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Variation in the form and distribution of dykes in the Mull swarm, Scotland

R. J. H. JOLLY and D. J. SANDERSON

Department of Geology, University of Southampton, Southampton, SO17 1BJ, U.K.

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Abstract—The dykes of the Mull swarm, part of the British Tertiary Igneous Province, have been examined in a series of well exposed coastal sections. Traverses through the dyke swarm show systematic changes in the thickness and spacing of dykes, both of which are typically log-normally distributed. Both the geometric mean thickness and spacing of dykes increase with distance from the Mull centre, concordant with a decrease in crustal extension. Variations in the thickness and spacing result from changes in character of the magma flow. It is inferred that the magma flux was fairly evenly distributed near the Mull centre, but farther away from the source it becomes focused into larger dykes. The form, orientation and opening direction are also observed to vary with distance away from the volcanic centre on Mull. The dykes intrude a range of pre-existing fractures, the range of fractures used decreases with distance from the centre. This, together with other features of the form of the dykes have been interpreted in terms of the varying magma pressure and regional stress, which is expressed as the *R*-ratio. Analysis of the variable strikes of fracture-filled dykes is consistent with decreasing magma pressure with distance from the Mull centre, assuming that regional stresses were relatively invariant across the same distance.

INTRODUCTION

Dykes form major pathways for the transfer of magma in the upper crust. They can be found in a number of settings, for instance, extensional plate margins, such as the Mid-Atlantic Ridge, or associated with mantle plumes providing conduits for magma to reach the surface, such as Hawaii. Dykes rarely occur in isolation, more commonly in swarms, either in parallel or subparallel arrays (Harker 1904, Richey 1939, Anderson 1951), or in radial arrays (Odé 1957, Smith 1987). A dyke swarm is defined as "an assemblage of dykes intruded during the same period of activity" (Speight *et al.* 1982). Treated as mode I fractures, dykes have been used to infer the orientation of the main horizontal compressional stress (Richey 1939, Anderson 1951). The form and geometry of the dykes are, however, dependent on the stresses present during intrusion (Odé 1957, Vann 1978, Delaney *et al.* 1986, Smith 1987, Baer *et al.* 1994). The mechanics of intrusion of a swarm, and in particular the stress responsible for dyke formation, can be inferred from the geometrical form, opening directions, orientations, thickness and spatial distributions (Delaney *et al.* 1986).

Well exposed sections are examined through the Mull swarm in Argyll, Scotland. These dykes form part of the British Tertiary Igneous Province (Harker 1904, Bailey *et al.* 1924), and their petrology has been extensively studied (Bailey *et al.* 1924, Lamcraft 1979, Thompson 1982, MacDonald *et al.* 1988). The orientation and frequency of the dykes has been used to infer the amount of dilation around the volcanic centre (Sloan 1971, Speight 1972, Knapp 1973) and Vann (1978) used finite elements to model the stress field at the time of emplacement of the dykes around Arran.

A series of continuously exposed traverses within the SE part of the Mull swarm (Fig. 1) allows a systematic investigation of the dyke geometries, orientations, thickness and spacing. This information is then combined in a model that explains the intrusive styles of the dykes in relation to the changes in the stress field with distance from the volcanic centre.

GEOLOGICAL SUMMARY

The British Tertiary Volcanic Province (BTVP) consists of a series of volcanic centres, well exposed along the west coast of Scotland and NE Ireland. Associated with the volcanic centres are lava piles and sets of linear NW–SE-trending dykes. The Mull centre has one of the most extensive swarms of dykes, some of which extend as far as the NE of England. The lavas on Mull have been dated using ^{40}Ar–^{39}Ar, with extrusion between 59.4 Ma and 61.1 Ma (Musset 1986). The intrusion of the dykes both pre-dates and post-dates the lavas. Dagley *et al.* (1987) proposed that the igneous activity for the emplacement of the dykes and the lava piles, took place over a period of some 3.5 Ma.

The dykes in the Mull swarm comprise basalts, olivine-basalts, dolerites, olivine-dolerites, gabbros, felsites, and quartz-porphyrys (Allison 1936, Bailey *et al.* 1924, Lamcraft 1979). The felsic dykes are closely associated with the central felsic chamber, but in the regions away from Mull, the dykes are almost entirely mafic. The parental magma for the dykes of the swarm has been described as a magnesium-rich olivine tholeite, typical of ocean ridge magmatism (Thompson 1982). In this paper only the mafic dykes are considered.

Much of Mull comprises the lava pile associated with

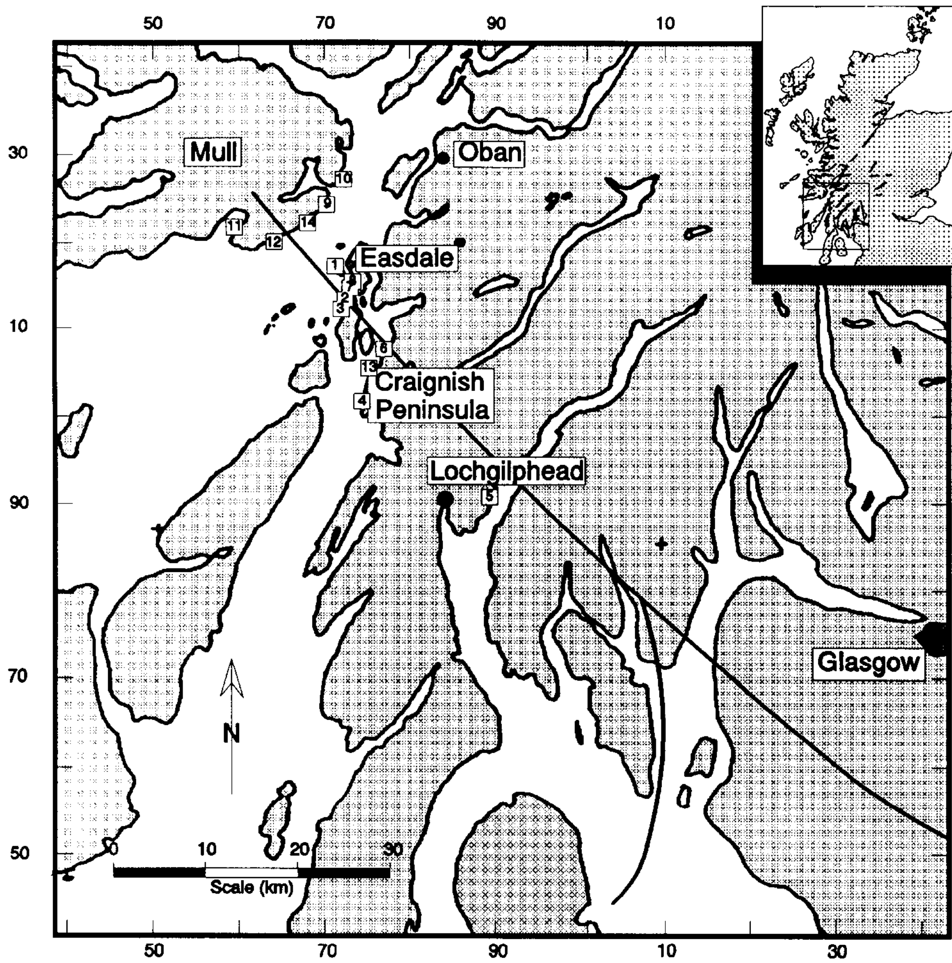

Fig. 1. Map of the Argyll region showing the traverse locations (numbered boxes) and the position of the axis of the Mull dyke swarm (solid line, after Speight *et al.* 1982). Inset shows the location of the region within Scotland.

the Tertiary volcanic centre. There are however some areas of coastal exposure where there are Mesozoic and older rocks. Traverses were mainly recorded within the Mesozoic sedimentary units, as these provide a complete history of intrusion, with no loss of dykes due to burial by the lava pile.

The host-rocks in the Easdale area (Fig. 1) are dark pyritic slates interbedded with dark grey limestones of the Dalradian Supergroup. The slates have a well-developed S_1 cleavage dipping steeply to the SE. An S_2 cleavage is less well developed, causing crenulations of the S_1 cleavage planes, and dips gently to the SE. The axes of the F_1 folds plunge gently to the southwest. At Easdale there is also a dominant joint set trending NW–SE, which is steeply dipping; this joint set is often exploited by the dykes (Fig. 8).

In the Craignish and Loch Fyne Areas, the host rocks are lower Dalradian phyllites and psammites with occasional, laterally non-extensive metadolerite sills, typically about 3 m thick. These rocks are folded, with fold axes plunging gently to the northeast. The cleavage is generally almost parallel to bedding.

The dyke swarms of all the volcanic centres along the west coast of Scotland generally trend NW–SE, although locally they deviate to become more north–south, especially between Mull and Arran and between Mull and Skye. Two explanations have been proposed for this: (1) that the dykes are deflected due to the presence of the other volcanic centres at the time of intrusion (Harker 1904), or (2) that locally they exploit north–south zones of weakness (Richey 1939, Tyrrell 1949, Auden 1954, Knapp 1973 and McIntyre *et al.* 1975).

