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Palaeomagnetic study of the Cairnsmoor of Fleet Granite and Criffel-Dalbeattie granodiorite contact aureoles: Caledonian tectonics of the Southern Uplands of Scotland and Devonian palaeogeography

J. D. A. PIPER*, N. J. McARDLE & Y. ALMASKERI

Geomagnetism Laboratory, Department of Earth and Ocean Sciences, University of Liverpool, Liverpool L69 7ZE, UK

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Abstract – The plutons of Cairnsmoor of Fleet (392 ± 2 Ma) and Criffel-Dalbeattie (397 ± 2 Ma, both mineral isochron ages) comprise two of four major post-tectonic granitic complexes emplaced into the Southern Uplands, an Ordovician–Silurian back-arc and foreland basin complex formed at the northern margin of the Iapetus Suture. To expand the palaeomagnetic record of the Southern Uplands we have studied palaeomagnetism and magnetic fabrics in traverses spanning contacts of these intrusions with host mudrocks. A uniform anisotropy of magnetic susceptibility (AMS) fabric across the Cairnsmoor of Fleet contact has been enhanced by recrystallization into hornfels near the contact and records a late Acadian regional stress operative during, or soon after, emplacement of the pluton in Middle Devonian times. Magnetization during slow cooling recorded a dual polarity ('A') remanence in granite and hornfels with mean direction D/I = 92/−2° ($\alpha_{95} = 6.5°$) yielding a palaeopole (Q = 6) at 2° N, 265° E linked to cooling at *c.* 392 Ma. Subsidiary magnetizations are overprints imparted during Variscan tectonism ('B', D/I = 194/6°) and Jurassic rifting within the adjoining Irish Sea Basin ('C', *c.* 160–140 Ma, D/I = 172/−52°). The Criffel-Dalbeattie pluton has more complex AMS fabrics recording both deformation and emplacement effects. Hematite of secondary hydrothermal origin is a significant feature of the rock magnetic record in the aureole, which is otherwise dominated by paramagnetism. The granodiorite is more strongly magnetized than the country rocks, accounting for a positive aeromagnetic anomaly. A fairly dispersed dual polarity remanence (mean D/I = 115/55°, $\alpha_{95} = 18°$) in granodiorite and late tectonic porphyrite dykes is probably the oldest magnetization preserved in this pluton because it correlates with an excursion of Britain into southerly palaeolatitudes at *c.* 410 Ma and indicates an Early Devonian emplacement age. The palaeofield at *c.* 397 Ma, the currently accepted isotopic age, is recorded by a minority overprinted remanence (mean D/I = 272/2°, $\alpha_{95} = 12°$) similar to the record in the Cairnsmoor of Fleet pluton and granites from the adjoining Lake District terrane. Granite complexes of the Southern Uplands Block collectively record regional rotation and excursion of Britain into southerly latitudes between *c.* 410 and 390 Ma. Comparable Silurian–Devonian palaeomagnetic poles identify common apparent polar wander (APW) in paratectonic and orthotectonic terranes from the Variscan Front in the south to the Laurentian foreland in the north following climactic Acadian deformation. APW between 430 and 390 Ma embracing the (post-closure) history of the Caledonian orogen is a loop executed at rates much higher than typical rates of plate motion and appears to record a component of true polar wander. The ∼110° arc length is identical to polar shift identified between mid-Silurian and Lower–Middle Devonian poles from Gondwana. The two paths superimpose to show that the western margin of Gondwana was in proximity to the SE margin of Laurentia during Acadian deformation in Early–Middle Devonian times and remote from the Caledonides; the residual Rheic Ocean subsequently closed by a combination of pivotal and left lateral strike-slip motions.

Keywords: palaeomagnetism, Devonian, Caledonian, granites, Gondwana, palaeogeography.

1. Introduction

Formation of the British Caledonides in Early Palaeozoic times involved the consumption of a major ocean basin, the Iapetus, in Ordovician times and orogenic deformation in a collisional zone between the Laurentian continent of Greenland and cratonic North America in the north and the Avalonian Block to the south. The latter includes the basement of England and Wales north of the Variscan suture and incorporates rocks with a geological history commencing in the Neoproterozoic. Terrane emplacement and deformation of arc-related sedimentary and volcanic sequences accompanied the ensuing orogeny, whilst block rotations and strike-slip motions along major faults continued into Silurian and Devonian times (e.g. Hutton, 1987; Soper & Woodcock, 1990). The end result was the juxtaposition of medium metamorphic-grade terranes comprising the

*Author for correspondence: sg04@liverpool.ac.uk

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Grampian and Northern Highlands of Scotland (the Orthotectonic Caledonides) against low-grade terranes (the Paratectonic Caledonides) including the Southern Uplands of Scotland, the Lake District and Wales.

Widespread partial or complete overprinting of older magnetizations by Carboniferous–Permian remanence has complicated resolution of movements leading to the emplacement of these terranes. An exception is the Late Ordovician calc-alkaline igneous suites that have generally yielded an integral primary record identifying a history of terrane rotation following consumption of the Iapetus Ocean (McCabe & Channell, 1990; Trench *et al.* 1991; Piper 1997*a*,*b*; Piper, Stephen & Branney, 1997). Granitic rocks, which form a major component of the Caledonian igneous record, are not intrinsically satisfactory palaeomagnetic material because they usually have ferromagnetic contents comprising only small amounts of magnetite, typically with multidomain properties. However, thermal aureoles can provide a useful palaeomagnetic signature of the granite magnetization where mudrocks of a more varied primary chemistry have been recrystallized into hornfels (Piper, 1997*b*).

The Southern Uplands Terrane lies at the northern margin of the Iapetus Suture; with the exception of the Midland Valley block where the basement is largely buried, all other Caledonian terranes of the Paratectonic Caledonides in Britain (the Lake District and Wales) occur to the south of the suture. The kinematics of the Southern Uplands are currently constrained only by some relatively old palaeomagnetic data from the *c.* 396 Ma Cheviot Complex (Thorning, 1974). To determine the wider palaeomagnetic signature and evaluate its relationship to adjoining Caledonian orthotectonic terranes to the north and paratectonic terranes to the south, we have investigated the aureoles and margins of the Cairnsmoor of Fleet granite and Criffel-Dalbeattie granodiorite plutons. These comprise two of four major intrusions (the others being Loch Doon and Cheviot) emplaced into the Ordovician–Silurian terrane of the Southern Uplands following major Caledonian tectonism (Fig. 1).

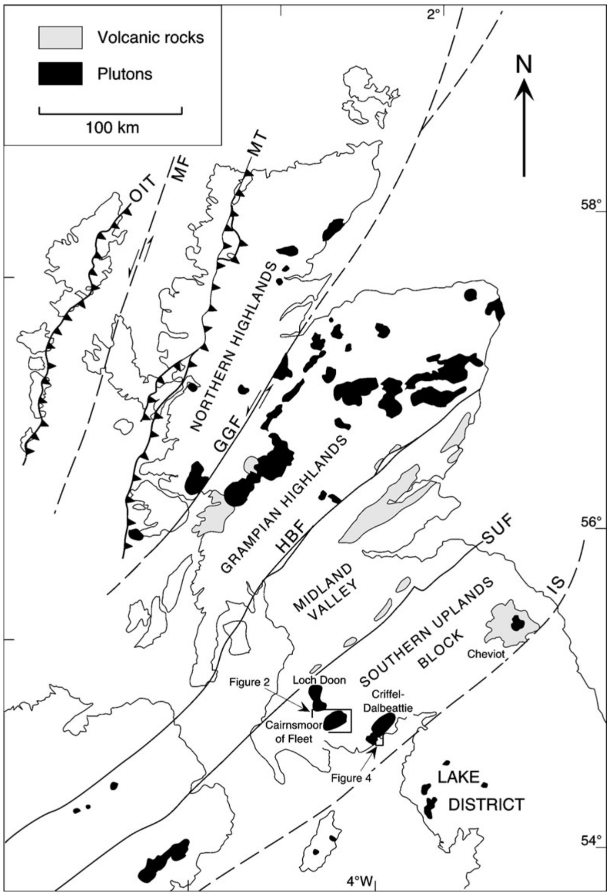

Figure 1. Outline geological map showing the distribution of igneous rocks in the Caledonides of northern Britain and outcrops of the Loch Doon, Cairnsmoor of Fleet, Criffel-Dalbeattie and Cheviot granite complexes in the Southern Uplands Block. Major tectonic boundaries are indicated as: OIT – Outer Isles Thrust, MF – Minches Fault with a sinistral strike-slip displacement of 97 km (Piper, 1992), MT – Moine Thrust, GGF – Great Glen Fault with a sinistral strike-slip displacement of ~160 km (Winchester, 1973), HBF – Highland Boundary Fault, SUF – Southern Uplands Fault, IS – Iapetus Suture.

2. Geological framework

The Southern Uplands of Scotland preserve a thick Early Ordovician to Late Silurian (at least until Wenlock, 428–423 Ma) sedimentary succession deposited in an unstable tectonic environment and subject to strong deformation. This region was formerly interpreted as an example of an ancient accretionary prism (McKerrow, Leggett & Eales, 1977; Leggett, McKerrow & Eales, 1979; Leggett & Soper, 1983) developed at the northern margin of the Iapetus Ocean. Later assessments have tended to consider it as a back-arc and foreland basin thrust duplex that formed when the Iapetus Ocean was already small; this interpretation is supported by the partial derivation of material from the south and the recognition that it was the site of an ensialic Late Ordovician basin (Stone *et al.* 1987). The Ordovician and Silurian rocks are mostly mudstones, shales and greywackes showing a complex deformational history. Structures fall into four sequential divisions comprising: (a) down-slope gravity-driven structures in poorly lithified sediment, (b) structures developed during accretion within rocks in which cementation and compaction were essentially complete, (c) late accretion to collision-related structures associated with arrival of continental crust at the subduction zone, and (d) post-collisional adjustments in the accretionary complex (Knipe & Needham, 1986). The last phase includes brittle kink bands with steeply plunging axes and is associated with strike shortening, an early record of strike-slip adjustments within the consolidating orogen. This was the last phase of deformation before the emplacement of major plutons during Late Silurian and Early–Middle Devonian times.

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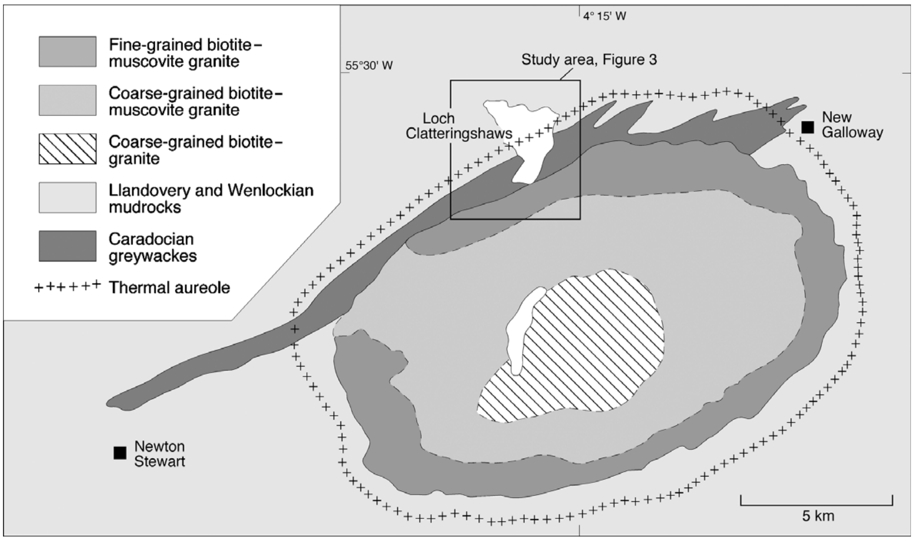

Figure 2. Outline geological map of the Cairnsmoor of Fleet Granite and aureole simplified after Gardiner & Reynolds (1937). The box encloses the study area spanning the contact aureole and expanded in Figure 3.

The latter magmatism comprised three major plutons (Loch Doon, Cairnsmoor of Fleet and Criffel-Dalbeattie) and a large volcanic-intrusive region in the Cheviot Hills. The Loch Doon Complex has yielded a mean Rb–Sr biotite age of 408 ± 2 Ma (Halliday, Stephens & Haron, 1980), and three small high-level complexes at Cockburn Law, Priestlaw and Cairnsmore of Carsphairn yield whole rock and mineral Rb–Sr age determinations of 413 ± 4.2, 408.5 ± 5.6 and 410.4 ± 4 Ma, respectively (Thirlwall, 1988). Collectively these ages identify the acidic magmatism along the northern margin of the block close to the Southern Uplands Fault as Early Devonian in age (Lochkovian and Pragian), which is similar to the age of comparable magmatism in the Midland Valley (Thirlwall, 1988). In the southern part of the Southern Uplands Block, age determinations are younger: biotite–whole rock–plagioclase isochrons on the Criffel and Fleet plutons are 397 ± 2 and 392 ± 2 Ma, respectively (Halliday, Stephens & Haron, 1980). Rb–Sr (Thirlwall, 1988) and K–Ar (Mitchell, 1972) studies of the Cheviot Complex also suggest an Early Devonian age and yield estimates of 395.9 ± 2.9 Ma for the granite and 395.9 ± 3.8 Ma for the lavas (Thirlwall, 1988), consistent with a comagmatic origin. Thus magmatism in the southern part of the block (and closer to the Iapetus Suture) appears to have occurred somewhat later than in the north and at approximately the same time as the youngest granites of the Lake District on the opposite side of the suture such as Shap (397 Ma: Rundle, 1992; Millward, 2002) and Skiddaw (399 Ma: Shepherd *et al.* 1976; Rundle, 1992).

The Cairnsmoor of Fleet Granite is an oval pluton approximately 11 × 18 km in size with a long axis oriented ENE–WSW, parallel to the regional post-Wenlock tectonic strike. It intrudes deformed greywackes of Caradoc–Ashgill age and a range of mudrocks of Early–Middle Silurian (Llandovery–Wenlock) age metamorphosed to quartz-biotite hornfels within a few hundred metres of the contact, with lower degrees of metamorphism recognized within an aureole zone; as defined by the first appearance of biotite, this extends between 0.5 and 1.5 km from the contact (Gardiner & Reynolds, 1937 and Fig. 2). Compositionally it is a biotite granite with coarse-grained margins grading inwards into muscovite granite and then into a fine-grained biotite-bearing interior phase (Gardiner & Reynolds, 1937; Parslow, 1968).

The pluton has an internal foliation parallel to the contact, with minimal chilling effects suggesting that the magma was emplaced in a relatively cool semi-crystalline state (Parslow, 1968; Cassidy, 1981). Radiogenic elements do not show a concentric behaviour in this intrusion as they do in the Loch Doon body, and their distribution appears to be the result of both primary and secondary processes with remobilization occurring during hydrothermal activity and differentiation of the fine-grained central granite in the roof of the intrusion and close to the present erosion level (Brown *et al.* 1979; Cassidy, 1981). Age determinations of 390 ± 6 Ma by K–Ar and U–Pb (Brown, Miller & Grasty, 1968; Pidgeon & Aftalion, 1978) and 392 ± 2 Ma by Rb–Sr isochron (Halliday, Stephens & Haron, 1980) indicate a Middle Devonian (Eifelian) age of emplacement. Relatively low initial $^{87}Sr/^{86}Sr$ ratios of 0.7062–0.7078 (Halliday *et al.* 1979) and absence of an inherited zircon component (Pidgeon & Aftalion, 1978) are consistent with a lower crustal or upper mantle source and limited assimilation of upper crustal material during magma ascent. Cairnsmoor of Fleet is the most acidic and highly differentiated of the three major Southern Uplands granites, and the concentric distribution of igneous lithologies has been interpreted in terms of the evolution of a single magma in response

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to increasing differentiation and water vapour pressure responsible for decreasing biotite and increasing muscovite (Parslow, 1968; D. R. Cook, unpub. Ph.D thesis, Univ. St Andrews, 1979; Cassidy, 1981).

