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LATE CALEDONIAN DYKE-SWARMS OF NORTHERN BRITAIN: SOME PRELIMINARY PETROGENETIC AND TECTONIC IMPLICATIONS OF THEIR PROVINCE-WIDE DISTRIBUTION AND CHEMICAL VARIATION

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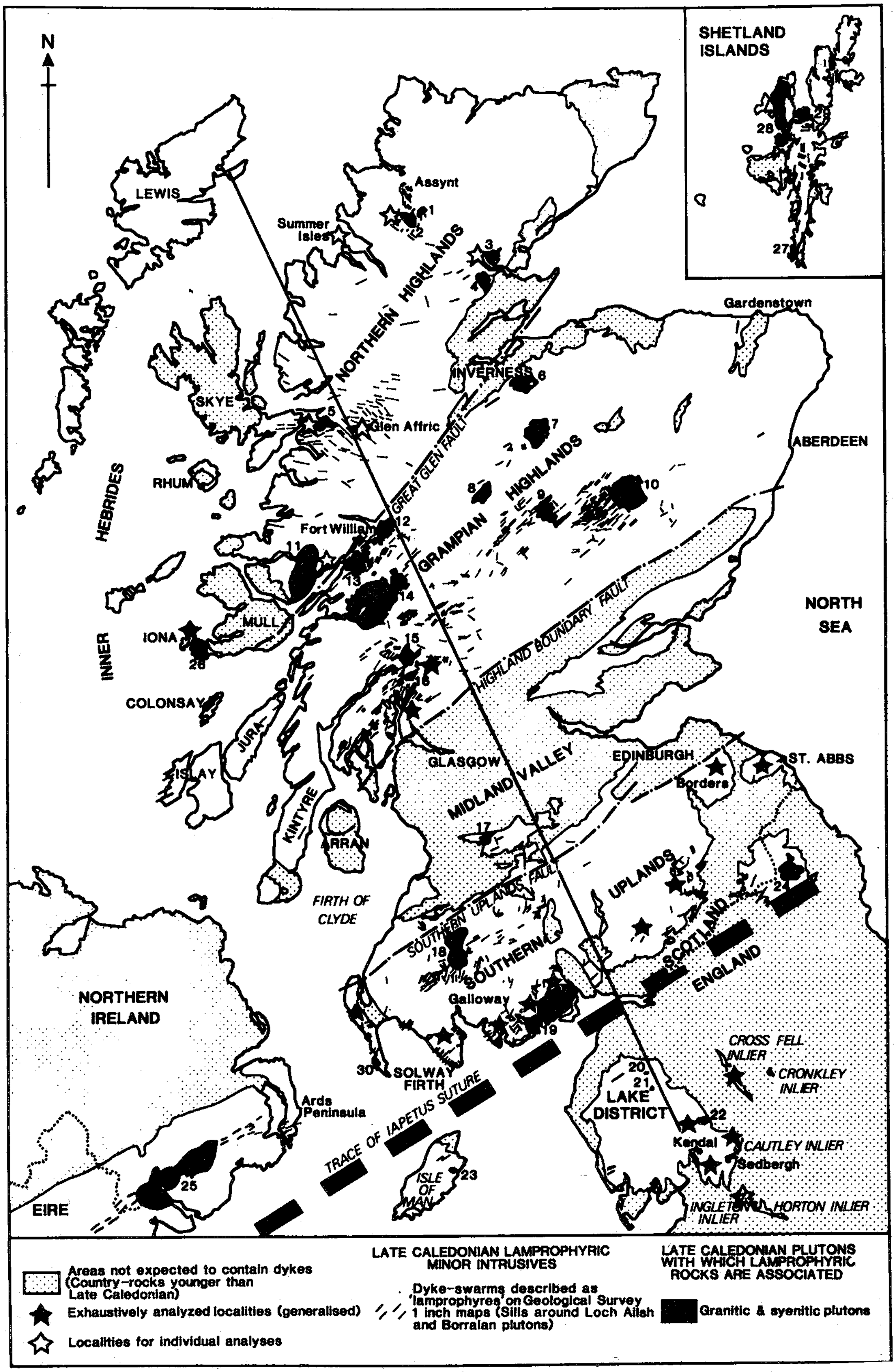
Abstract

Up-to-date distribution, age and field data for Siluro–Devonian (*ca.* 430–390 Ma) lamprophyre dykes reveal clear spatial, temporal and probably genetic associations with about 15 contemporaneous ("Newer") granitic and syenitic plutons. Such plutons are multiple, passively emplaced, 'wet', and have diverse basic–acidic chemistry; plutons dominated by crustally derived granites have few associated lamprophyres. In southern Scotland, biotite lamprophyres are largely confined to one *regional*, >300×10 km swarm, coincident with (but partly predating) granitic plutons, whereas hornblende lamprophyres dominate two *central* swarms around the Doon and Criffell plutons. By contrast, intermediate dykes are represented by 'central' swarms around all granitic bodies, whereas acidic dykes are mainly confined to a 'central' swarm above the subcropping "Tweedale Batholith". Biotite lamprophyres are less closely associated with granites and have higher Ca, K, P, Rb, Ba, Zr, Nb and *LREE* but lower Si than the hornblende lamprophyres, implying generation at higher pressures (>80–100 km, 26–27 kbar), where CO_2 rather than H_2O controls melting of mantle source-materials. Lamprophyres immediately north of the 'Iapetus Suture' (Scottish Southern Uplands) have lower Th and Sr than those farther south (English Lake District), probably reflecting distinct basement characteristics. Primitive lamprophyres (SiO_2 < 60%; mole % Mg/(Mg+Fe) > 60; Cr > 200 ppm; Ni > 75 ppm) reveal two tectonically significant types of province-wide variation normal to the Suture, which complement known variations in Siluro–Devonian lavas: (1) Sr, Ba, P, Rb, Y, Zr, Nb, and possibly K, increase outward from minima in central Scotland, not only toward the northwest (Assynt), *but also toward the southeast* (English Lake District), possibly providing the first chemical evidence for simultaneous northward and southward subduction. These mirrored trends are *not* centered on the supposed Suture, however, but some coincide with a known boundary between granites with and without inherited zircon, whereas other trends reach minima still farther north. (2) K/Th possibly increases monotonically from southeast to northwest, which may alternatively imply northward subduction from a suture considerably south of the Lake District. K-rich lamprophyric magmatism represents an important link between the orthotectonic and paratectonic Caledonides *prior to* fusion of the Celtic and Laurentian plates, and can no longer be ignored in tectonic modelling.

Keywords: Caledonian magmatism, dyke-swarm, granite, Iapetus Suture, lamprophyre, plutonism, subduction, Scotland, England.

Sommaire

Les données mises à jour sur la distribution, l'âge et les relations de terrain des dykes de lamprophyre siluro–dévoniens (calédoniens: environ 430–390 Ma) montrent une nette association dans l'espace et dans le temps, et donc tout probablement une filiation génétique, avec environ 15 complexes intrusifs granitiques et syénitiques contemporains. Ces plutons ont été mis en place par intrusions multiples et passives de magmas relativement près d'une saturation en eau, et qui montrent un chimisme diversifié impliquant roches felsiques et mafiques. Les plutons dans lesquels prédomine une influence crustale possèdent un cortège très épars de lamprophyres. Dans le sud de l'Ecosse, les lamprophyres à biotite se présentent surtout dans un essaim d'étendue *régionale* (>300 × 10 km) qui coincide avec les plutons granitiques (mais qui les précède en partie), tandis que les lamprophyres à hornblende prédominent dans deux essaims à foyer autour des plutons Doon et Criffell. Par contre, les dykes de composition intermédiaire sont présents sous forme d'essaims *centrés* autour de tous les massifs granitiques, tandis que les dykes felsiques se trouvent surtout dans un essaim centré situé au dessus du batholite de Tweedale, sousjacent. Les lamprophyres à biotite montrent une association moins frappante avec les granites, et possèdent une plus forte concentration de Ca, K, P, Rb, Ba, Zr, Nb et terres rares légères et une plus faible concentration de Si que les lamprophyres à hornblende. Ces caractères impliqueraient un site de génération à haute pression (qui surpasserait 80–100 km, 26–27 kbar), dans un milieu où c'était plutôt le CO_2 que l'eau qui régissait la fusion des matériaux du manteau. Les lamprophyres situés immédiatement au nord de la suture Iapetus, dans la région dite "Southern Uplands" de l'Ecosse, contiennent moins de Th et de Sr que ceux situés plus au sud, dans le "Lake District" de l'Angleterre, résultat probable des différences dans le socle. Les lamprophyres primitifs (SiO_2 < 60%, % en mol. Mg/(Mg + Fe) > 60, Cr > 200 ppm, Ni > 75 ppm) se regroupent en deux types qui ont une signification tectonique; chacun montre une variation perpendiculaire à la suture qui vient compléter les variations connues dans les laves siluro-dévoniennes: (1) la concentration


