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A NEW MAGNETIC SURVEY OF LUNDY ISLAND, BRISTOL CHANNEL

C. L. ROBERTS AND S. G. SMITH

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A ground-based proton magnetometer survey on Lundy Island reveals that intrusive dykes can be recognised by their signatures of positive—negative paired anomalies. These characteristic signatures are used to trace dyke trends and to produce a map of implied field relations. Dykes show a radial distribution pattern superimposed on a west-north-west — east-south-east regional trend.

C. L. Roberts, Department of Geography and Geology, Cheltenham & Gloucester College of Higher Education,
Shaftesbury Hall, St. Georges Place, Cheltenham, Gloucestershire, GL50 3PP.
S. G. Smith, Department of Earth Sciences, Open University, Walton Hall, Milton Keynes, Buckinghamshire, MK7 6AA.

INTRODUCTION

This paper presents the results of a three year project by the authors and members of the Open University Geological Society, the survey being part of a major geochemical and geological study of Lundy Island, initiated by the late Dr. Richard Thorpe of the Open University (Thorpe *et al.*, 1990; Thorpe and Tindle 1991, 1992). Data were collected over six field week periods, involving up to three proton magnetometers and approximately 550 hours of operation. The methodology and results are compared with those of McCaffrey *et al.* (1993).

The main objectives of the survey were to determine if dykes on Lundy could be recognised by magnetic profiling, to map dyke trends by magnetic geophysical methods and to ascertain whether dykes cropping out in the western cliffs extend through the island to crop out along the eastern coastline.

GEOLOGICAL SETTING

The island of Lundy in the outer Bristol Channel forms part of the most southerly expression of Tertiary volcanism in the British Isles and, as such, constitutes an important part of the British Tertiary Volcanic Province (BTVP), as illustrated in Figure 1. Central intrusive complexes within the BTVP are characterised by positive gravity anomalies (e.g. Bott and Tuson, 1973) and both positive and negative magnetic anomalies (e.g. Brown and Mussett, 1976). Dykes emanating from centres commonly display a north-west — south-east trend (Emeleus, 1991), the result of a north-east — south-west extensional stress field associated with the opening of the North Atlantic in the Lower Tertiary.

Lundy is composed almost entirely of Tertiary granite, with Variscan-deformed Devonian sediments cropping out in the south-east part of the island, the contact possibly being faulted (Dollar, 1941). Dollar also noted about 200 intrusive dykes up to 4 m in thickness. The dykes were described as predominantly basic, but about 9% trachytic, and having a dominant trend of north-west — south-east, a view supported later by Mussett *et al.* (1976). Edmonds *et al.* (1979) suggest that the dykes on Lundy may be a south-easterly extension of a north-west — south-east dyke swarm postulated by Cornwell (1971), but also note a radial pattern based on coastal outcrops of dykes. McCaffrey *et al.* (1993) report a north-west — south-east trend for land-based dykes on Lundy from magnetic evidence.

It should be noted that the dyke swarm around Lundy, as shown on the geological map compiled by Hains *et al.* (1983), is inferred from marine-based magnetic evidence, whereas the trend for dykes on mainland Britain and Northern Ireland has been measured directly from solid outcrops. The marine magnetic measurements will only locate the larger dykes, as smaller ones will be at too great a depth to produce an anomaly. Interpolation of dyke trends between profiles (separation not published) is subjective, whereas the method used in this survey, which locates small as well as larger dykes, traces their paths without having to Interpolate between profiles.

