The Cleveland Dyke in southern Scotland

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Synopsis

There have been a number of recent papers on 'giant dykes', i.e. dykes exceeding 100 km in length. This paper extends the known length of the Tertiary (Palaeogene) Cleveland Dyke (CD) by about 64 km, giving a total proven length of c. 260 km. The results of a detailed investigation using ground magnetic surveys have discovered 26 additional exposures in southern Scotland, allowing magnetic, petrographic and geochemical measurements and magnetic modelling to be carried out, resulting in one of the most detailed studies of a 'giant' dyke.

The structure of the CD complex in the Southern Uplands of SW Scotland has been influenced by pre-existing structures, in particular faults and granitic intrusions. It is chemically heterogeneous without systematic trend along its length. This heterogeneity, plus segmentation along strike, numerous offsets, in particular one of 5 km along the Water of Ken, en-echelon structure, narrow width at many localities (2.3-0.8 m) with lack of baking of adjacent country rocks, all argue strongly against lateral intrusion from the Mull intrusive complex, as has been proposed. Instead, aeromagnetic surveys and wide-angle seismic and gravity surveys make it probable that the dyke relates to a regional magma reservoir beneath the Southern Uplands.

Introduction

Early Tertiary igneous activity in Britain, mainly in western Scotland and Ireland, consisted of intrusive centres, lavas and dykes. Most of the dykes radiate from the centres and are concentrated along approximately NW–SE axes through the centres, and decrease in number with distance from the centre; in particular, few of the Mull swarm reach as far SE as the Southern Uplands Fault (SUF). However, a few dykes occur much further from a centre, the most notable being the Cleveland Dyke (CD) which Holmes & Harwood (1929) linked to Mull. It extends through northern England – with gaps and offsets – almost to the North Sea coast (Teall 1884) and has a thickness exceeding 20 m in places, considerably greater than that of the majority of the near-centre dykes, though it is less than 1 m wide in others. The CD broadly forms an arc trending approximately WNW–ESE at its eastern end, to NW–SE at the SUF, roughly as far it has now been traced towards Mull. Numerous exposures are known in northern England, but prior to this study only four in Scotland, with none further NW than Troston Loch [NX 700 905] (Fig. 1).

The paucity of known exposure in southern Scotland, in contrast to northern England prompted the present study. The objectives were, firstly, to determine the course of the CD in Scotland in greater detail using ground magnetic surveys, and thereby to find more exposures, and then, using petrography and geochemical analyses, to check if they were indeed the CD. Magnetic modelling aided by palaeomagnetic measurements were to be used if possible to refine the position of the dyke and estimate its width at depth. In turn, this information was to be used to see if its course was influenced by pre-existing faults, structural trends in the country rocks or major intrusions. Lastly, a major objective was to investigate whether the CD was intruded laterally from the Mull intrusive complex or vertically from a regional magma reservoir.

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The Cleveland Dyke and host rocks

Two basaltic dykes in the Southern Uplands of probable Tertiary age, ‘one on Troston Hill [later referred to as Troston Loch], four miles W of Moniaive, the other on Craigmuie Moor, half-a-mile S of Castlefairn’, were first recorded by Horne in Geikie et al. (1877, p. 36). Geikie (1897, p. 144) suggested the Troston Loch outcrop and another NW-trending basic dyke further to the SE ‘a little to the east of the mouth of the Nith’ (subsequently referred to as the Shearington outcrop) marked the NW continuation of the CD into the Southern Uplands of Scotland.

A number of suggestions have been made for the possible continuation of the CD into the Midland Valley (e.g. MacGregor in Eyles et al. 1949) (as discussed later), and more recent work (Hornung et al. 1966; Macdonald et al. 1988; Mitchell et al. 1989) has focused on whether the CD exhibits regional geochemical variation which might enable the direction of emplacement of the magma forming the dyke to be determined. However, no other outcrops had been identified as CD before the present survey.

The greater part of the area surveyed lies within the Southern Uplands terrane (Trewin 2002, and references therein) which comprises Lower Palaeozoic beds (Ordovician–Silurian) striking NE–SW and frequently steeply inclined. They are predominantly turbidite sandstones with subordinate conglomerate and shale horizons divided into structural tracts by a series of major NE–SW trending faults. Emplaced within the terrane are the late Caledonian granite plutons of Criffel and Cairnsmore of Carsphairn. In the SE at Shearington the CD is emplaced in Permian sandstones.

Magnetic surveys, outcrop and structure

Earlier magnetic surveys

Bruckshaw & Robertson (1949) carried out ground magnetic surveys of the CD in the north of England and southern Scotland, though none were in the area covered by the present survey. They showed that it was reversely magnetized and in the north of England some of their profiles suggested that, in some locations, the dyke may be represented by more than one intrusion, that there may be breaks in continuity with the line of one segment offset from that of the next, and in some cases the offset segments may overlap (Bruckshaw 1950).

In southern Scotland the aeromagnetic survey of Great Britain contour map (IGS 1964) shows a series of negative features orientated east–west to ESE–WNW from the Solway to Troston Loch [NX 700 905] which mark the path of the CD (Fig. 2). NW of Troston no clear anomaly can be seen in the profiles. However, a more recent high resolution survey in the area NE of Carsphairn shows a prominent NW–SE trending negative anomaly which Dawson et al. (1977; Kimbell, pers. comm.) attributed to a reversely magnetized Tertiary dyke. This aeromagnetic anomaly extends NW of the Water of Ken to Jedburgh Knees [NS 615 030] as a series of elongated segments (Fig. 3). If this anomaly represents a single dyke, there appears to be a major offset of c. 5 km from Troston Loch. The magnitude of this offset and the fact that there were no recorded outcrops meant that the anomalies could not be ascribed to the CD with certainty at that time. Although the CD cannot be readily distinguished on the original aeromagnetic contour map (IGS 1964) north of Troston [NX 700 905], nor on the high resolution map (Dawson et al. 1977) north of Jedburgh Knees [NS 615 030], an image-processed version, with illumination from the north (Kimbell in Floyd 1999; Kimbell, pers. comm.) does show an anomaly in the region of [NS 500 165] north of the SUF on the projected line of the CD.

This survey

Starting points of the traverses were based on the projected line of the dyke defined by the known outcrops and the aeromagnetic anomalies. A total of 323 ground traverses have been made, using proton-precession magnetometers, from Shearington [NY 041 661], near the mouth of the Nith, to Polmuth Burn [NS 5490 0911], 1.5 km north of the SUF, a distance of over 64 km. Station spacing along a traverse was usually 5 m, measured by tape, but was larger for reconnaissance surveys and as little as 1 m where sharp changes of field were observed. Traverse lengths varied, some extending up to 2 km. Some traverses crossed known outcrop and others were close enough that, where anomalies were found, it can be certain that they represent the CD.