N
SHETLAND ISLANDS
LEWIS
Assynt
Summer Isles
NORTHERN HIGHLANDS
SKYE
Glen Affric
INVERNESS
Gardenstown
ABERDEEN
RHUM
HEBRIDES
GREAT GLEN FAULT
GRAMPIAN HIGHLANDS
Fort William
MULL
IONA
INNER
COLONSAY
JURA
ISLAY
HIGHLAND BOUNDARY FAULT
NORTH SEA
GLASGOW
MIDLAND VALLEY
EDINBURGH
Borders
ST. ABBS
KINTYRE
ARRAN
FIRTH OF CLYDE
SOUTHERN UPLANDS FAULT
SOUTHERN UPLANDS
SCOTLAND
ENGLAND
Galloway
NORTHERN IRELAND
SOLWAY FIRTH
TRACE OF IAPETUS SUTURE
CROSS FELL INLIER
CRONKLEY INLIER
LAKE DISTRICT
Kendal
CAUTLEY INLIER
Sedbergh
Ards Peninsula
ISLE OF MAN
INGLETON INLIER
HORTON INLIER
EIRE
Areas not expected to contain dykes (Country-rocks younger than Late Caledonian)
Exhaustively analyzed localities (generalised)
Localities for individual analyses
LATE CALEDONIAN LAMPROPHYRIC MINOR INTRUSIVES
Dyke-swarms described as 'lamprophyres' on Geological Survey 1 inch maps (Sills around Loch Ailsh and Borralan plutons)
LATE CALEDONIAN PLUTONS WITH WHICH LAMPROPHYRIC ROCKS ARE ASSOCIATED
Granitic & syenitic plutons

de Sr, Ba, P, Rb, Y, Zr, Nb et, avec moins de certitude, K, augmente vers la périphérie, à partir de valeurs minimales dans le centre de l'Ecosse, non seulement vers le nord-ouest (Assynt), *mais aussi vers le sud-est* (Lake District), ce qui constituerait la première évidence de subduction simultanée vers le nord et vers le sud. Ces variations symétriques *ne sont pas* centrées sur la supposée suture, mais dans certains cas, elles coïncident avec une limite connue entre granites porteurs de zircon hérité et granites sans celui-ci. Dans d'autres cas, les variations atteignent des valeurs minimales plus au nord. (2) Le rapport K/Th augmenterait de façon monotonique du sud-est vers le nord-ouest, ce qui pourrait plutôt indiquer un système de subduction vers le nord à partir d'une suture bien au sud du Lake District. Le magmatisme qui a produit les lamprophyres riches en K représente un lien important entre les Calédonides orthotectoniques et paratectoniques avant la fusion des plaques celtique et laurentienne; on ne saurait continuer de l'ignorer dans les reconstructions tectoniques.

(Traduit par la Rédaction)

Mots-clés: magmatisme Calédonien, essaim de dykes, granite, suture Iapetus, lamprophyre, plutonisme, subduction, Ecosse, Angleterre.