The Criffel-Dalbeattie granodiorite is a more complex intrusion emplaced into Llandovery and Wenlockian strata with an earlier more basic member (GI) intruded by an intermediate member (GII) and then more acid (GIII) member (Macgregor, 1937). The GI Member occupies most of the eastern outcrop, where it can be divided into a marginal foliated granodiorite and a central porphyritic granodiorite with gradational contact between them (Phillips, 1956). Emplacement was accompanied by considerable deformation of the country rocks (Phillips, 1956), and the original oval form (more prominently aligned with the regional tectonic grain than Cairnsmoor of Fleet) has been distorted by southward displacement of the western part of the complex by faulting. Quartz diorites were emplaced in advance of the main granodiorite, possibly by metasomatic processes and assimilation of hornfels (Macgregor, 1937; Phillips, 1955). Xenoliths are abundant, especially near the southern and eastern margins, and contribute to a gradual density increase towards the margins that precludes a simple modelling of the gravity anomaly; the latter, however, suggests a batholith with contacts sloping outwards and extending to at least 12 km depth (Bott & Masson-Smith, 1960). A secondary foliation is well developed around the margins and appears to have been imparted during forceful injection accompanying lifting and dilation of the roof of the pluton by hydrostatic forces (Phillips, 1956). Abundant dykes of 'porphyrite' and lamprophyre with NW trend are unaffected by this foliation but are not found in the centre of the pluton and appear to have been intruded whilst the core was still consolidating. A second suite of intrusions emplaced as wider and more irregular lenses of porphyrite with roughly E–W trend occur close to the southern margin (Phillips, 1956). Near the granite margin the host mudrocks are recrystallized into fine-grained hornblende-diopside and biotite hornfelses, and signs of recrystallization are evident in country rocks up to 2 km from the contact.

Whole rock K–Ar ages of 391 ± 8 and 397 ± 8 Ma have suggested a late Early or early Middle Devonian emplacement age (Brown, Miller & Grasty, 1968), which appears to be confirmed by an Rb–Sr isochron age of 397 ± 2 Ma (Halliday, Stephens & Haron, 1980). However, Criffel-Dalbeattie is the least evolved of the granitic magmas and the most deformed of the major intrusions in the Southern Uplands and, as reported here, has a magnetic signature which, together with some isotopic evidence, suggests that the emplacement age could be appreciably older. Detritus in the local Upper Old Red Sandstones shows that it had already been unroofed by Late Devonian times.

The regional gravity field over the Southern Uplands has been modelled to show two granite bodies rising from a slab of granodioritic density at ~10 km depth (S. I. El-Batroukh, unpub. Ph.D. thesis, Univ. Glasgow, 1975); one crops out as the Criffel-Dalbeattie Granite and the other two divide at 3 km depth to form the Loch Doon and Cairnsmoor of Fleet granites. The gravity analysis indicates that the granite contact is less steep at depth and that the present erosion level is close to the original roof of the pluton (Parslow, 1968; Parslow & Randall, 1973), which may have lain ~1.5 km above the present erosion level.

3. Field and laboratory methods

The present study of the Cairnsmoor intrusion has investigated magnetic properties on a traverse exposed along the shore of Loch Clatteringshaws at the northern margin of the pluton (Fig. 3). One hundred and eighty short 2.4 cm diameter cores were drilled at 20 sites using a gasoline-powered hand drill and oriented by sights on the Sun and magnetic compasses. Three sites (18–20) were collected within the granite, three come from hornfels close to the contact (15–18), 4–11 are in mudrocks within the mapped aureole (extending approximately 2 km from the contact; see Gardiner & Reynolds, 1937) and three (1–3) are in country rock mudstones out to a maximum orthogonal distance of 2.5 km from the granite contact. The majority of these cores were collected to evaluate the changes in magnetic susceptibility and fabric of magnetic susceptibility from the intrusion into the country rock uninfluenced by contact metamorphism, and it was anticipated that only those samples showing a strong thermal imprint near the contact would carry useful palaeomagnetic signatures.

The most continuous exposure of the Criffel-Dalbeattie contact occurs south of Dalbeattie and has been sampled at 13 sites in a south to north traverse along the east side of the Urr Water estuary from site 1 in Wenlockian mudstones at Castle Point to site 18 in grey granodiorite at Kippford (Fig. 4). This section also includes five sites in the E–W-trending porphyrite intrusions. Two additional sites (19, 20) were sampled in mudrocks within the aureole close to the granodiorite contact elsewhere at locations (NX $^{3}868$ $^{5}661$ and $^{3}909$ $^{5}558$) where field measurements with a hand-held kappameter identified high magnetic susceptibilities.

All field cores were trimmed into 2.4 cm long cylinders and their bulk magnetic susceptibilities measured using a Bartington bridge. The anisotropy of the magnetic susceptibility (AMS) was then determined using a KLY-3 Kappabridge. Natural Remanent Magnetizations in the Cairnsmoor samples are very weak and all measurements were performed on a nitrogen SQUID (FIT) magnetometer. Samples from the Dalbeattie granite and aureole were variably more strongly magnetized and measured by both SQUID and spinner magnetometers. Subsequent thermal demagnetization was concentrated on the samples close to, or within, the

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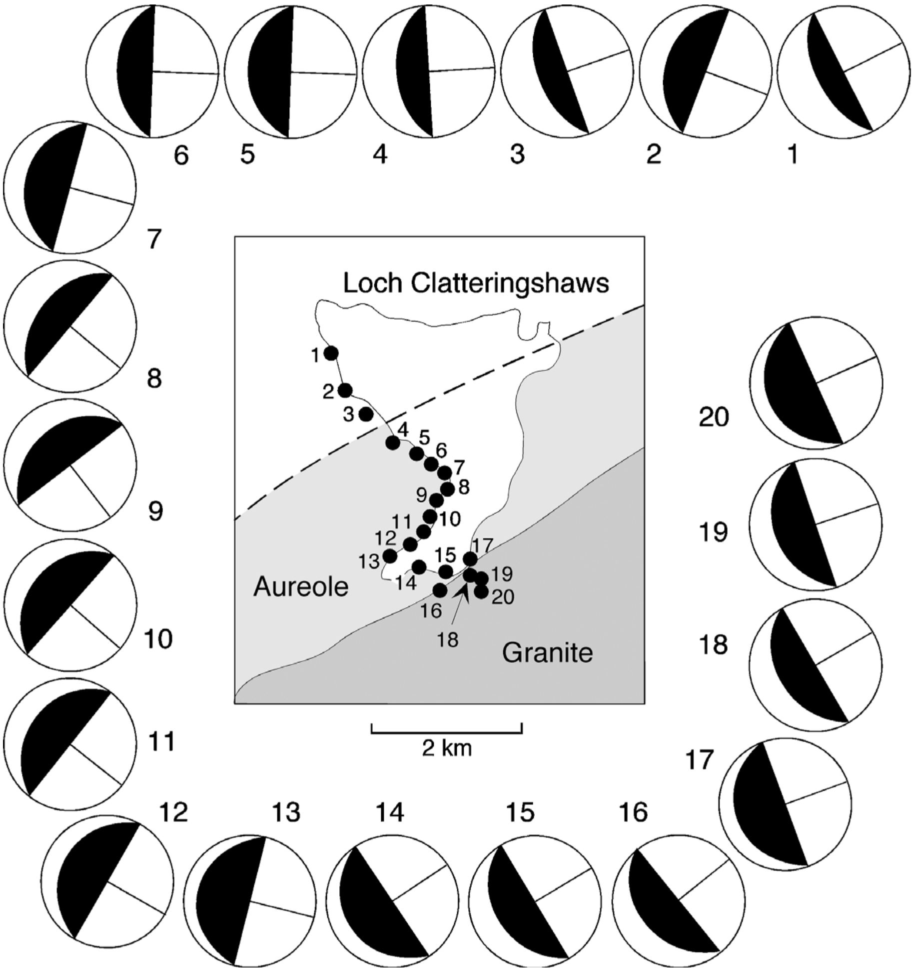

Figure 3. Sampling sites across the aureole of the Cairnsmoor of Fleet Granite showing the orientations of the susceptibility ellipsoids. The site mean foliation planes are plotted on lower hemisphere stereographic projections and are the planes including the maximum and intermediate susceptibility ellipsoid axes. The strike of the foliation plane is a diameter and the greater the black area, the shallower the inclination of the plane. The direction of the minimum axis is the radial line perpendicular to the strike of the foliation.

igneous contact zones and proceeded in steps of 50 °C to 500 °C and then in steps of 20 °C to the Curie points of the magnetic carriers. Sample magnetizations were projected onto horizontal and vertical planes to produce conventional orthogonal plots; successive components isolated by the demagnetization were identified by eye and equivalent directions calculated by principal component analysis. Additional core material was used to evaluate rock magnetic properties including the determination of isothermal remanent magnetizations, hysteresis properties by vibrating sample magnetometer and thermomagnetic properties using a Curie balance.

4. The Cairnsmoor of Fleet Granite

4.a. Magnetic fabrics, granite contact and aureole

The anisotropy of magnetic susceptibility (AMS) is approximated by a triaxial ellipsoid with orthogonal maximum (k_1), intermediate (k_2) and minimum (k_3) axes. A range of parameters has been used to define properties of the ellipsoid (Tarling, 1983; Tarling & Hrouda, 1993), of which the simplest and most commonly used are the lineation $(P_1) = k_1/k_2$, the foliation $(P_3) = k_2/k_3$ and anisotropy degree $(P_2) = k_1/k_3$).

Foliation planes on this traverse are steeply dipping in the country rocks and dip variably to the west; they swing around to westerly orientations with shallower dips as the granite is approached (Fig. 3). Bedding orientations within the country rocks are variable and are unrelated to AMS orientation (Table 1); hence the latter appear to record fabrics imparted by tectonic stress with an older tectonic fabric in the country rock progressively overprinted by a later SW shallow-dipping fabric linked to granite emplacement. The hornfels fabrics are preserved into sites 18–20 within the marginal facies of the granite, which have similar orientations to fabrics in the bordering hornfels (Fig. 3).

Kafafy & Tarling (1985) also examined the change of magnetic susceptibility and fabric of susceptibility along traverses across the eastern and western margins of the Cairnsmoor pluton and found that magnitude of susceptibility and degree of foliation increase within

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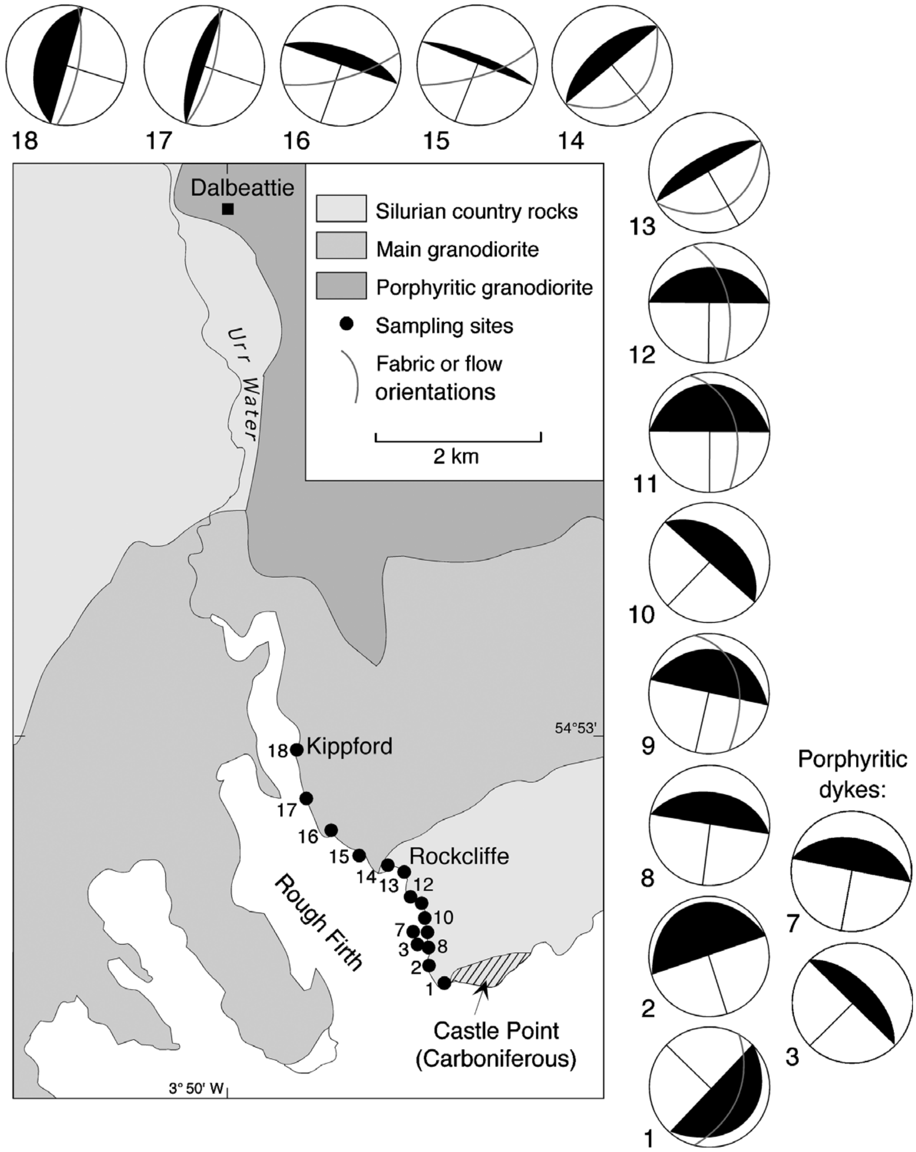

Figure 4. Outline geological map of the southwestern part of the Criffel-Dalbeattie granodiorite complex and adjoining aureole and country rocks cut by Urr Water and Rough Firth. The sampling sites for this study are shown together with AMS ellipsoids. The strike of the foliation plane is a diameter and the greater the black area, the shallower the inclination of the plane. The direction of the minimum axis is the radial line perpendicular to the strike of the foliation. Note that sample sites 19 and 20 are outside of the area of the complex shown here and sited at grid references NX $^{3}868$ $^{5}661$ and $^{3}909$ $^{5}558$, respectively.

1 km of the granite contact; they then fall to low values within the granite. A smaller but comparable variation is observed on our traverse (Fig. 5; Table 1) and suggests that recrystallization to produce hornfels has produced small amounts of magnetite or hematite from paramagnetic minerals in the mudrocks. Kafafy & Tarling (1985) found foliation to be dominant in the country rocks, although they identified no clear relationship between fabric orientation and trend of the regional grain or the granite contact.