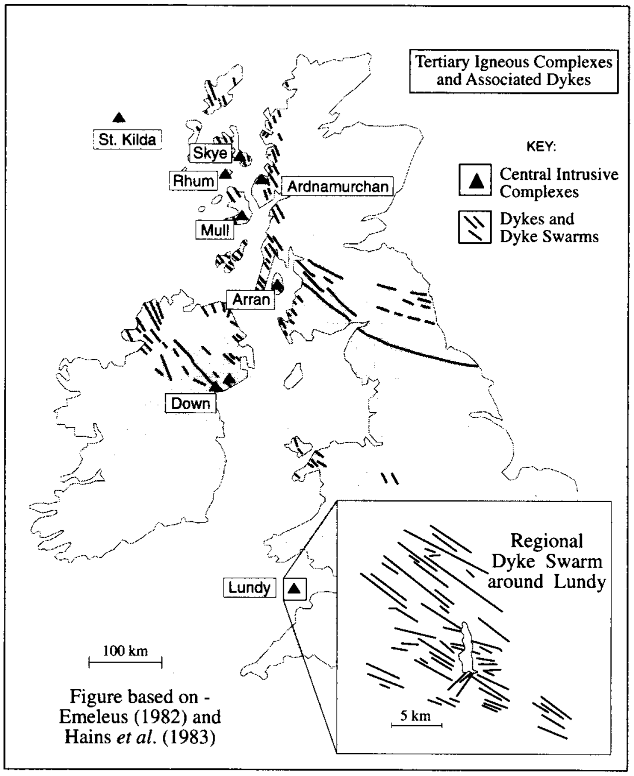

Figure based on - Emeleus (1982) and Hains *et al.* (1983)

Figure 1. Central intrusive complexes within the British Tertiary Volcanic Province and their associated dykes. The dyke swarm around Lundy (inset) is inferred from marine-based magnetic data and based on Hains et al. 1983.

Thorpe and Tindle (1992) have completed a detailed geochemical study of Lundy dykes and report an anorogenic bimodal dolerite/basalt-trachyte/rhyolite association. Both trachyte and rhyolite are interpreted as representing extensive fractional crystallisation from a dolerite magma, where the rhyolite achieved peralkaline composition. However, they also note that rarer subalkaline rhyolites did not achieve peralkaline composition and suggest fractionation from a different dolerite source. In conclusion, they propose that emplacement of basalt, trachyte and rhyolite magmas within the

Lundy granite possibly indicates the development of a composite bimodal basalt-(minor trachyte)-rhyolite volcano in the area.

In this paper, basalt and dolerite are described as basic rocks, trachyte represents intermediate rocks and rhyolite is considered acidic in composition.

METHODOLOGY

Magnetic surveying was carried out using Geometrics 816 proton magnetometers and an OMNI IV proton magnetometer, which measure the total magnetic field at any one station, and display the magnetic field strength in nanoteslas (nT). During the summer of 1991, the geomagnetic field at the south end of Lundy Island had a total field value of 48041 nT, calculated from the 1991.5 geomagnetic reference field, decreasing by 18nT per year (pers comm, E. Harris, Geomagnetism Group, BGS).