DATA COLLECTION

Data were collected along linear traverses through completely exposed coastal sections. A tape was laid out, approximately normal to the main strike of the dyke swarm and, in general, 30 m sections were established and these joined to produce the total traverse. The orientation of each section was recorded, measurements being made of the orientation and thickness of each dyke and the point of intersection of the centre of the dyke with the traverse line. In addition the nature of the host rock and details of the intrusive form of the dyke, such as side-stepping, horn structure (Fig. 7), flow structure and branching, were recorded.

Fourteen traverses, with a total length of 11,734 m,

Table 1. Basic data and percentage extension for individual traverses and areas, the locations of which are indicated on Fig. 2. Explanation of the calculations of extension and dyke frequency are given in the text

Location and traverse	Distance from the Mull centre (km)	Traverse length (m)	Number of dykes	Total dyke thickness (m)	Amount of extension (%)	Dyke frequency (km^{-1})
Mull: 9	11	100.0	10	17.4	20.7	100.0
10	13	740.0	24	33.0	4.5	32.5
11	8	670.0	9	9.6	1.9	13.0
12	10	540.0	34	41.5	8.2	63.0
14	10	1320.0	165	162.5	12.4	125.0
Easdale: 1	16	700.0	28	48.8	7.0	40.0
2	20	620.0	22	42.0	4.7	70.0
3	21	725.0	17	49.9	7.5	23.4
7	19	592.0	14	21.0	4.3	23.6
8	19	1371.0	51	80.7	6.3	37.2
Craignish: 4	31	1365.0	6	35.0	3.5	4.4
6	26	384.6	9	36.9	7.9	23.4
13	27	1925.0	11	39.0	2.3	5.7
Loch Fyne: 5	47	661.7	10	21.9	3.1	15.1
Mull, Total	10	3370.0	242	264.1	7.8	71.8
Mull, seds.	10	2600.0	223	237.0	9.1	85.8
Easdale	19	4008.0	132	223.0	5.6	33.2
Craignish	28	3695.0	26	111.0	3.0	7.0
Loch Fyne	47	661.7	10	21.9	3.1	15.1

were recorded across 413 dykes (Table 1). These traverses were grouped into four locations (Fig. 2):

(1) Mull;
(2) the area between Easdale and the island of Luing;
(3) the Craignish peninsula;
(4) part of the northern coast of Loch Fyne.

The locations of the traverses, largely controlled by the available exposure along the coastal areas, were selected at varying distances from the source region of Mull. Unbroken exposure is fundamentally important, in order to allow complete sampling of all of the dykes within the traverse section. It was also important that transects were approximately perpendicular to the main trend of the swarm to maximize the number of dykes recorded and to obtain direct estimates of spacing.

THE ORIENTATION AND FORM OF DYKES

Orientation

The Mull dyke swarm trends NW–SE (Harker 1904, Sloan 1971); the dykes within the swarm also generally trend NW–SE though this is not always consistent, and there are places within the swarm where the dykes have a trend that is oblique to the swarm.

The mean trend and percentage of dykes that strike within 20° of this are as follows; Mull—140°, 55%; Easdale—130°, 63%; Craignish—130°, 81%; Loch Fyne—147°, 40%. From Mull to Craignish there is an increase in the alignment of strikes. The dykes are generally steeply dipping with 81% (Mull), 93% (Easdale), 98% (Craignish) and 90% (Loch Fyne) of dips within 20% of the vertical.

Stereograms of the poles to dykes recorded on the traverses show some bias towards the NW–SE striking dykes as traverses generally lie NE–SW. It is possible to correct for this effect with the Terzaghi correction (Terzaghi 1965, La Pointe & Hudson 1985) (Fig. 4), by weighting dykes in inverse proportion to their probability of intersecting the traverse line. This weighting (w) value is:

$$w = \frac{1}{\cos \theta}, \qquad (1)$$

where θ is the angle between the pole to the dyke and the traverse direction. It can be seen from Fig. 4 that for localities with a fairly pronounced preferred orientation of dykes, such as Easdale, the correction produces little significant change to the distribution, since most dykes intersect the traverses at high angles. Where dyke orientations are more variable, as on Mull, the Terzaghi correction increases the frequency of dykes which trend at low angles to the traverse (Fig. 4).

The degree of preferred orientation of the dykes can be analysed using the sum of the squares and cross products of the direction cosines of their poles (Mardia 1972, pp. 222–226). The eigenvalues of the resulting matrix are given in Fig. 3. The ratio of the maximum to minimum eigenvalues gives a crude measure of the degree of preferred orientation (Woodcock & Naylor 1983). The data from Mull have the lowest eigenvalue ratio of 7.03, whereas at Easdale the ratio is 15.3. This analysis supports the hypothesis of increasing alignment of dykes with distance from the Mull centre.

Opening direction

The opening direction of dykes can be determined using a variety of markers in the wallrocks, such as veins,

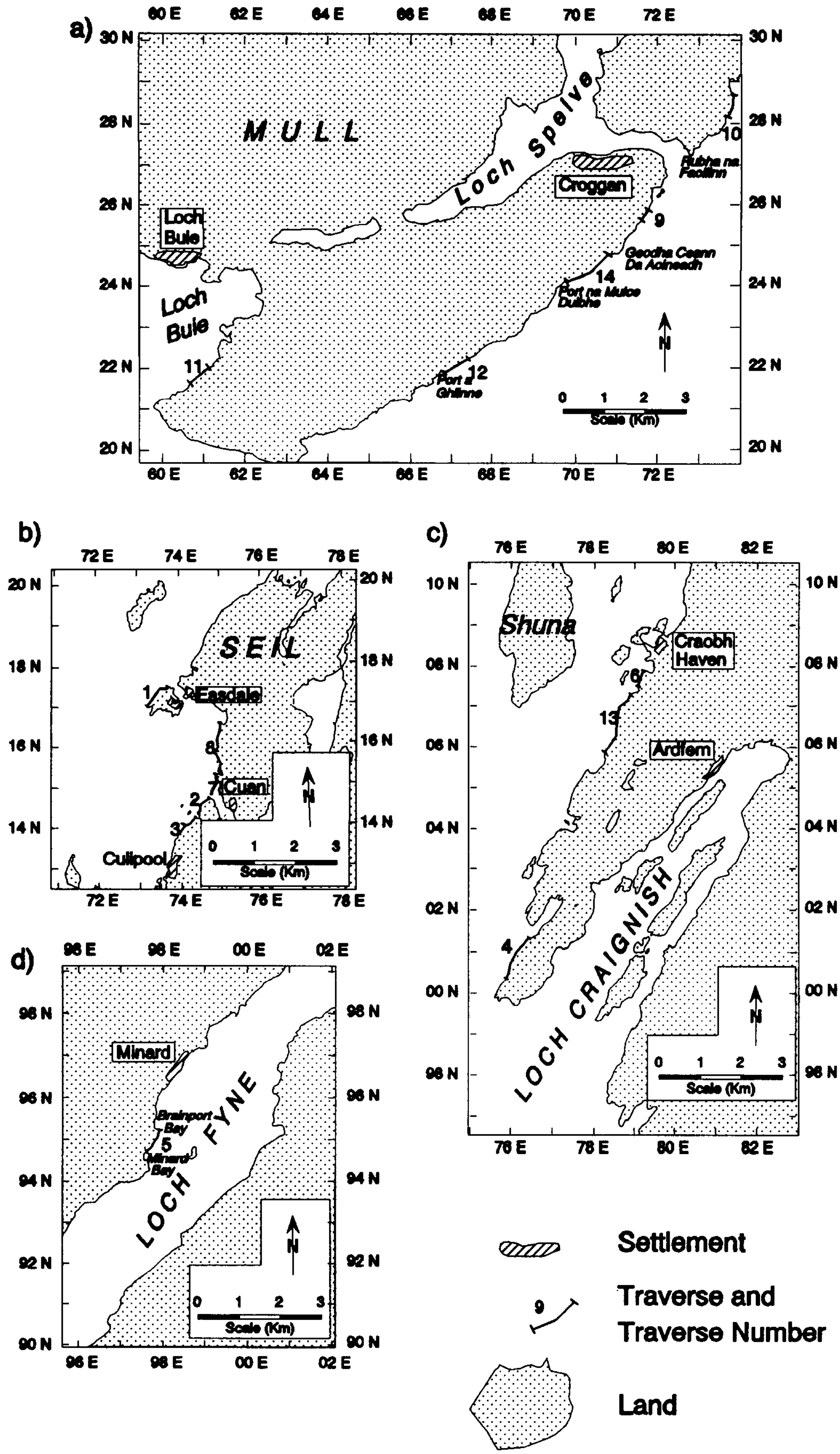

Fig. 2. Locations of the measured traverses (numbered lines) within four areas: (a) southeast of Mull; (b) Easdale, Seil and Luing; (c) Craignish; (d) Loch Fyne.