This study finds that AMS orientations are much more systematic across the northwest contact (Fig. 3), although they correlate with the trend of the granite margin (or WNW–ESE tectonic trends imparted by pre-granite deformation) only in the middle part of the aureole (sites 8–12, Fig. 3). The progressive lateral changes and the consistency of fabric between granite, aureole and country rocks indicates that the granite was emplaced under an Early Devonian (late Acadian) stress regime that moved around from the typical NE–SW Caledonian tectonic orientation to a near-orthogonal direction during late Caledonian emplacement; this latter stress field evidently persisted during early stages of the emplacement of the pluton. AMS lineation does not increase appreciably towards the contact (Fig. 5), although the foliation rises significantly and is responsible for enhancing the degree of anisotropy. Hence the imprint of the regional stress field is most strongly recorded where granite heating has promoted recrystallization of the country

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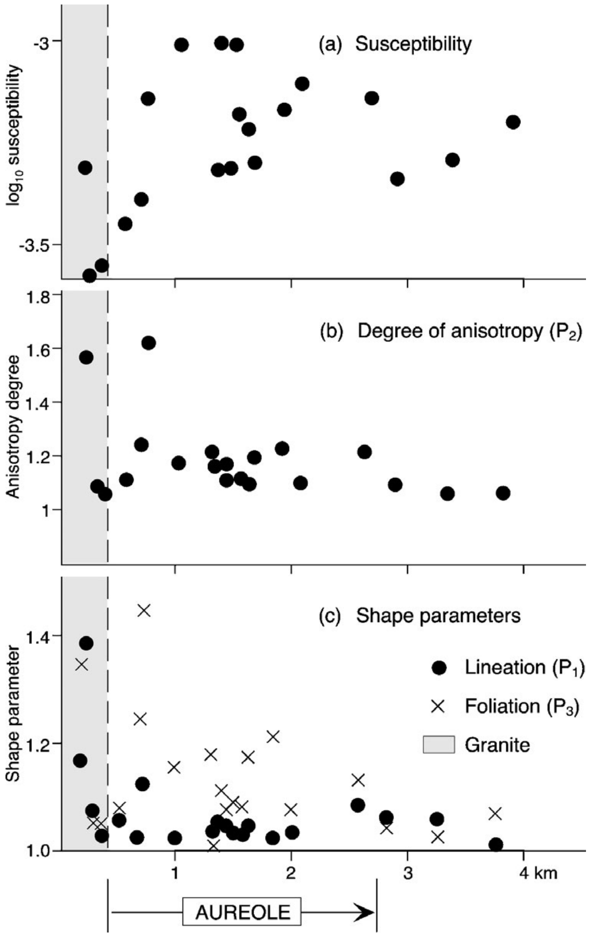

Figure 5. Magnitude of bulk susceptibility (log normalized mean of sample site data in SI units), degree of AMS anisotropy and the degrees of lineation and foliation as a function of distance from the contact of the Cairnsmoor of Fleet Granite.

Table 1. Summary of directions of AMS ellipsoids at palaeomagnetic sites traversing the aureole of the Cairnsmoor of Fleet Granite, Southern Uplands of Scotland

Site no.	N	Bedding orientation (direction/dip)	Degree of anisotropy	k_1	k_2	k_3
Country rock and aureole						
1	7	310/90	1.18–1.21	334/10	225/62	69/26
2	9	350/10	1.08–1.14	323/34	218/20	105/49
3	9		1.09–1.13	319/33	195/40	74/32
4	5		1.09–1.14	328/31	213/35	88/40
5	8	20/20	1.14–1.18	324/33	213/28	93/44
6	8	15/25	1.11–1.22	357/3	263/42	88/47
7	8	350/25	1.13–1.20	11/8	270/31	109/58
8	12	0/90	1.07–1.15	18/28	266/35	137/41
9	10	0/75	1.07–1.15	11/25	260/37	126/43
10	10	0/40	1.07–1.08	359/22	258/27	123/54
11	8	10/20	1.08–1.14	5/20	261/29	124/54
12	9	350/25	1.09–1.57	5/12	269/21	121/65
13	9		1.25–1.99	349/13	254/20	110/66
14	9		1.10–1.16	179/18	277/24	57/60
15	11	325/60	1.08–1.13	173/22	281/36	59/46
16	7	325/55	1.18–1.25	186/17	273/26	62/60
17	5	300/60	1.22–1.29	168/22	273/32	48/49
Granite margin						
18	13	–	1.05–1.11	179/21	280/38	60/44
19	7	–	1.09–1.77	179/20	282/39	67/45
20	8	–	1.11–1.77	178/17	275/22	53/59

Axial directions in the lower hemisphere are given as declination (°E)/inclination. N is the number of samples used to derive the mean.

rock. Evidence elsewhere in this region suggests that granitic magmas were being emplaced during late stages of orogeny in Middle Devonian times because porphyrite dykes on the coast west of Gatehouse-of-Fleet, apparently related to the Cairnsmoor intrusion, were intruded between F1 and F2 structures and again between F3 and F4 structures (Weir, 1968).

4.b. Rock magnetism

Isothermal Remanent Magnetizations were progressively applied to a sample from each site up to a maximum field of 2700 milliTesla (mT) using a pulse magnetizer. With the exception of red granite from site 20, all granite and hornfels samples saturate in low fields and identify magnetite as the dominant ferromagnet (samples 14 and 19 in Fig. 6). Away from the strongly hornfelsed sites (14–17), however, Isothermal Remanent Magnetization curves exhibit more variable behaviours. Most sites (Site 2 in Fig. 6) show continuous increase to the limiting laboratory field, indicating that hematite (which has a saturation remanence only 1–2 % of that of magnetite) is the dominant ferromagnetic phase; Kafafy & Tarling (1985) also report this dominant behaviour from elsewhere in the Cairnsmoor aureole.

Thermomagnetic curves were obtained using a computer-controlled horizontal translation Curie balance and Curie temperatures estimated from the curves using the method of intersecting tangents. With the exception of some granite and contact sites (e.g. Site 20 in Fig. 6), curves are dominantly asymptotic and identify a saturation remanence dominated by paramagnetic constituents obeying the Curie law. A slight signature of magnetite and/or a hematite 'tail' is present in some of the aureole sites and alteration of the former mineral during the heating frequently produces a slight fall in the saturation remanence during cooling (Fig. 6). Site 9 also exhibits a Curie point at 350 °C, which largely disappears during cooling and is a typical signature of the ferromagnet pyrrhotite. The presence of this mineral would not be compatible with the high Isothermal Remanent Magnetizations indicative of hematite, and recognition solely at this site suggests local precipitation during later mineralization.

Hysteresis curves were also produced for samples from each site using a Vibrating Sample Magnetometer with maximum saturating field of 1 Tesla. Hysteresis parameters determined from this application are saturation remanence, M_s, residual saturation remanence, M_{rs}, coercive force, H_c, and high field susceptibility. Key results are summarized in Table 2 with the ratio M_{rs}/M_s. When this ratio is > 0.1, a significant fraction

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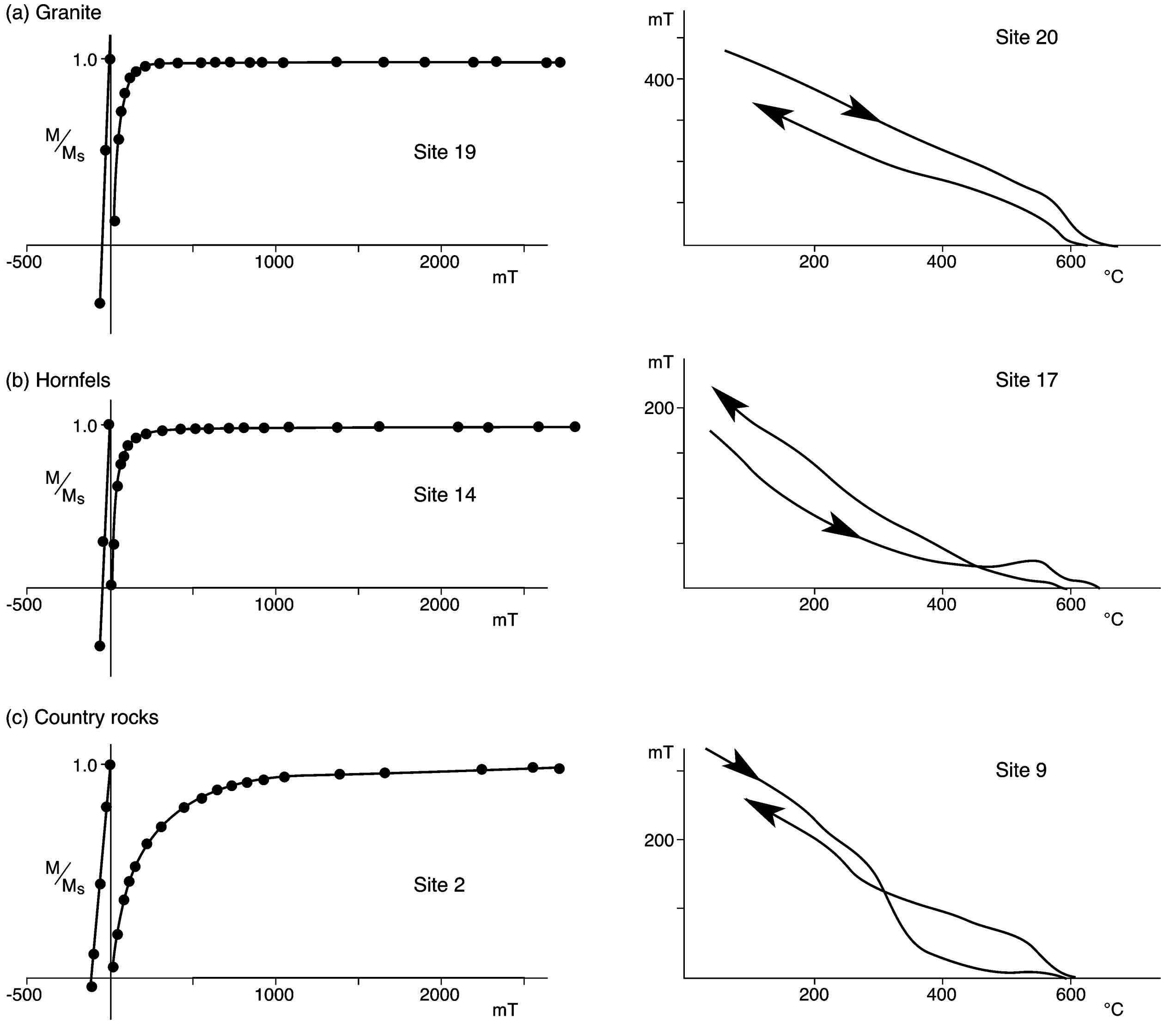

Figure 6. Examples of Isothermal Remanent Magnetization (IRM) spectra and thermomagnetic curves (saturation magnetization, M_s, as a function of temperature) from samples of the granite, hornfels and country rock in the Cairnsmoor of Fleet aureole.

of the magnetite is in single domain (SD) form, whereas values < 0.1 are indicative of predominantly multidomain magnetite. The hysteresis curves in mudrocks of the aureole are nearly linear with positive slope identifying a dominance of paramagnetism, although a variable hysteresis inflection due to ferromagnetism is always present and tends to become more prominent towards the granite contact. Separation of the two limbs of the loops is only marginal due to low values of M_{rs} and H_c. Only five sites have $M_{rs}/M_s > 0.1$ indicative of dominant single domain character in the magnetite; elsewhere it is predominantly of multidomain character.

4.c. Palaeomagnetic results

The palaeomagnetic record in large slowly cooled igneous intrusions is typically complex, and its analysis presents challenges similar to the study of magnetic remanence in deeply exposed metamorphic basement. Two facets of this environment specifically influence analysis and interpretation. Firstly, cooling of remanence through a blocking temperature spectrum will certainly have extended far beyond cycles of secular variation and the components resolved will therefore represent long time-averages of the ancient field and record palaeomagnetic rather than virtual geomagnetic directions; it is sometimes observed (as in some examples in this study) that a reversal of the ancient field is recorded within an individual core. Secondly, the conditions of slow cooling are likely to vary from place to place and depend on such factors as access of fluids, local temperature gradients and variations in ferromagnetic mineral content. In these circumstances the analysis aims to identify common populations of directions; not all members of each population may have the same magnetic properties, but directional commonality is a strong indication that the same period of time is being recorded.

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Table 2. Summary of thermomagnetic and hysteresis properties across the Cairnsmoor of Fleet Granite and aureole

Site no.	Curve type	T_c	RM	M_s (Am^2/kg)	M_{rs}/M_s
1	P	–	0.80	0.0420	0.008
2	F	660	1.18	0.0055	0.074
3	P	–	0.90	0.0011	0.014
4	P	–	0.88	0.0021	0.281
5	P	–	0.95	0.0094	0.052
6	F	590	1.12	0.0010	0.087
7	F	–	0.98	0.0033	0.075
8	P	–	0.88	0.0024	0.065
9	F	680	1.10	0.0094	0.017
10	F	680	1.29	0.0014	0.002
11	P	–	1.00	0.0030	0.043
12	P	–	0.86	0.0033	0.043
13	M	590	1.31	0.0027	0.104
14	P	–	0.80	0.0026	0.091
15	F	360, 585	0.89	0.0248	0.354
16	F	590	1.31	0.0079	0.051
17	F	590	0.89	0.0032	0.242
18	F	590	0.80	0.0212	0.045
19	F	590	0.85	0.0033	0.141
20	M	590	0.76	0.0137	0.023

T_c is the Curie point; P, F and M refer to paramagnetic, ferromagnetic and mixed thermomagnetic curves respectively. RM is the ratio of the saturation magnetization at 100 °C after cooling/before cooling. M_s is the saturation remanence and M_{rs} is the residual saturation remanence after the applied field has been removed.