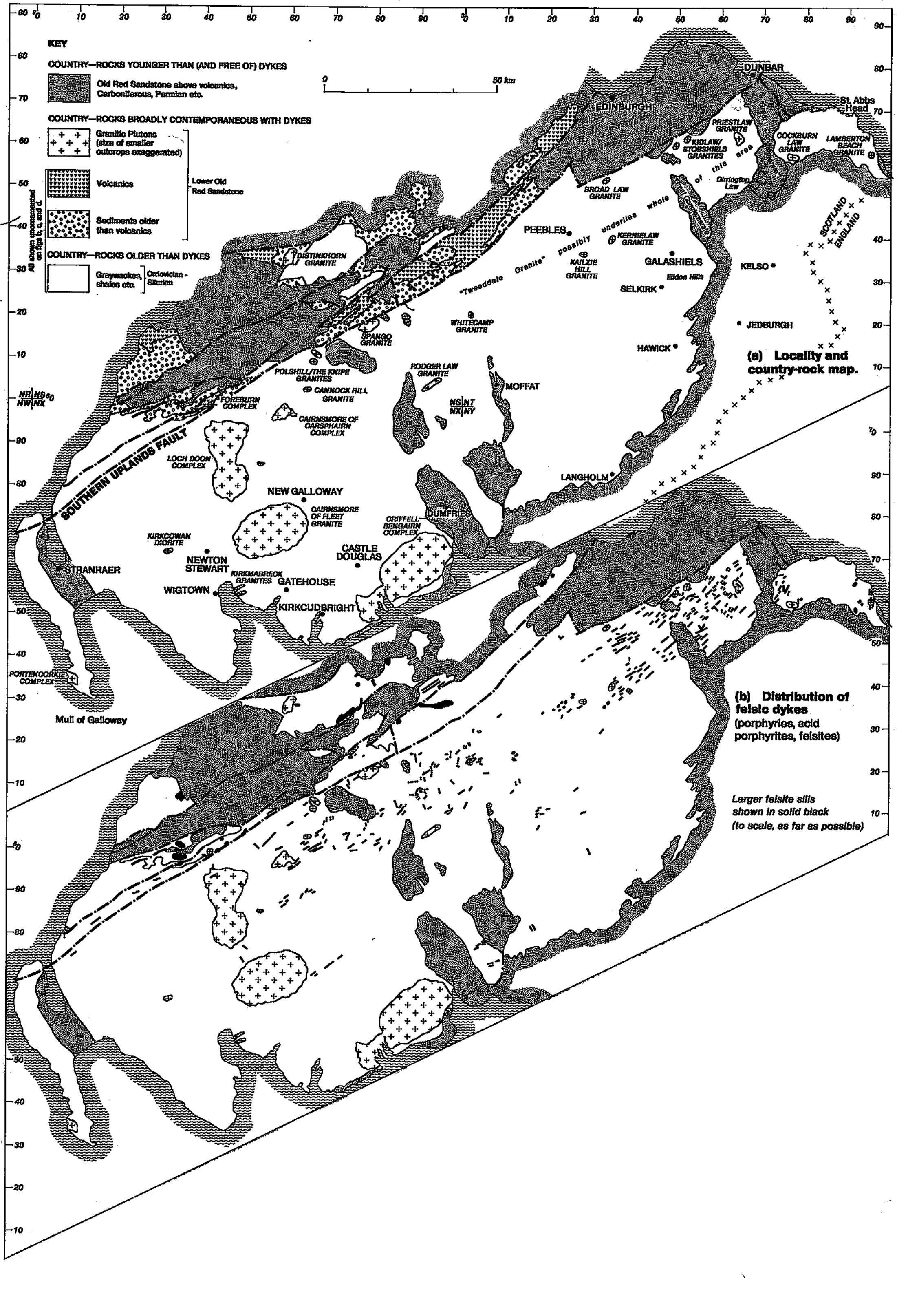
Introduction

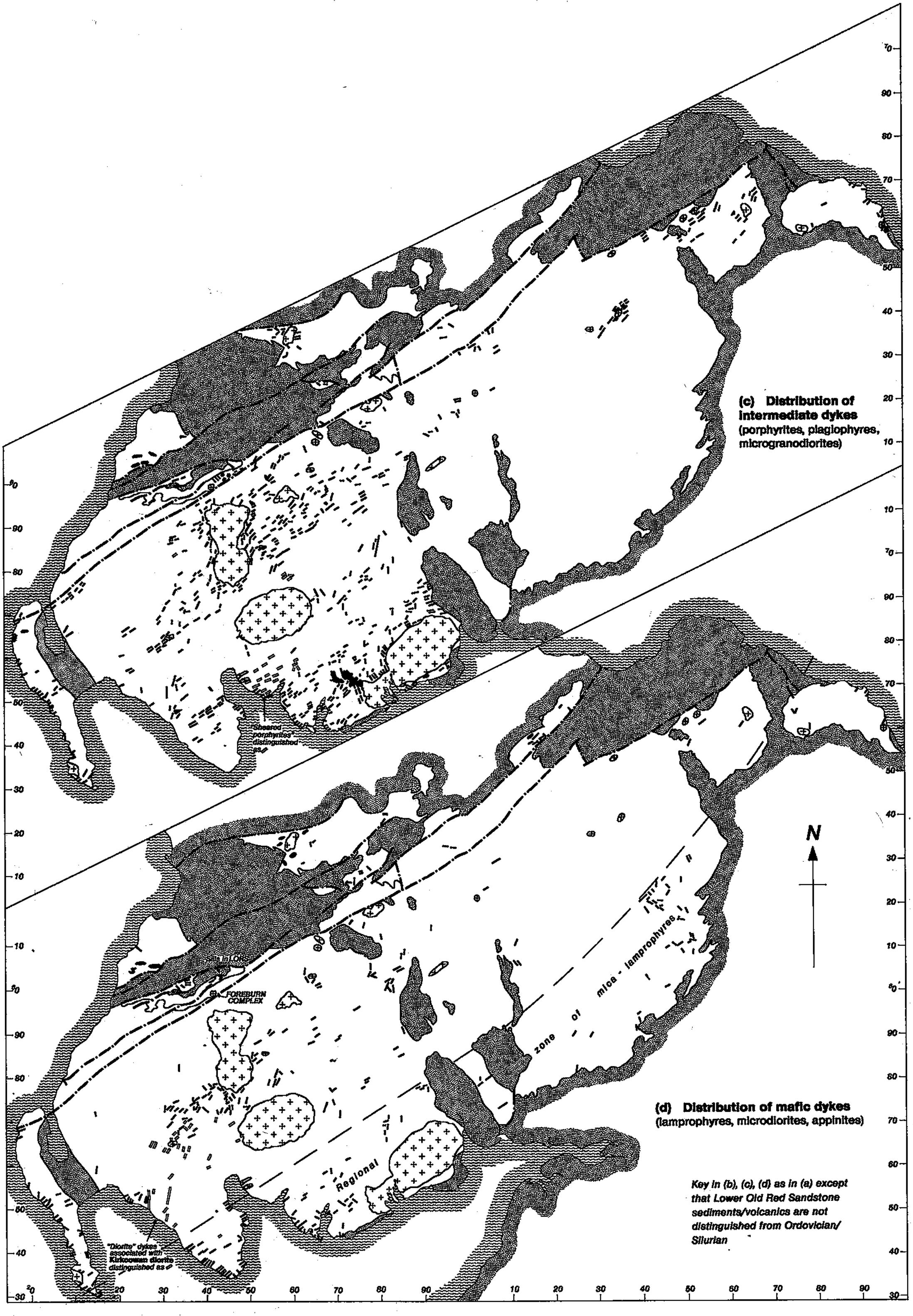
Regionally extensive and voluminous dyke-swarms are a major but long-neglected part of the Caledonian magmatic province in the British Isles, probably forming as much as 10-20% of the total volume of igneous rocks (Watson 1984). Interest in these dykes has recently revived, and several studies (Thompson *et al.* 1984, Barnes *et al.* 1986, Macdonald *et al.* 1986, Rock *et al.* 1986a,b, Rock & Hunter 1987, Gaskarth *et al.* 1988) have revealed primitive, K-rich compositions for the more mafic (calc-alkaline lamprophyre) dykes, and intimate local relationships between lamprophyre dykes and granitic plutons. The dyke-swarms are of interest not only to igneous petrologists, but also to tectonic and structural specialists, for they provide important constraints on palaeotectonic models — specifically on the interpretation of the Southern Uplands of Scotland (Fig. 1) as an accretionary prism (Barnes *et al.* 1986, Rock 1987b, Rock *et al.* 1986b). There is also increasing evidence worldwide that lamprophyres can be closely related to gold and other metallic mineralization (*e.g.*, McNeil & Kerrich 1986, summary in Rock 1987a, 1988a); they appear to show such a relationship with disseminated gold mineralization in southern Scotland (Rock *et al.* 1987).

Richey (1939) provided the only previous, brief summary of the distribution of Late Caledonian dykes in Scotland, at a time when substantial areas of the Scottish Highlands had not even been mapped in detail. Smith (1979) updated information for the Northern Highlands only. This paper aims to update information throughout northern Britain (Scotland and northern England), to highlight some important petrological relationships between coeval lamprophyre dykes, and to point out some hitherto unsuspected compositional variations across the province, which may have important consequences for regional tectonic modelling.

FIG. 1. Simplified regional distribution of Late Caledonian (*ca.* 430–390 Ma) calc-alkaline lamprophyre dykes in Northern Britain. Compiled from British Geological Survey (BGS) 1″ and 1:50,000 maps, Smith (1979) and the authors' unpublished information. In a few areas (*e.g.*, Cowal) the distribution is provisional because available BGS maps are several decades old; they give rock names not always in accord with modern terminology, and in some cases may confuse Late Caledonian, Permo–Carboniferous and Tertiary dykes, which all coexist locally (Richey 1939). Only those granitic plutons are shown which appear to have spatially associated dykes. Areas of younger cover are distinguished, to indicate where dykes are not expected. Filled stars indicate general areas where exhaustive recent sampling and analysis have been completed; open stars indicate locations for isolated data. Names of numbered plutons as follows: 1 Loch Ailsh (syenite); 2 Loch Borralan (syenite); 3 Migdale; 4 Fearn; 5 Glenelg–Ratagain (transitional granite-syenite); 6 Moy; 7 Monadhliath; 8 Strathspey; 9 Glen Tilt; 10 Lochnagar; 11 Strontian; 12 Ben Nevis; 13 Ballachulish; 14 Glen Etive–Cruachan; 15 Garabal Hill; 16 Arrochar; 17 Distinkhorn; 18 Loch Doon; 19 Criffell–Bengairn–Dalbeattie; 20 Skiddaw; 21 Threlkeld; 22 Shap; 23 Foxdale; 24 Cheviot; 25 Newry; 26 Ross of Mull; 27 Spiggie; 28 Northmaven; 29 Graven; 30 Portencorkie.

FIG. 2. Regional distribution of Late Caledonian (*ca.* 430–390 Ma) dykes of all compositions in the Late Palaeozoic turbidite terrane of Southern Scotland (Southern Uplands and part of the Midland Valley). Information based on BGS 1″ and 1:50,000 maps, Cameron & Stephenson (1985), and more particularly on the authors' exhaustive resampling and petrographic examination of most known dykes, plus 372 whole-rock analyses to date (Table 3). This figure is therefore considerably more reliable than Figure 1. The three categories of dykes in b,c,d, correspond broadly to the traditional definitions of 'acidic', 'intermediate' and 'basic'; individual rock-types are defined by a combined petrographical–chemical classification (Barnes *et al.* 1986). The lamprophyres and appinites correspond broadly to K-rich (basaltic) andesites, the porphyrites to andesites–dacites, and the acid porphyrites and porphyries to rhyodacites and rhyolites. Plagiophyres are highly altered, plagioclase-phyric andesitic rocks. See also pp. 39–40 of Cameron & Stephenson (1985). See text for probably distinct distributions of hornblende and mica lamprophyres within Figure 2d.