The magnetic signatures are generally asymmetrical with a negative part to the south and positive part to the north. This requires that the total, and hence the remanent magnetization is reversed. This is consistent with that of the CD in the north of England. The negative part of the profile is, in nearly every case, much larger than the positive part, indicating that the inclination of the remanent magnetization is steep. Because the negative part of the anomalies is so dominant, in the absence of outcrops, the minima are taken to mark the location of the dyke (Fig. 4).

Outcrop

As a result of the magnetic surveys, 26 new outcrops have been discovered (Appendix B). The survey also confirmed that the small outcrop on Craigmuie Moor [NX 738 861] recorded by Horne (in Geikie et al. 1877), but not included by Geikie (1897), is part of the CD. During this survey the Troston Loch exposure could not be found because of afforestation, although an anomaly was located. Including the four previously known and six found by the BGS Southern Upland regional survey during recent mapping (A. McMillan, pers. comm.) there are now 36 outcrops, of varying quality, of the CD known in southern Scotland. Observed widths range from 0.3 m to 23 m, averaging 6.7 m (std. dev. 6.4 m, N=35). In addition, nine ‘boulder localities’ have been found where boulders produced when road and building
excavations or farming activities intersected the dyke. They are adjacent to magnetic anomalies associated with the CD and have been shown by petrographic and geochemical analysis to belong to it. Many of these exposures would not have been found without the magnetic surveying.

Figures 2 and 3. Aeromagnetic contour maps for part of southern Scotland based on IGS (1964). Segments of the major boundaries and faults (black lines) are shown where they are intersected by the CD. From NW corner: SUF, Southern Uplands; CF, Carcow; LHF, Leadhills; SHF, Stelhead; FMF, Fardingmullach; GFF, Glen Fumart; OBFR, Orlock Bridge; MSZ, SE margin of Moniaive Shear Zone; SF, Sandhead; GBF, Gillespie Burn; GBFe, SE splay of Gillespie Burn; GHF, Garheugh; LF, Laurieston; IF, Innerwell; LNF, Lochanhead; NF, Nith. Black triangles mark localities.
Structure, offsets and variation in trend along the dyke

The average regional trend of the localities shown in Figures 4 and 5 is 320°, a trend characteristic of Tertiary dykes and presumably reflecting a regional NE-SW stress field when the dykes were intruded. However, locally there are gaps, offsets and many marked deviations from this trend, indicating that the CD is a
complex structure. Some examples, from SE to NW, are described below; possible interpretations are discussed later.

Shearington to Lochanhead The trend at Shearington is c. 295° which projects towards Lochanhead [NX 9167 7202]. However, there is a large offset northwards of about 2 km between Townfoot [NX 00445 68210] and Conheath [NY 00345 70510] (Fig. 6a). NW from Boreland [NX 01383 71034] the dyke curves from NW–SE to become more east–west at Keltonbank [NX 9875 7118]. Segments from the River Nith to the SE of Moss-side [NX 94308 72624] and from Moss-side to Hillhead [NX 93060 72425] trend at 285° and east–west, respectively. Then offset 500 m to the north at Woodfoot Wood [NX 93077 73069] a c. 500 m segment trends east–west. The next anomalies occur 1 km to the SW of Woodfoot Wood, at Lochanhead, where three dykes (c. 2 m wide) crop out, en-échelon, with trends of 301°, 310° and 325°. The whole of the segment from Boreland to Woodfoot is offset to the NE of the line through Shearington and Lochanhead (Fig. 6a) skirting the Criffel pluton.

The arcuate CD aeromagnetic anomaly between Shearington and Lochanhead (Fig. 2), part of which corresponds to the magnetic lineament M10 of Lintern & Floyd (2000, fig. 7), follows a similar path.

Braco to Skeoch The anomalies follow the regional NW–SE trend from Lochanhead to Braco [NX 8733 7576], near Shawhead, where two juxtaposed dykes with differing petrography and geochemistry crop out; both trend north. A further outcrop 130 m to the north [NX 8735 7588] extends for 42 m, its trend varying from 22° in the south to 350° in the north. North of Shawhead [NX 8725 7600], over a distance of 1 km, there is a series of anomalies lying on a north–south line before the trend again becomes NW–SE towards Skeoch [NX 8640 7800] (Fig. 6a). The two NW–SE trending segments are dextrally offset by c. 500 m across the Innerwell Fault (IF).

Skeoch to Bishop Forest Hill The magnetic anomalies in the area of Skeoch Hill reveal a zone of en-échelon structure: a series of short, sub-parallel segments, some apparently no more than a few metres long (Fig. 6b), with similar trends. On the southern slopes of the hill two NW–SE trending dykes crop out c. 100 m apart. That exposed lower down the slope (14 m wide) is on one of the short intermediate segments trending 310°. The more northerly (22 m wide) trends at 320° and is offset dextrally by 350 m relative to the line of the dyke to the SE.

It is possible that the en-échelon structure is related to the Laurieston Fault (LF) (Akhurst et al. 2001). Models of the profiles from ground magnetic surveys indicate that the dyke segments widen considerably with depth in a plane approximately parallel to the fault. Models for flight line T146, which crosses the area, also indicate at depth a wider and thicker body than elsewhere. A possible explanation is that basic magma has been channelled preferentially up the fault to form a plug at shallow depth from which NW–SE trending dykes have risen.

Bishop Forest Hill to Craigdasher Hill The trend between Skeoch Hill and the exposure at Bishop Forest Hill [NX 8528 7964] is 330° but NW of this exposure the dyke becomes more east–west (Fig. 6c). NW of Muil Hill [NX 8174 8086] there are two segments; the easternmost segment trends 256° and the westernmost 295°. On the SE slopes of Darngarroch Hill there are discontinuous exposures over 310 m trending 310° [NX 80805 81435 to NX81035 81240]. On the summit of the hill [NX 8035 8159] the dyke is 15 m wide and can be traced for 150 m in a NW direction, but its SE end is observed to terminate as an easterly trending apophysis, 35 m long and c. 5 m wide. NW of Darngarroch Hill there is an offset of c. 750 m northward to Craigdasher Hill [NX 7950 8250] (Fig. 6c). This offset occurs across the eastern splay of the Gillespie Burn Fault (GBFe) (McMillan 2002, p. 35, fig. 15).