Sixty of 172 cores studied from the Cairnsmoor contact traverse defined components of magnetization with progressive thermal demagnetization; the bulk come from hornfels near the granite contact. Examples of demagnetization behaviours are illustrated in Figures 7 and 8, and a stereoplot of all component directions is shown in Figure 9. A relatively low unblocking temperature magnetization with a direction similar to the present geomagnetic field ('R') is weakly represented, mainly in the country rock mudrocks (Table 3). The commonest component direction has shallow inclination and easterly or westerly direction. Dual polarities are isolated by progressive thermal demagnetization of single cores at some sites (e.g. examples from sites 7, 17 in Fig. 7 and 18 in Fig. 8) and imply that slow cooling of the granite contact through the magnetic blocking temperature spectra embraced reversals of the geomagnetic field. These ('A') magnetizations have distributed spectra unblocked up to 560–580 °C (Table 3) with the mean axis presumed to define a long term average of the palaeomagnetic field (Table 4) and linked to primary cooling. The angle between the normal and reversed axes of magnetization

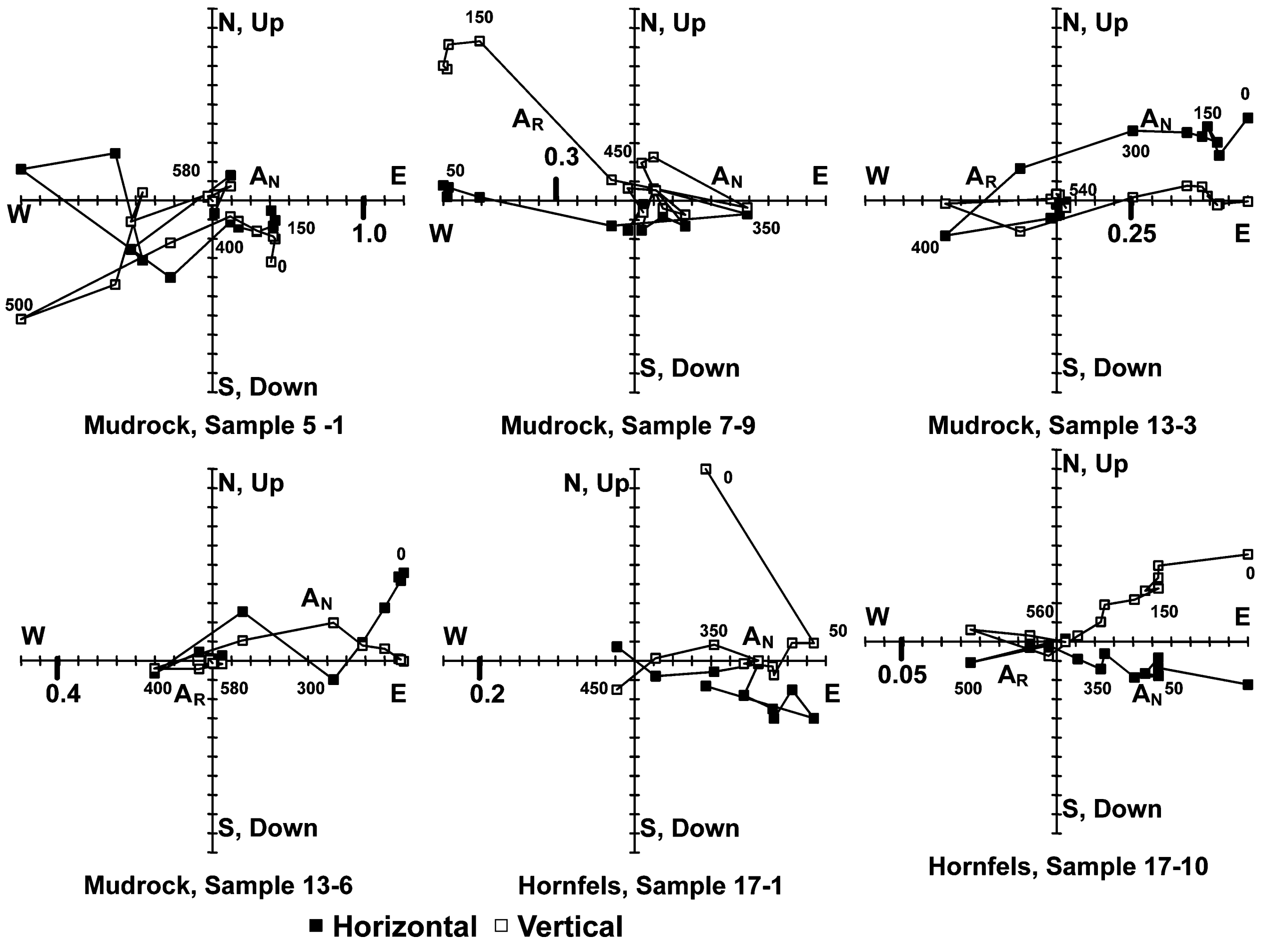

Figure 7. Orthogonal projections of the magnetization vectors onto the horizontal (closed symbols) and vertical (open symbols) planes illustrating behaviours of Cairnsmoor of Fleet Granite and aureole samples to thermal demagnetization. Magnetization intensity values on the axes are $\times 10^{-5}$ A m^2/kg. Assignments of magnetizations to populations 'A' are indicated where the 'N' and 'R' suffixes refer to normal and reversed polarity, respectively.

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Table 3. Summary of magnetic component populations in rock facies in the Cairnsmoor of Fleet granite and aureole

Component: Mean unblocking temperature (°C):		A 324 (±146)	B 351 (±113)	C 291 (±122)	R 216 (±97)
Aureole sites					
	13	6	4	2	8
	14	–	1	–	–
	15	11	6	1	2
	16	7	3	–	2
	17	8	4	2	1
Granite					
	18	6	10	2	–
	19	4	–	3	–
	20	6	6	1	–
	Total number	48 (44%)	33 (29%)	16 (15%)	13 (12%)

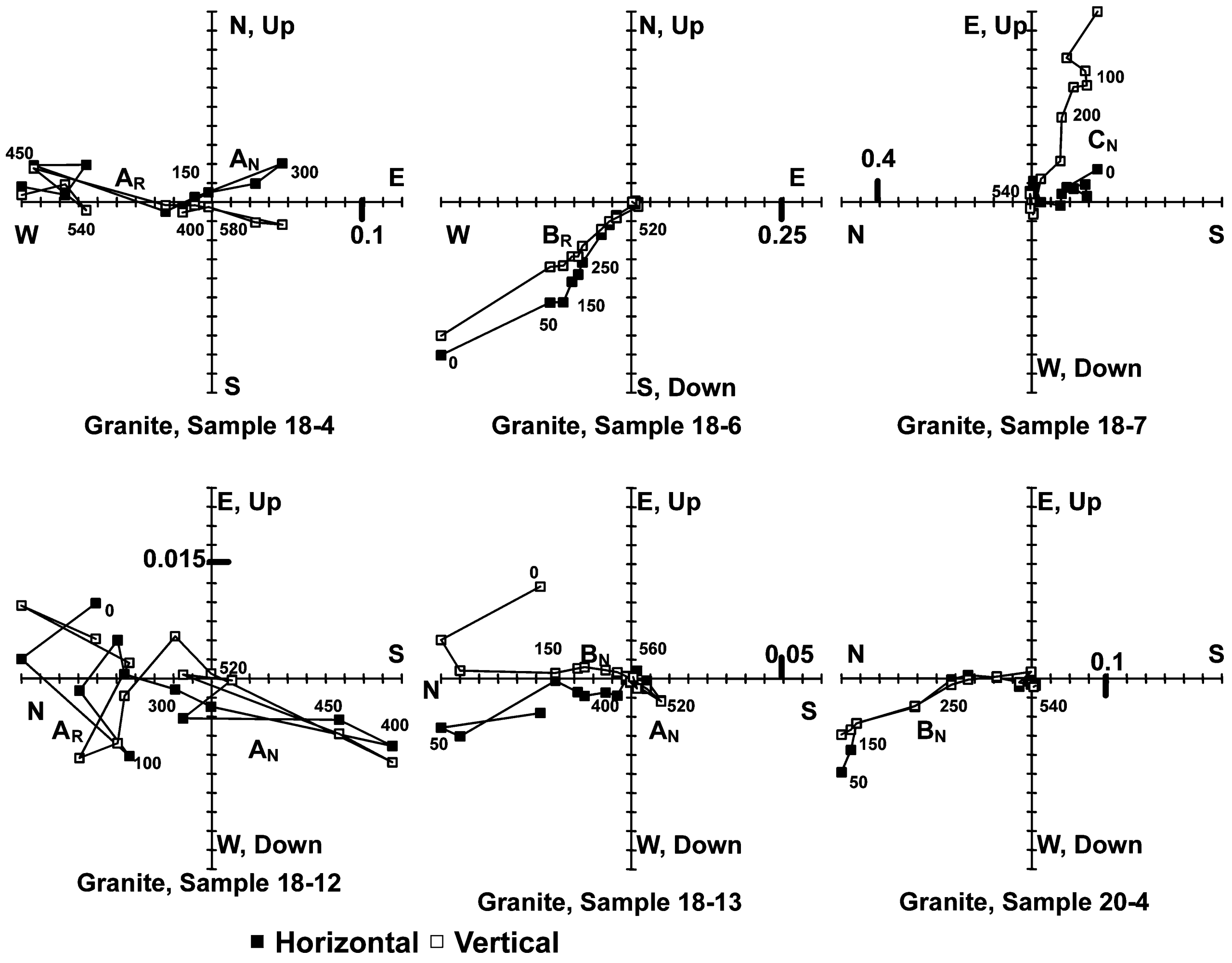

Figure 8. Cairnsmoor of Fleet Granite sample magnetization behaviours during thermal demagnetization shown as projections of vectors onto the horizontal (closed squares) and vertical (open squares) planes; magnetization intensity values on the axes are $\times 10^{-5}$ A m^2/kg. Assignments of magnetizations to populations 'A', 'B' and 'C' are indicated where the 'N' and 'R' suffixes refer to normal and reversed polarity, respectively.

is 9.8°, which is less than the critical angle of 13° for this population and yields a category C reversal test (McFadden & McElhinny, 1990).

A subsidiary ('B') magnetization has southerly and northerly declination, again with shallow inclinations (examples 18-6, 18-13 and 20-4 in Fig. 8). It tends to have somewhat higher average unblocking temperatures than 'A' (Table 3) and an overall mean direction (D/I = 194/6°) corresponding to the regional palaeofield direction calculated from the Eurasian apparent polar wander path (APWP) at 310–320 Ma (Irving & Irving, 1982). It is therefore

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Table 4. Group mean palaeomagnetic results from the Cairnsmoor of Fleet Granite contact

Component	D/I	N	R	α_{95}	k	Pole position °N	Pole position °E	dp/dm
A+	94.8/1.8	26	23.49	9.5	10.0	−2.0	81.2	4.7/9.5
A−	269.2/6.7	22	20.40	8.9	13.1	2.3	268.3	4.5/8.9
All A	92.2/−2.2	48	43.72	6.5	11.0	2.1	264.5	3.3/6.5
B+	9.4/−8.2	15	13.96	10.8	13.5	−30.4	344.9	5.5/10.9
B−	197.2/3.6	18	16.45	10.9	10.9	−31.4	335.4	5.4/11.0
All B	193.6/5.7	33	30.32	7.6	11.9	−31.0	339.8	3.8/7.6
C	171.9/−52.4	16	15.1	9.1	17.5	67.3	193.5	8.6/12.5
R	11.9/53.7	13	12.15	11.4	14.1	67.7	148.9	11.2/16.0

D and I are the mean declination and inclination derived from N component direction yielding a resultant R. Alpha 95 is the radius of the cone of 95% confidence about the mean direction and k is the Fisher precision parameter (=(N-1)/(N-R)). Dp and dm are the radii of the oval of 95% confidence about the pole position in the colatitude direction and at right angles to it, respectively.

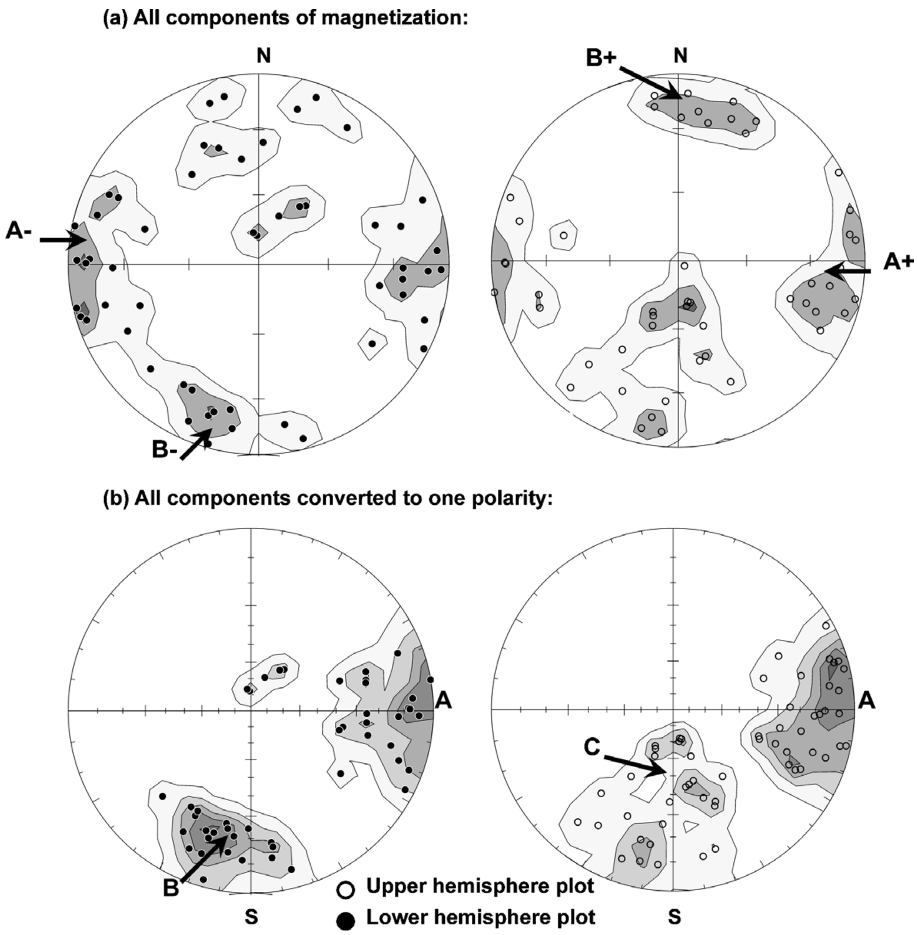

Figure 9. Distributions of component directions of magnetization in the Cairnsmoor of Fleet Granite and aureole plotted on equal area projections and contoured with component populations identified in the text.

likely to be a Variscan overprint, although since both polarities are present it would appear to have been acquired, at least in part, prior to the Carboniferous–Permian Superchron (*c.* 320–250 Ma). Comparable magnetization directions are widely represented as overprints elsewhere in the British Isles and in this instance are perhaps due to incipient oxidation of magnetite grains by hydrothermal fluids. A third (‘C’) magnetization is more sporadically present (Fig. 9), mostly as a reversed polarity component with steeper negative inclination (e.g. sample 18-7 in Fig. 8). The mean (D/I = 172/−51°) correlates most closely with the regional palaeofield direction at 160–140 Ma (D/I = 185/−55°) calculated from the Eurasian APW path (Irving & Irving, 1982). A similar palaeofield is recorded by mineralization linked to normal faulting during formation of the adjoining Irish Sea Basin (Crowley & Piper, unpub. data) and is interpreted as a regional magnetic signature of fluid expulsion during extensional tectonism.

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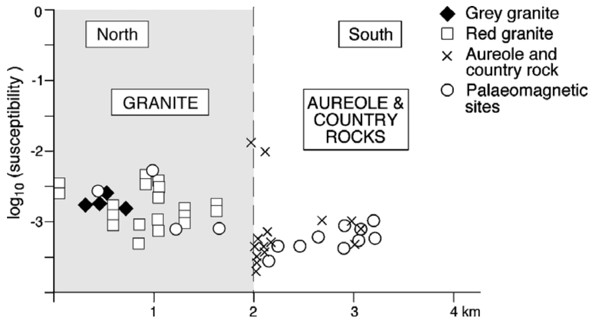

Figure 10. The variation in magnetic susceptibility across the southern contact zone of the Criffel-Dalbeattie granodiorite. Field measurements are the mean values of ten determinations made at outcrop using a hand-held kappameter. The large circles are the means of values derived from the palaeomagnetic samples.