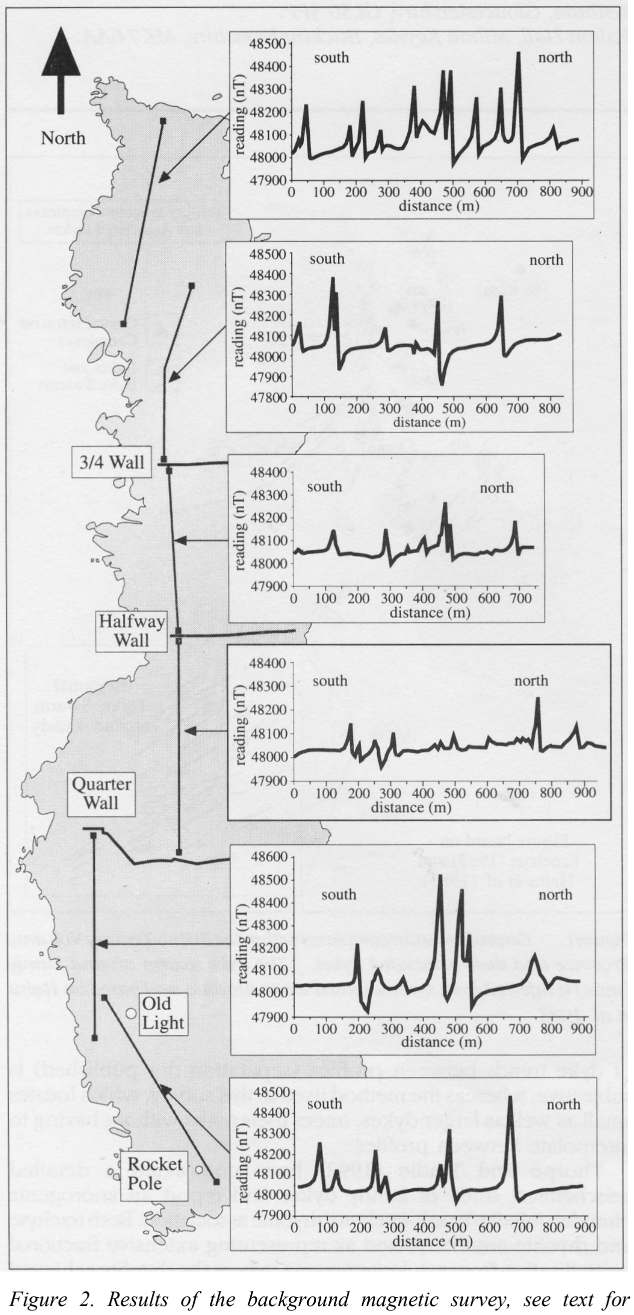

Figure 2. Results of the background magnetic survey, see text for details. The total magnetic field strength (in m) is plotted against distance (in m) for six traverses. All magnetic data have been corrected for the effects of diurnal drift.

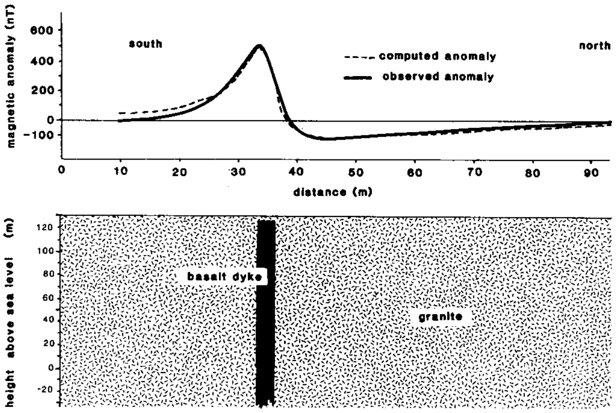

*Figure 3. An individual observed paired anomaly profile from a typical dyke on Lundy. Readings were taken at 1 m intervals and corrected for diurnal drift. Hand augering confirms the presence of basic material. The computed response to a hypothetical model with the dyke top 2.5 m below the surface is also shown, given a Köenigsberger ratio (**M** /c **H**, where **M** is the intensity of natural remanence and **H** is the field strength) equal to 03. After Roberts, 1992.*

An initial reconnaissance of the island was undertaken in June 1991, to highlight the background signature and to delineate areas of interest (Figure 2). Total field readings were taken every 5 m and the effects of diurnal drift were monitored by looping to a number of base stations throughout the survey period. More precise diurnal drift corrections were obtained at a later date by correlation with magnetograms from Hartland Magnetic Observatory, approximately 25 km to the south-south-east. The orientation of the reconnaissance lines was approximately north-south in most cases, with oblique trends where man-made artefacts such as walls and fences might have caused interference to magnetic readings.

Dykes on Lundy present paired anomaly profiles with positive anomalies to the south and small negative anomalies to the north (Roberts, 1992), as shown in Figure 3. The main method of prospecting for dykes in the surveys of August 1991 and September 1992 was to locate the position of magnetic 'highs' and to trace their trends in the field by locating and following the highest readings. When a high was located, another reading was taken 5 m away along the postulated trend of the dyke. If the new reading was lower, further readings were taken to each side of the line to locate the new high position. The positions of magnetic high readings were marked on the ground with flags and their trends transferred onto field slips, as shown in Figure 4. Where dykes converged or had cross cutting relationships, short north-south traverses at 5 m spacing were undertaken to reveal the characteristic signature, and hence indicate the positions of peak readings. In a few places, the destructive interference of adjacent dyke signatures made it difficult to record dyke trends with any degree of accuracy, thus small areas of ambiguous dyke positions were not mapped.