Craigdasher Hill to Craigmugie Moor There is a change of trend across Castramon Burn, which coincides with the main Gillespie Burn Fault (GBF) (McMillan 2002, fig. 15), from NW–SE to the SE of the burn to roughly east–west on the NW side (Fig. 6d). About 800 m west of the burn, on the slopes of Castramon Hill [NX 7820 8350], two 1 m wide dykes are exposed c. 100 m apart which, individually, trend 320° and 345°. On Craigneay Moor, where it crosses the Sandhead Fault (SF), the dyke is offset northwards by 1250 m to Shillingland [NX 7780 8498]; the dyke then follows a regional trend of 285° to Craigmugie Moor (Fig. 6d, e). However, outcrops on Lochurr Hill [NX 7595 8565] appear to trend 350°.

Craigmugie Moor to Troston Loch In the middle of Craigmugie Moor [NX 74430 85925] a dog-leg-shaped dyke is exposed: the eastern segment trends 285°, the western one 350°. Other exposures trend 310° and 336°. Evidence from magnetic traverses indicates that the lengths of the segments with a more northerly trend are short. NW of Craigmugie Farm the trace of the anomalies curves from c. 285° at Craighmugie Farm to c. north–south at Castlefairn [NX 7355 8705]. NW of Castlefairn for c. 300–400 m the trace is c. 300° before following a line at c. 30° on the hill slopes north of Castlefairn (Fig. 6e). An outcrop was discovered at a point 205 m SE of Shield Burn [NX7340 8782] and the 950 m segment from there to the outcrop at NX 7271 8847 includes the most extensive exposures of the CD in the Southern Uplands: NW of Shield Burn the 14 m wide dyke is exposed for 180 m. Locally the southern end of this outcrop, 12 m wide, trends north–south but when traced northwards becomes 340° and finally 310° at Shield Burn: this is the average trend from this point to Troston [NX 71414 89605]. Between Craigmugie Moor and Shield Burn the regional structure of the dyke has been dextrally offset by 1250 m.

Troston Loch to Glenhastel The NW trending Troston Loch segment appears to die out before reaching the B729 road, which coincides with the Glen Fumart Fault (GFF), as no anomalies were found on several traverses made between Troston Loch and the road. North of the road, in Auchenstroan Forest (Fig. 6f), magnetic
FIG. 6. Enlarged parts of Figure 4 showing offsets and changes of trend. Symbols for minima as in Figure 4, outcrop as in Figure 5, faults (dark grey) and localities as in Figure 2 with additional localities. The 3 km, 5 km and 7 km depth contours of the Carsphairn Granite Platform (f) are based on the gravity model of Dawson et al. (1977). (a) Detailed trace between Shearington to Skeoch. (b) Detailed trace around Skeoch Hill. (c) Detailed trace between Bishop Forest Hill and Craigdasher Hill. (d) Detailed trace between Craigdasher Hill and Shillingland. (e) Detailed trace around Craigmuie Moor and Shield Burn. (f) Detailed trace between Troston and Midrig. (g) Detailed trace between Glenhastel and Polmath Burn.
anomalies define a north–south trending feature extending for 1250 m which, on the basis of the form of the magnetic anomaly, is thought to be due to the CD. However, no outcrop was found in this segment so it cannot be conclusively proved to be part of the CD.

Several long traverses (c. 2.5 km) crossing the NW–SE regional structure between Troston Loch and Carroch Hill (c. 4 km) failed to show any evidence of the CD, but anomalies were found on the western slopes of Carroch Hill and for c. 2.6 km westwards defining the Cornharrow segment with the regional NW–SE trend. A ‘boulder’ locality of CD [NX 6678 9233] was discovered in the segment. Four further segments with the same trend were located between this one and Midrig [NS 64940 00270], each offset to the north giving the large total overall offset of 5 km. A similar offset of c. 5 km is shown by the residual aeromagnetic lows which form two well-defined NW trending lineaments (see M20 and M21 in fig. 26 of Floyd 1999; M4 and M5 in fig. 7 of McMillan 2002) attributed to the CD (Kimbell, pers. comm.). Outcrops have been found in the Dodd Hill [NX 65175 98787] and Midrig segments. The trend of the dyke segment on the NE slopes of Dodd Hill is 340° and that on Midrig c. 330° but between them there is a dextral offset of c. 500 m about 350 m SE of the Leadhills dextral offset of c. 1.25 km from the line defined by the Glenhastel-Monquhill anomalies. North of Polga Burn the anomalies define a north-south trending feature extending for 1250 m which, on the basis of the form of the magnetic anomaly, is thought to be due to the CD. However, no outcrop was found in this segment so it cannot be conclusively proved to be part of the CD.

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From Midrig to Glenhastel the trend of the dyke defined by the ground magnetic anomalies is generally NW–SE (Fig. 6f), with minor offsets between Glenluce and Glenhastel. An outcrop of a 2.3 m dyke trending 317° was found in a drainage ditch on the western slopes of Jedburgh Knees [NS 6155 0299] and, 400 m NW of this locality, boulders of very fresh CD were found on the north side of a forest ride where a trench for electric cables had been dug [NS 6126 0323].

Glenhastel to Polmath Burn Cropping out in the bed of the Glenhastel Burn [NS 59850 06100] and forming a crag on the valley slopes to the west is a 1.3 m wide dyke; its trend is at variance with the regional (320°) trend of the CD. From Glenhastel to Monquhill [NS 59000 06850] the trend defined by magnetic anomalies becomes more northerly (Fig. 6g). The 1 m dyke that crops out on the south side of Polga Burn [NS 57500 07595] trends 290°. It is offset, sinistrally, by c. 1 km from the line defined by the Glenhastel–Monquhill anomalies. North of Polga Burn the anomalies define a trend of 298°.

Magnetic profile interpretation

The CD produces a well-defined, isolated magnetic anomaly at most localities (e.g. Fig. 7a, c) as a result of the marked contrast between the magnetic properties of the CD and the country rocks, mainly sandstones.

**Magnetic properties**

Values of the magnetic properties can aid modelling of profiles to estimate width, depth to the top surface of the dyke and deeper structure. They could also help to distinguish the CD from other Tertiary dykes and from non-Tertiary dykes.

**Natural remanent magnetization (NRM)**

Prior to this study results from ten sites in northern England have been reported (Appendix C), but no published data were available for the CD in Scotland. For this study measurements have been made on cores drilled from outcrop at 31 locations (Appendix C). They show that the mean magnitude of the NRM of samples studied is 3.2 A/m (std. dev./std. error of the mean 3.9/0.3 A/m); however, NRM varies across a single outcrop. Particularly large values were obtained for the samples from Castramon, Cornharrow, Dodd Hill, Glenhastel, Polga Burn and Polmath Burn. All these are very fine-grained rocks from the Water of Ken–Windy Standard–SUF sector. The majority of the samples are reversely magnetized with directions not very different from those reported for the CD elsewhere (Appendix C).