Table 5. Anisotropy degree and orientation of AMS ellipsoids at palaeomagnetic sites at the Criffel-Dalbeattie granodiorite contact, Southern Uplands

Site number	Rock type	Degree of anisotropy	k_1 (D/I°)	k_2 (D/I°)	k_3 (D/I°)
1	Mudrock	1.01–1.02	72/15	170/26	315/49
2	Mudrock	1.03–1.08	304/12	37/12	165/72
3	Acid dyke	1.01–1.02	90/50	328/24	224/30
7	Acid dyke	1.04–1.08	85/16	338/43	191/43
9	Aureole	1.03–1.05	305/11	40/22	193/65
10	Aureole	1.01–1.04	346/32	102/34	224/40
11	Aureole	1.02–1.08	79/14	337/39	183/48
13	Hornfels	1.04–1.23	271/47	45/33	152/24
14	Hornfels	1.01–1.02	36/27	268/49	141/28
15	Granodiorite	1.04–1.01	96/55	299/32	203/11
16	Granodiorite	1.05–1.14	88/44	307/45	199/23
17	Granodiorite	1.10–1.28	228/61	12/25	109/16
18	Granodiorite	1.07–1.13	252/55	8/17	107/29

5. The Criffel-Dalbeattie granodiorite

5.a. Magnetic fabrics

In country rocks surrounding the Loch Doon granite (see Fig. 1 for location) magnetic susceptibilities are stronger than within the granite complex except in the margins bordered by norite (Piper, 2007). The country rocks at Cairnsmoor of Fleet have comparable magnetic susceptibilities to the granite, and susceptibilities only rise locally in the hornfels near the contact (Fig. 5; see also Kafafy & Tarling, 1985). In contrast, magnetic susceptibilities rise from the country rocks into the intrusion at the Criffel-Dalbeattie contact (Fig. 10). This increase is recognized by both laboratory susceptibility measurements on palaeomagnetic cores and by field observations using a hand-held kappameter (Fig. 10) and has been found at the northwestern margin of the intrusion by Kafafy & Tarling (1985). These contrasts are reflected in the aeromagnetic signature over the Southern Uplands where Loch Doon correlates with a negative anomaly, Cairnsmoor is neutral and Criffel-Dalbeattie is significantly positive (Fig. 11).

AMS foliations tend to be stronger in the granodiorite than in the country rocks (Table 5); steep AMS foliations are close to mineral fabrics within the intrusion but become divergent from these fabrics towards the margin (sites 15 to 18 in Fig. 4). Fabrics in contact hornfels (13 and 14) then swing around from NE–SW trends parallel to the margin to more E–W-striking foliations

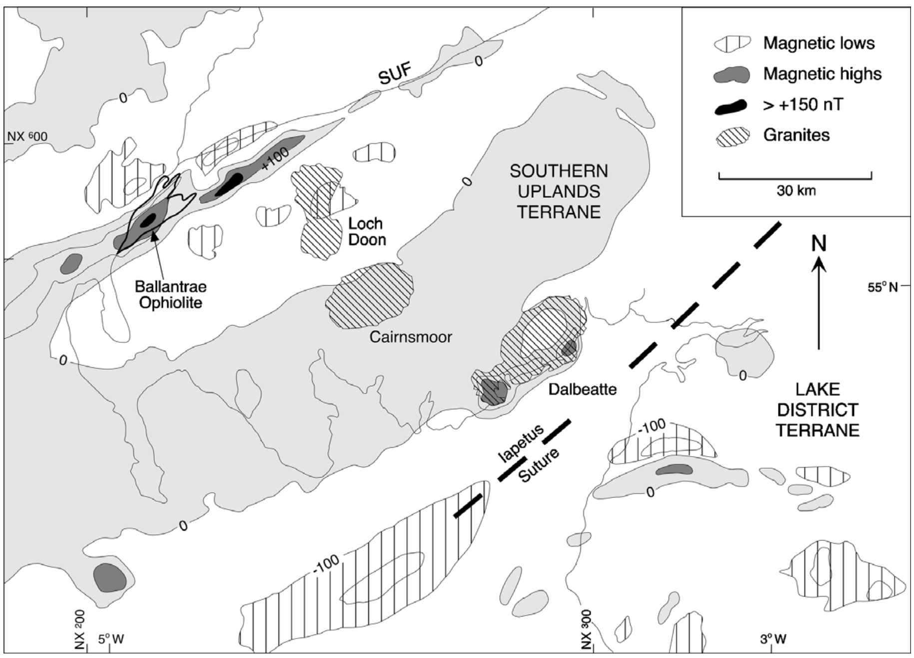

Figure 11. Aeromagnetic anomaly map over the Southern Uplands Block and adjoining areas of the Scottish Borders after the 1:625 000 U.K. Aeromagnetic Map published by the Ordnance Survey; contours are in nanoTesla and simplified to show the zones of positive and negative anomaly. Note the correlation of the Loch Doon outcrop with a negative anomaly. The younger Cairnsmoor of Fleet and Criffel-Dalbeattie Caledonian granites have neutral and positive signatures, respectively. The Ballantrae Ophiolite complex comprises coastal outcrop to the northwest.

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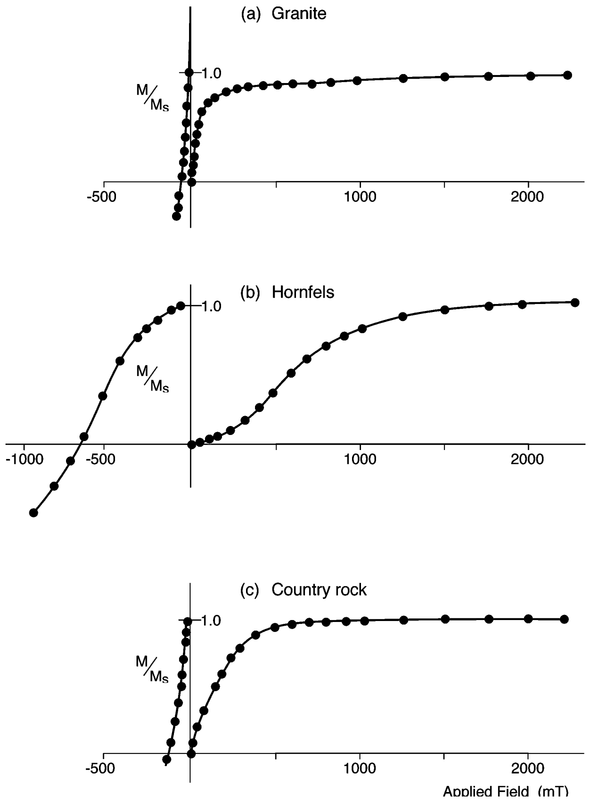

Figure 12. Examples of Isothermal Remanent Magnetization (IRM) spectra and thermomagnetic curves (saturation magnetization, M_s, as a function of temperature) from samples of the granite, hornfels and country rock at the Criffel-Dalbeattie granite contact.

with shallower and more variable dips (12-8). These intermediate aureole fabrics are divergent from relict bedding but likely to have composite origins related to tectonic stresses and emplacement of the pluton. Only near the limits of the aureole does AMS foliation move into conformity with the bedding in country mudrocks (sites 1 and 2). The rotation of AMS foliation in the Criffel-Dalbeattie aureole is reminiscent of the progressive fabric rotation in the Cairnsmoor of Fleet aureole (Fig. 3) although it is not as regular, possibly reflecting the more complex emplacement and uplift history (Phillips, 1956). In each case, typical Caledonian E–W- to NE–SW-striking and northward-dipping foliations are recorded within the aureoles but fabrics move to near N–S trends within the intrusion and suggest that a tectonically imparted fabric within the aureole is progressively replaced by an emplacement-related fabric into the pluton. AMS fabrics in two acid dykes (3 and 7) show no direct link to their vertical E–W orientations and probably also record a Late Acadian deformation. Comparable porphyrite dykes along the eastward strike continuation of this outcrop are subject to shearing (Blyth, 1949); they are also reported to show mineral foliation and are cut by shear joints filled with quartz veining (Leeder, 1971).

5.b. Rock magnetism

Isothermal Remanent Magnetization (IRM) studies show magnetic saturation indicative of magnetite carriers reached at only two sites in the hornfels (10, 11) and at two sites in the country rocks (1, 2, Fig. 12). Elsewhere, acquired magnetizations continue to climb in higher fields, indicating that hematite is a significant ferromagnetic component in both pluton and aureole. Kafafy & Tarling (1985) detected hematite IRM signatures in all samples beyond 200–300 m from the granite contact, although here we find it in the granite as well. Incipient reddening by hydrothermal mineralization is widely evident, especially close to fault planes and along joint surfaces (Phillips, 1956). Hematite is also a prominent signature on the thermomagnetic curves (Fig. 13, Table 6) and is seen as a convex component to a dominant asymptotic signature of paramagnetism

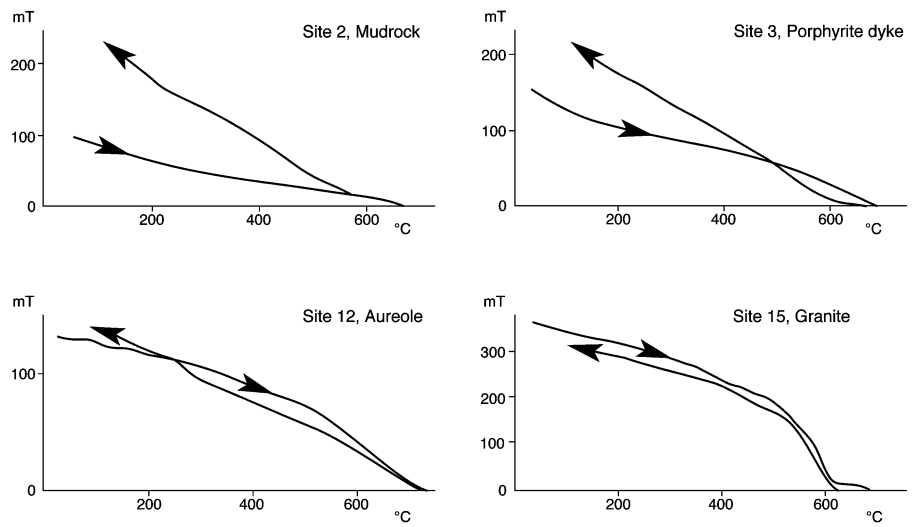

Figure 13. Thermomagnetic (saturation magnetization, M_s, v. temperature) determinations on rock samples from the Criffel-Dalbeattie granodiorite and aureole. The arrows refer to heating and cooling trajectories.

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Table 6. Thermomagnetic properties in Dalbeattie granodiorite and aureole

Site no.	Rock type	Curve	T_1	T_2	RM
1	Mudrock	P+F	580	680	2.42
2	Mudrock	P+F	–	675	2.56
3	Porphyrite dyke	P+F	–	700	1.83
7	Porphyrite dyke	F	590	680	1.34
8	Aureole	P+F	–	690	1.46
9	Aureole	P+F	–	680	1.18
10	Aureole	P+F	590	680	1.21
11	Aureole	P	–	–	1.69
12	Aureole	F+P	–	695	1.10
13	Hornfels	P+F	–	690	3.36
14	Hornfels	P+F	–	690	2.42
15	Granodiorite	F	580	690	1.42
16	Granodiorite	F	585	680	1.22
17	Granodiorite	F	590	–	1.01
18	Granodiorite	F	595	680	0.91

Thermomagnetic curves are defined as P = paramagnetic (asymptotic) and F = ferromagnetic (convex down). T_1 and T_2 are titanomagnetite and titanohematite Curie points, respectively. RM is the ratio of the saturation magnetization (M_S) at 100°C during heating to M_S at the same temperature on cooling.

(sites 2 and 3 in Fig. 13), as a 'tail' extension to a dominant magnetite signature in the granite (15 in Fig. 13), and rarely as a pure hematite signature (12 in Fig. 13). This mineral does not, however, contribute significantly to the remanence in these rocks, which proves to be dominated by magnetite demagnetization spectra (see next Section).

5.c. Palaeomagnetism

Palaeomagnetic samples were stepwise thermally demagnetized in increments of 50 °C, decreased to steps of 20 °C either to Curie points of the magnetic carriers or until directional behaviours ceased to be systematic; a small number of cores were demagnetized in alternating fields (a.f.). The most useful palaeomagnetic material came from sites 13–17 spanning the granite contact, sites 4–6 from porphyrite dykes and from sites 19 and 20 hornfels at the granite margin. Component groupings yielded by three or more cores from individual sites yield means summarized in Table 7. Typical demagnetization behaviours are illustrated as orthogonal projections in Figures 14 and 15, and a stereoplot of all component directions is shown in Figure 16.

The distribution of ChRMs is more complex in the Criffel-Dalbeattie margin and aureole compared with the signature in the comparable traverse across the Cairnsmoor of Fleet aureole (cf. Figs 9b and 16b). The 'A' component which is the main feature of the latter is found in only isolated cores from Criffel-Dalbeattie (e.g. 1-3A in Fig. 14, 16-12 and 17-10 in Fig. 15), as are examples of the N–S shallow axis assigned to 'B' (20-7 in Fig. 15); 15 components of the latter yield a mean (defined by $I < 30°$) of $D/I = 18/17°$. The most important features of the remanence record in the Criffel-Dalbeattie margin are a NE+ distribution (e.g. 13-2 and 15-10 in Fig. 14) comparable to the 'C' direction at Cairnsmoor of Fleet, and a fairly dispersed E+ to SE+ distribution. Since the latter includes site means from sites 4, 5 and 6 in porphyrite dykes and similar antiparallel magnetizations in granodiorite sites 15 and 17 (e.g. 15-10 in Fig. 14), the mean of these five sites is probably the best representative of this population (denoted 'E') for interpretation (Table 7).

6. Interpretation

6.a. Late Caledonian magnetization history and regional rotation of the Southern Uplands Block

As noted in Section 4.c, the 'B' and 'C' magnetizations are interpretable in the context of overprints acquired during the post-Caledonian history. The first correlates with the palaeofield direction at the time of Variscan orogeny in Britain, which was responsible for concentric folding and oblique-slip block faulting in northern Britain (e.g. Underhill *et al.* 1988) with potential for sporadic rather than comprehensive remagnetization.

Table 7. Summary palaeomagnetic results from the Criffel-Dalbeattie granodiorite and aureole

Site no.	Rock type	D	I	N	R	α_{95}	k
Site mean 'E' components							
4	Porphyrite dyke	105	51	3	2.98	13	96
5	Porphyrite dyke	96	62	6	5.93	8	75
6	Porphyrite dyke	92	70	3	2.98	14	82
15	Granodiorite	144	53	5	4.93	10	56
17	Granodiorite	302	−33	7	6.83	10	35
19	Aureole mudrock	267	63	9	8.68	10	25
20	Aureole mudrock	150	55	4	3.89	18	27
Group mean directions							
B: N–S shallow, (15N, 2R)		18	17	15	14.73	5	53
		Palaeomagnetic pole: 42.0°N, 150.7°E (dp/dm = 3/6°)					
A: E–W shallow axis (7N, 8R)		272	2	15	13.82	12	12
		Palaeomagnetic pole: 2.3°N, 262.9°E (dp/dm = 5.8/11.6°)					
E: Sites 4–6, 15, 17		115	55	5*	4.80	18	20
		Palaeomagnetic pole: 17.8°N, 44.3°E (dp/dm = 17.8/25.1°)					

*Sites, other calculations are based on sample components. Symbols are as for Table 4.

