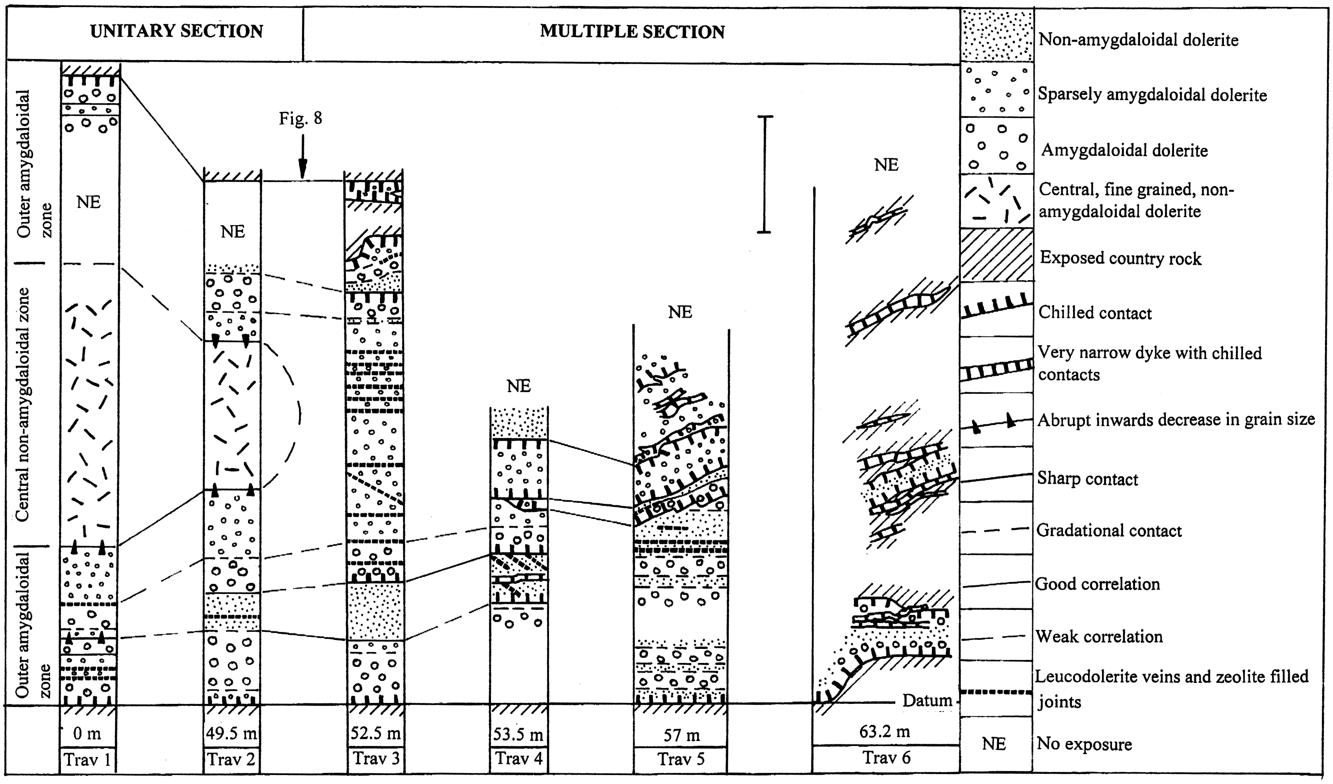

Fig. 7. Logs of traverses across the dyke complex at the Loch Brittle site. The datum plane is a conspicuous, straight wall of country rock on the western side of the dyke. Distances are given southwards from traverse 1.

magma than the main dyke fissure, could all contribute to the region becoming solid before other parts of the dyke fissure. The two walls are thus locked together so any further dilation of the main fissure must create new fractures in this region, affecting both external country rock and newly crystallised dyke material (Fig. 9a and b).