**Volume specific susceptibility (χ)**

Values of χ range from 1.56 × 10⁻² to 5.98 × 10⁻² SI about a mean value of 2.97 × 10⁻² SI (std. dev./std. err. 0.81/0.07 × 10⁻² SI). Repeated measurements on the weakest and strongest samples showed that the typical overall measurement error in the χ of a sample was c.1.4%, i.e. much smaller than the variations between some of the samples. Thus there is a clear difference between the two adjacent dykes at Braco. No systematic trend of χ can be seen along the dyke. The CD is fine-grained and Fe₂O₃-rich, and it is not surprising that these values of χ are generally larger than those for many Tertiary basaltic dykes. However, they are not sufficiently different to distinguish between the CD and other Tertiary dykes in the Southern Uplands. They are, however, much larger than typical values for the country rocks. The only large values of χ reported in country rocks (up to 4.5 × 10⁻² SI) are for the Marchburn Formation in the Northern Belt (Floyd & Trench 1989; Barron et al. 2004). Mean values for each location are given in Appendix C.

**Magnetic profile interpretation**

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Fig. 7. Examples of ground level magnetometer profiles from this survey. (a) Single anomaly, reduction-to-pole and second derivative: traverse LU971 on Lochurr Hill. (b) Compound anomaly and second derivative indicating two closely spaced dykes: traverse DL9912 alongside exposure in Polga Burn. (c) Observed profile for traverse CR4 on Craigmuie Moor and profile calculated for model shown in (d). (d) GRAVMAG model for profile CR4 in (c).

Location, width and depth from ground profiles

Location The minimum on each traverse provides a good estimate of the position of the dyke because the anomalies are so clearly defined. A more precise location is obtained by reduction-to-the-pole (RTP), where the shape of the anomaly is analytically modified to what it would be if the magnetization were vertical. The more nearly symmetrical anomalies which result are centred over the body, but the differences from that defined by the position of the observed minimum is not significant, being only 1.4 m (std. dev. 1.2 m), so we have used the latter.

Width The majority of the anomalies are narrow, suggesting that they are due to a relatively narrow body; simple rule-of-thumb estimates give 10–20 m.

For a more precise analysis the second derivative of the RTP data can be used (e.g. Blakely & Simpson 1986) and hence the width of the body in the direction of the traverse (Fig. 7a). Where profiles were taken across outcrop the result can be compared with the observed width; the second derivative estimates give a mean of 6.9 m (std. dev. 4.1, N=36), the observed 6.7 m (std. dev. 6.4, N=35). For particular outcrops the RTP results are not always consistent with the width of outcrop observed, and for some the analysis shows an additional anomaly indicating a hidden body. The mean of RTP results for all 382 anomalies analysed is 9.0 m (std. dev. 5.6 m). These analyses make some assumptions.

Firstly, for a dyke of given width the anomaly, and hence the RTP result, increases as the depth to the top increases, but as the evidence indicates that for most of the traverses the dyke is close to the surface this effect should not be great. Secondly, it has been found that for very narrow bodies, even when they crop out, the second derivative analysis used exaggerates the width. This effect is most serious for dykes of width <5 m and probably explains many of the discrepancies between the RTP estimates and the measured values. Further, if a body widens with depth it has been found from modelling that the negative part of the profile is wider at various fractions of the peak amplitude and the positive part is flatter in comparison with the profile for a parallel-sided body. In these cases the RTP width lies between the near-surface width and the greater width of deeper sections. This may be the situation at a number of places along the dyke so that differences could arise because the complete width is not exposed, the dyke tapers near the surface, or that the simple assumptions of the interpretation techniques are not met.

Widths of the body causing an anomaly can also be found from the GRAVMAG modelling program (Pedley 1993). The average values of \( \chi \) and NRM measured for the samples collected (see above) were used as a starting point and it has been assumed that \( \chi \) and NRM of the country rock are effectively zero.

In some cases a match to the profile was achieved by using two or more adjacent bodies. Combining the separate widths reduces the number of narrow bodies and increases the number of wider ones. Using all 53
bodies needed to fit the peaks associated with outcrop, a mean width at the top surface of 5.9 m (std. dev. 4.2 m) is obtained; if some of the bodies are combined the mean is 7.6 m (std. dev. 6.0 m, N=33).

Fits to the observed anomalies have been obtained using models coming to within a few metres of the surface (see below) but, in many cases, to produce a match between observed and model anomalies it is necessary to postulate a widening of the body (or bodies) with depth. This could possibly correspond to a rounding near the ground surface or to a rhomboidal section extending to depth (Fig. 7d), so the narrow widths observed at outcrop may simply represent the tip of a thicker body. An example of the CD terminating upwards with a domed top has been described by Teall (1984), and Gudmundsson (1996) reports examples of dykes tapering and terminating upward in Iceland.

Several authors have pointed out some of the problems associated with interpretation of magnetic profiles. For example, Goultz et al. (1984) claim that if the width of the dyke is less than its ‘observational depth’, i.e. the distance between sensor and the body, it may not be possible to distinguish the anomaly of a narrow dyke from the anomaly of a more weakly magnetized, wider dyke, and Kirton & Donato (1985) say that the width cannot be reliably resolved if the depth-to-width ratio is significantly > 1. However, these qualifications probably do not apply for the ground surveys as the dyke is so near the surface.

Depth to top and vertical extent of body The narrowness of many of the anomalies suggests that, where it does not crop out, the dyke is buried at not more than a few metres for most of its length. Nevertheless, the range of amplitudes, 100 to almost 4000 nT, and width of the profile must reflect differences in the depth of burial and/or the strength of magnetization. The depth to the top of the dyke has been estimated from the profiles since, although the depth of drift cover may be known from field observations, the dyke may terminate upwards at a greater depth in the Lower Palaeozoic country rocks (similar to the situation reported by Teall 1984).

The method of ‘Euler deconvolution’ (Thompson 1982) does not require a particular geological model to be assumed, but it is necessary to assume that the magnetization is uniform and the profile perpendicular to the dyke trend. This technique gives a mean depth of 7.6 m (std. dev. 7.5 m) for 335 anomalies examined, lending strong support to the view that the dyke is shallowly buried. These estimates could place the top of the dyke at too great a depth because it has been assumed that the source is a narrow (width/depth ratio < 0.5), two-dimensional dyke at the pole, for which the ideal ‘structural index’ is 1.0 (Thompson 1982); however, for wider dykes and as a rule of thumb, Thompson (1982) showed that a lower ‘structural index’ of 0.5 would give a better and lower estimate of the depth to the top surface. (The ‘structural index’ is the power, n, of the factor (1/r)n which determines the rate at which the magnetic field decreases laterally with distance from the body and depends on the form of the body).