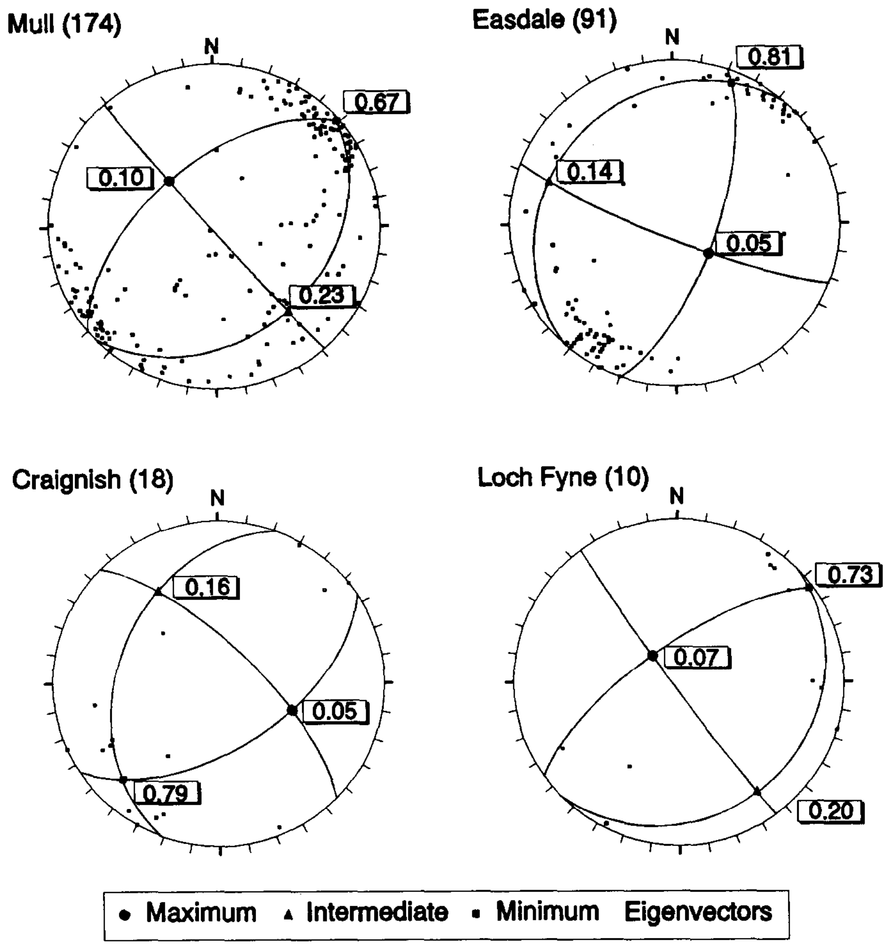

Fig. 3. Equal-area stereograms of poles to dyke walls in the four areas, based on dykes measured on individual traverses, together with the eigenvectors and eigenvalues of the resultant distribution.

fold hinges and distinctive beds, as well as from side-steps in the dyke wall. Planar markers can be correlated from opposite walls of the dykes and their horizontal separation across the dyke determined. Where two markers intersect to form a unique line, the piercement points provide a record of the finite opening direction in three dimensions. Most of the opening directions determined in three dimensions at Easdale show a major component of horizontal opening (Roberts & Sanderson 1971, Jackson 1992), a conclusion strongly supported by the similarity of separations of differently oriented planes in maps of dykes in this area.

Figure 5 summarizes the horizontal components of the opening directions. There is a large range of opening directions on Mull, 000–180°, whereas there is only a limited range (030–070°, mean 042°) at Easdale. Roberts & Sanderson (1971) found the mean opening direction for the dykes at Easdale of about 056°.

Geometric form

Dykes rarely consist of simple, planar, parallel-sided walls, but consist of segments linked by sudden side-steps, horn structures, and broken bridges (Fig. 6) (Nicholson 1985, Nicholson & Pollard 1985).

On Mull, the dykes utilise fractures of a range of orientations, and as a result often have cross-cutting relationships (Fig. 7). Dyke segments rarely show changes of strike greater than 45°, and horn structures and broken bridges are not abundant (Fig. 7). Single intrusive events tend to dilate individual fractures, or branching fractures, with cross-cutting of dykes rather than simultaneous use of a variably orientated fracture sets.

In contrast, at Easdale, dykes simultaneously intruded a variety of fractures and the cleavage to form abrupt side-steps (Fig. 8). The result is to produce irregular dykes, many of which maintain an average trend of c.130°, parallel to the swarm, but with frequent side-steps as described by Roberts & Sanderson (1971), who give many examples. Segments that are normal to the opening direction are thicker than those which are oblique to the opening direction within the same dyke (Fig. 8).

At Craignish the dykes also use pre-existing fractures to produce abrupt side-steps, though the frequency with which these occur is less than at Easdale. There are also fewer horn structures and broken bridges, associated with the side-steps.

At Loch Fyne, dykes utilise a more limited range of fracture orientations and adjacent segments rarely show changes of strike greater than 60° (Fig. 9). There are also fewer horn structures and broken bridges than at the other locations, Easdale and Craignish.

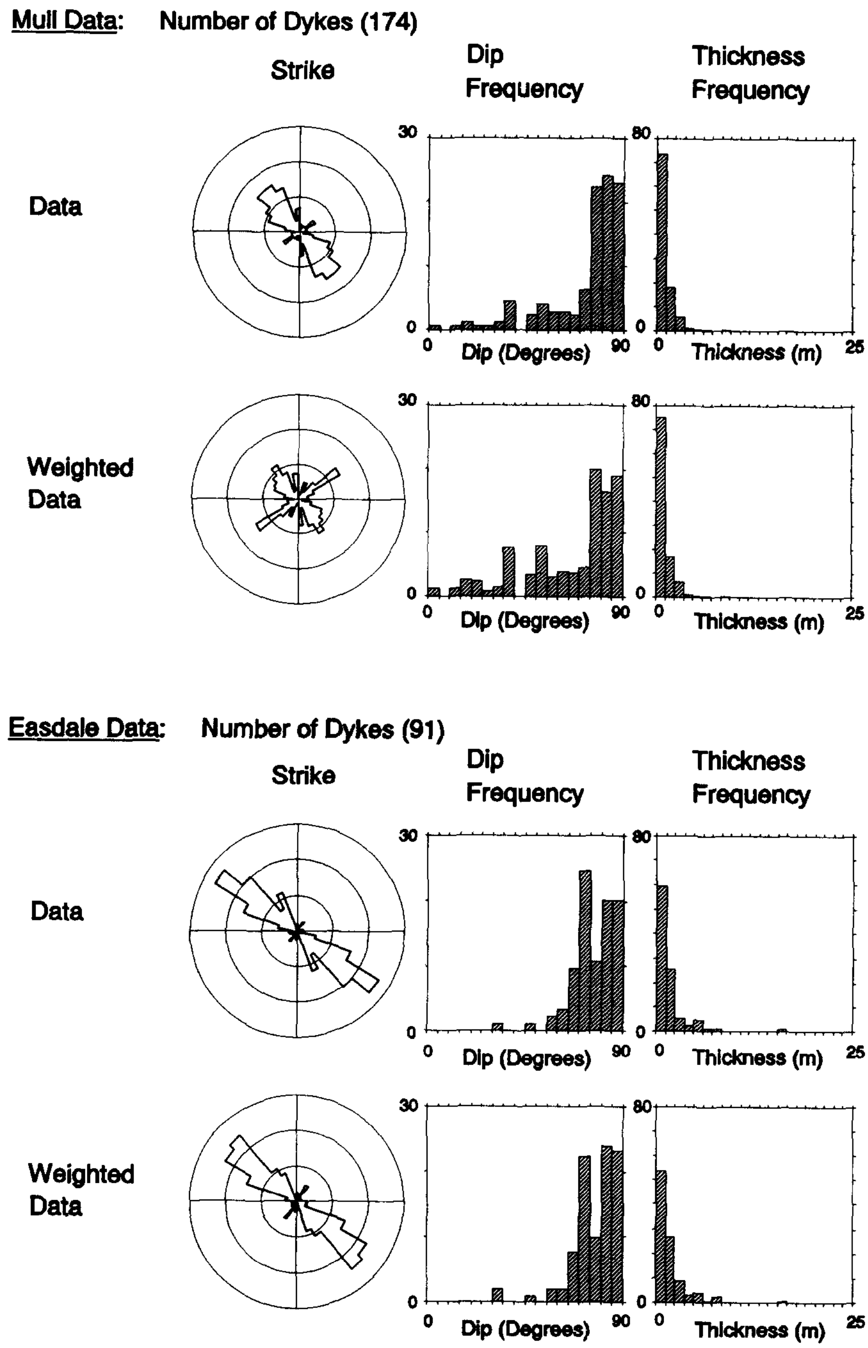

Fig. 4. Data on the trend, dip and thickness of dykes measured at Mull and Easdale. Measurements are shown as original data and weighted data, the latter being weighted to reduce the bias due to the orientation of the individual line traverses using the Terzaghi correction (for explanation see text).