RESULTS

1. Magnetic Susceptibility Results

Mussett *et al.* (1976) carried out detailed palaeomagnetic work on 66 dykes from Lundy, both basic and intermediate in composition, and note a strong correlation between natural intensity and magnetic susceptibility, defined empirically by the relationship:

$\mathrm{Log}_{10}\,\mathbf{M} = 1.09\chi + 2.26$

where, $\mathbf{M}$ = Natural Remanent Intensity ($10^{-4}\mathrm{Am}^2\mathrm{kg}^{-1}$)

χ = Magnetic Susceptibility (dimensionless, SI units)

Transposed into SI units, they report a bimodal log-normal distribution pattern for magnetic susceptibility, with peak values of

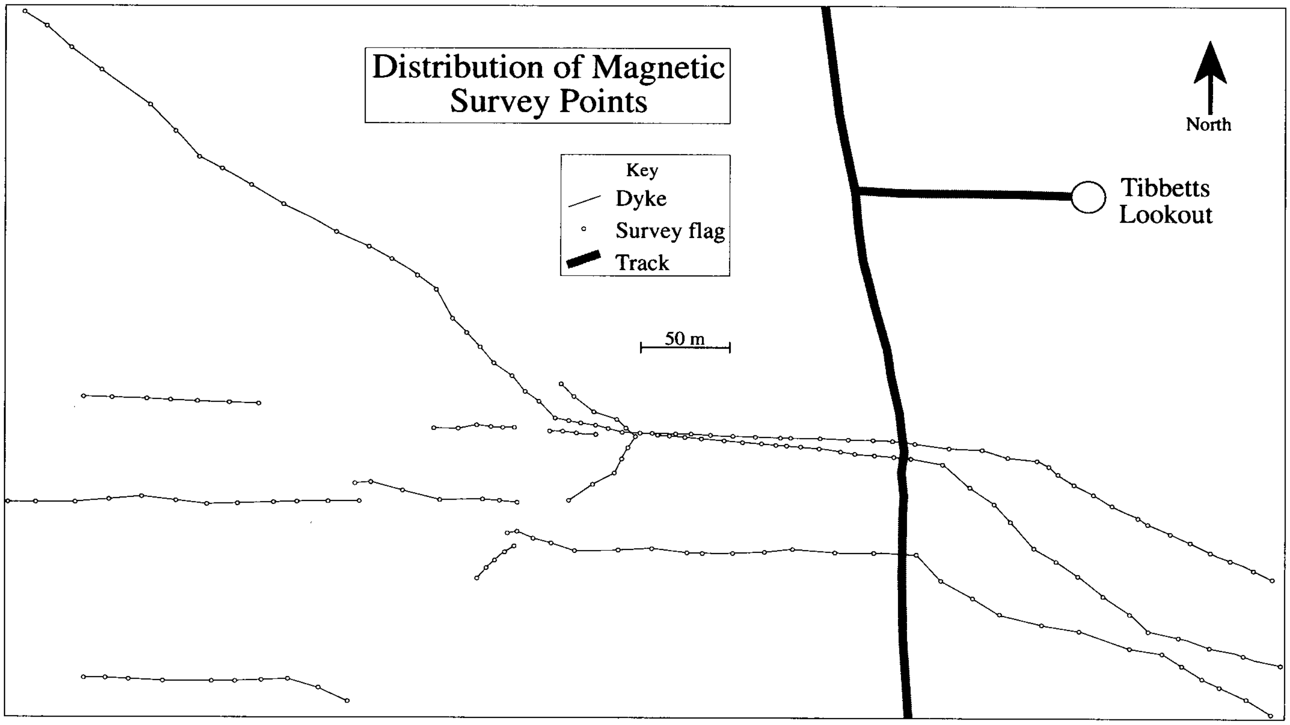

Figure 4. A sample of the distribution of observation points. Trends of dykes were determined by taking readings every 5 m and marking positions with fluorescent flags. These were placed at points of directional change or every 10 - 20 m, and bearings recorded with a siting compass. See Figure 5 for the location of Tibbetts Lookout.

0.0004 and 0.03. The present authors note a similar distribution, with an additional peak at 0.095, N =152. The higher two values are obtained from basalts and dolerites, whereas the lowest value correlates with trachytic rocks. Both granite and rhyolite have susceptibilities in the order of 10^{-6} Acid dykes would not therefore be expected to be located by magnetic prospecting, due to their low magnetisation.