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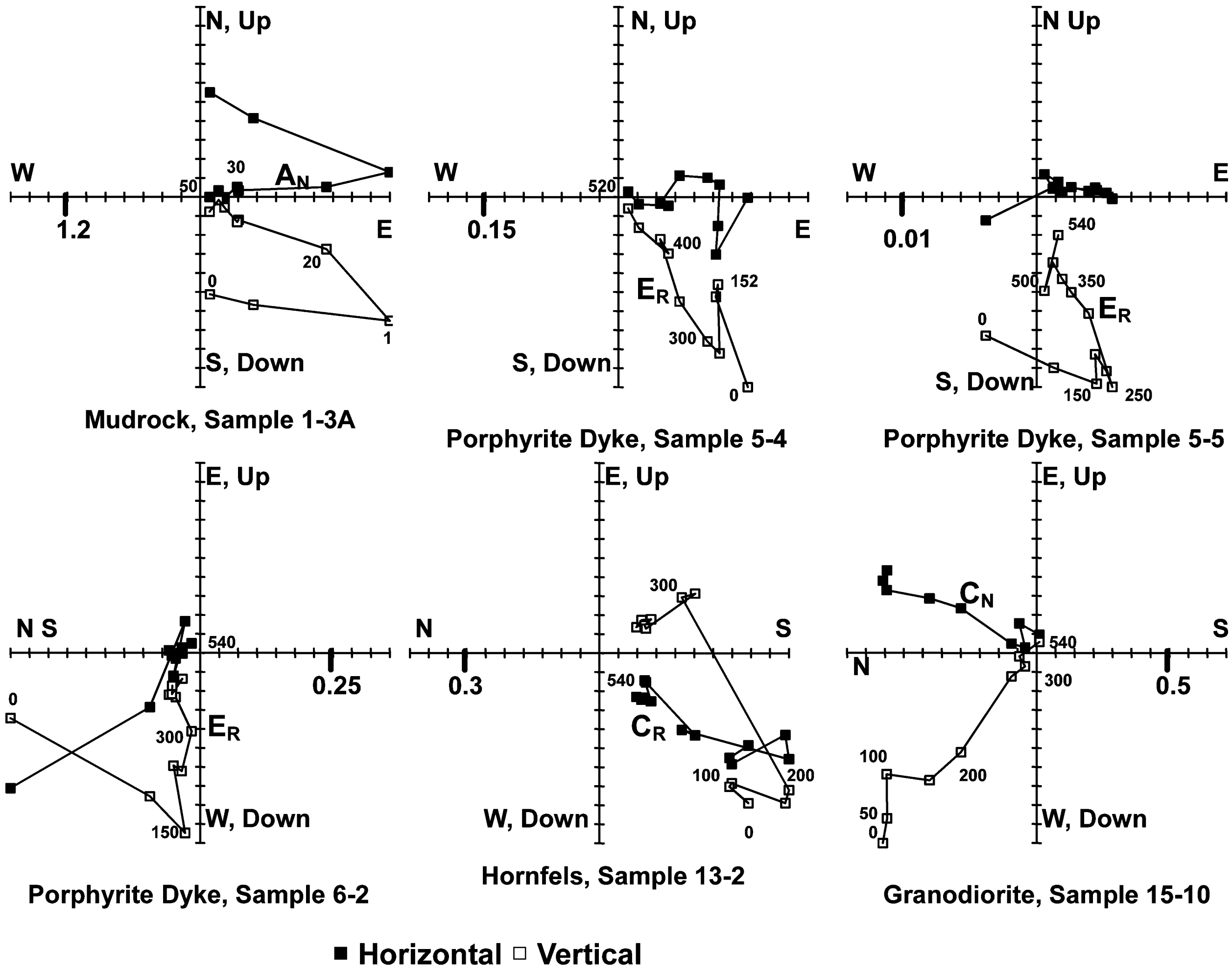

Figure 14. Orthogonal projections of the magnetization vectors onto the horizontal (closed symbols) and vertical (open symbols) planes, showing behaviours of samples from aureole and porphyrite dykes to thermal demagnetization. Magnetization intensity values on the axes are $\times 10^{-5}$ A m^2/kg. Assignments of magnetizations to populations 'E', 'A' and 'C' are indicated.

The 'C' direction is comparable with the Mesozoic palaeofield at *c.* 160–140 Ma and seems likely to have a varied origin imparted by fluid flow during extensional tectonism during these times. Comparable magnetizations are described by Turner *et al.* (1995) from the Penrith Sandstone in the Vale of Eden and attributed to lateral migration of evaporitic fluids beneath a sealed Lower Triassic layer. Although the youngest sediments now exposed on land in this region are Triassic, it is likely that a substantial later Jurassic and Cretaceous succession was deposited and subsequently eroded during Cimmerian and mid-Tertiary uplifts; differential loading by these Jurassic and Cretaceous strata therefore seems likely to have been the cause of fluid migration and protracted but incipient overprinting (Turner *et al.* 1995).

Although magnetite is reported as the primary mineral in the Criffel-Dalbeattie pluton and all magnetizations found here were resolved in magnetite spectra, hematite is extensively present on joints and as staining near to fracture systems cutting the granodiorite. It is also reported to be associated with precipitation of quartz (Phillips, 1956) and was detected by Kafafy & Tarling (1985) in Isothermal Remanent Magnetization spectra and widely recognized in thermomagnetic spectra from the aureole zone. The Cairnsmoor of Fleet intrusion appears to have experienced similar redox conditions, either at a post-emplacement phase or during much later fluid migration. Conversely, the ferromagnetic sulphide pyrrhotite is not detected at Criffel-Dalbeattie and is indicated at only one site in the Cairnsmoor of Fleet study. This contrasts with the Loch Doon aureole, where redox conditions during consolidation appear to have been reducing with pyrrhotite precipitation in the outer aureole (Piper, 2007).

The 'A' components in the Cairnsmoor of Fleet Granite and aureole yield a well-defined E–W shallow axis of magnetization and pole position satisfying six of seven reliability criteria (Van der Voo, 1993). These are a well-determined age (392 ± 2 Ma), sufficient resolved components (48), demagnetization resolving component structure (Figs 7, 8), a field (contact) test (see Table 3 with disappearance of the 'A' remanence beyond site 15 from the contact, although absence

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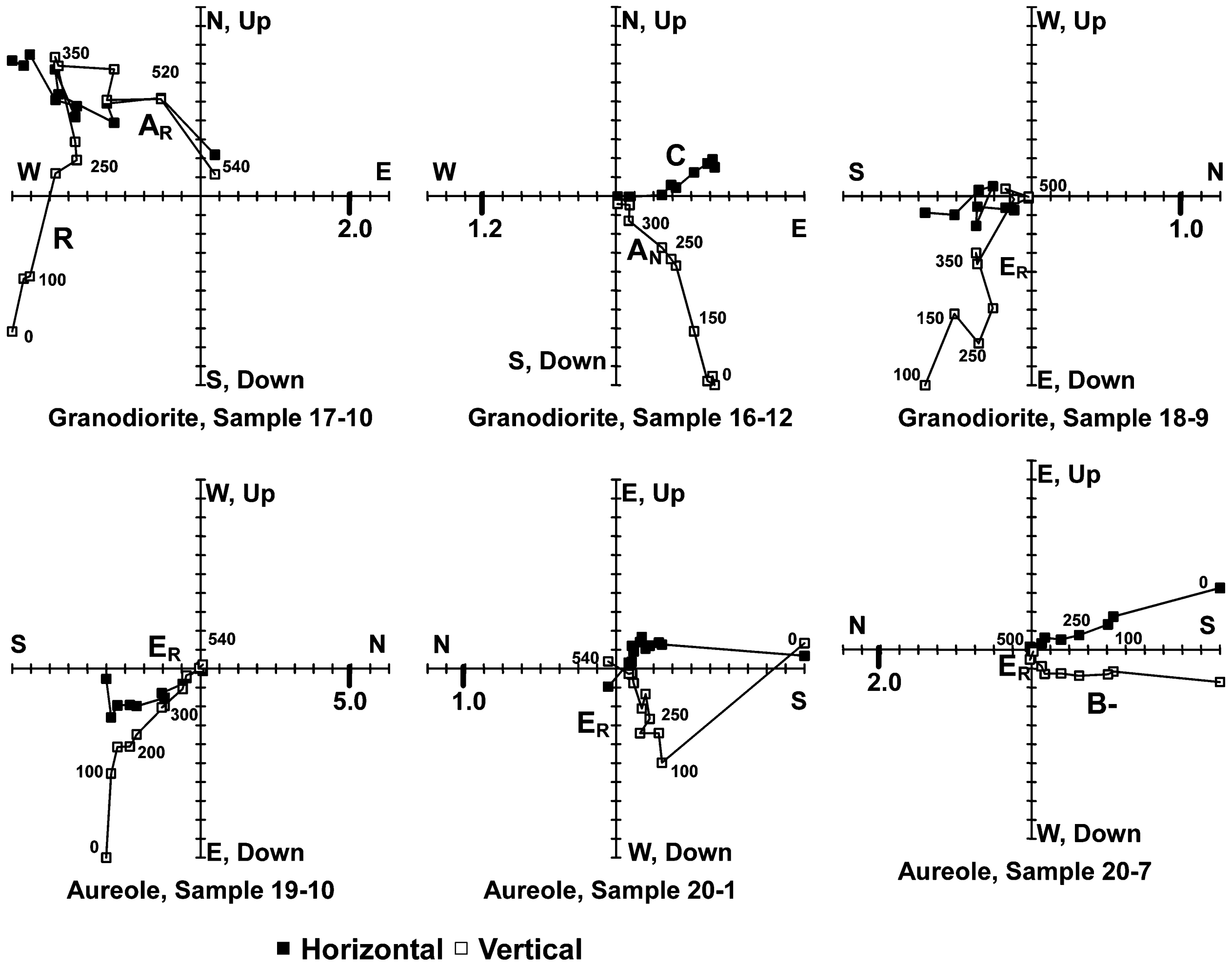

Figure 15. Granodiorite and aureole sample magnetization behaviours during thermal demagnetization shown as projections of vectors onto the horizontal (closed squares) and vertical (open squares) planes. Symbols are as for Figure 13. Sample 1-3A is an example of a.f. demagnetization and the treatment fields are in milliTesla.

of a clear pre-emplacement remanence fails to fully satisfy this criterion), structural control, presence of reversals and no resemblance to poles of younger age. The influence of appreciable later tilting on the ‘A’ component of the Cairnsmoor of Fleet can be discounted because (a) this body is post-tectonic, (b) the thermal aureole is of uniform width (Fig. 2) and (c) any tilting of this broad (∼12 km wide) intrusion about the dominant ENE–WSW Caledonian axis would have minimal effect on the E–W axis of primary magnetization. Much of the isotopic sample from the Cairnsmoor of Fleet intrusion studied by Halliday, Stephens & Haron (1980) comes from a continuation of our traverse into the pluton, and the 392 Ma Rb–Sr age assignment is supported in general terms by isotopic and geochemical evidence which shows this to be the most evolved of the Southern Uplands granites, having the highest $^{87}Sr/^{86}Sr$ and Rb/Sr ratios, as well as the highest sedimentary contribution to the primary melt (Halliday, Stephens & Haron, 1980). It is also supported by a comparable 390 ± 6 Ma U–Pb zircon age (Pidgeon & Aftalion, 1978), giving confidence to a Middle Devonian (Eifelian) age assignment to the ‘A’ pole position.

The axis of magnetization defined by ‘A’ (D/I = 272/2°) is also close to the dual polarity remanences derived from the Shap (D/I = 278/17°) and Skiddaw granites (D/I = 282/6°: Piper, 1997*b*) in the adjoining Lake District Block to the south. Age determinations on Shap (397 ± 7 Ma: Wadge *et al.* 1978; Rundle, 1992) and Skiddaw (399 ± 8 Ma: Shepherd *et al.* 1976; Rundle, 1992) conform closely to the assigned Eifelian (Middle Devonian) age of Cairnsmoor of Fleet. Although these granites were emplaced within Caledonian terranes on either side of the Iapetus Suture (Fig. 1), the post-suture strike-slip fault boundaries were evidently established by the time of their emplacement (e.g. Hutton, 1987) and, since they are essentially straight, would have been unable to permit appreciable later differential rotation between the two regions. This E–W axis of magnetization is therefore established as the palaeofield direction for northern Britain in late Early to early Middle Devonian times at *c.* 390–399 Ma.

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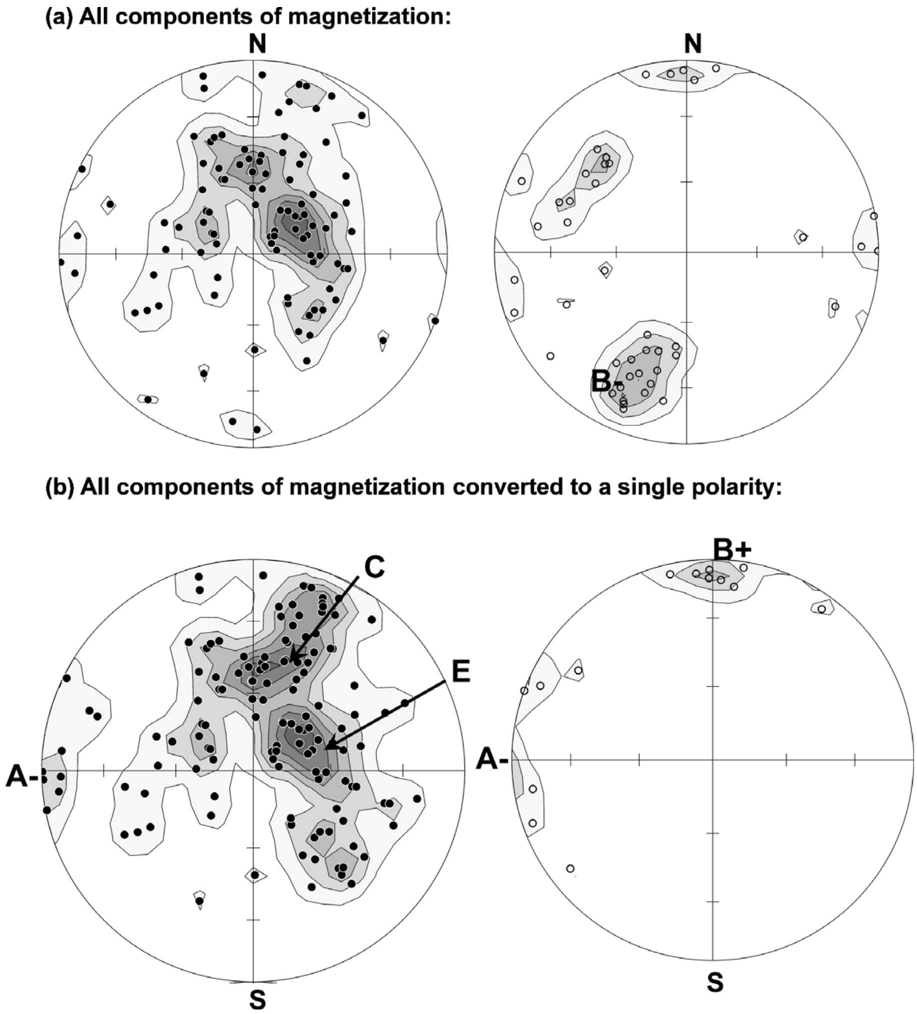

Figure 16. Directions of component magnetizations in the Criffel-Dalbeattie granodiorite and aureole plotted on equal area projections and contoured. Symbols are as for Figure 9 and populations discussed in the text are identified.

The palaeomagnetic record in the Criffel-Dalbeattie pluton and contact is less readily interpreted. Although the current assigned age (397 ± 2 Ma) is comparable to Cairnsmoor of Fleet (as well as Shap and Skiddaw), a comparable palaeomagnetic record is found in only 14 % of the resolved components and nowhere is it present in more than two components at a site. We therefore conclude that the magnetization age is substantially different from the mineral isochron age on the pluton. The problem is exacerbated by the failure of much of the contact profile in the country rock to yield useful palaeomagnetic data. However, the most substantial component record in the Criffel-Dalbeattie sample has easterly to southerly declinations and positive inclinations loosely grouped as the 'E' magnetization and recorded in porphyrite dykes and some granodiorite sites. This cannot be an overprint because it correlates with no later palaeofield direction from Britain and was evidently acquired before the radiometric age of 397 Ma; the directional distribution further shows that it does not record a single magnetization event with the arcuate distribution of declinations, indicating that rotation of the pluton may have been occurring during relatively slow regional cooling (Fig. 16).