R-ratio

Delaney *et al.* (1986) analysed the orientation of fractures in relation to the magma pressure and the regional stress field. For a fracture to dilate and fill with magma, the magma pressure (P_m) must exceed the normal stress on the fracture wall (σ_n) (Fig. 10); this is expressed as:

$$P_m \geq \sigma_n \tag{2}$$

By expressing σ_n in terms of the maximum (S_H) and minimum (S_h) principal stress within a plane, and the angle (θ) between the maximum principal stress (S_H) and the normal to the dyke (Fig. 10), Delaney *et al.* (1986) derive the R-ratio:

$$R = \frac{(P_m - S_H) + (P_m - S_h)}{(S_H - S_h)} \geq \cos 2\theta \tag{3}$$

As can be seen from equation (3) the terms involving the principal stresses are the mean stress ($\bar{\sigma} = (S_H + S_h)/2$) and the maximum shear stress ($\tau_{max} = (S_H - S_h)/2$), so the R-ratio (R) can be expressed more simply as:

$$R = \frac{P_m - \bar{\sigma}}{\tau_{max}} \geq \cos 2\theta \tag{4}$$

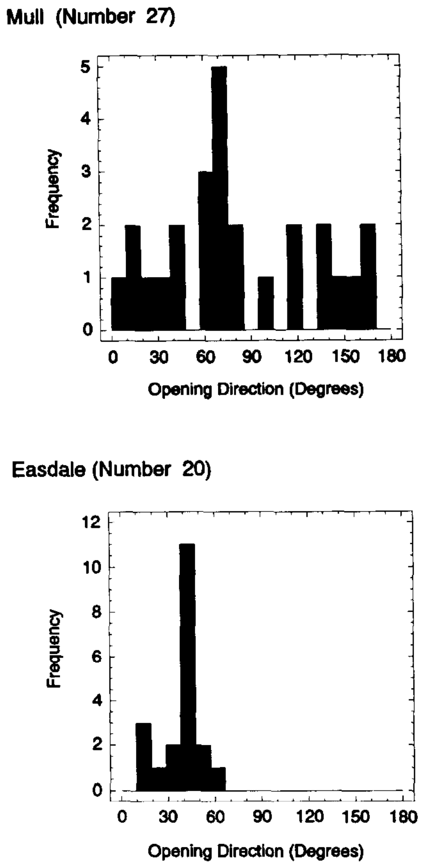

Fig. 5. Frequency histograms of the horizontal component of opening directions for Mull and Easdale. On Mull there is a large range of opening directions, whereas at Easdale there is only a limited range of opening directions.

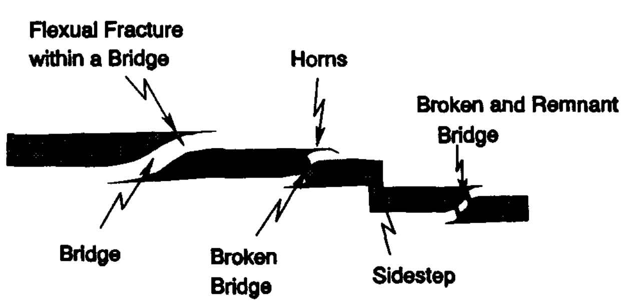

Fig. 6. Schematic diagram of features seen in a side-stepping dyke (after Nicholson and Pollard 1985).

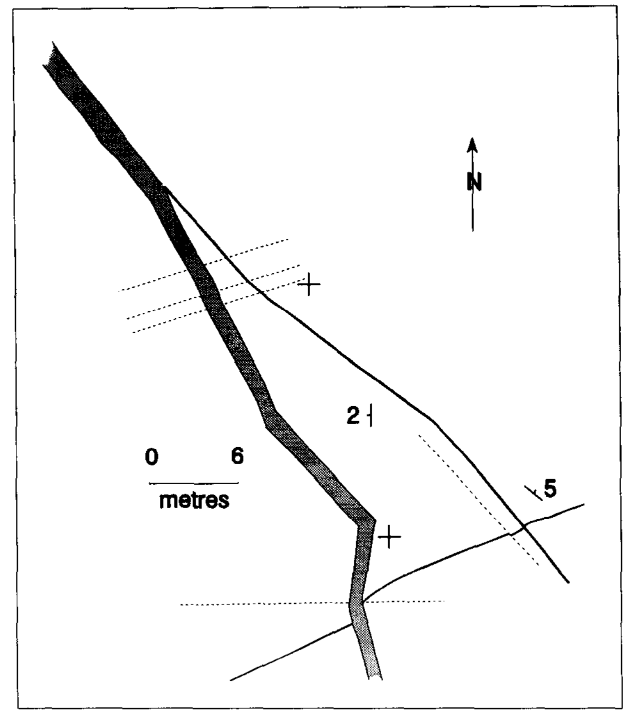

Fig. 7. Map of a dyke from Carsaig, Mull (552 210), showing a cross-cutting nature and the gradually varying orientation of dyke segments. The dashed lines are joints and the dips are of the flat-lying bedding.

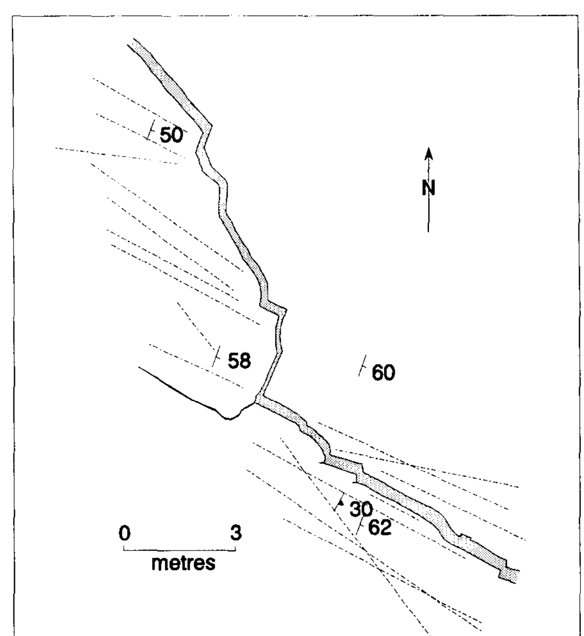

Fig. 8. Map of a dyke from Easdale, Seil (750 164), segments occupy a wide variety of fracture orientations and produce branching and side-stepping of the dyke. The dashed lines represent prominent joints and the dips are of the bedding and the S1 cleavage.

The relationship between R and θ is represented graphically in Fig. 11. It is clear that the value of R controls the range of fractures that are able to dilate and will have a dramatic effect on the form of the dykes and on the way in which magma intrudes a fractured rock mass.

Another feature of a dyke that can be related to the stress regime is its opening direction (μ), again measured relative to the normal to the dyke wall (Fig. 10). The opening direction may be directly related to the angle θ and the stresses (Delaney *et al.* 1986), as follows:

$$\tan \mu = \frac{\tau}{P_m - \sigma_n} = \frac{\sin 2\theta}{R - \cos 2\theta} \qquad (5)$$

which is represented graphically in Fig. 12.

When the R-ratio tends to infinity, the opening direction is effectively normal to the dyke walls (Fig. 12). When the R-ratio is $+1$, $P_m = S_H$, $\mu = 90 - \theta$ and the dykes open consistently in the direction parallel to the S_h (Fig. 13). Where $1 > R > -1$, the opening direction is dependent on the orientation of the fracture, but the

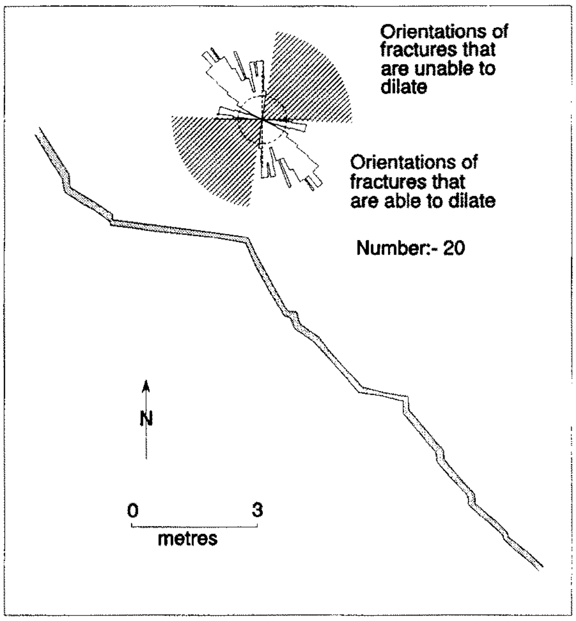

Fig. 9. Map of a dyke from Loch Fyne (976 945). The rose diagram (inset) shows the range of fractures that have been able to dilate, the shaded area is the orientation of fractures that are unable to dilate.