KEY
COUNTRY—ROCKS YOUNGER THAN (AND FREE OF) DYKES
Old Red Sandstone above volcanics, Carboniferous, Permian etc.
COUNTRY—ROCKS BROADLY CONTEMPORANEOUS WITH DYKES
Granitic Plutons (size of smaller outcrops exaggerated)
Volcanics
Sediments older than volcanics
Lower Old Red Sandstone
COUNTRY—ROCKS OLDER THAN DYKES
Greywackes, shales etc.
Ordovician - Silurian
All shown unornamented on figs b, c, and d.
0
50 km
DUNBAR
EDINBURGH
St. Abbs Head
PRIESTLAW GRANITE
KIDLAW/ STOBSHIELS GRANITES
COCKBURN LAW GRANITE
LAMBERTON BEACH GRANITE
BROAD LAW GRANITE
Dirrington Law
PEEBLES
KERNIELAW GRANITE
"Tweeddale Granite" possibly underlies whole of this area
KAILZIE HILL GRANITE
GALASHIELS
Eildon Hills
SELKIRK
KELSO
SCOTLAND
ENGLAND
JEDBURGH
HAWICK
DISTINKHORN GRANITE
WHITECAMP GRANITE
SPANGO GRANITE
POLSHILL/THE KNIPE GRANITES
CANNOCK HILL GRANITE
RODGER LAW GRANITE
MOFFAT
NR NS
NW NX
NS NT
NX NY
FOREBURN COMPLEX
CAIRNSMORE OF CARSPHAIRN COMPLEX
SOUTHERN UPLANDS FAULT
LOCH DOON COMPLEX
LANGHOLM
NEW GALLOWAY
CAIRNSMORE OF FLEET GRANITE
CRIFFELL-BENGAIRN COMPLEX
DUMFRIES
KIRKCOWAN DIORITE
NEWTON STEWART
CASTLE DOUGLAS
STRANRAER
KIRKMABRECK GRANITES
GATEHOUSE
WIGTOWN
KIRKCUDBRIGHT
PORTENCORKIE COMPLEX
Mull of Galloway
(a) Locality and country-rock map.
(b) Distribution of felsic dykes (porphyries, acid porphyrites, felsites)
Larger felsite sills shown in solid black (to scale, as far as possible)


(c) Distribution of intermediate dykes
(porphyrites, plagiophyres, microgranodiorites)
Sheared porphyrites distinguished as
N
FOREBURN COMPLEX
zone of mica - lamprophyres
Regional
"Diorite" dykes associated with Kirkcowan diorite distinguished as
(d) Distribution of mafic dykes
(lamprophyres, microdiorites, appinites)
Key in (b), (c), (d) as in (a) except that Lower Old Red Sandstone sediments/volcanics are not distinguished from Ordovician/Silurian

Regional Distribution of the Dykes

Northern Britain as a whole

Figure 1 summarizes the regional distribution of lamprophyres over northernmost England, Scotland, and part of Ireland, based on the most recent work available. Dykes also occur farther south and west in Ireland (*e.g.*, McArdle 1974), but their countrywide distribution has not been recently described. On a province-wide scale, the distribution of intermediate and felsic dykes *broadly* follows that of lamprophyres, though concentrations, particularly of felsites, occur locally where there are few or no lamprophyres (*e.g.*, Smith 1979; Fig. 2 here; see also British Geological Survey [BGS] 10-mile map, 1979). Ignoring areas of younger cover, where they are not expected, dykes are seen to occur in most areas except where Caledonian magmatism as a whole is virtually unrepresented (*e.g.*, Outer Hebrides: Fettes *et al.* 1988). Dykes are most abundant in the Southern Uplands, the southwestern and central Grampian Highlands, and the central Northern Highlands. Dykes are almost the *only* representatives of Caledonian magmatism in the pre-Caledonian Foreland, Kintyre, the Hebrides, and the Palaeozoic inliers of NW England (Fig. 1).

Although magma volumes are necessarily difficult to estimate, something of the order of 10^4 dykes, each typically several meters wide and in some cases traceable for up to several tens of kilometers, must be equivalent to several additional plutons in the province. Indeed, one remarkable dyke-complex at Black Stockarton Moor, adjacent to the Criffell pluton (Fig. 2), is by itself equivalent to a pluton. It was originally mapped (BGS sheet 5W) as quasi-plutonic masses covering some 30 km^2; recent work (Leake & Cooper 1983) indicates internal crustal extensions of up to 50%. Again, dykes are so abundant in parts of the Etive–Cruachan pluton (Fig. 1), that the whole shape of the body has been modified (elongated) by their emplacement.

Southern Scotland

Figure 2 complements Figure 1 by providing a far more detailed breakdown for three distinct ranges of dyke composition over some 10,000 km^2 of southern Scotland. The distributions of mafic (lamprophyre), intermediate (porphyrite) and felsic (porphyry) dykes are seen to be quite distinct. This feature was formerly concealed by 'lumping' of different compositions on, for example, the BGS 1:625,000 map. *Mafic* dykes are most abundant in a 10-km-wide regional zone in the extreme south (Rock *et al.* 1986b), and in a swarm centered on the Loch Doon pluton (Fig. 2d). *Intermediate* dykes are mostly centered on the three large granitic plutons in the southwest (Fig. 2c). *Felsic* dykes are almost confined to a zone in the northeastern part of the area (Fig. 2b), apart from one or two around the Fleet and Doon plutons. Similar distinctions in distribution can be confirmed on a smaller scale, for example south of Wigtown (Figs. 2a,c,d), where porphyrite dykes are confined to a 2-km-wide zone within an intense swarm of lamprophyres (Barnes *et al.* 1986). The regional zone of felsic dykes almost certainly corresponds with the geophysically inferred subcrop of the "Tweedale granite batholith" (Lagios & Hipkin 1979), which emerges in several places as small cupolas (Fig. 2a).

Comparison of Figure 2b–d implies that nearly all felsic and intermediate dykes from 'central' swarms around plutons, to which they are consequently even more closely linked than the lamprophyres, which form both 'central' and 'regional' swarms. This is logical, since the felsic-intermediate dykes correspond compositionally with the granites–granodiorites of the plutons, whereas the lamprophyres have no immediate plutonic equivalents. Dykes are also contemporaneous with calc-alkaline *volcanic rocks* in the Midland Valley, in the Glencoe–Ben Nevis–Etive areas and, less markedly, at Cheviot (Figs. 1,2).

Timing and Relationship of Dykes to Granitic and Syenitic Plutons

On any realistic large-scale geological map, the intense dyke-swarms around certain Caledonian granitic and syenitic plutons, and their apparent lack around other felsic plutons, constitute one of the most eye-catching features. However, despite numerous [and, according to Brown *et al.* (1985), largely overgeneralized] attempts to classify the Caledonian plutons according to age, geophysical signature, petrology and style of emplacement, no review of the province has yet even considered the presence or absence of dykes as a classification tool, let alone what actually controls whether dykes are present or absent.

Such relationships may in fact be crucial for understanding *both* plutonism *and* dyke magmatism. Granitic and syenitic plutons are spatially associated with lamprophyric swarms not only in the British Caledonides, but worldwide and throughout the geological record (Rock 1984). Although some recent summaries (*e.g.*, Carmichael *et al.* 1974) have regarded granite–lamprophyre associations as fortuitous (the dykes supposedly invading fracture patterns induced by the earlier and unrelated pluton), most early mappers — notably those in Scotland, with their legendary field acumen — regarded such associations as real and quite unequivocal (*e.g.*, Hill *et al.* 1905).

Evidence that dyke–pluton spatial relationships are also temporal and probably genetic

(1) The few direct age determinations on dykes are mostly within analytical error of far more numerous published ages for associated plutons (Table 1a), but field evidence in many other cases is sufficient to prove the contemporaneity of dykes and plutons (Table 1b).