The depth to the top can also be estimated using the methods of Parasnis (1986) provided it is assumed that the dyke can be represented by a uniformly magnetized, regular rectangular slab, infinite in the strike direction and with a horizontal top surface. These methods give mean depths of 10.1 m (std. dev. 11.2 m, N=173) for the near-symmetrical features and 5.6 m (std. dev. 5.0 m, N=117) for asymmetrical ones, which support the view that the dyke is shallowly buried. However, McGrath & Hood (1970) show that for a similar analytical method the depth estimated will be in error if the ‘half-strike length’ is less than ten times the depth and, because of the segmentation of the dyke, this could be the case for parts of the CD.

It is difficult to estimate the vertical extent of the body because the contribution of parts at increasing depths give wider, smaller amplitude anomalies which are not distinguishable from the background. For the ground profiles it is found that, depending on the thickness, the contribution by parts below 50–100 m is generally not resolved, consequently an arbitrary cut-off of 100 m has been used for the models. No doubt the dyke extends to greater depths.

Compound magnetic anomalies On a number of traverses, two anomalies separated by c. 100 m were found so that two distinct sub-parallel dykes must be inferred. The relationship between such bodies was investigated by making several parallel traverses and in the case of Skeoch Hill, for instance, the anomalies show that the outcrops represent offset and overlapping segments of the ‘dyke’.

However, a surprising number of the profiles show compound features, that is two (or more) anomalies are closely spaced or only partially resolved (Fig. 7b). In some cases this is true even where only a single narrow outcrop was found (e.g. 1 m wide at Polga Burn). The RTP technique helps resolve complex features into separate anomalies and this suggests the presence of two or more narrow, closely spaced dykes (Fig. 7b) (see also Kirton & Donato 1985). Alternatively, this anomaly pattern could result from variation in the depth of burial or variation of magnetic properties across the dyke. Although it is possible to model the profile with two (or more) separate bodies, because the shape of an anomaly is less sensitive to the deeper parts of the causative body, these may join to become a single body at depth.

Aeromagnetic flight line interpretation: width and depth

Original flight line records from the 1959–65 survey (IGS 1964) provided by the BGS Regional Geophysics Group (Kimbell, pers. comm.) have been hand digitized for lengths around the CD. The lines, T130–T155, are orientated south–north along eastings 2 km apart from 254 to 304 km east. An anomaly on the projected line of the CD can be recognized; it is relatively small superimposed on a larger regional feature. Usable profiles
were generated for the lines T138 (270 km east, near Troston) to T147 (288 km east, near Braco) but it proved impossible to extract analysable data for the others.

For the following analysis a simple (linear) background has been subtracted and, as no downward continuation has been applied, the amplitudes of the anomalies are those appropriate to the average flight height of 305 m. Because of the topography, the actual observational surface is 'draped', sometimes higher, sometimes lower, than the average. As the anomalies are small, estimates of width and depth of burial will be sensitive to the background used and there will also be some uncertainty in the depth (below ground level) because of the deviation from the average flight height.

The Euler method gave depths of 0.37 km (std. dev. 0.14 km, N=9) and the Parasnis method 0.43 km (std. dev. 0.35 km, N=9).

RTP estimates of the width at the top gave a mean of 0.77 km (std. dev. 0.23, N=9). The Parasnis method also gave a mean of 0.77 km (std. dev. 0.59 km, N=6). For the flight lines the ratio of body width to its distance below the sensor is such that the width/magnetization compensation could apply. It has not been possible to differentiate between the possibilities but, using GRAVMAG, all of the various trials made gave bodies hundreds of metres wide, probably extending to depths of several kilometres.

The measured values of magnetization for surface rocks have been used for these estimates but it is not known how the NRM varies with depth of burial. The magnetization of the surface rocks could have been reduced due to weathering, or could be less at depth because of the temperature increase. As for the most part the dyke samples collected are remarkably fresh as seen in thin section, and the temperature effect should be small over the depths involved, it must be concluded that there is a wider body at depth.

The CD crosses the area between Dodd Hill [NX 65175 98787]-Holm of Dalquharn [NX 6554 9900] and Calf Knees [NS 61257 03226] covered by the more detailed survey of Dawson et al. (1977). Although the flight lines were parallel to the trend of the CD, a line of anomalies with a NW trend clearly due to the deeper structure of the dyke can be identified, and a number of profiles have been extracted from the magnetic contour map. This survey was flown at low altitude (c. 50 m) using a helicopter, so the estimates of width and depth obtained will indicate the structure of the body at depths intermediate between those inferred from the earlier aeromagnetic and the ground surveys. Euler analysis gave an average depth of 244 m (std. dev. 43 m, N=9) and RTP an average width of 187 m (std. dev. 48 m, N=9). GRAVMAG models were achieved with widths 68 m (std. dev. 27 m, N=9) and depths of burial 118 m (std. dev. 59 m, N=9) and vertical extents of between 400 and 1000 m.

As noted above, the ground profiles are insensitive to the vertical extent of the causative body, the deeper parts producing a broad, low-amplitude anomaly which can be lost in the background. On the other hand, if the anomalies of the ground traverse and ‘50 m height’

models are continued upward to the flight height (305 m) of the aerial survey, not only are their amplitudes much reduced but also the widths become very small compared to the flight line sampling interval, so the near-surface bodies may not be seen. Hence, it is not clear to what extent there is a mis-match between the ground and aeromagnetic models. The results suggest that there could be a shallow crustal magma chamber from which narrower blades have risen to form the CD. The form of the aeromagnetic contours suggests that along the length of the CD there could have been a series of small, shallow basaltic magma chambers, each having a slightly different petrogenic history, feeding the dyke, which could account for the geochemical variability of the CD (see below).

Analysis of samples

Petrography

Teall (1884), Holmes & Harwood (1929), Hornung et al. (1966) and Macdonald et al. (1988) have described in detail the petrography of the CD. What follows is a summary based on our observations of the dyke in the Southern Uplands.

The CD is a porphyritic fine- to medium-grained rock containing phenocrysts of plagioclase, clin- and orthopyroxene. The content of phenocrysts is variable, the maximum being 6% with plagioclase predominating over pyroxene, but there is one exposure (Braco) which is non-porphyritic. The plagioclase phenocrysts (An50-55, determined optically), which range up to 4 mm in length with the majority being 2 mm, occur both as discrete euhedral crystals and in glomerophyric aggregates. Oscillatory, normal and reverse zoning are ubiquitous and the presence of reverse zoning, which is common, may indicate rapidly induced supercooling accompanying the emplacement of magma (Lofgren 1980).