The magnetic susceptibility values quoted by McCaffrey *et al.* (1993) of 0.8 for basalt and 0.015 for trachyte are based on one field reading for each rock type. This is statistically questionable and may have resulted in artificially inflated values. McCaffrey *et al (1993)* also state that the most magnetically susceptible rocks on the island are the Devonian metasediments, with a maximum value of 3 (SI units) and a mean of 0.04 (SI units) for 30 readings. The present authors obtained a lower average magnetic susceptibility value of 0.007 from 20 cores of sedimentary material from the island. Differences between susceptibility readings of McCaffrey *et al.* (1993) and the present authors probably arise from the method of measurement; the former use field measurements with a Geoinstruments JH8 hand-held magnetic susceptibility meter, whereas the latter utilise laboratory measurements of cores with a Molspin magnetic susceptibility bridge.

McCaffrey *et al.* (1993) conclude that a circular positive anomaly centred over the south-eastern corner of Lundy can be ascribed to magnetic metasediments. This seems geophysically inappropriate and is disputed by the present authors, who agree with the suggestion of Burley (in Edmonds *et al.,* 1979) that the positive anomaly may be a basic fraction of the Lundy Igneous Complex.

2. Background Magnetic Survey

Figure 2 shows the results of the reconnaissance magnetic survey. Positive-negative paired anomaly profiles are discernible, with wavelengths between 50 and 90 m and amplitudes up to 600 nT, over a relatively flat background. The background has a value of about 48040 nT at the south end of the island, decreasing slightly towards the north end. Readings toward the centre of the island are slightly reduced in amplitude, due to a greater depth to the top of the dykes, as there is thicker soil cover in this area, whereas readings at the north end are more spiky, because the soil cover is either absent or very thin. The anomalies are thought to reflect geological features rather than human artefacts.

3. Main Magnetic Survey

The results of the full magnetic survey are presented in Figure 5. The survey revealed an average amplitude of 400 to 450 nT with 50 to 90 m wavelengths for larger anomalies, with largest amplitudes of 800 to 900 nT for some signatures. Anomalies lower than 100 nT amplitude, although probably overlying dykes, were arbitrarily chosen as too low to be traced with any degree of accuracy in the field. Such anomalies were not numerically significant for the most part, which suggests that the majority of detectable dykes are represented by the survey.

DISCUSSION

Use of Spiral and Linear Surveys

McCaffrey *et al.* (1993) used a spiral survey between Old Light and the Quarter Wall with 50 m spacing to determine the orientation of magnetic anomalies. Readings were taken every 10 m along the spiral line, data then being interpolated and contoured to produce an anomaly map, the maximum anomaly amplitude being 40 nT (see Figs. 2b and 2c, McCaffrey *et al*., 1993). We note that such magnetic anomalies are an order of magnitude smaller than those quoted by this paper (cf. Figure 2), and that the northern end of the spiral is close to a magnetic 'high' of +700 nT above background levels. Field observations in this paper also indicate that the induced magnetisation of dykes can fluctuate over short distances by up to ±100 nT, which is greater than the total sensitivity of the spiral survey of McCaffrey *et al.* (1993).

The geological interpretations derived from their anomaly contour map are dubious, in that linear dykes are construed from circular and ovoid contours of fairly low magnetic anomaly amplitude. Survey line spacings of 50 m with 10 m reading intervals are probably too widely spaced to represent adequately the relatively high magnetic relief observed on the ground, and orientations derived from interpolations may be false. It is therefore considered by the present authors that the spiral survey has not interpreted the predisposition of dykes correctly and that correlations with underlying geology are unfounded.

Similarly, we consider a sample line separation of 180 m used in their linear survey too great to allow for accurate interpolated orientations.

Implied Field Relations of Dykes

Individual dykes present paired anomaly profiles up to 900 nT in amplitude and can be traced in the field to a high degree of accuracy. Where possible, dykes were visually correlated with known outcrops and/or well developed basalt soil horizons in gullies. Hand augering for a random selection of paired anomaly profiles over the island surface confirmed the presence of dyke material. A small percentage of dykes were traced from coast to coast, although difficult access sometimes prevented definitive connections to be made at cliff edges.