(2) Hornblendic lamprophyres appear to be heteromorphic (review in Rock 1984) with rocks of the Appinite suite (appinite, kentallenite, *etc.*), which form extensive clusters of pipes and diatremes, notably around the Ballachulish, Etive, Garabal Hill and Ardara (NW Ireland: Hall 1967) plutons (Fig. 1). The appinite suite in turn is unequivocally contemporaneous with the earlier magmatism within each pluton (*e.g.*, Pitcher & Berger 1972). This suite, though concentrated in the Scottish Highlands and Ireland, is also represented in the Southern Uplands (Barnes *et al.* 1986) and English Lake District.

(3) In widespread composite dykes, lamprophyres coexist with (and may grade into) acidic porphyries which closely resemble spatially associated granitic rocks (*e.g.*, Iona, Cross Fell: Fig. 1); such dykes are particularly strong evidence not only of simultaneous emplacement but also of a strong genetic connection between lamprophyric and granitic magmas (Arthurton & Wadge 1981, Rock 1984, Rock & Hunter 1987, Gaskarth *et al.* 1988).

(4) Certain lamprophyres around the Criffell–Bengairn–Dalbeattie pluton (Southern Uplands, Fig. 1), have both the chemical and isotopic characteristics required for parent magmas to the pluton itself (Macdonald *et al.* 1986): progressive interaction between lamprophyre magmas and country rocks has generated a contaminated–differentiated suite of dyke rocks that closely mimics variations within the pluton. The same may well apply to lamprophyres around the Ross of Mull pluton, Inner Hebrides (Rock & Hunter 1987).

(5) Harmon *et al.* (1984) and others have inferred that Late Caledonian granites had Sr, Ba and K-rich, basic parent magmas, to explain their chemical peculiarities, but have not proved unequivocally that these magmas reached the surface. Lamprophyres are the only exposed rock-types which fit all the characteristics inferred by these authors.

No volume problem is necessarily involved in having minor intrusions as parents to large plutons, since the lamprophyres acted at least partly as a heat source for crustal melting, rather than as actual end-member components. On the contrary, Harmon *et al.* (1984) surmised that overall Caledonian magmatism could be explained by a volume of basic rocks less than 20% of the whole, which corresponds

TABLE 1. EVIDENCE FOR CONTEMPORANEITY OF LATE CALEDONIAN GRANITIC PLUTONS AND THEIR SPATIALLY ASSOCIATED LAMPROPHYRIC DYKE-SWARMS

(a) Direct dating

Name of pluton (Fig. 1)	Age of pluton,Ma	Age of associated dykes,Ma	References (in addition to Brown *et al.* 1985)
Threlkeld,N.England	438±6[a] }		
Shap, N.England	397±7[a,b,c] }	409±12,410±12,420±13	Nixon *et al.* (1984)
Criffell, S.Scotland	397±2[a]	Range 397–>418[a,b]	Rock *et al.* (1986b)
Cockburnlaw,S.Scotland	408±5[a]	400±10[b]	Rock & Rundle (1986)
Iona/Ross of Mull,Hebrides	414±3[a]	406±10–420±20[a,b]	Beckinsale & Obradovich (1973); Authors' unpublished data
Råtagain, N.Highlands	415±5[a]	413±10–431±10[b]	Authors' unpublished data

(b) Representative types of field evidence

Name of pluton	Age,Ma	Evidence for overlapping dykes/plutonism	Selected references
Numerous[d]	c.400	Early dykes hornfelsed/veined by pluton; later dykes cut pluton	Bowes (1962); Grant (1966); Cameron & Stephenson (1985)
Ben Nevis,Highlands	?400	Dykes cut outer 'granite' of pluton, but absent from (or altered by) core 'granite'	Bailey (1960)
Strontian, Highlands Ratagain,Highlands	435 415	Appinite/lamprophyre xenoliths in pluton; lamprophyre dykes cut pluton	Sabine (1963)
Ratagain,Highlands	415	Acidic dykes closely related to granites both cut and are cut by lamprophyre dykes.	Smith (1979)

[a] Rb-Sr isochron measurements.
[b] K-Ar biofite, hornblende and whole-rock measurements.
[c] Field and palaeomagnetic evidence suggests the dykes may be related to either or both of these bodies, which may form part of a complex underlying pluton (the "Lake District batholith" - e.g. Macdonald *et al.* 1985, fig. 1). See further discussion in Rock (1984, p.214).
[d] Includes Ballachulish, Criffell, Distinkhorn, Doon, Etive, Newry, Ross of Mull.

remarkably closely with Watson's (1984) estimate for the volume of dyke rocks within the province.

Central (pluton-related) versus regional (pluton-independent) dyke-swarms, and the episodicity of dyke emplacement

At least one fully regional, subparallel, 10-km-wide zone of dykes reaching for over 300 km has a less obvious connection with the plutons. This swarm extends from Northern Ireland across the entire Southern Uplands to St.Abbs (Figs. 1, 2d), and though it fringes several plutons, many of its dykes substantially predate the granites by up to 20 Ma (Rock *et al.* 1986a,b, Barnes *et al.* 1986). This 'regional' zone, in areas away from plutons (*e.g.*, Ards, Rhinns of Galloway and Wigtown Peninsulas, Berwickshire, Hawick area), is dominated by biotite lamprophyres. Hornblende lamprophyres become much more abundant in the immediate vicinity of the Criffell pluton, however, and also dominate the 'central' swarm around the Doon pluton just to the north (Fig. 2d). Moreover, biotite lamprophyres are confined to the southern tips of the Wigtown and Rhinns Peninsulas, whereas hornblende lamprophyres are geographically unrestricted (Barnes *et al.* 1986). All this implies a petrological distinction between central (dominantly hornblendic) and regional (dominantly micaceous) swarms, which happen to overlap in the Criffell area. A similar distinction may also apply in the Highlands (based on much less information), but it is not universal: lamprophyres associated with the Ross of Mull pluton (Fig. 1), for example, are dominantly micaceous in the immediate vicinity of the pluton but dominantly hornblendic on Iona to the west (Rock & Hunter 1987).

The existence of both 'central' and 'regional' swarms probably reflects the great episodicity and regional spread of dyke magmatism: dykes were repeatedly emplaced probably from before 430 Ma to after 395 Ma. The earliest lamprophyric dykes in many areas are cleaved, sheared or foliated, offset or crushed by Caledonian faults, or incorporated as xenoliths in later acidic rocks; an unusually extensive (but long-neglected) swarm of 'sheared porphyrites' occurs in southwestern Scotland (Fig. 2c). The latest lamprophyres, by contrast, locally invade Lower Devonian conglomerates (themselves derived by erosion of the Caledonides), and thus represent the youngest of all Caledonian igneous rocks (Smith 1979, Rock & Rundle 1986).

Furthermore, several distinct dyke phases can be distinguished within the best exposed and most concentrated swarms (*e.g.*, 4 phases at Black Stockarton Moor: Leake & Cooper 1983). Locally paradoxical field relationships (*e.g.*, A cuts B, but B also cuts A) are also quite common (*e.g.*, Table 1b). Within apparently contiguous swarms in other areas, where field evidence is less abundant or less well understood, 'central' and 'regional' dykes of different ages, or even distinct 'central' swarms related to more than one pluton, may therefore coexist. This is one possible explanation for the clear macroscopic division (Barrow *et al.* 1905) around the Glen Tilt pluton (Fig. 1), into brown, mostly biotite-rich, "lamprophyres of Kinloch Rannoch type" and green, mostly hornblendic, "lamprophyres of Carn Dearg type". This juxtaposition emphasizes the now urgent need for detailed resampling with combined petrographical and chemical examination of these dyke-swarms on a regional basis. Such sampling is no less required to determine whether any local or regional, progressive changes of magma type occurred with time. At present, far too few even of the analyzed dykes have been dated (either absolutely or relatively) to throw any light on this important aspect.