The pyroxene phenocrysts vary from euhedral to anhedral in shape, with an average size of 0.5 mm. Some phenocrysts consist of cores of orthopyroxene enclosed by clinopyroxene. The pyroxenes are usually fresh, with the only alteration, which is more prevalent in orthopyroxene, being the development of chlorite along irregular fractures. An exception to this is found 200 m NW of Shield Burn where the most evolved chemistry (CD4 and CD46) occurs and the pyroxene phenocrysts have been pseudomorphed by chlorite.

The matrix consists of plagioclase laths, equigranular pyroxene, Fe-Ti oxide, apatite needles, amphibole, alkali feldspar, quartz, and varying amounts of acid mesostasis, which most likely represents devitrified glass. The mesostasis can form as much as 40% of the rock and, depending on the amount, the texture varies from interstitial to hyalophitic.

Small amygdales, 1 mm in diameter, are either lined by chlorite with a quartz centre or more frequently a quartz rim with a calcite centre.

Although only forming about 1% by volume, a feature that has not been previously described from the CD is
the presence in some rocks of segregation vesicles, i.e. vesicles that contain residual magmatic material (Anderson et al. 1984, and references therein). The segregation vesicles are spherical, mostly 1 mm in diameter, but can be 2 mm in diameter when they occur in coarser-grained matrix (CD52). Sometimes the vesicles are bordered by a rim of tangentially arranged plagioclase laths which can give the vesicles a faceted outline. The infilling magmatic material is very dark coloured and often contains microlites of plagioclase, acicular pyroxene and skeletal Fe-Ti oxide. The material in the vesicles is often finer in grain size than the host rock. In the finer-grained facies of the CD, material similar to the vesicle infilling occurs interstitially. Not all vesicles are completely filled with magmatic material; in some the magmatic material forms a crescent shape with the rest of the vesicle filled with calcite and/or quartz. Segregations vesicles represent residual liquid produced by gas effervescence during crystallization, a process referred to as gas filter-pressing (Anderson et al. 1984).

The presence of both amygdales and segregation vesicles is thought to indicate that the CD was emplaced at a high level in the crust.

**Geochemistry**

The total alkali versus silica (TAS) classification for volcanic rocks (Le Maitre 2002) shows that of the 55 analysed samples of the CD in the Southern Uplands there are 31 basaltic andesites, one basaltic trachyandesite, four trachyandesites, 18 andesites and one dacite (Fig. 8). The raw data from the analyses are given in Appendix E; the oxide values for the graphs and quoted below have been recalculated to 100% on a volatile-free basis.

Selective plots of SiO$_2$ versus other major oxides and trace elements (Fig. 8) show that the CD along its length is geochemically heterogeneous. The SiO$_2$ contents vary from 53 to just over 65 wt%, with the majority of rocks occurring between 54 and 59 wt%. To analyse the geochemical variation in greater detail and to determine whether there is a systematic variation in composition along the length of the dyke, the dyke has been divided into eight geographical sectors. These eight sectors differ from those defined in Dagley et al. (1998), a consequence of the increased number of analyses. From SE to NW the eight sectors are: east of the River Nith (ERN, four analyses); Lochanhead (LNH, six); Braco (BRA, five); Skeoch Hill–Darngarroch Hill (SKD, ten); Castramon Hill (CAS, four); Craigmuie Moor (CRM, six; Shield Burn (SHB, ten); Water of Ken–Windy Standard–SUF (WST, ten).

Although the chemical variation shown by the dyke is appreciable (Fig. 8) there is no systematic variation along the c. 64 km length sampled. Many of the individual sectors exhibit a considerable chemical variation; for instance the Shield Burn sector varies in silica content from 53.94 to 65.04 wt%, the Braco sector from 54.58 to 59.19 wt% and the Skeoch Hill–Darngarroch Hill sector from 55.44 to 59.44 wt%. However, the Water of Ken–Windy Standard–SUF sector, which extends over c. 20 km and in which six dyke outcrops and three boulder localities were found, has a fairly consistent chemistry, the SiO$_2$ content only varying between 55.92 and 57.51 wt%. These findings are totally at variance with the views of Hornung et al. (1966) and Macdonald et al. (1988) who concluded from their geochemical data, mainly obtained from the north of England, that the CD was relatively homogeneous along its length. It is important to note that these authors sampled the CD at only two localities within the Southern Uplands: Shearington and Troston Loch.

In addition to SiO$_2$ there are other chemical differences between the sectors. For similar values of SiO$_2$ the Lochanhead sector differs from both the Skeoch Hill–Darngarroch Hill and Shield Burn sectors by having lower K$_2$O, significantly higher CaO and CaO/Al$_2$O$_3$, and slightly higher Fe$_2$O$_3$.

The Braco sector is of particular importance because of the occurrence of two juxtaposed dykes [NX 873457 75765] which differ in petrography and chemistry. The 4.4 m wide dyke on the east side of the outcrop is a non-porphyrity quartz–dolerite whereas the 10.5 m wide dyke on the west side possesses the characteristic petrographic features associated with the CD, having phenocrysts of plagioclase and pyroxene in a ground-mass containing a high proportion of devitrified glass. The difference in chemistry between the two dykes is appreciable, the eastern dyke (CD57, Appendix E) has SiO$_2$ 54.58 wt%, CaO 6.93 wt%, K$_2$O 1.68 wt% and TiO$_2$ 1.49 wt% whereas the western dyke (average of two analyses, CD58 and CD59, Appendix E) has SiO$_2$ 58.02 wt%, CaO 5.83 wt%, K$_2$O 2.94 wt% and TiO$_2$ 1.18 wt%. Although the eastern dyke is petrographically different from any other member of the CD, it should be stressed that chemically it does belong to the CD complex. This is the first recorded evidence from one locality of two separate intrusions of chemically different magmas being involved in the emplacement of the CD. Unfortunately, the contact is not exposed.

When determining the mode of emplacement of the CD it is important to consider the chemical variation along the length of a sector. The Shield Burn sector is ideal for such an analysis because it has the greatest chemical variation of the eight sectors, containing both the most basic (CD8) and the most acid (CD46) rocks of the CD within the Southern Uplands. A traverse from the Burn Gorge to the NW illustrates this variation. A sample (CD8) from the gorge has a SiO$_2$ content of 53.94, 100 m to the NW the content is 57.27 (average of three analyses, CD7, CD6 and CD47), at 142 m the SiO$_2$ value is 54.42 (CD5), at 240 m SiO$_2$ is 61.73 (CD4) and at 250 m it is 65.04 (CD46). The next outcrop of the dyke, 400 m to the NW of CD46, has SiO$_2$ 55.92 (CD2), a further 75 m NW an outcrop yielded a SiO$_2$ value of 58.51 (CD1).