3.1.2. At small scale offsets

Once the bridge at an offset is broken and substantial continuity achieved between the dyke segments further dilational events will not be recorded (Fig. 10b). There is no need for further fractures to develop, space being accommodated in the fluid portion of the fissure fill. Once broken, the bridge region may become part of the gross flow regime of the dyke and ceases to be a region of near static magma, and so wall accretion of solid material slows to values similar to the rest of the dyke (Fig. 10b). If continuity is limited (Fig. 10a), as in the case illustrated in Fig. 3(c) here and also figure 2(b) in Platten (1995), then the small orthogonal thickness of the linking narrow dyke section permits relatively fast cooling which may weld both sides of the dyke together. This restores a solid bridge, which will have to break or deform if dilation is resumed. This effect is likely to also occur in thicker dykes if magma flow is parallel to the edges of the offset when flow in the narrow section may be slower than the bulk flow (Fig. 10c and d).

Simple offsets indicate that initial dilation was sufficiently rapid that only a thin skin of chill had time to develop. This was too thin and too plastic for fracturing to occur in it. Where dilation is normal to the main fractures, fissure continuity at offsets is not achieved until dilation is equal to the amount of offset. Thus the amount of offset at simple offsets gives an indication of the minimum amount of initial rapid dilation. For example the 1.7-m-thick Port na Long dyke (figure 3 in Platten and Watterson, 1987) shows a step of 0.45 m so at least 26% of the total dilation took place rapidly relative to wall crystallisation. Offsets of this type are quite common so rapid initial dilation with rapid magma influx is considered to be a common feature in the Skye dykes.

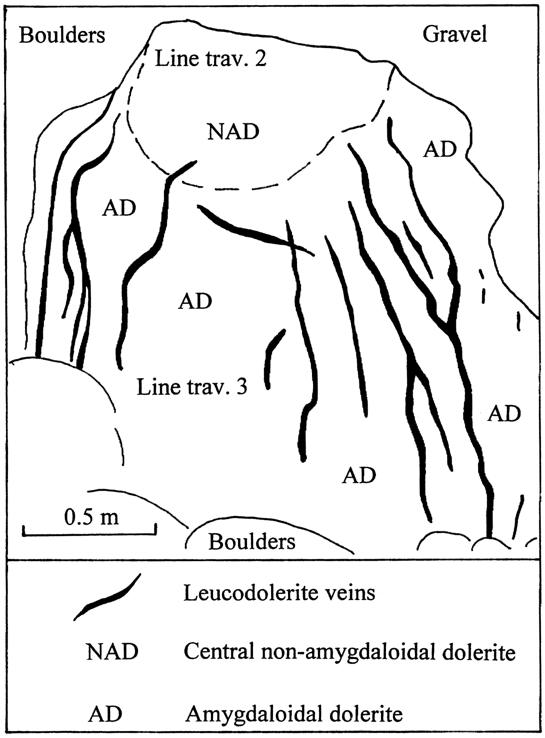

Fig. 8. Outline sketch of an upstanding exposure of the Loch Brittle dyke showing the distribution of leucodolerite segregation veins around the southern termination of the axial non-amygdaloidal dolerite. The approximate position of traverses 2 and 3 from Fig. 7 are shown to provide correlation with the logged sections. The observer is looking NW.