Results of Palaeozoic palaeomagnetic studies in the Southern Uplands Block are summarized in Table 8, where the first three probably comprise the record from the pre-Devonian history. The Slockenray Formation in the Ballantrae Ophiolite (see Fig. 11 for location) is an overprint, although directions from clasts of this formation in a conglomerate of Llandeilo age appear to be random (Trench, Bluck & Watts, 1988). Since vertical axis rotations in the ophiolite are unconstrained, this result is regarded as a palaeolatitude indicator for Early–Middle Ordovician times. Results 2 and 3 from intrusions into the Ballantrae Complex are older studies based mainly on a.f. treatment and end-point analysis (Piper, 1978), and directions from result 2 are smeared; it remains possible that they are Ordovician in age, although this seems unlikely. These directions are comparable to the Criffel-Dalbeattie 'E' direction (bearing in mind that the latter is relatively poorly defined due to dispersal of declinations) and to

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Table 8. Summary of Palaeozoic palaeomagnetic results from the Southern Uplands of Scotland

	Rock unit	Age (Ma)	D/I	Pole position °E	Pole position °N	dp/dm (°)	Reference
1	Slockenray Formation	485 – 465	248/48	299	12	4/6	Trench, Bluck & Watts, 1988
2	Ballantrae Serpentinite		148/32	207	12	6/10	Piper, 1978
3	Byrne Hill Gabbro		148/36	206	9	11/19	Piper, 1978
4	Loch Doon 'E'		147/33	205	5	9/15	Piper, 2007
5	Criffel-Dalbeattie Granodiorite 'E'		115/55	224	−18	18/25	This paper
6	Criffel-Dalbeattie Site 19		267/63	298	34	–	This paper
7	Loch Doon 'A'	408.3 ± 1.5	237/64	316	21	5/7	Piper, 2007
8	Cheviot Volcanics	395.9 ± 2.9	229/53	320	11	18/18	Thorning, 1974
9	Cheviot Volcanics and Granite	395.9 ± 2.9	224/50	321	4	12/17	Thorning, 1974
10	Criffel-Dalbeattie Granodiorite 'A'	397.3 ± 2.1	272/2	263	2	6/12	This paper
11	Cairnsmoor of Fleet Granite 'A'	391.6 ± 2.1	272/2	265	2	3/7	This paper
12	Loch Doon C'		286/2	253	10	6/12	Piper, 2007

Symbols are as for Table 4.

a minority direction (result 4 in Table 8) within the Loch Doon pluton to the northwest (Piper, 2007). The characteristic remanence in Loch Doon is linked to the isochron age of the body (408 ± 2 Ma) and rotated in declination by more than 80° to the west (result 7), comparable to the remanence in site 19 at Criffel-Dalbeattie (Table 7). Hence there is palaeomagnetic evidence, albeit circumstantial, indicating that the Criffel-Dalbeattie body was magnetized some 10–15 Ma before the 397 Ma isochron age. Progressive anticlockwise rotation of the Southern Uplands Block is then indicated by the migration from the 'E' directions through the Loch Doon and site 19 magnetizations to the Cairnsmoor 'A' axis by *c.* 392 Ma. The minority 'A' magnetization in Criffel-Dalbeattie is then explained as an overprint related to widespread emplacement of the Cairnsmoor and other late Lower–early Middle Devonian granites at *c.* 395 Ma. Results from the Cheviot Complex (Table 8) are compatible with the pattern of declinations implied by regional clockwise rotation between Loch Doon 'E', 'A' and 'C' and Dalbeattie 'A' and 'E' magnetizations but have an inclination steeper than implied by the 396 Ma radiometric age (Table 8), suggesting that the latter assignment is also somewhat too young.

An age for Criffel-Dalbeattie older than the currently defined radiometric age is suggested by the substantially greater structural complexity of this body compared with Cairnsmoor of Fleet and Loch Doon. The outcrop is more elongate than the former and although originally oval in plan, has been disrupted as fault movements have caused southward displacement of the western sector. The NE regional trend of the Silurian strata also shows marked deflections at either end of the complex, and in the northeast the sedimentary carapace and concordant dykes have been rotated into parallelism with the margins of the granodiorite (Phillips, 1956). A prominent flow foliation is also developed in the outer non-porphyritic granodiorite subparallel to the margins and inclined outwards, together with a secondary foliation that affects aplite and quartz veins formed after consolidation of the granodiorite. In addition, the granodiorite is dissected by two sets of dislocations (NW–SE and NNE–SSW). Although the relative contributions of regional tectonic stresses and forceful magma emplacement to these fabrics are not clear, Phillips (1956) describes mylonite occurrences indicating the localized importance of the former and anticipating that the AMS fabrics recorded here (Fig. 4) are likely to be composite. The porphyrite sheets emplaced near the margins of the body and yielding 'E' magnetizations were probably emplaced at an intermediate stage of intrusion because dykes do not occur within the centre of the pluton, they are incipiently tectonized (Blyth, 1949) and they appear to have been influenced by Acadian deformation. The more primitive composition of the Criffel-Dalbeattie magma compared with Cairnsmoor of Fleet and Loch Doon granites also suggests an earlier origin. Both diorite and granodiorite compositions at Criffel-Dalbeattie have substantial hornblende with relict diopside and with biotite variably replacing hornblende (Phillips, 1956). The relatively greater importance of these paramagnetic minerals is presumably the major cause of the positive aeromagnetic anomaly over this pluton (Fig. 11), an effect that is also clearly detectable by ground survey (Fig. 10; see also Kafafy & Tarling, 1985).

There is also isotopic evidence suggesting an older age for Criffel-Dalbeattie intrusion. A U–Pb zircon age of 406 ± 15 Ma for this intrusion is (unlike Cairnsmoor of Fleet) substantially older than the Rb–Sr mineral age (Pidgeon & Aftalion, 1978). Although error limits are larger, this is possible closer to the emplacement age because Halliday, Stephens & Haron (1980) note metasomatic growths on some of their samples and find low $^{87}Sr/^{86}Sr$ and Rb/Sr ratios contrasting with the Cairnsmoor of Fleet body and comparable to the older Loch Doon intrusion.

6.b. Lower–Middle Devonian Apparent Polar Wander

Palaeomagnetic directions and pole positions from the British Caledonides embracing the rocks of this study and covering the Silurian–Devonian interval

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Table 9. Summary of Mid-Silurian to Late Devonian (*c.* 430–370 Ma) palaeomagnetic results from British Caledonides

Rock unit	Age	D/I	Pole position °E	Pole position °N	Q	Reference/Code
(a) Orthotectonic Caledonides, Lewisian Foreland Block and Central Valley of Scotland						
Ross of Mull Complex A	413 ± 3	159/50	12	−1	xxx.xx.	Piper, 1998/8252
Ben Loyal Complex	410 − 440	177/46	358	−4	..x.xx.	Turnell & Briden, 1983/109
Borrolan Ledmorite (margin)	430 ± 4	164/37	10	−10	xxx.xx.	Turnell & Briden, 1983/106
Borrolan Leucitite	430 ± 4	177/16	358	−24	x.x.xx.	Turnell & Briden, 1983/107
Peterhead Granite	400 − 430	180/22	358	−21	.xx.x..	Torsvik, 1985*b*/864
Helmsdale Granite	400 ± 15	181/2	355	−31	..x.xx.	Torsvik, Løvlie & Storetvedt, 1983/1460
Strontian Granite	400 − 435	190/23	344	−21	.xx.xx.	Torsvik, 1984/853
Foyers Granite	400 − 453	188/9	347	−27	.xx.xx.	Torsvik, 1984/852
Appenite Suite	400 − 430	189/29	346	−17	.xx.xx.	Esang & Piper, 1984/1473
N. Highland Dolerites	400 − 430	188/32	348	−15	.xx.xx.	Esang & Piper, 1984/1474
Ratagain Complex	$419 \pm 3^{+}$	188/32	347	−15	x.x.xx.	Turnell, 1985/135
Ross of Mull Amphibolites A/B	400 − 440	190/36	345	−14	.xx.xx.	Piper, 1998
Borrolan Syenite (interior)	430 ± 4	207/19	327	−18	xxx.xx.	Turnell & Briden, 1983/108
Achmelivech Dyke	∼430	204/24	331	−17	..x.x..	Turnell & Briden, 1983
Canisp Porphyry	∼430	203/36	333	−10	..xxxx..	Darabi & Piper, 2004
Garabal-Glen Fyne Complex	406 ± 4	212/43	326	5	xx..x..	Briden, 1970/3042
Alkaline Dykes	∼430	210/23	325	−16	..x.x..	Turnell & Briden, 1983/111
Loch Ailsh Complex	416 − 449	213/22	321	−16	.xx.x..	Turnell & Briden, 1983/110
Arrochar Complex	410 − 440	213/37	324	−8	.x.xx..	Briden, 1970/3043
Moine Metasediments	410 − 500	227/35	310	−5	.xx.xx.	Watts, 1982/704
Ross of Mull Amphibolites A	400 − 430	220/54	322	7	.xx.xx.	Piper, 1998
Glen Coe Lavas	412 ± 5	216/54	329	6	xx..x..	McMurry, 1970
Lorne Plateau Lavas	416 ± 6	220/49	321	2	xx.xx..	Latham & Briden, 1975/2582
Lower ORS Ignimbrites	416 ± 6	210/43	330	4	xxxxx..	Trench, & Haughton, 1990/6615
Comrie Intrusion	$412 \pm 4^{+}$	255/30	287	6	xxx.x..	Turnell, 1985/136
Foyers Complex	400 − 453	194/6	340	−29	xx.xxx.	Kneen, 1973/2515
Strathmore lavas	394 − 411	221/40	320	4	x.xxxx.	Sallomy & Piper, 1973/2532
Midland Valley Lavas	394 − 411	225/46	318	2	xxxxxx.	Torsvik, 1985*a*/866
Sarclet Sandstone	392 − 407	211/33	327	−9	..x.xx.	Storhaug & Storetvedt, 1985/1577
Midland Valley ORS	359 − 423	212/29	323	−15	xxxxxx.	Torsvik *et al.* 1989
Orkney Lavas	359 − 398	205/8	330	24	..xxxx.	Storetvedt & Petersen, 1972/2994
John O'Groats Sandstone	385 − 392	209/6	325	−24	x.x.x..	Storetvedt & Carmichael, 1979/21
Eday Group lavas	385 − 392	194/41	344	−7	xxxxx..	Robinson, 1985/1579
Hoy lavas and baked sediments	384	208/9	326	−23	x.xxx..	Storetvedt & Meland, 1985/1581
Caithness ORS	385 − 398	205/3	329	−27	xxx.xx.	Storetvedt & Torsvik, 1985 /1462
Foyers Old Red Sandstone	385 − 398	186/7	349	−29	.xx.x..	Storetvedt *et al.* 1990/6108
Esha Ness Ignimbrite	359 − 391	220/3	315	−21	.xxxxx.	Storetvedt & Torsvik, 1985/855
(b) Paratectonic Caledonides of England and Wales						
Browgill Formation	431	163/24*	14	−22	xxxxxx.	Channell, McCabe & Woodcock, 1997/7091
Ennerdale Granophyre	420	175/26	2	−22	.xx.xx.	Piper, 1997*b*/8777
NE–SW Carrock Dyke swarm	450 − 350	211/31	327	−14	x.x.x..	Piper, 1997*b*
Skiddaw Hornfels	399 ± 8	282/6	259	9	x.x.xx.	Piper, 1997*b*/8779
Shap Granite	397 ± 7	278/17	264	7	xxxxxx.	Piper, 1997*b*/8780
(c) Borders of the Paratectonic Caledonides in Wales						
Anglo-Welsh Cuvette	398 − 416	246/38	298	3	.x..x..	Chamalaun & Creer, 1964
ORS Welsh Borderlands	398 − 423	232/32	307	7	.xxxxx.	Channell, McCabe & Woodcock, 1992/6964
ORS South Wales	398 − 423	246/38	297	3	.xx.x..	Setiabudidaya, Piper & Shaw, 1994/7217

The Q factor shows the score of the seven criteria listed by Van der Voo (1993) comprising a well-determined rock age, sufficient number of samples, adequate demagnetisation, field tests, structural control, presence of reversals and no resemblance to younger poles. The numbers following the reference in the right-hand column refer to the result number in the Global Palaeomagnetic Database (GPMDB) of March 2005; other symbols are as for Table 4. *This unit rotated 60° anticlockwise to adjust for post-Late Ordovician rotation of the Lake District block (Piper, 1997*a*). ⁺Adjusted after Thirlwall (1988). The palaeolatitudes as plotted in Figure 18 are derived from the standard geocentric axial dipole equation $\tan I = 2 \tan\lambda$.

c. 430–370 Ma are summarized in Table 9. The main feature of declination change during this interval is a rapid clockwise rotation which took the palaeofield to directions resolved from bodies such as Cairnsmoor of Fleet, Shap and Skiddaw and then a rapid anticlockwise rotation that returned the palaeofield near to a N–S axis so that declinations at *c.* 430 Ma and *c.* 380 Ma are comparable and S to SE. The equivalent polar track is the flattened outward and return loop shown in Figure 17. Since the data of Table 9 are derived from tectonic blocks within the orthotectonic and paratectonic Caledonides separated by major faults, the results from adjacent terranes will clearly only be comparable following consolidation of these boundaries and a decrease in relative movements below palaeomagnetically detectable levels. This is likely to have been early in Devonian times, following the peak of Acadian Orogeny and during Emsian times (Soper, Webb & Woodcock, 1987; Soper & Woodcock, 1990). The block boundaries are straight

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Table 10. Late Silurian–Devonian palaeomagnetic results from the Scandinavian Caledonides

Rock unit	Assigned age	D/I	Pole position			Reference/Code
			°N	°E	Dp/dm	
Basal Gneiss Complex A	420–386	222/24	9	325	5/9	Piper & Poppleton, 1990
Jotun Nappe Goup 1	420–386	251/24	−2	301	3/5	
Jotun Nappe Goup 2	420–386	238/23	4	312	2/3	
Jotun Nappe Goup 3	420–386	231/21	7	318	2/3	
Jotun Nappe Goup 4	420–386	223/22	10	325	2/4	
Ringerike Sandstone	398–423	206/16	−19	344	5/9	1556
Kvamshesten Old Red Sandstone	359–398	194/12	−22	350	5/10	3083

Symbols are as for Table 9.