Reasons for the absence of lamprophyric dyke-swarms around other Caledonian granitic plutons

Perhaps half of the 70-odd Caledonian granitic plutons figured by Pankhurst & Sutherland (1982) and Brown *et al.* (1985) have no dykes obviously associated with them, for one or more of the following reasons:

(1) Some of these plutons are 'older' (> 500 Ma), 'Type 1' (440–480 Ma) or late (*ca.* 400 Ma) '*S*-type' bodies, including migmatitic complexes, all of which were derived by partial melting of crustal materials (Brown *et. al.* 1985), and would not therefore be expected to show such a close relationship to primitive, K-rich, ultimately mantle-derived (Rock 1987a) lamprophyric magmas. Perhaps the clearest example is in the Southern Uplands, where the '*I*-type' (diorite–granite) Doon and Criffell plutons have vast dyke-swarms, whereas the contemporaneous '*S*-type' (dominantly 2-mica) granite of Cairnsmore of Fleet has virtually none (Figs. 1, 2). These older, pre- to synorogenic granites, moreover, were forcefully emplaced in compressional tectonic regimes, which would not be conducive to dyke emplacement.

(2) Some plutons are relatively uniform bodies of biotite granite alone (*e.g.*, Cairngorm, Aberdeen on Fig. 1); though derived from subcrustal sources (Brown *et al.* 1985), their lack of basic plutonic rocks leads to a not unexpected lack of basic dykes.

(3) In other cases, poor exposure may mask the real distribution of dykes. For example, the East Grampian Highlands (Fig. 1) includes over a dozen granitic plutons, but inland exposure is so notoriously bad that no less than an entire 10 km^2 pluton — the Auchlee granite — has mysteriously vanished from the latest editions of BGS map-sheet 87 (Aberdeen)! Its existence was previously inferred from gra-

nitic veins, which ultimately proved misleading. The chances of small dykes being exposed inland are therefore infinitesimal, although their actual occurrence in the area is confirmed along the coast, for example around Gardenstown (Fig. 1 and BGS sheet 96).

In general, the progressive relaxation of the crust with time (Brown *et al.* 1985) encouraged maximum emplacement of dykes during the later stages of the magmatic cycle. The 'typical' pluton with a well-represented dyke-swarm is therefore post-tectonic, passively emplaced, 'Type 2' (440–410 Ma) or 'Type 3' (415–396 Ma: Pankhurst & Sutherland 1982), of diverse petrology (basic-acidic, usually with well-represented dioritic/appinitic rocks), and complex, multiple intrusion. Although no detailed comparisons have yet been made, more subtle (or cryptic) differences may explain differences in dyke abundances around some adjacent plutons sharing all these 'typical' characteristics (*e.g.*, Etive and Rannoch Moor, which also are contemporaneous). For example, Hall (1967) noted that Caledonian granites associated with appinites plot toward a higher pressure liquidus minimum in the Qtz–Ab–Or system (*i.e.*, crystallized under higher water pressures) than those without appinites.

TABLE 2. REPRESENTATIVE NEW COMPOSITIONS OF LAMPROPHYRES FROM THE SCOTTISH BORDERS

Type	Hornblendic		Mica lamprophyres				
Sample	NX1396	NX1411§	NX1421*	NX1422*	NX1423*	NX1473	NX1511
U.K.NGR	7860	7741	9189	9189	9175	9682	5263
[NT]	5972	6050	6847	6847	6806	5898	6219
SiO_2	55.92	57.76	54.53	53.00	50.09	51.90	50.68
Al_2O_3	14.71	15.69	11.98	12.19	11.26	12.74	13.80
Fe_2O_3	7.51	6.95	5.76	6.56	5.85	5.18	6.49
MgO	6.81	4.83	6.08	5.76	5.19	6.38	5.71
CaO	6.11	6.09	5.10	5.31	8.68	7.55	7.47
Na_2O	2.84	3.04	0.35	0.10	0.95	2.79	2.69
K_2O	2.75	2.75	5.31	5.67	3.74	3.31	4.24
LOI	2.68	2.09	8.70	9.06	11.46	7.72	7.47
TiO_2	0.81	0.93	1.43	1.47	1.30	1.47	1.09
P_2O_5	0.27	0.33	0.64	0.67	0.63	1.13	0.93
MnO	0.14	0.15	0.09	0.12	0.10	0.12	0.12
Total	100.55	100.61	99.97	99.91	99.25	100.29	100.69
Trace elements (ppm), in order of atomic number							
V	164	133	143	139	153	164	158
Cr	280	127	505	506	513	466	349
Ni	72	61	209	185	201	199	170
Cu	54	64	28	42	19	41	62
Zn	94	69	52	46	52	105	74
Rb	50	58	129	119	115	80	97
Sr	908	925	236	262	485	725	1177
Y	24	26	24	24	22	40	21
Zr	167	212	763	814	733	421	308
Nb	9	11	16	17	17	27	19
Ba	1065	972	1343	1394	1326	1178	1627
Th	10	11	13	15	15	24	21
U	3	4	6	6	6	6	4

All data by P.Shand using conventional XRF methods at Aston University. Most of the above analyses were performed on two separate machine calibrations, with consistent results.

• Three analyses of the same lamprophyre dyke dated by Rock & Rundle (1986), sampled in two localities.
§ Gradational to porphyrite, with some feldspar phenocrysts.

TABLE 3. SOURCES AND NUMBERS OF ANALYSES FOR BRITISH LATE CALEDONIAN DYKE-ROCKS

Area (*listed from NW to SE*)	Total[1] dykes	Lamps[2] only	Primitive[3] lamps only	Sources of data
Summer Isles,-do-	1	1	1	Thompson *et al.* (1984)
Assynt(Loch Borralan),-do-	3	3	3	Sabine (1953)[4]
Ratagain,-do-	1	1	1	Thompson *et al.* (1984);Thompson & Fowler(1986)
Migdale,-do-	1	1	1[8]	Read *et al.* (1926)[4]
Glen Affric,N.Highlands	2	2	2	Author's new data; see Table 4
Iona/Ross of Mull,Hebrides	88	36	23	Rock & Hunter(1987)
Strontian,Great Glen	1	1	1	Gallagher (1963)[4]
Appin area,Grampian Highlands	??	12	??	Wright & Bowes (1979)[9]
Arrochar area,-do-	17	10	8	Authors' unpublished data
Loch Lomond/Loch Fyne,-do-	??	7	??	Wright & Bowes (1979)[9]
Northeast Southern Uplands	18	17	13[8]	Table 3 & authors' unpublished data
Southwest Southern Uplands[6]	155	123	110	Rock *et al.* (1986a,b), Table 3 & authors' unpubl. data
Cross Fell inlier,N.England	18	9	9	Burgess & Holliday (1979);Macdonald *et al.* (1985); Gaskarth *et al.*(1987)
Shap area,-do-	15	6	2	Macdonald *et al.*(1985)
Kendal area,-do-[7]	6	6	6	-do-
Sedbergh area,-do-	26	22	21	-do-; Thompson *et al.* (1984); Nixon *et al.* (1984)
Ingleton inlier,N.England	1	1	1	-do-
GRAND TOTALS	>372	258	>202	

1 Total analyses for *all* types of dyke-rocks (lamprophyres, porphyrites, porphyries, etc.)
2 Total analyses of lamprophyres only, as used in Table 4.
3 Analyses of *primitive* lamprophyres only, as defined on Figure 4.
4 No trace element data available.
5 Dykes from Borders and Lothian Regions (Lammermuir Hills, St.Abbs etc.)
6 Dykes mostly from the Criffell-Wigtown Peninsula areas, with a few from around Hawick (Fig.1), but all from the regional lamprophyre zone (Fig. 2d) adjacent to the Iapetus Suture trace (Rock *et al.* 1986b).
7 Includes dykes from Long Sleddale, Furness and Docker Fell.
8 Not included on Figure 4 as these areas lie off the orthogonal traverse of Figure 1.
9 Original raw data unavailable; only averages published for lamprophyres.