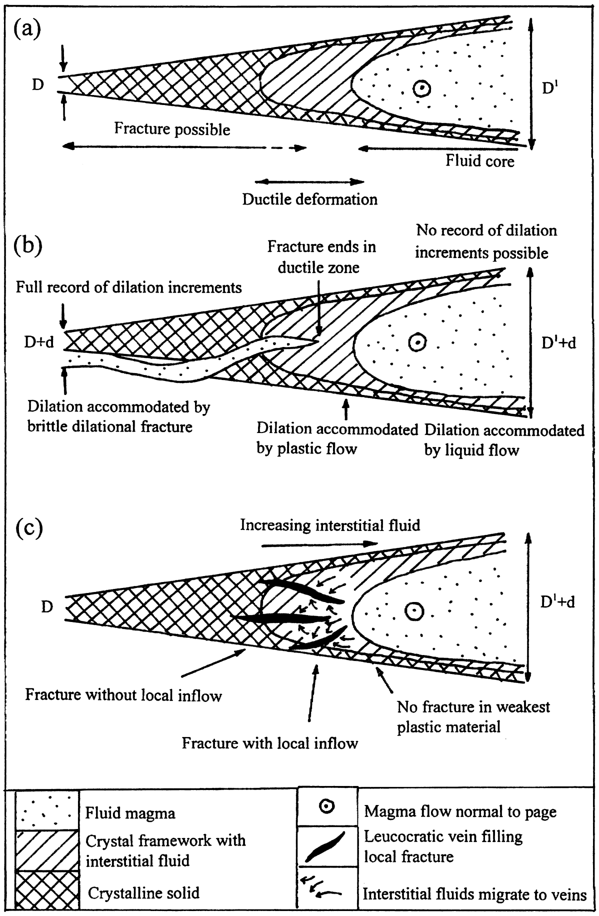

Fig. 9. Schematic views of the effects of incremental dilation on a dyke tip with flow parallel to the tip line. (a) Distribution of crystalline and magmatic material and its inferred mechanical properties after some flow and crystallisation. (b) Dilation of the structure in (a) by an increment ‘d’. (c) Generation of segregation veins in the structure illustrated in (a) by a small increment of dilation.

3.1.3. Local deformation of partly crystalline initial dyke material during later dilation

The termination of late narrow dykes within the initial dyke material means that, between the solidified and fractured part of the initial dyke and that part of the initial dyke fissure still containing axial magma, there must be some other form of deformation to accommodate the dilation increments (Fig. 9). The nature of this deformation has not been observed directly in the present study at the Coire Lagan and Tarscavaig sites though it is inferred to involve deformation of a crystal framework with interstitial liquid. En masse this material behaves plastically and does not fracture.

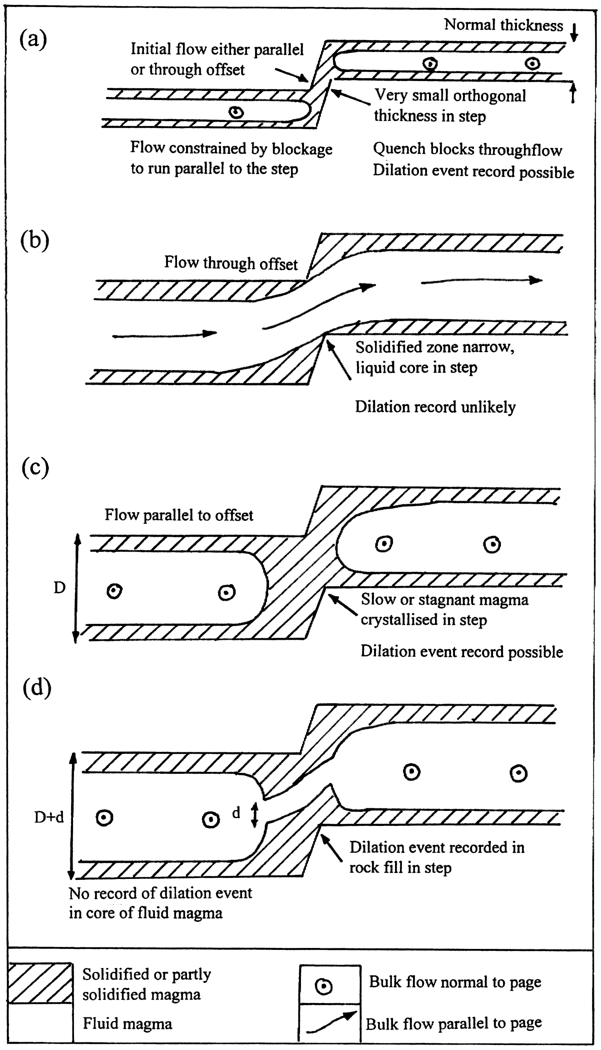

Fig. 10. Schematic views of wall accreted material and magma flow at offsets showing the effects of a small later dilational increment. (a) Small initial dilation gives very small orthogonal thickness to dyke at offset leading to rapid sealing of neck of offset. Later dilation can fracture the sealed offset. (b) Large initial dilation with regional magma flow across the offset, little accretion of material at walls and dyke centre remains fluid magma (cf. offsets described in Platten and Watterson, 1987). Any additional dilation is accommodated in the magma and has no physical record. (c) Large initial dilation with magma flow parallel to the edges of the offset. Magma flow in narrow section is slow and leads to crystallisation on the walls and sealing of the offset. Localised magma flow paths near solid–liquid interface omitted. (d) Dilation increment affecting (c) to produce a discrete new fracture in the rock filling the neck of the offset.