A more detailed geochemical study would be needed in this sector to determine whether the geochemical variations are gradational or whether there are discontinuities.
Fig. 8. Geochemical classification and selected plots. Geochemical classification according to the TAS model (Le Maitre 2002). Normalized total oxides, 100%. Fields: A, andesite; B, basalt; BA, basaltic andesite; BTA, basaltic trachy-andesite; D, dacite; TA, trachy-andesite; TB, trachy-basalt. Sample groups: BRA, Braco; CAS, Castramon; CRM, Craigmuie Moor; ERN, East of River Nith; LNH, Lochanhead; SHB, Shield Burn; SKD, Skeoch-Darngarroch; WST, Windy Standard.
Examination of the major oxide and trace element versus SiO$_2$ plots for the CD complex indicates that the chemical variation within the eight sectors can be accounted for by the crystal fractionation of plagioclase and clinopyroxene, both of which occur as porphyritic phases. The decrease in Sc and V abundances (Fig. 8) and CaO/Al$_2$O$_3$ ratios with increasing SiO$_2$ content is consistent with clinopyroxene fractionation. The fractionation of plagioclase resulted in decreasing Sr with increasing SiO$_2$, Sr being partitioned into plagioclase rather than other phases. The decrease in Sr abundance is consistent with clinopyroxene fractionation. The fractionation of plagioclase and clinopyroxene, both of which occur as porphyritic phenocrysts, often glomerophyric, in a fine-grained matrix containing magmatic segregation vesicles. For the same levels of SiO$_2$, the Dalgig Burn and Vennel dykes have lower Fe$_2$O$_3$, Fe$_3$O$_4$/MgO, TiO$_2$, V and Y, and higher Al$_2$O$_3$, CaO and Cr compared with the CD complex.

The average magnetic susceptibility of the Dalgig Burn dyke ($9.4 \times 10^{-2}$ SI) is considerably lower than the average for the CD, while that for a sample of the Vennel dyke ($2.21 \times 10^{-2}$ SI) is closer to the CD average. Small negative anomalies are found across both dykes.

The petrography, chemical and magnetic properties are consistent with the proposal by MacGregor (in Eyles et al. 1949) that the Dalgig Burn and Vennel dykes are parts of the same dyke. However, they rule out the possibility that the two dykes represent the continuation of the CD in the Midland Valley as he advocated. Macdonald et al. (1988) also concluded that these New Cumnock dykes were not part of the CD.

Sampling locations and analytical details for other Tertiary dykes sampled in the Southern Uplands are given in the Appendices.

Mode of emplacement

The mode of emplacement of the CD can be considered in two parts: the structural control that determined the form of the dyke fissure(s), and the direction of emplacement of magma.

Structural control

The average trend of the CD in this area is NW, the same as the regional dyke swarms associated with the Tertiary igneous activity of Scotland (Speight et al. 1982) which indicate a dominant NE-SW directed extension (England 1988). However, the deviations outlined earlier suggest that local geological structures and contrasted lithologies have modified the regional stress field. The two most important influences on the path of the CD are the Lower Palaeozoic NE-SW trending boundary faults and two Caledonian granitic plutons.

Faults

The most important effect is the offsetting which occurs in the neighbourhood of some of the faults. In the southern part of the region the offset is always dextral: Innerwell (IF), 500 m; Laurieston (LF), 350 m; Gillespie Burn (eastern splay, GBFe), 750 m; Sandhead (SF), 1250 m; Orlock Bridge (OBF), 1250 m. Although the regional NW trend of the CD has been offset across the IF and OBF, the dyke is continuous across the faults, witness the north-south trend where it crosses the faults (Fig. 6a, e). In the neighbourhood of the Laurieston Fault (LF) (Akhurst et al. 2001) the overall offset is the result of an en-échelon structure.

Between Craigmuie Moor and Shield Burn the changes of trend and offset occur within the NE-SW
trending Moniaive Shear Zone (MSZ), a 2.5 km wide major ductile zone (Phillips et al. 1995), and the OBF, a strike-slip fault separating the Ordovician and Silurian turbidity sequences which marks the NW margin of the MSZ. No change of trend or offset occurs at the SE margin of the MSZ or in the immediate vicinity of the OBF, but the location of the features suggests that it is the latter structure that has influenced the dyke trend.

In the north there are sinistral offsets: c. 1 km between Monquhill and Polga Burn and c. 700 m at the SUF. To account for the c. 1 km offset, difference in trend and break in continuity north of Monquhill, we speculate that there may be a fault along Connel Burn which could be the Carcow Fault (Floyd 1994).

Faults are also associated with changes in trend where no offset is seen, e.g. Gillespie Burn (main splay, GBF) (Fig. 6d) and Glen Fumart (GFF) (Fig. 6f).

Some of the offsetting might suggest that the faults have moved in Tertiary times, but no evidence for this has been found, so it is more likely that the faults have modified the regional stress pattern. The large offsets and differences in regional trend of the CD on either side of the Sandhead (SF) and Orlock Bridge (OBF) faults are mirrored by the NW trending aeromagnetic anomalies. This implies that the deeper structure of the CD has been, in places, also influenced by the NE trending faults (Fig. 2). If the aeromagnetic anomaly represents the magma reservoir that fed the CD, then the offsets and different trends across the faults must have been initiated at a deep level, suggesting that the faults extend to deep levels within the crust.

Granitic plutons The two Caledonian granitic plutons of Criffel and Cairnsmore of Carsphairn have locally controlled the structure of the CD.

The trace of the CD is offset to the NE from the line through Shearington and Lochanhead, but there is no offset across the Lochanhead fault (LNF) (Fig. 6a). However, the dyke segments together form an arcuate trend which is roughly parallel to the surface outline of the Criffel pluton (Figs. 4 and 6a). The trace lies very close to the 10 km depth contour of the pluton estimated from the gravity models (Bott & Masson-Smith 1960; Kimbell pers. comm.).