Genetic relationships between lamprophyres and syenitic plutons

Although syenitic rocks are relatively rare in the Caledonides, genetic relationships between syenites and lamprophyres are at least as strong as those between granites and lamprophyres. One extensive lamprophyre–felsite swarm (Sabine 1953) intimately associated with the K-rich Loch Borralan pyroxenite–syenite pluton (Fig. 1) is an excellent example (in global terms) of 'association B' of Rock (1984) – 'shoshonitic' lamprophyres associated with 'shoshonitic' intrusive bodies. Another well-developed lamprophyric dyke-swarm is associated with the uniquely transitional (alkaline/calc-alkaline) Glenelg–Ratagain pluton (Fig. 1), which contains significant amounts of syenite and quartz syenite. Thompson & Fowler (1986) have shown from whole-rock geochemistry that these lamprophyres are close analogs to the parent magmas for all Caledonian syenitic plutons (*i.e.*, Loch Ailsh, Loch Loyal, and Glen Dessarry, as well as Borralan and Glenelg–Ratagain on Fig. 1). These authors suggest that the sequence of increasing silica oversaturation: Borralan → Ratagain → granitic pluton, is one of increasing crustal contamination of these parent lamprophyric magmas, combined with fractionation (fractionation alone yielding syenites).

AVAILABILITY OF CHEMICAL DATA (TABLES 2,3,4)

Since our earlier reports on progress in the Southern Uplands (Rock *et al.* 1986a,b), numerous dykes have been analyzed from areas previously barren of data; Table 2 cites representative examples of our most recent analyses for one such area, the Scottish Borders (Fig. 1). A start also has been made with the vast Highland swarms, with new analyses from Iona (Rock & Hunter 1987), Arrochar and Glen Affric (Table 4) — all areas with no previous data. As older individual analyses for the Highlands are few and inconveniently scattered (Table 3), Table 4 brings them together for the first time, along with lamprophyre means for all areas we now regard as satisfactorily covered. Although 372 dykes have already been analyzed, Figure 1 indicates the

TABLE 4. COMPILATION OF MEAN AND INDIVIDUAL COMPOSITIONS FOR CALEDONIAN LAMPROPHYRES ACROSS NORTHERN BRITAIN

Block*	NORTHERN HIGHLANDS OF SCOTLAND									
Area*	Summer Is	Assynt			Ratagain	Migdale	Glen Affric¶		Iona	Strontian
N#	1	1	1+	1+	1	1+	1	1	36	1
SiO_2	43.06	47.22	52.47	54.09	58.10	44.90	45.60	51.80	52.61	46.1
Al_2O_3	9.95	13.06	12.15	15.02	15.46	9.64	10.70	13.20	16.70	12.4
Fe_2O_3	9.17	4.20	3.47	4.12	5.16	2.30	2.40	3.08	7.93	3.1
FeO	na	7.34	5.25	5.15	na	4.40	4.90	4.34	na	6.1
MgO	15.37	11.16	9.94	7.28	5.69	7.42	11.00	7.11	5.00	9.7
CaO	10.08	7.74	9.71	7.72	5.26	10.22	8.30	5.82	5.44	11.4
Na_2O	0.74	2.33	2.81	1.99	4.81	1.36	3.30	1.75	4.41	0.4
K_2O	5.52	2.38	2.26	3.55	4.32	5.71	2.80	5.71	2.88	4.4
TiO_2	2.08	1.05	na	na	0.90	1.80	1.28	1.45	1.51	2.8
P_2O_5	3.10	0.59	na	na	0.80	3.31	1.39	0.96	0.57	1.93
MnO	0.14	0.26	na	na	0.08	0.26	0.11	0.10	0.12	0.11
Trace elements (ppm), in order of atomic number										
Li	na	na	na	na	na	na	na	36	na	na
Be	4	na	na	na	3	na	na	na	na	na
Sc	na	na	na	na	na	na	na	na	14	na
V	na	na	na	na	na	na	na	80	158	na
Cr	551	na	na	na	153	na	na	150	165	na
Co	na	na	na	na	na	na	na	40	na	na
Ni	445	na	na	na	106	na	na	173	60	na
Cu	42	na	na	na	21	na	na	na	24	na
Zn	121	na	na	na	79	na	na	93	82	na
Ga	15	na	na	na	29	na	na	na	na	na
Rb	135	na	na	na	75	na	22	209	48	na
Sr	1687	na	na	na	4631	na	422	1105	917	na
Y	32	na	na	na	21	na	21	22	19	na
Zr	709	na	na	na	622	na	275	308	222	na
Nb	32	na	na	na	18	na	14	20	18	na
Ba	9024	na	na	na	2650	na	71	2856	1331	na
La	na	na	na	na	na	na	280	118	42	na
Ca	na	na	na	na	na	na	30	209	90	na
Hf	16	na	na	na	9	na	na	na	na	na
Pb	12	na	na	na	19	na	na	na	8	na
Th	16	na	na	na	11	na	11	16	6	na
U	4	na	na	na	3	na	3	na	na	na

Areas listed from northwest to southeast, as in Table 3 and Figure 4.

TABLE 4 (contd.)

	GRAMPIAN HIGHLANDS			SOUTHERN UPLAND		NORTHERN ENGLAND				
Area	Appin	Arrochar	L.Lomond	Borders	Criffel	CrossF	Shap	Kendal	Sedbergh	Ingleton
N#	12	10	7	123	9	6	6	22	1	
SiO_2	49.00	53.89	56.23	53.60	51.92	53.32	55.90	49.43	46.51	45.00
Al_2O_3	13.82	15.00	15.71	13.62	13.73	14.28	13.29	15.28	11.45	12.34
Fe_2O_3	2.07	3.33	2.20	7.03	6.94	5.80	3.86	3.74	5.08	2.83
FeO	6.32	4.26	5.10	na	5.09	5.15	3.16	4.80	4.84	5.67
MgO	8.62	6.28	4.90	5.89	8.06	6.94	4.15	7.37	8.43	8.88
CaO	7.73	4.87	6.28	6.85	6.56	5.15	6.19	6.80	9.00	8.61
Na_2O	2.79	3.49	3.11	2.03	2.84	2.67	2.34	2.32	1.18	1.16
K_2O	2.14	2.75	2.25	4.04	2.69	3.54	5.11	4.00	4.14	5.10
TiO_2	0.76	0.99	1.00	1.34	1.03	1.21	1.04	1.43	1.11	1.65
P_2O_5	0.28	0.34	0.22	0.71	0.55	0.76	0.60	0.78	0.97	1.04
MnO	0.13	0.14	0.14	0.12	0.13	0.32	0.19	0.16	0.20	0.19
Trace elements (ppm), in order of atomic number										
Li	14	36	na	na	na	90	na	na	na	na
Be	na	na	na	na	na	na	na	na	6	na
Sc	34	na	22	na	na	17	21	23	27	na
V	222	147	214	152	183	122	130	190	166	213
Cr	316	201	142	329	479	346	122	266	567	411
Co	46	28	28	na	na	28	22	40	40	42
Ni	126	102	46	148	178	155	75	174	299	250
Cu	121	32	47	50	46	14	42	na	41	na
Zn	89	78	80	68	70	92	58	na	54	na
Ga	12	na	22	na	na	11	na	na	14	na
As	na	na	na	18$	na	na	na	na	na	
Rb	57	75	67	89	68	116	143	78	118	147
Sr	942	696	482	738	633	623	911	897	1567	484
Y	15	20	na	24	23	26	29	28	31	30
Zr	102	200	210	461	186	254	281	240	296	360
Nb	5	8	12	18	12	19	26	18	18	24
Sn	na	1	na	na	na	na	na	na	na	na
Sb	na	na	na	na	1$	na	na	na	na	na
Cs	na	na	na	na	na	na	3	3	7	na
Ba	825	1073	621	1740	1704	1514	1537	1452	2992	1545
La	34	40	11	na	na	na	112	na	92	na
Ce	48	80	22	na	77	195	276	254	234	182
Hf	na	na	na	na	na	8	7	6	9	na
Au	na	na	na	na	0.14$	na	na	na	na	na
Pb	24	12	14	8	13	na	na	na	24	na
Th	6	6	23	14	10	28	41	26	32	50
U	na	2	na	5	4	na	7	5	7	na

\# Number of analyses averaged: N = 1 means only one analysis is available for the area; N > 1 means the data are the arithmetic mean for N rocks from the same general area. Means for different elements in some areas are based on smaller N, owing to varying element-sets analyzed by different authors. Note that figure here correspond to the *middle* column in Table 3, i.e. *unscreened* lamprophyre analyses; they complement rather than equal to those of *primitive lamprophyres only* used in Figure 4.