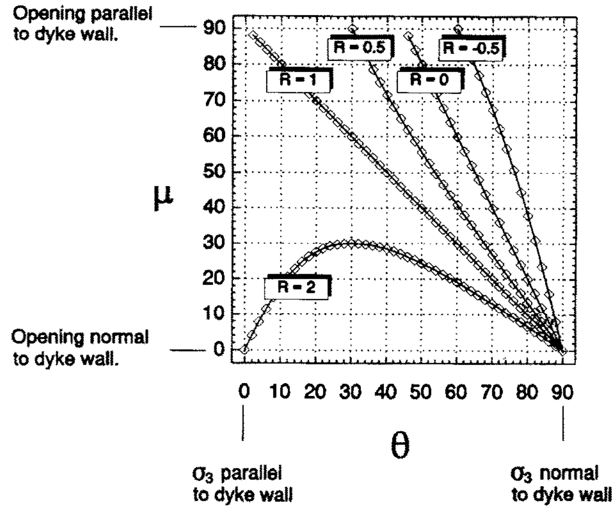

Fig. 12. Plot of angle μ between the opening direction and the normal to the dyke and θ, the angle between the maximum principal stress and the normal to the dyke, based on theory of Delaney *et al.* (1986).

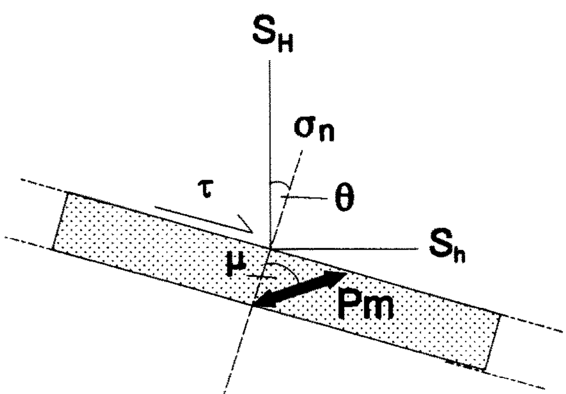

Fig. 10. The notation used in the analysis of stress and opening of dykes. Compressive stresses are regarded as positive; the solid arrow indicates the opening direction of the dyke walls.

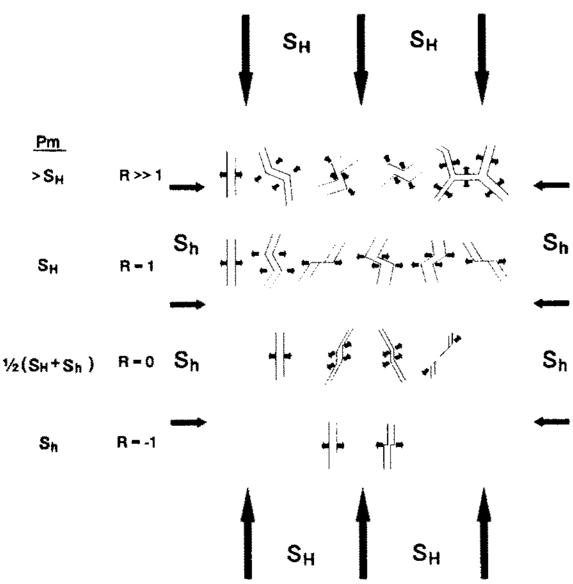

Fig. 13. The variation of dyke form due to the changes in the R-ratio (Delaney *et al.* 1986). $R = -1$ only planar parallel fractures normal to the minimum principal stress are able to dilate. $R = 0$ allows a greater range (± 45) of fracture orientations to dilate, with opening directions which are generally oblique to the minimum principal stress. $R = 1$ allows all fracture orientations to dilate, but all opening directions are parallel to the minimum principal stress direction. For $R \gg 1$ fractures of any orientation can open with any opening direction, in an extreme case producing 'net veining'.

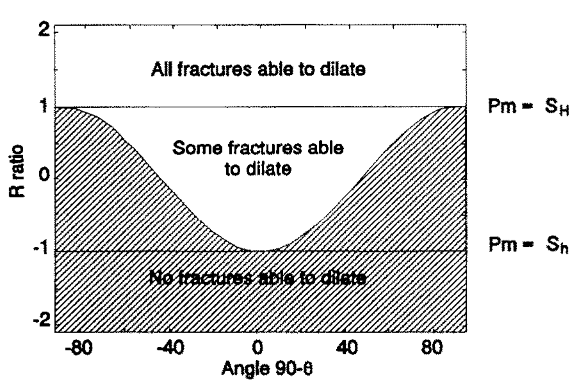

Fig. 11. Plot of the R-ratio against $90 - \theta$, indicating the conditions under which fractures may have opened (unshaded area) (after Delaney *et al.* 1986).

ranges of fractures that are able to dilate is restricted (Fig. 13). When $R = -1$, $P_m = S_h$ and only fractures that are normal to S_h are able to dilate and they can only open parallel to S_h (Figs. 12 and 13).

A change in the R-ratio can, therefore, produce different forms of dykes, dependent on the fracture orientations, principal stresses, and the magma pressure (Fig. 13). This relationship between the R-ratio and the form of the dykes is well illustrated within the Mull swarm. It is likely that the dykes on Mull were intruded with a R-ratio greater than 1, since there is a large range

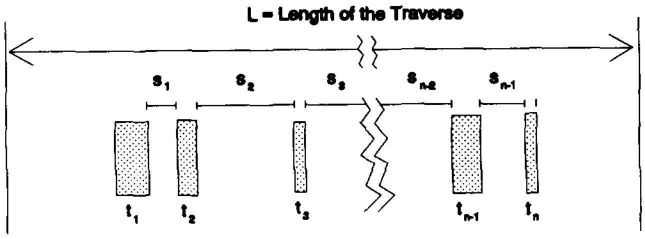

Fig. 14. The conventions and nomenclature used in the calculation of extension along a traverse.

of orientations of dykes (Figs. 3 and 4) and opening directions (Fig. 5). At Easdale, *R*-ratios are about +1, since there again is a wide range of fractures which were able to dilate (Figs. 3 and 4), but a fairly consistent opening direction (Fig. 5). Dykes with orientations that are greatly oblique to the general trend are thinner than those that are parallel to the dyke trend (Fig. 8). At Loch Fyne the *R*-ratio was probably close to 0, as the dykes have a restricted range (±45°) of orientations (Fig. 9). These observations suggest that the *R*-ratio decreases with distance from the Mull centre.

THICKNESS AND SPACING OF DYKES

Extension and frequency

The amount of crustal extension can be determined from the thickness (t) and spacing (s) of the dykes. The percentage extension is given by:

$$\textit{True extension} = \frac{\sum_{i=1}^{n} t_i - \frac{1}{2}(t_1 + t_n)}{\sum_{i=1}^{n-1} s_i} \times 100. \qquad (6)$$

This expression estimates extension between the centre of the first and last dykes in any traverse (Fig. 14). Where Σt_i is small in relation to the length of traverse (L), then an approximate estimate of the percentage extension is obtained from:

$$\textit{Extension} = \frac{\Sigma t}{L} \times 100 \qquad (7)$$

The extension estimates, based on equation (6), are summarized in Table 1.

On Mull, the estimated extension ranges from 2% to 20%. The large variation between different traverses is, at least in part, due to sampling in areas where the host rock is lava, where the broad contemporaneity of dykes and lavas leads to minimal estimates of crustal extension. However, the traverses in the Mesozoic rocks, still show a relatively high variation in the amount of extension compared to the other areas. The narrowing of the swarm towards the central chamber on Mull causes a steep gradient, with greater extension in the central axis and less extension in the peripheral areas of the swarm (see also Sloan 1971).

At Easdale the amount of extension is more consistent, ranging from 4% to 7%. This is due to the consistency of the character of the host rocks and the fact that all traverses lie in the broader central part of the swarm. There is a marked decrease in the mean extension compared with the traverses from Mull.

At Craignish the amount of extension ranges from 2% to 7%, slightly more variable than the dykes at Easdale, but with a further decrease in the mean extension. The traverse at Loch Fyne shows a similar extension to that at Craignish.

These observations are in accord with those of previous workers (Anderson 1951, Sloan 1971) and demonstrate a general increase in crustal extension due to dyke intrusion towards the volcanic centre on Mull.

The dyke frequencies, number of dykes per kilometre, for the traverses are given in Table 1. These results follow a similar pattern to the extension estimates, with a high mean on Mull (c. 80 km^{-1}) falling to c. 30 km^{-1} at Easdale and to <20 km^{-1} farther from the centre at Craignish and Loch Fyne.

Dyke thickness

The thicknesses of dykes, measured normal to their walls, vary considerably, from <1 cm up to a maximum recorded thickness of 20 m; thicker dykes are known from elsewhere in the Tertiary Igneous Province. Before examining variations in mean thickness within the swarm it is important to determine a suitable model for the distribution of thicknesses at individual sites. The data from traverses were compared with the normal (Gaussian), log-normal, negative exponential and power-law distributions by using cumulative frequency plots (Fig. 15). These plots provide a graphical representation of the data in a form suitable for visual estimation of the fit to the distribution models. In the case of normal and log-normal distributions the cumulative frequency is plotted against thickness, or log(thickness), using normal probability scaling; a straight line plot indicates conformity in the normal (or log-normal) frequency distribution. For a negative-exponential distribution a plot of log(cumulative thickness) against thickness is a straight line, whereas for a power-law distribution log-(cumulative thickness) against log(thickness) yields a straight line.