The trace of the dyke in the ‘Water of Ken’ zone between Troston and Glenhastel (Fig. 6f), with the several short en-échelon segments and large overall dextral offset of 5 km, lies just to the east of the Cairnsmore of Carsphairn pluton. Three-dimensional modelling of the gravity surveys of Dawson et al. (1977) indicates that the Carsphairn Granite is a steep-sided body which merges with a granite platform at depth (Floyd 1999). The platform underlies the area at a depth of about 3 km and extends down to 7 km (Floyd 1999, fig. 24). The north-south trending series of anomalies at Auchenstroan is parallel to, and to the east of, the position of the 7 km depth contour of the granite platform, and the dyke segments of the ‘Water of Ken’ zone generally follow this structure and lie between the 7 km and 3 km depth contours. The offset near the Leadhills Fault (LHF), occurs where the trace of the dyke crosses the edge of the granite platform as indicated by the 5 km and 7 km depth contours (Fig. 6f). To explain these features we propose that the granite platform acted as a homogeneous barrier to the propagation of the NW trending dyke fissures. The minor offsets between Glenluce and Glenhastel are also probably associated with the granite platform.

Other structures Other structures that have locally controlled the trend of the CD are the prominent, north-trending vertical joints in the Gala Group country rocks on Craigmie Moor, and the dip and strike of the country rocks in Glenhastel. On Craigmie Moor the orientation of several short dyke segments is close to that of prominent, north-trending, vertical joints developed in the country rocks. In Glenhastel the trend of the dyke is 240°, the same as the strike of the vertically dipping Ordovician greywackes, although the regional trend of the CD is 320°.

The change of trend NW of Bishop Forest Hill (Fig. 6c) is similar to that noted in the aeromagnetic anomaly by Kimbell (in Lintern & Floyd 2000, p. 18, fig. 2) which they suggested was controlled by a deep structure, but no specific structure has been identified.

We cannot account for the structural control of the east-west trending segment of the dyke in Polmath Burn as the country rocks are poorly exposed Old Red Sandstone basalt and basaltic andesite lavas.

Direction of magma emplacement

Two theories have been advanced for the source of the magma responsible for the CD (Richey 1939): lateral flow from the reservoir which underlay the Mull central intrusive complex, or upwards flow from a regional reservoir.

This survey has shown that the CD is a complex regional structure with segmentation, numerous offsets (in particular the 5 km offset along the Water of Ken) and en-échelon segments. This structure does not seem consistent with lateral intrusion. The proponents of lateral intrusion (e.g. Macdonald et al. 1988) did not discuss how the structures (segmentation, offsets, etc.) already known in northern England were produced.

Furthermore, at many localities the dyke is very narrow: Lochanhead, three dykes 2.0 m, 1.6 m and 1.3 m wide; Castramon Hill, two parallel dykes each 1 m wide; along the 15 km between Dodd Hill and Polmath Burn, just north of the SUF, Dodd Hill, 2.2 m; Midrig, c. 1.0 m; Windy Standard, 2.3 m; Glenhastel, 1.3 m; Polga Burn, 1.0 m; and Polmath Burn, 0.8 m. It is extremely difficult to reconcile these narrow widths with the lateral flow of a large volume of magma from the Mull Centre, c. 160 km to the NW, especially as the country rocks, predominantly sandstones, adjacent to the dyke margins show little to no baking.

The localized chemical variation without systematic trend along the CD in the Southern Uplands (Fig. 8) casts doubts on the findings of Hornung et al. (1966) and Macdonald et al. (1988) that the CD is relatively homogeneous along its length and was emplaced by lateral
flow of magma from Mull. We believe that the non-systematic chemical variation of the CD, as shown by the eight sectors and the two juxtaposed dykes of different chemistry and petrography at Braco, is further evidence against lateral intrusion and in favour of vertical emplacement of the dyke from localized high-level magma chambers.

Positive evidence for a regional magma reservoir beneath the Southern Uplands is provided by Al-Kindi et al. (2003) who, from their modelling of wide-angle seismic data and gravity observations, predicted a 2–3 km thickness of magmatic underplating of the lithosphere by the Iceland plume. These authors propose that the underplating was generated when a hot sheet impinged on the lithosphere lid causing decompressional melting; this produced large quantities of high temperature basaltic magma, which may be essential in the formation of long dykes (McHone et al. 2005). When intruded into the crust this magma could have become contaminated by an acid melt generated by partial fusion of sialic crustal rocks. This process would account for the high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7123 reported by Moorbath & Thompson (1980) for the CD in Cumbria. This reservoir fed a ridge of magma whose orientation was controlled by a dominant NE–SW extensional stress field which acted throughout the depth of the crust (England 1988). Support for such a heterogeneous magma chamber that could have fed the CD is given by the conspicuous NW trending negative aeromagnetic anomaly along the length of the CD (Fig. 2).

Conclusions

In the present survey a series of closely spaced traverses have been used to link magnetic anomalies to known outcrops so that the presence of the CD complex can be asserted. In this way the survey has established the continuity of the ‘dyke’ as far NW as Polmath Burn, 1.25 km NW of the SUF, and in the process discovered 26 previously unknown outcrops. The identity of these outcrops with the CD has been confirmed by petrographic and geochemical examination.

The anomalies show the dyke to be a complex structure; at some localities it appears as a single feature and at others as two or more sub-parallel dykes. It is made up of a series of segments, which sometimes overlap; in general the pattern is en-échelon, with, in some cases, offsets between segments of more than 1 km. There are sometimes considerable changes in trend from segment to segment, and within several of the segments the dyke bends through angles as large as 90°.

Modelling the magnetic anomalies shows that, where it is not exposed along a traverse, the dyke is buried by no more than a few metres. Widths measured at outcrop and estimated by modelling range from 1 m to 23 m, typically about 10 m. Modelling does not provide a good estimate of the vertical extent of the body, but the aeromagnetic expression suggests that it extends at least several hundred metres. The exposures, and the ground traverse anomalies, do not always lie central to the aeromagnetic feature, often exhibiting a different trend. The deeper parts revealed by the aeromagnetic data are much wider than the near-surface expression, suggesting that the upper parts could be thin blades rising from a larger body. The discontinuities observed in the near-surface trace of the CD are due to the influence of structures in the country rock on the path of these blades.

A geochemical study shows that the CD is laterally heterogeneous without systematic trend along its length. This heterogeneity and the two juxtaposed dykes with differing petrography and geochemistry at Braco indicate that the CD was emplaced vertically from a series of small high-level magma chambers that were fed from a regional reservoir beneath the Southern Uplands (Al-Kindi et al. 2003).

The chemical signature shows that the CD is not the same as the Stevenson-Coylton–New Cumnock dykes as proposed by MacGregor (in Eyles et al. 1949).

The chemical heterogeneity and lack of any systematic variation of chemistry, dyke width or anomaly amplitude with position, the discontinuities and lack of baking of adjacent country rocks strongly suggest that the dyke was emplaced vertically.

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