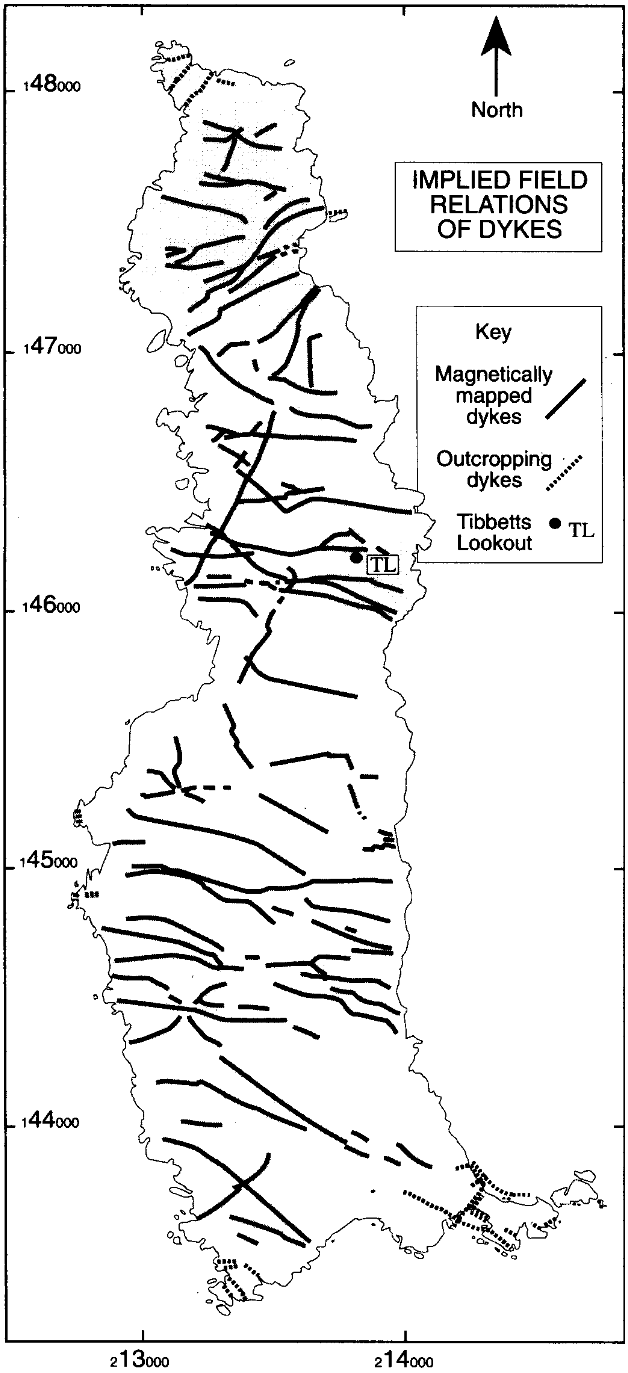

Figure 5. Map of implied field relations for dykes on Lundy Island, based on magnetic prospecting procedures. The figure also contains trends of dykes where conventional mapping is possible, e.g. the south-east aspect of the island. Numbers at the side and bottom of the figure refer to National Grid co-ordinates (in metres).

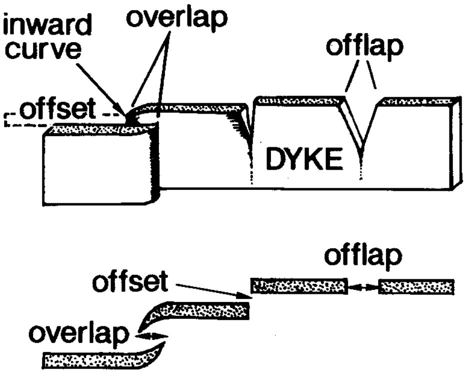

Figure 6. The offlap, overlap and offset of dykes. The top diagram is an idealized three-dimensional section and the lower diagram is a plan view of the same dyke. After Thorpe and Brown, 1985.

Many dykes display curved trends in the field and abrupt directional changes are common. Discontinuous dyke signatures, which are also commonly recorded, may be the result of offlap, offset or overlap, all three being regular features of dyke morphology, see Figure 6. It is thus imperative to record the position of dykes in the field with accuracy over short distances, otherwise false conclusions can be derived and incorrect field relations noted.