None of the data on dyke thicknesses from the Mull swarm conform to the normal distribution. Most of the data had a good fit to the log-normal distribution (Figs. 15 and 16), a feature supported by the similarity of the median and geometric mean for most samples (Table 2). On Mull, however, the negative-exponential distribution provides a somewhat better model. Since negative-exponential models characterize random (Poisson) processes, this may suggest that locally, near the magma source, the thickness distribution of the dykes is effectively random.

Dyke thickness is clearly not fractal (i.e. scale in-

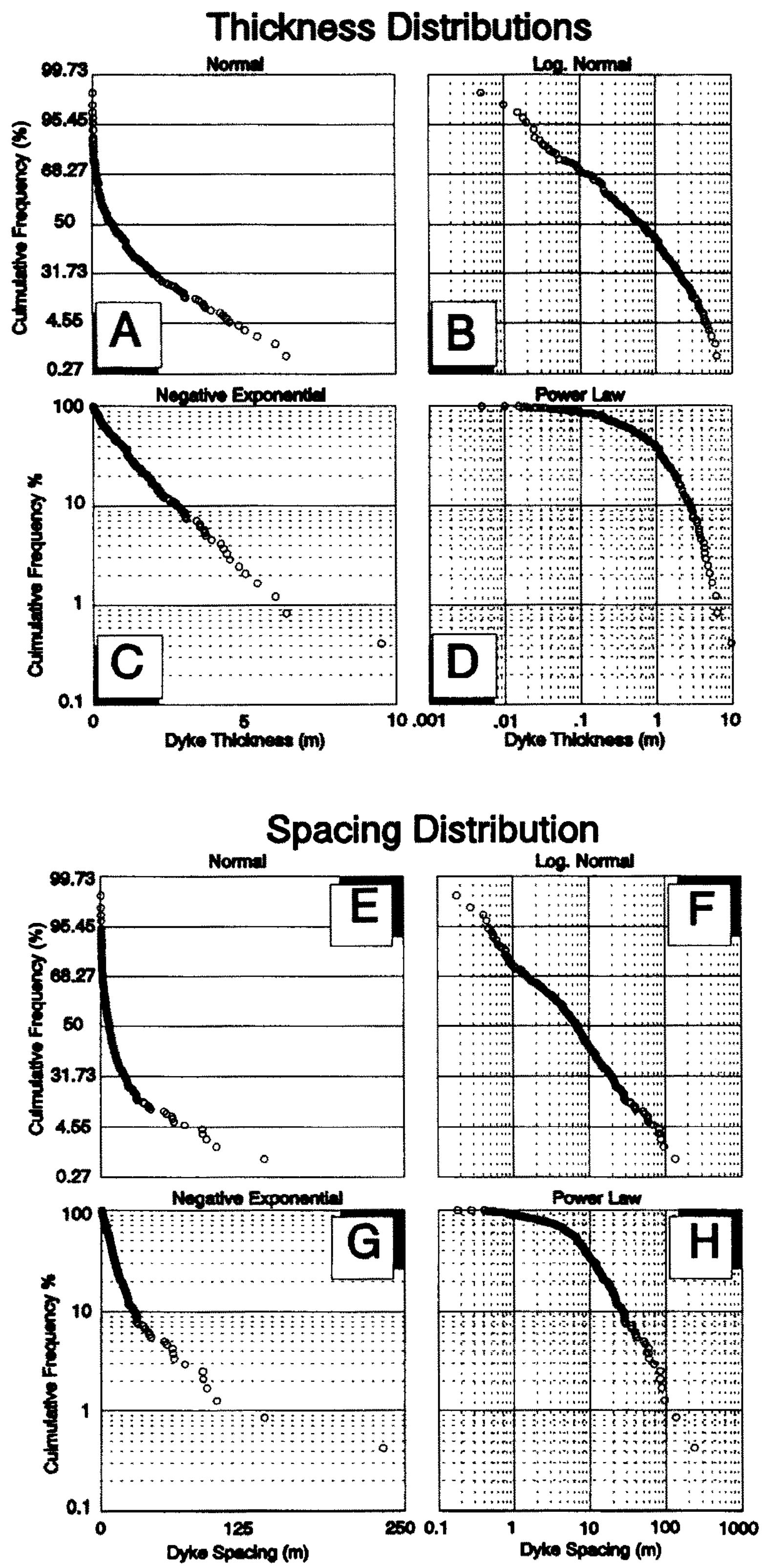

Fig. 15. Thickness and spacing of dykes on Mull plotted on cumulative frequency graphs to allow assessment of the distribution. Data should lie on straight lines for distributions which are normal (A & E), log-normal (B & F), negative exponential (C & G), and power-law (D & H). In the case of Mull, dyke thickness has a log-normal or negative exponential distribution, and spacing is log-normal.

variant), such as has been reported for many fracture-related phenomena, for example fault displacement (Walsh *et al.* 1991, Jackson & Sanderson 1992, Pickering *et al.* 1994, etc.) and for some dykes (Kruhl 1994), as the data do not conform to a power-law distribution. This is most obvious in the flattening off of the cumulative frequency at a dyke thickness of <0.1 m (Fig. 15d), indicating that there are far fewer narrow dykes than

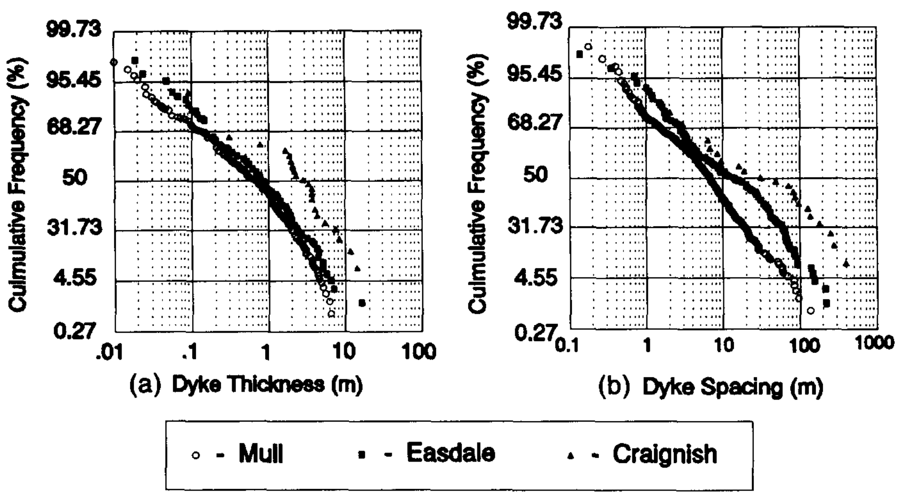

Fig. 16. Cumulative frequency plotted against log (thickness) or log (spacing), for the dykes from Mull, Easdale, and Craignish. In almost every case the data plot on an approximate straight line, hence, showing a reasonable correspondence to a log-normal distribution.

Table 2. Statistical parameters of the thickness and spacing of dykes for individual traverses and for geographical areas (see Fig. 2 for locations)

	Thickness					Spacing				
Location traverse	Median (m)	Arith. mean (m)	Std. dev. (m)	Geom. mean (m)	Log. std. dev.	Median (m)	Arith. mean (m)	Std. dev. (m)	Geom. mean (m)	Log. std. dev.
Mull: 9	1.4	1.74	1.51	1.24	0.39	5.61	7.58	7.08	4.80	0.47
10	1.0	1.38	1.51	0.62	0.67	18.70	31.37	37.71	16.47	0.56
11	1.2	1.07	0.62	0.82	0.39	37.25	55.50	74.46	25.86	0.65
12	0.5	1.22	1.46	0.47	0.71	8.25	15.26	23.81	7.38	0.58
14	0.6	0.99	1.24	0.60	0.60	5.95	7.91	7.98	4.81	0.48
Easdale: 1	1.4	1.74	1.74	0.99	0.54	13.63	25.26	32.08	10.29	0.69
2	0.5	0.95	1.25	0.47	0.54	9.41	20.74	34.51	8.48	0.59
3	1.1	2.94	4.72	1.36	0.55	21.74	39.03	49.18	15.53	0.74
7	0.7	1.50	1.98	0.63	0.67	27.14	32.97	25.35	25.32	0.34
8	0.8	1.58	2.59	0.73	0.58	12.24	25.26	28.66	11.57	0.60
Craignish: 4	3.8	5.84	6.66	4.04	0.37	135.90	176.20	127.35	147.80	0.28
6	2.3	4.10	4.66	1.82	0.71	13.95	42.29	48.93	17.51	0.70
13	2.8	3.55	3.69	1.46	0.78	23.38	142.90	250.78	25.93	0.93
Loch Fyne: 5	1.2	2.19	2.37	1.08	0.61	58.95	63.24	62.18	28.83	0.70
Mull, total	0.7	1.09	1.30	0.52	0.61	6.90	12.81	22.41	6.09	0.54
Mull, seds	0.6	1.06	1.30	0.49	0.62	6.80	11.47	16.37	5.83	0.53
Easdale	0.9	1.68	2.61	0.77	0.58	14.17	27.04	33.17	12.05	0.62
Craignish	3.1	4.27	4.70	1.99	0.68	47.63	115.18	180.47	33.02	0.81
Loch Fyne	1.2	2.19	2.37	1.08	0.61	58.95	63.24	62.18	28.83	0.70

predicted by the power-law model. Since dykes of 0.01 to 0.1 m would be easily observed in the continuously exposed section, their scarcity is a real feature of the distribution and not due to poor or truncated sampling (see Jackson & Sanderson 1992, Pickering *et al.* (in press) for fuller discussion of these sampling effects).