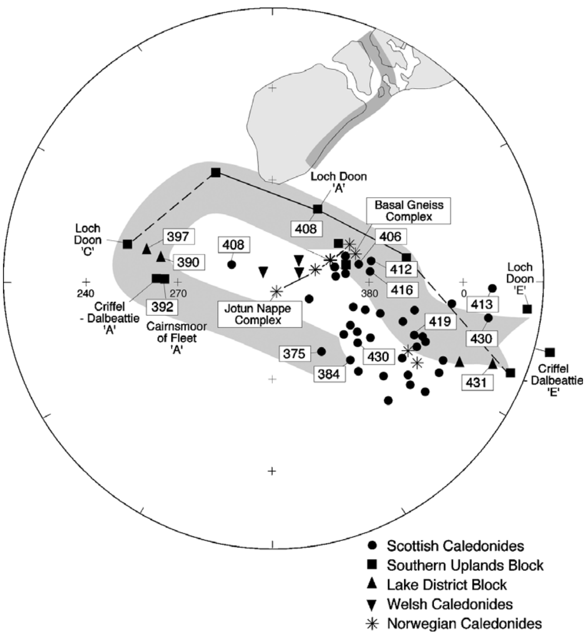

Figure 17. Palaeomagnetic poles from the British Caledonides assigned to the mid-Silurian to Late Devonian interval *c.* 430–370 Ma. Details of the poles are summarized in Table 9, and isochron age dates are indicated together with the APW loop defined by relative ages and the distribution of poles derived from the Southern Uplands Block. The location of the Appalachian–Caledonian orogen is also shown. Note that the Criffel-Dalbeattie and Loch Doon 'E' magnetizations probably pre-date Acadian suturing and are therefore not directly comparable with results from the Scottish Caledonides.

(Fig. 1) and provide little scope for subsequent relative rotation (and therefore declination contrast) between the terranes. Contemporaneous results from the Scandinavian Caledonides complement results from the British Caledonides (Table 10) and plot near the beginning of the APW loop (Fig. 17). However, the single APW trajectory from this sector, which is derived from the Jotun Nappe Complex (Piper & Poppleton, 1990), is rotated anticlockwise with respect to the British data (Fig. 17) by an amount compatible with the contrasting WSW–ENE and NNE–SSW tectonic trends of the British and Scandinavian Caledonides; it would appear, therefore, to reflect later differential rotation between the Laurentia and Baltica forelands and was presumably accommodated by strike-slip motions along the British–Scandinavian sector of the Caledonian orogen after Early Devonian times.

An Emsian age for establishment of fault zones bounding the Southern Uplands Block would mean that the 'E' magnetizations in Criffel-Dalbeattie and Loch Doon are unlikely to be directly comparable with the Scottish poles in Figure 17, although there appears to be a merging of the data, probably including the characteristic *c.* 408 Ma remanence in Loch Doon, by *c.* 410 Ma with the subsequent path continuing to the Cairnsmoor of Fleet pole and comparable overprints in Loch Doon and Criffel-Dalbeattie by *c.* 395 Ma (Table 9; Fig. 17). These poles define a hairpin in the APW track including the Shap and Skiddaw poles from the adjoining Lake District terrane.

The polar loop shown in Figure 17, and apparently executed in less than 30 Ma, cannot be directly equated with continental movement because much of the APW records changes in declination. However, it was also accompanied by large inclination changes recording latitudinal movement. An earlier phase of ∼35° of latitudinal motion is recorded by extensive investigations of igneous suites within the Orthotectonic Caledonides of Scotland (Table 9), and the total motion during the interval *c.* 408–395 Ma was at least 44° (Fig. 18); since much of this motion is from post-tectonic bodies and recorded within the Southern Uplands Block alone, it cannot be explained in terms of local or regional tectonics. The latitudinal migration was at least 5100 km over an interval of *c.* 15 Ma implying a continental velocity of ∼34 cm/year; the age estimates linked to the Cheviot Complex palaeopoles and inclusion of results from the Lake District Block (Table 9) suggest that actual continental velocity could have been twice as large as this.

Such rates of movement are well in excess of plate velocities; bending stresses associated with subduction of oceanic lithosphere at destructive plate margins appear to impose a speed limit to plate motions of about 20 cm/year (Conrad & Hager, 2001); this approximate figure is also implied by an inference that upper mantle convection is unable to drive plates at velocities greater than ∼25 cm/year due to drag forces at the base of thickened lithosphere (Gurnis & Torsvik, 1994). The

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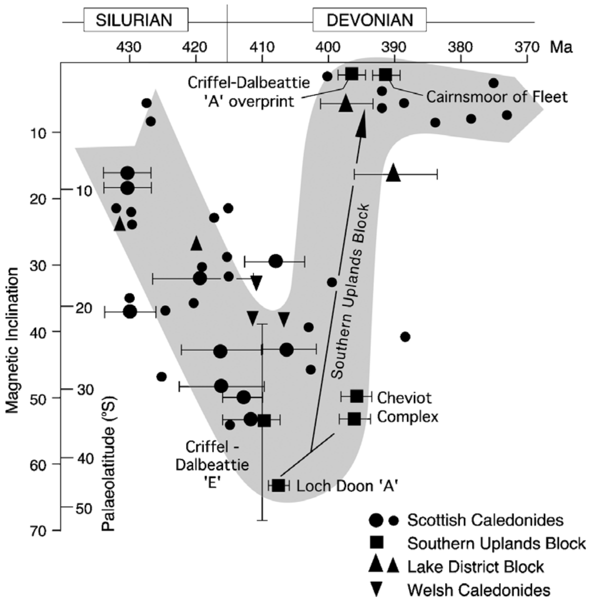

Figure 18. Magnetic inclinations of palaeomagnetic studies from the British Caledonides summarized in Table 6 plotted as a function of age. The large symbols are palaeomagnetic studies linked to isochron ages and the small symbols are poles linked to approximate age estimates (see Table 9); where the pole is linked to an age interval it is plotted against the mean age.

latter authors use finite element modelling to show that this limiting velocity is reached when a continent with thick lithosphere root is subject to a push force away from a region of elevated deep-mantle temperatures or a push force towards a deep-mantle cold region.

Hence the rate of plate movement at *c.* 408–390 Ma was significantly higher than motions resulting from plate tectonics. True polar wander (TPW) is the apparent explanation for such rapid movement and an episode of TPW during this time interval has already been proposed by Van der Voo (1994). TPW occurs when the geographic reference frame moves relative to the spin axis (the dynamically conserved angular momentum vector of the Earth). This is expected to arise from redistribution of mass within the mantle by a mechanism such as uprise of new plumes or reorganization of the mantle convection system. The APW movement defined by palaeomagnetic study then represents the resultant of two components, the motion of the block as a result of plate tectonic forces and the TPW component of whole-mantle migration relative to the rotation axis (Evans, 1998). The TPW component is recognized by a common APW motion in all plates. A variant of TPW occurs when mantle density changes alter the magnitudes rather than the orientations of the principal inertia axes in a prolate Earth. This is Inertial Interchange True Polar Wander (IITPW) and has long been acknowledged as a possible cause of rapid rotation of the outer silicate Earth (Goldreich & Toomre, 1969). It is expected when these changes cause the axis of maximum inertia, I_{max}, to become less than the intermediate inertial axis I_{int} and result in the entire mantle and crust rotating rapidly around I_{min} to align the new I_{max} with the rotation axis. Because I_{max}, I_{int} and I_{min} are orthogonal, Inertial Interchange True Polar Wander results in a 90° interchange of inertial axes. Such an event cannot be ruled out for the smaller motion resolved from inclination changes (Fig. 18) because a maximum of 90° interchange will only be observed in continents sited furthest from the I_{min} axis. The present Earth viscosity profile suggests that an Inertial Interchange event could occur within 5–15 Ma (Spada, Ricard & Sabadini, 1992; Steinberger & O'Connell, 1997). This is the approximate time interval represented by the APW loop described in Figure 17 and suggests that the APW loop described here could be the record of such an event.

From the point of view of regional geological analysis, the definition of the APW loop of Figure 17 and the latitudinal motion of Figure 18 provide a means for constraining ages of magnetization. In Figure 18 the plot of magnetic inclination as a function of age defines motion of Britain from palaeolatitudes of ~10° S at *c.* 430 Ma to ~45° S by *c.* 410 Ma. The comparable Cairnsmoor of Fleet, Shap and Skiddaw results define the rapid return of Britain to equatorial palaeolatitudes by *c.* 395 Ma. The relatively high inclination derived from the Criffel-Dalbeattie 'E' magnetization of 55 ± 18° suggests that this remanence is about 410 Ma in age (Fig. 17) and, as a magnetic record in the aureole and related bordering porphyrite sheets, provides an estimate for the emplacement age of the pluton. The current age assignment of 397 Ma to this body is more likely to correlate with emplacement of the structurally less complex Cairnsmoor of Fleet Granite and to be recorded by the minority 'A' population of magnetizations within Criffel-Dalbeattie (Fig. 17). Clearly, reassessment of the isotopic record in Criffel-Dalbeattie is merited.

6.c. Devonian palaeogeography

Large APW movements comparable to those described here from the British Caledonides have been identified from Gondwana, and a number of strikingly different paths (see review by McElhinny, Powell & Pisarevsky, 2003) have been proposed to reconcile pre-425 Ma and post-370 Ma poles from this supercontinent. Data relevant to the time interval in question are compiled in Figure 19 after McElhinny, Powell & Pisarevsky (2003), Anderson, Lackie & Clark (2004) and Anderson *et al.* (2004). Most key data points from this interval come from the Tasman Fold Belt of eastern Australia, a zone subject to terrane tectonics during much of Palaeozoic times, and the above authors have evaluated the geology of these terranes and their associated databases to identify poles that may legitimately be included in the assessment of Gondwana APW. Three dated poles from Africa are also included. The Silurian

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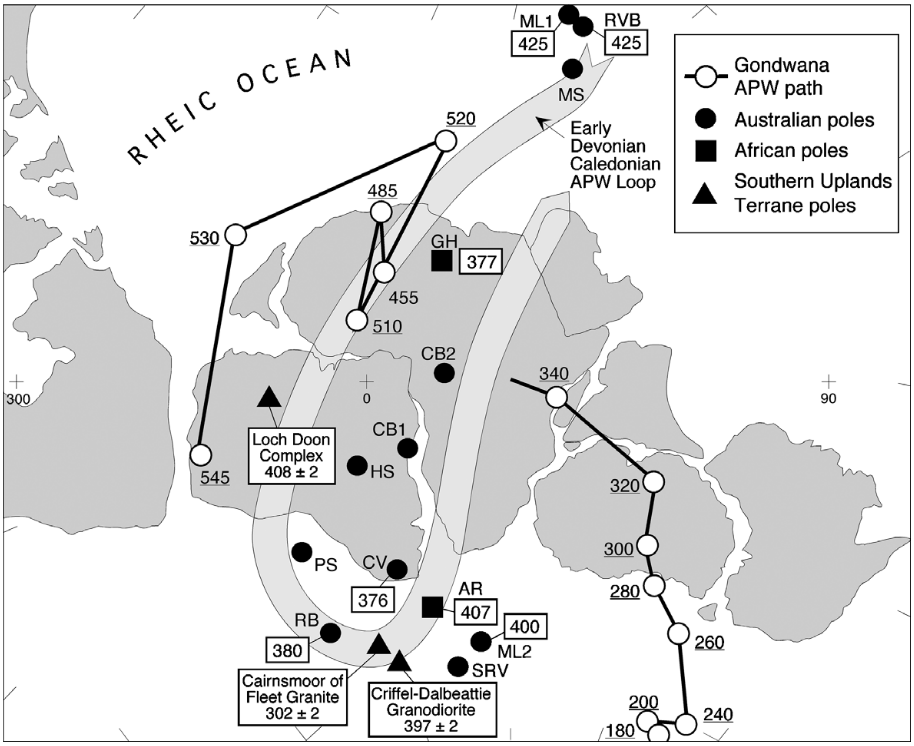

Figure 19. The TPW Track of Figure 17 as identified from the Southern Upland and related Caledonian results superimposed onto the Silurian and Devonian palaeomagnetic APW path from Gondwana and rotated into an African reference frame. The Gondwana poles with codes and assigned ages after McElhinny, Powell & Pisarevsky (2003) are: (Africa) Air Ring Complex, Niger (AR, 407 ± 8 Ma); Gilif Hills Ring Complex, Sudan (GH, 377 ± 5 Ma); (Australia) Mereenie Sandstone (MS, 417–443 Ma); Ravenswood Batholith (RVB, 422–428 Ma); Silurian Dykes, Mount Leyshon (ML1, 422–428 Ma); Devonian Dykes, Mount Leyshon (ML2, 382–415 Ma); Snowy River Volcanics (SRV, 398–416 Ma, Early Devonian); Retreat Batholith (RB, 370–390 Ma); Parke Siltstone (PS, 377–391 Ma); Comerong Volcanics (CV, 376 ± 6Ma, Middle–Late Devonian); Hermannsberg Sandstone (HS, 367–381 Ma); Canning Basin Reef Complexes (CB1, CB2, 365–374 Ma, Late Devonian). The Gondwana APW path before middle Silurian and after middle Carboniferous times is shown as dated mean poles (open circles). Australia is rotated to Africa by −55.2° about an Euler pole at 22.7° N, 117.7° E and North America is rotated to Africa by 115° about an Euler pole at 321° E, 33.5° N.

pole position for Gondwana plotting north of Arabia formerly had poor temporal control with the pole from the Mereenie Sandstone of cratonic Australia (MS), constrained only to a post-Ordovician and pre-middle Devonian interval, but this position is now supported by 425 ± 3 Ma poles from the Ravenswood Batholith (RVB) and Mt Leyshon Silurian dykes (ML1) of the Lolworth-Ravenswood terrane. It is removed by ∼110° (statistically identical to the APW motion between 10° E and 250° E in Fig. 17) from a cluster of late Early to early Late Devonian Australian poles and pole AR from the Air Ring Complex of Niger (407 ± 8 Ma). Results from the Canning Basin reef complexes (CB1, CB2) indicate a return of the APW path to a position in central Africa by latest Devonian times, a conclusion supported by pole GH from the Gilif Hills Complex of Sudan (377 ± 5 Ma). The suite of younger mean poles in Figure 19 defines the Carboniferous and later APW path of Gondwana after McElhinny, Powell & Pisarevsky (2003) and tracks the movement of Gondwana across the South Pole as widely recognized in the palaeoclimatic evidence for high latitude locations.

When the APW loop defined in Figure 17 from the Silurian–Devonian data from the British Caledonides is superimposed onto the Gondwana data (Fig. 19), the loop embraces the Gondwana poles and yields a conventional reconstruction without continental overlap and with Laurentia–Baltica–Avalonia sited to the west of South America. We therefore infer that the distribution of Gondwana Silurian–Devonian palaeomagnetic poles is a record of substantially the same polar movement as that identified from the Caledonian data.

The last pulse of subduction within the British Caledonides occurred in Late Ordovician (Caradocian) times when accretion of the Southern Uplands terrane was in progress and fore-arc (Lake District) and back-arc (North Wales) terranes at the northern rim of Avalonia were emplaced against the orthotectonic margin (Soper & Woodcock, 1990; Piper, 1997*a*). Contemporaneous convergence between Laurentia and the margin of Gondwana emplaced island arcs originating within the Iapetus Ocean against the Laurentian margin to produce the Taconic Orogeny. A complex series of strike-slip movements followed the suturing

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in Silurian–Devonian times to produce the terrane-bounding faults defining the present-day block boundaries (Fig. 1 and Hutton, 1987). Baltica and Siberia were converging towards Laurentia–Avalonia with Baltica and Laurentia sutured by Early Devonian times; the reconstruction of Figure 19 indicates that Acadian orogeny was not, however, related to Gondwana collision. Instead, the Caledonides and Gondwana were separated by the Rheic Ocean which widened to the east (Fig. 19). This basin was soon to be rapidly closed by a combination of pivotal motion and right lateral transpression later in the Devonian (Hutton, 1987; Soper, Webb & Woodcock, 1987).

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