The Loch Brittle site shows some evidence of rupture within the zone of partly crystalline material separating rigid, fully crystalline, dolerite from the magma filled zone near a local dyke termination. Radiating fractures around the end of the northern axial non-amygdaloidal dolerite (Figs. 8 and 9c) record a dilational fracturing with the fractures filled with an evolved liquid that is not chilled against the host material. This evolved material is interpreted as a locally derived exudate from incompletely crystallised host dolerite. These fractures all taper out towards the north, and they do not merge with the axial dolerite. They had no direct access to the primitive magma flowing in the fissure. This indicates a northwards change in the host rock structure at Loch Brittle, probably an increase in the proportion of interstitial fluid that allows it to show bulk plastic deformation (Fig. 9c).

3.1.4. Late dyke propagation and magma flow

The late multiple dykes may taper and close within the already solidified part of the initial dyke (Coire Lagan and Uamh Tarskavaig) or may be open laterally to the unitary section of the initial fissure and its axial zone of magma (Coire Lagan and Loch Brittle). The former can only be fed from below and have been shown to be propagated upwards within the termination or offset zone. The latter may be either propagated laterally from their visible connection with the main dyke or vertically with later lateral extension to link with the unitary dyke section. Magma flow may potentially be either vertical or lateral. Vertical flow is required at locality B in Coire Lagan (Fig. 3c) whilst at locality C (Fig. 2) the continuity of the axial porphyritic zone of the unitary dyke with the axial porphyritic zone of the late dyke would permit, but does not require, lateral flow.

The relative abundance of late narrow dykes closing within the solidified portion of the initial dyke may indicate that it is difficult to initiate renewed fracture in the plastic, partly crystalline material at the junction between magma and the solidifying plug at the dyke termination. Renewed fracture may be initiated in fully crystalline material or external wall rock and then propagate through the plastic zone if there is sufficient additional dilation.

3.1.5. The time scale of incremental dilation

The narrow ($\ll 1$ m) dykes characteristic of horns and the multiple dyke systems described here crystallise in days or hours whether filled with flowing or static magma (Jaeger, 1967; Delaney, 1987; Bruce and Huppert, 1990). They thus provide a crude timescale for the dilation history. Simple steps must open in a shorter time, i.e. hours. The thicker initial dykes at Uamh Tarscavaig and Loch Brittle sites will take longer, months or even over a year, to crystallise a plug of static magma at the initial dyke termination. These show a longer minimum interval between initial dilation and the later recorded increments to the dilation. In all cases however the dilation recorded in the second and subsequent events is building up rapidly by comparison with the deformation rates shown by most tectonic processes. This rapid change would be consistent with the dilation increments being controlled by variations in local magma pressure. It does not however provide evidence directly relevant to the initial fracture event.

3.2. Application to other aspects of dyke emplacement

The features described here not only provided information on dilation increments but allow a variety of other aspects of dyke emplacement mechanisms to be investigated.

3.2.1. Possibility of detecting fissure closure

Dilation in dyke fissures has been shown to vary with time but only increases in dilation have been demonstrated. If increased dilation is the result of an increase in magma pressure (Lister and Kerr, 1991) then it may be a corollary that falling magma pressure may result in a reduction of dilation, i.e. partial closing, of the dyke fissure walls in those segments still occupied by fluid magma. The features illustrated here do not demonstrate such an event. However, if the sum of dilations of narrow dykes in a bridge, offset zone or termination were to exceed significantly the dilation measured in the main dyke, then partial closure will have occurred of that part of the fissure that contained fluid magma. It is certainly worth looking for this effect elsewhere.