Establishing that dyke thickness has a log-normal distribution allows the analysis to be taken in two further directions; (1) areas may be compared using the geometric mean as a measure of dyke thickness, and (2) further statistical tests may be carried out, such as analysis of variance (ANOVA) techniques.

The cumulative frequency plots for the thickness of dykes from different regions are compared in Fig. 16(a). There is little change in the log standard deviation, but there is a general increase of the log-mean with a decrease in the dyke frequency (Table 2, Fig. 16a). The average geometric means range from c. 0.5 m, on Mull, through 0.8 m at Easdale, to 2.0 m at Craignish (Table 2).

Many previous workers have analysed the thickness variations of dykes (Tomkieff 1933, Walker 1975, Sloan 1971), and have noted a general increase in the arithmetic mean thickness with increasing distance from Mull (Allison 1936, Sloan 1971). The median or geometric mean are, however, better measures of this thickness change.

Dyke Spacing

The spacing between the dykes was analysed in a similar way to the dyke thickness. The spacing distributions were found to have a good fit to a log-normal distribution (e.g. Fig. 15f), with poor fits to the normal, negative-exponential and power-law distributions. This result is similar to analyses of spacing of joints and faulting (Priest and Hudson 1976, 1981, Gillespie *et al.* 1993), although the preference for the log-normal over the negative-exponential model is more clearly defined in this study.

Again the poor fit of the data to power-law models, indicates that dyke spacing is not a simple fractal, but is related to a characteristic length scale, best described by the median or geometric mean spacing. The use of the log-normal model allows further statistical analysis, including the use of ANOVA techniques.

The geometric mean of the spacing ranges from c. 6 m on Mull, through c. 12 m at Easdale to c. 30 m at Craignish and Loch Fyne (Fig. 16b) (Table 2). Thus there is a general increase in spacing with distance from the Mull centre. Given the general increase in dyke thickness, this indicates that the overall decrease in extension is largely controlled by increased spacing.

Analysis of Variance (ANOVA)

Thickness and spacing data were collected from several traverses within four distinct areas and the results presented and discussed by comparison between these areas. To compare the variation between areas to that within areas (between traverses), an analysis of variance (ANOVA) was applied to the data. The F-ratio compares the variance (V_w) within the areas and the variance (V_a) between the areas, such that:

$$F = \frac{V_a}{V_w}. \tag{8}$$

As discussed in the previous section, the log-normal distribution model was chosen and a simple one-way analysis using the logarithms of both thickness and spacing data carried out. The comparison of the F-ratio statistic with the critical F-value, at the appropriate degrees of freedom, enables hypotheses of equal sample variance to be accepted or rejected at various confidence levels. There is a significant difference if the observed F-ratio is greater than the critical F-value.

No significant difference was found for dyke thickness within the areas (i.e. between traverses). At Mull, Easdale and Craignish, the F-ratios are 1.79, 1.95 and 0.85 respectively with critical F-values of 2.37, 2.37 and 3.37, at a confidence level of 95%. A significant difference was found between the areas with a F-ratio of 8.46 and a critical F-value of 3.41. Clearly dyke thickness varies with distance from the magma source.

The spacing data are slightly more complicated in that significant differences within the Mull area were detected, a F-ratio of 9.04 compared with a critical F-value of 2.37. If only the traverses near to the centre of the swarm (12 & 14) are considered, a F-ratio of 2.95 compared to a critical F-ratio of 3.84, suggest no significant difference between these two sites. This shows that dyke spacing is sensitive to the position of the traverses across the width of the swarm where it is at its narrowest on Mull. Clearly traverses 9, 10 and 11 are on the periphery of the swarm, and the traverses 12 and 14 are in the centre of the swarm. There is no significant difference within the other locations of Easdale and Craignish, with F-ratios of 1.38 and 2.45, and critical F-values of 2.37 and 3.37.

Information dimension

The thickness and spacing of dykes combine to produce a measure of the amount of material intruded within any traverse through part of the swarm. This measure may be analysed with the information dimension as follows. A traverse is divided into equal intervals of length r and the proportion of dyke material ($p_i(r)$) within each interval determined. The information function $I_{(r)}$ is calculated as follows (Takayasu 1990):

$$I_{(r)} = -\sum_{i=1}^{n} p_i(r) \times \mathrm{Log}\, p_i(r)$$

For a fractal, the information function $I_{(r)}$ is related to the interval size (r) by:

$$I_{(r)} \alpha - D_{\mathrm{I}} \log(r) \tag{11}$$

The information dimension (D_{I}) is thus found by plotting $I_{(r)}$ against log(r), which for a fractal pattern will produce a straight line, the slope of which is the information dimension (D_{I}). When $D_{\mathrm{I}} = 1$ the material is evenly distributed through the section at all scales, whereas when $D_{\mathrm{I}} < 1.0$ there is a scale invariant clustering of dyke material within the traverses. The data deviates from the straight line when the interval size reaches the maximum spacing within the traverse (typically c. 100–300 m).

Figure 17 shows that, for the longest traverse on Mull, there is a reasonably linear relationship between D_{I} and log(r), for an interval of between 0.1 and 1.2 km, i.e. an order of magnitude, suggesting a fractal distribution of dyke material over this range. The other traverses are shorter and yield fewer dykes, but when data are combined from the different areas they yield estimates of the information dimension. Figure 17 suggests that the fractal dimension D_{I} decreases from Mull (0.98) to Craignish (0.87), suggesting somewhat greater clustering away from the volcanic centre. The focusing of the material into clustered groups is in accord with the increase of mean thickness and spacing of the dykes and a decrease in the dyke frequency.

DISCUSSION AND CONCLUSIONS

The data and analysis presented in this paper allow a simple model for the dyke swarm around the Mull centre to be postulated, which may be applicable to other centres. The main features of the model are shown in

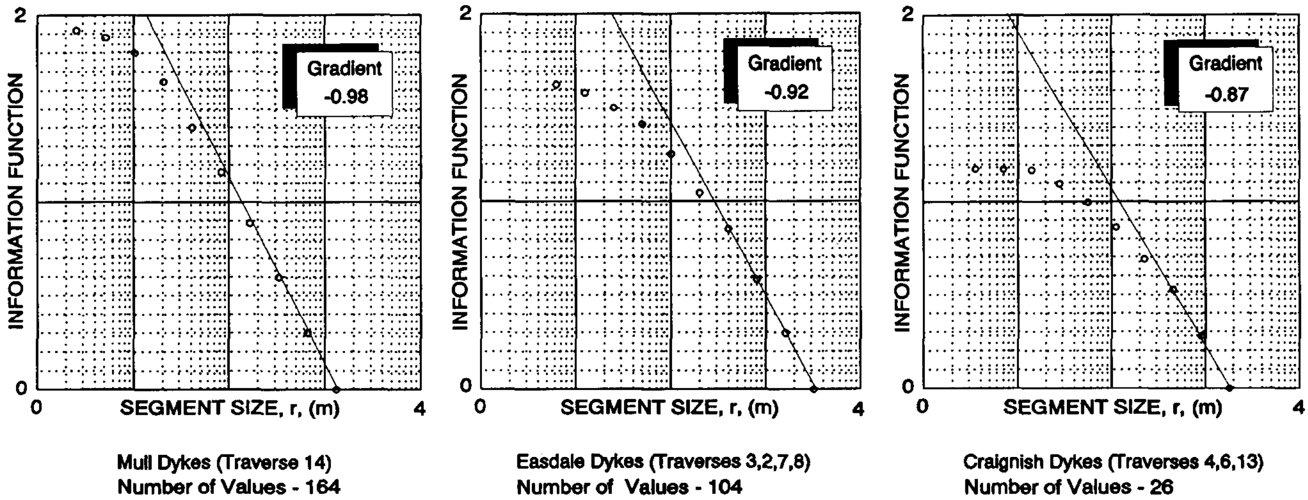

Fig. 17. Information function (I) plotted against log of the interval size (in metres). The gradient of the line gives the information dimension (D_I), which shows a steady decrease from Mull, through Easdale, to Craignish. The information function is defined in the text.