The dykes mainly have a north-west— south-east trend towards the south end of the island, a north-east — south-west trend towards the north end and a crude east-west trend towards the centre of the island. This implies a radial distribution pattern and reverse extrapolation suggests most of the dykes may have originated from a focus 2 to 3 km west of the island. A radial distribution of dykes is also noted from the measurement of dyke orientations in the cliffs and along coastal outcrops, as shown in Figure 7. In addition, a clear west-north-west — east-south-east trend can be seen to form part of the outcrop pattern. Such observations are compatible with Figure 5 and enhance the interpretation of the magnetic survey.

Origin of the Lundy Dyke Swarm

Although the main trend of the dykes on Lundy appears to be west-north-west — east-south-east (cf. Figure 5), there are numerically more dykes with other orientations showing a radiate disposition. It therefore seems likely that more than one process has been in operation to form the Lundy dyke swarm. K/Ar dates for the dykes range from 44.6 to 56.1 ±1.0 Ma (Mussett *et al.*, 1976; Edmonds *et al.*, 1979) and 56.4 ±0.3 Ma (Mussett *et al.*, 1988), determined by the ^{40}Ar/^{39}Ar dating method. The dykes not only post-date the Lundy granite (58.7 ±1.6 Ma; Thorpe *et al.*, 1990), but also indicate a relatively protracted intrusive episode by their age span. Speight *et al.* (1982) note the association of dyke swarms with central intrusive complexes within the BTVP and that small numbers of dykes (with respect to the main swarm) can be attributed to subswarms, with axes oblique to the main swarm trend. Ancient stress fields associated with the Lundy Igneous Complex may thus have varied with time.

If a radial distribution is indicated, reverse extrapolation implies a source to the west of the island. If not, it is possible that several storage bodies may have been active relatively near to Lundy. Thorpe and Tindle (1991) postulate that Lundy may be the remnants of a composite volcano situated somewhere in the outer Bristol Channel. Brooks and Thompson (1973) interpret a positive gravity anomaly to

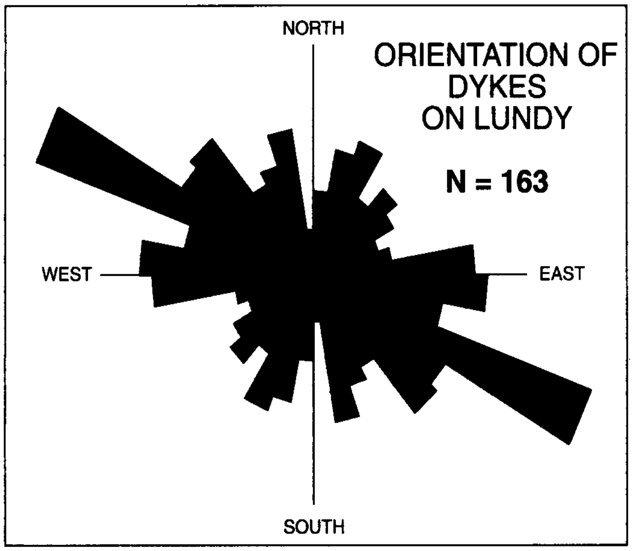

Figure 7. Orientations of coastal dyke outcrops, based on original notes by John Dollar and field measurements by CLR. Dykes include both basic and intermediate types, but not those of acidic composition, e.g rhyolite.

the northwest of Lundy as being the product of a basic body between 2.5 and 4 km in thickness, and lying at shallow depth. Both hypotheses may be related and it is tempting to assign the source of the dykes to a former magma chamber or chambers west of the island.

CONCLUSIONS

1. Basic volcanic dykes intruded into the Lundy granite can be detected in the field with a proton magnetometer and their trends traced across the island.
2. Dykes present paired anomaly profiles, each with a positive anomaly to the south and a small negative anomaly to the north. Average wavelength is 50 to 90 m and average amplitude is 400 to 450 nT, although anomalies up to 900 nT are recorded.
3. Amplitudes of anomaly profiles are governed by magnetic susceptibility and depth of dykes below ground level. Basic dykes present highest amplitude profiles, whereas acidic dykes are undetectable. Intermediate dykes present low amplitude profiles.
4. There is an underlying west-north-west — east-south-east trend for dykes on Lundy. Dykes are also radially disposed and reverse extrapolation may suggest an origin 2 to 3 km west of the island.
5. The methodology of McCaffrey *et al.* (1993) is statistically inappropriate and has resulted in an incorrect geological interpretation for land-based dykes on Lundy.

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