3.2.2. Linkage of dilation events to zonal patterns in unitary dyke interiors

Zonal textural patterns in groundmass and phenocrysts are inferred by Platten and Watterson (1987) and Platten (1995) to reflect sequential changes in the flow regime of magma in dyke fissures. The dykes described from Coire Lagan and Loch Brittle show direct and indirect correlation of internal textural changes with the elements of the multiple dyke system. This shows that in some cases events recorded in simple straight dyke sections are associated with dilation and hence strengthens arguments (Lister and Kerr, 1991) that dilation is controlled in part by the magma pressure at the site.

3.2.3. Elucidation of differential accretion of crystalline material at dyke walls and dyke tips

Comparing the unitary dyke sections with the multiple sections also allows a direct observation of the different rates of wall crystallisation between regions of mainstream flow and regions of largely stagnant magma (Figs. 9 and 10). Non-propagating dyke tips here are narrower than the main dyke sections and must have flow parallel to the tip line. These would be expected from the theoretical work (Lister and Kerr, 1991) to crystallise more rapidly. In Coire Lagan (Fig. 3c) the magma in the narrower dyke section in an offset is shown to have solidified whilst liquid magma remained elsewhere. Flow parallel to offsets would be expected to exhibit slowest flow in the narrowest section whilst flow through the offset will generate the highest velocity in the narrowest section. The features shown in Fig. 3(c), near the lateral termination of the Coire Lagan dyke, are consistent with stagnant magma in the narrow section and actively flowing magma in the thick section. In the Loch Brittle dyke (Fig. 7), the axial non-amygdaloidal dolerite in traverses 1 and 2 thickens northwards as the outer amygdaloidal dolerites thin. The sparsely amygdaloidal dolerite forming the initial axial fill in traverse 3 is thicker than the cumulative thickness of its extension into traverses 1 and 2 as the external amygdaloidal dolerites. The northwards thinning of wall layers and complementary thickening of the axial zone can be attributed to increasing flow rates away from the dyke termination reducing wall accretion of solid dolerite. This accounts for most of the northwards non-dilational thickening of the axial non-amygdaloidal dolerite.

3.2.4. Late dykes may record stress fields around initial dyke tips

The tendency of some of the late narrow dykes to diverge from the general regional trend around the unitary dyke tip (Fig. 2) may be providing information on the stress pattern around recently solidified dyke tips and so be worthy of further investigation. The pattern seen here has similarities with the local divergence of the maximum principal stress trajectories shown at the tips of dykes in the models of Pollard (1973).

3.2.5. Discrimination of injected damage zones from late increments of dilation

It is evident from this study that careful examination of chilled margin relationships will be essential in any investigation of both unrelated pre-existing fracture systems and genetically related damage zones forming as precursors to magma arrival (Delaney et al., 1986; Weinberger et al., 1995). The pattern of chilled margins will allow discrimination of injected precursor fractures from fractures produced sequentially during incremental dilation. Dilated early fracture systems will be expected to show a single chilled surface following all irregularities in the network of fissures. All chilled margins of narrow dykes in the country rock will be continuous with the chilled margin of the main dyke and all narrow dyke centres will merge with the main dyke centre. None of the narrow dykes will cut pre-existing dyke material.

4. Conclusions

The lateral passage of some unitary dykes into multiple dyke complexes has been demonstrated. Cross-cutting relationships within the multiple dyke complexes show that they formed by sequential fracturing and dilation and are not the result of simultaneous injection of magma into previously fractured ground or into damage zones formed as precursors to magma arrival. Elements of the multiple dykes cut and chill against the unitary dyke material showing that it was solid material subject to dilational fracture. The spatial association of the multiple dykes and the demonstration that some merge laterally with the main dyke indicate that all were fed from a common, magma filled fissure. The multiple complexes thus record incremental dilation events in the associated unitary dyke and underlying feeder system. Up to 11 increments of dilation have been recognised for some single fissures with examples of up to 60% of the final dilation occurring after initial magma emplacement in the fissure at the site of observation. It is shown that detailed structural studies of local dyke termination have additional contributions to make to the study of fracture, dilation, flow and crystallisation in dykes.

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