Fig. 18, which is based on five points relating to observed changes in the dykes with increasing distance from Mull:

(1) a decrease in the R-ratio (Delaney *et al.* 1986);
(2) a decrease in the amount of crustal extension;

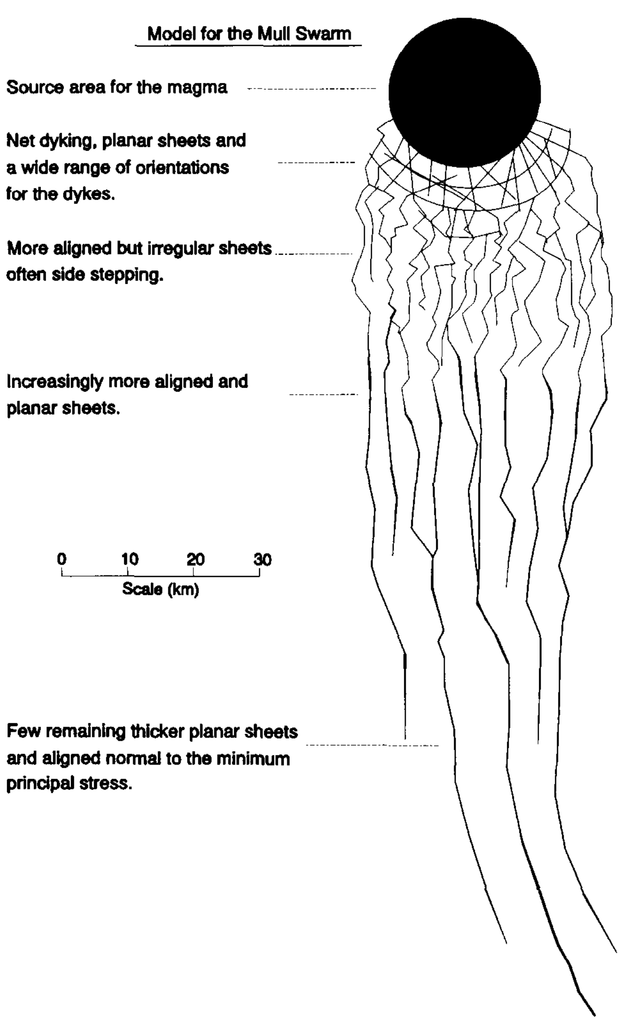

Fig. 18. Schematic diagram to show the variation in form of the dykes of the Mull swarm.

(3) a decrease in the frequency and, hence, increase in spacing, of dykes;
(4) an increase in average thickness of dykes;
(5) a slight decrease in the information dimension, supporting the proposition of some increase in the degree of clustering of the dykes.

Points (2) to (5) are closely interrelated, reflecting the change from greater numbers of thinner dykes to fewer, thicker dykes with increasing distance from Mull. There are two possible mechanisms by which this pattern could be generated: (1) through dykes merging as they are traced away from the centre; and/or (2) through thinner dykes dying out with increasing distance. Both these mechanisms probably contribute to the observed pattern.

Rubin (1993) has argued that there is a finite limit to the distance a magma can flow within a fracture before it will cool sufficiently to freeze, and that this distance is dependent on the dyke thickness. The observed decrease in the proportion of thin (say <0.1 m) dykes at Craignish and Loch Fyne supports Rubin's proposition. Some branching of thicker dykes could still produce occasional thin dykes at great distances from the magma source. The thicker dykes would accommodate most of the magma flow to regions away from the source (Lister & Kerr 1991).

Several observations support the view that some merging of dykes may also occur. The most direct argument is the local development of branching dykes at Easdale, with dykes joining when traced both towards and away from the Mull centre. The variability of orientation of segments of dykes, with their inferred high R-ratios, clearly permits both the divergence and convergence of flow in such networks. The maximum thickness of dykes is observed to increase away from Mull. In addition, the increase in the mean thickness whilst maintaining the log standard deviation is more consistent with thinner dykes merging to form wider ones than simple removal of the thinner dykes. The

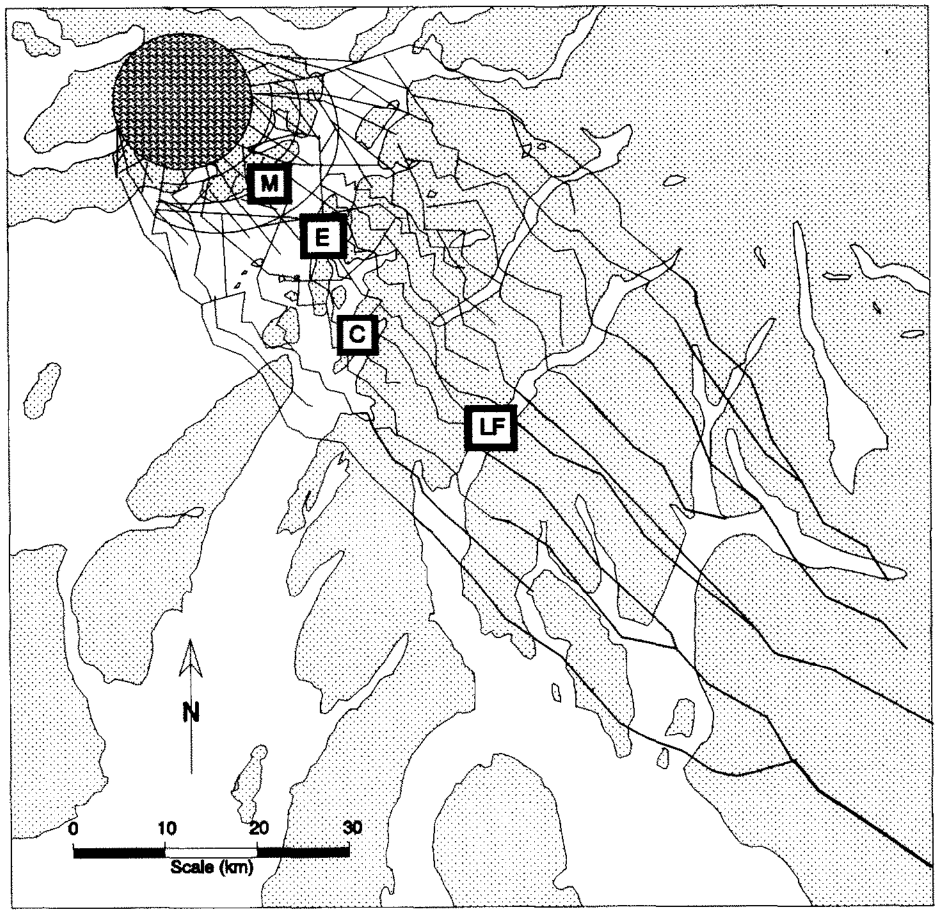

Fig. 19. The model for the Mull swarm (Fig. 18) superimposed over a map of the Argyll area. The lines on the map do not represent actual dykes, but indicate the different intrusive styles seen in the various areas. The letters M, E, C, and LF represent the areas of Mull, Easdale, Craignish, and Loch Fyne, respectively.

increased clustering of the dykes deduced from the information dimension also supports this model.

There are four separate intrusive styles that characterize the Mull swarm, which are typified by the regions examined (Fig. 18):

(1) On Mull (Fig. 19), where fractures of all orientations are used, individual dykes have a large variation in opening directions and are fairly planar. The magma pressure appears to exceed the normal stresses on all available planes, showing forms characteristic of a R-ratio value greater than 1. There is little clustering of the magma flux, the dykes are generally thin (median thickness c. 0.5 m) and with a high number of dykes per unit length.

(2) The second intrusive style is that which is typical of the Easdale area (Fig. 19). As on Mull, fractures of all orientations are able to dilate, but here there is a more restricted range of opening directions. The intrusive style becomes more influenced by the local stresses, the sheets have to sidestep many times to try to maintain a trend that is normal to the minimum principal stress (Roberts & Sanderson 1971), and as a result there is an increase in the number of structures such as horns and bridges. The R-ratio at Easdale is inferred to be approximately equal to 1. There is an increase in thicknesses and decrease in the frequency of dykes compared with Mull, style (1).

(3) The third intrusive style is that which is characteristic of Loch Fyne (Fig. 19), with Craignish falling some where between styles (2) and (3). The dykes still sidestep, but there is a limit in the range of fractures that are able to dilate. The form is typical of that expected when the R-ratio is approximately 0. There is a further increase in the median thickness and decrease in the frequency of the dykes.

(4) At greater distances from the source, dykes become much more planar. They intrude only those fractures normal to the minimum principal stress and open normal to the dyke walls. There are a few long, thick dykes. An extreme example of this style of intrusion is the Cleveland dyke which extends some 400 km from the Mull centre (Tyrrell 1917) and is over 25 m thick in places (Geikie 1897, MacDonald *et al.* 1988).

The boundaries between these intrusive styles are not distinct, dyke geometry gradually changes along, and to some extent across, the swarm.

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