\+ Analyses of suspect quality due to age, high totals, etc. (reasons elaborated in Rock 1984).

* As annotated in Fig.1 and Table 3; for literature sources, see Table 3.

¶ New analyses by U.K. Government Chemist using conventional XRF methods.

§ Analyzed samples (8) deliberately selected from those with *high* contents of As (Rock *et al.* 1987).

na = not analysed (no data available).

NOTE: means are regarded as inferior averages (relative to the various 'robust' estimates used in Figure 4) for data of this type; they are provided here merely because of their greater familiarity to petrologists.

sisyphean task still ahead! The significance of exceptionally high Au and correlated As contents in some Southern Upland dykes, reaching 523 ppb and averaging 140 ppb (Table 4), is discussed elsewhere (Rock *et al.* 1987).

Implications of Differences Between Biotite and Hornblende Lamprophyres

The preponderance of biotite and hornblende lamprophyres, respectively, in regional and central swarms was noted above. Barnes *et al.* (1986) further showed the two types to be chemically distinct in the Wigtown Peninsula (Fig. 1). New data (Table 3) confirm similar distinctions over a far wider area of Southern Scotland as follows (Fig. 3):

(a) Biotite lamprophyres tend to be higher in CaO, K_2O, P_2O_5, Rb, Ba, Zr, Nb and *LREE* but lower in Si contents (Fig. 3 a,c,e). Y shows rather more overlap, but is still stochastically higher (Fig. 3e).

(b) The two groups overlap completely in Ni, Cr, Mg and Ti contents (Fig. 3b,f), suggesting that the differences in other elements are a function neither of varying degree of partial melting of the source, nor of varying extents of crystal fractionation or accumulation.

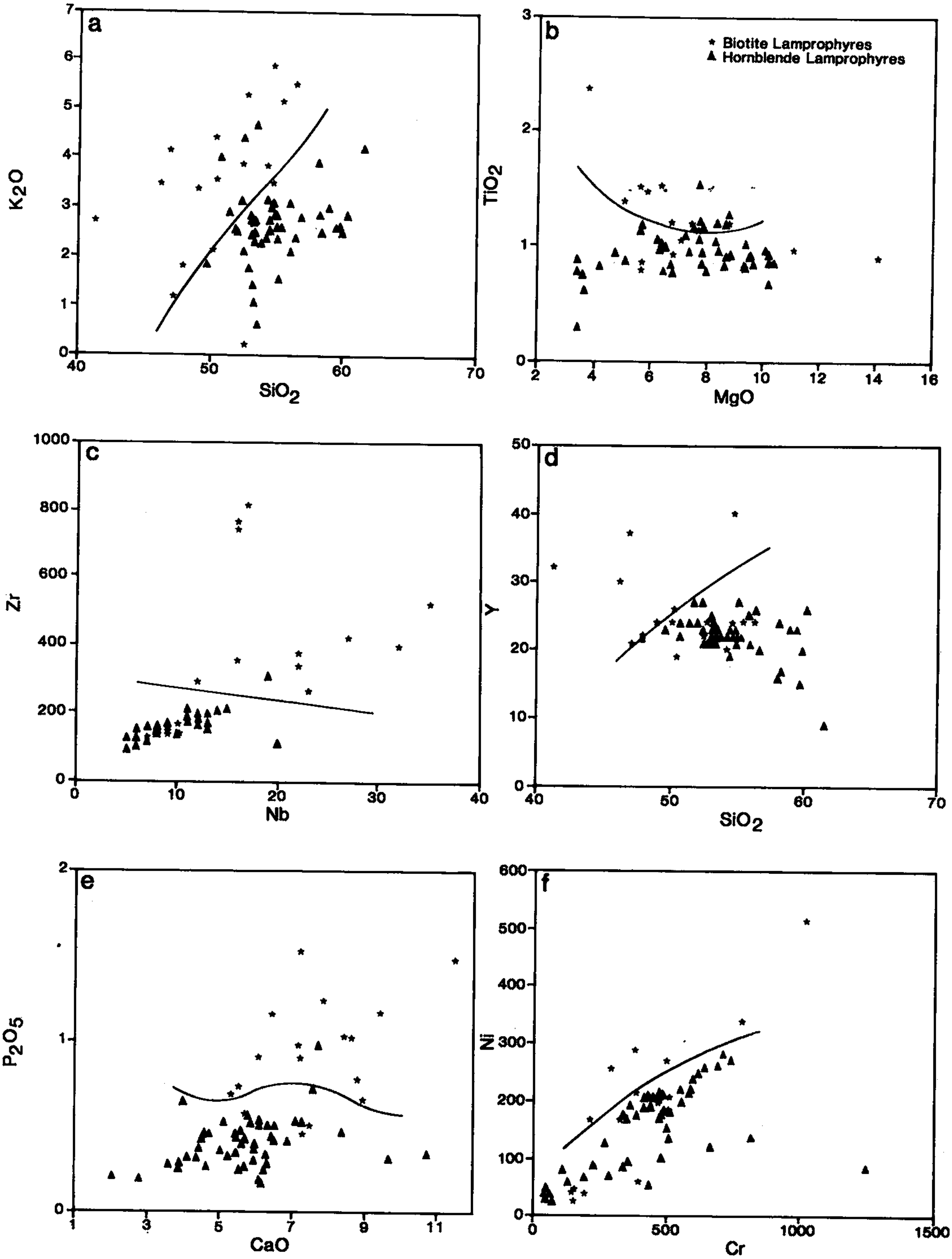


FIG. 3. Simple representative plots illustrating differences between the whole-rock chemistry of biotite and hornblende lamprophyres from the area of Figure 2. Data from Table 2 (and unpubl.). Dykes from the Wigtown Peninsula, Kirkcudbright, Criffell, Hawick, Sedbergh and St. Abbs areas (Fig. 1) are included. Only the lines on a, c and e can be considered to efficiently separate the two fields.

(c) The hornblende lamprophyres show much more tightly clustered values for Zr and Nb (*e.g.*, Fig. 3c).

Macdonald *et al.* (1985) and several other authors have inferred the balancing control of CO_2 *versus* H_2O over generation of lamprophyric (as opposed to other alkalic) melts from metasomatized mantle sources. The following experimental evidence implies that the same balance may control whether biotite or hornblende lamprophyres are produced: (i) the H_2O component of a fluid dominates mantle melting behavior at pressures up to above 25–26 kbar, owing to its higher solubility in melts, but at higher pressures CO_2 becomes the dominant control (Wyllie 1978, 1979, Morse 1980); the lower stability limit for most amphiboles, at 26–30 kbar, also coincides with the reduced dominance of H_2O. (ii) H_2O favors a much more siliceous melt (from any given source material) than does CO_2 (*e.g.*, Kushiro 1972). (iii) CO_2 transports *REE* (especially *LREE*) and probably Zr and Nb more efficiently than does H_2O (Wendlandt & Harrison 1979). Previously noted aspects of the chemistry and distribution of the biotite lamprophyres are thus consistent with their ultimate origin at greater depths (>*ca.* 80–100 km) than the hornblende lamprophyres, in a more CO_2-dominated melting regime, which generally precludes a close association with granites. The Caledonian granites clearly crystallized under 'wet' conditions, which precluded their eruption (due to the negatively sloping *P–T* solidus curve for wet melts), but favored their association with hornblende lamprophyres. Further studies on these aspects are now in progress.

Chemical Variations in Lamprophyre Dykes across the Iapetus Suture and Caledonian Province as a Whole

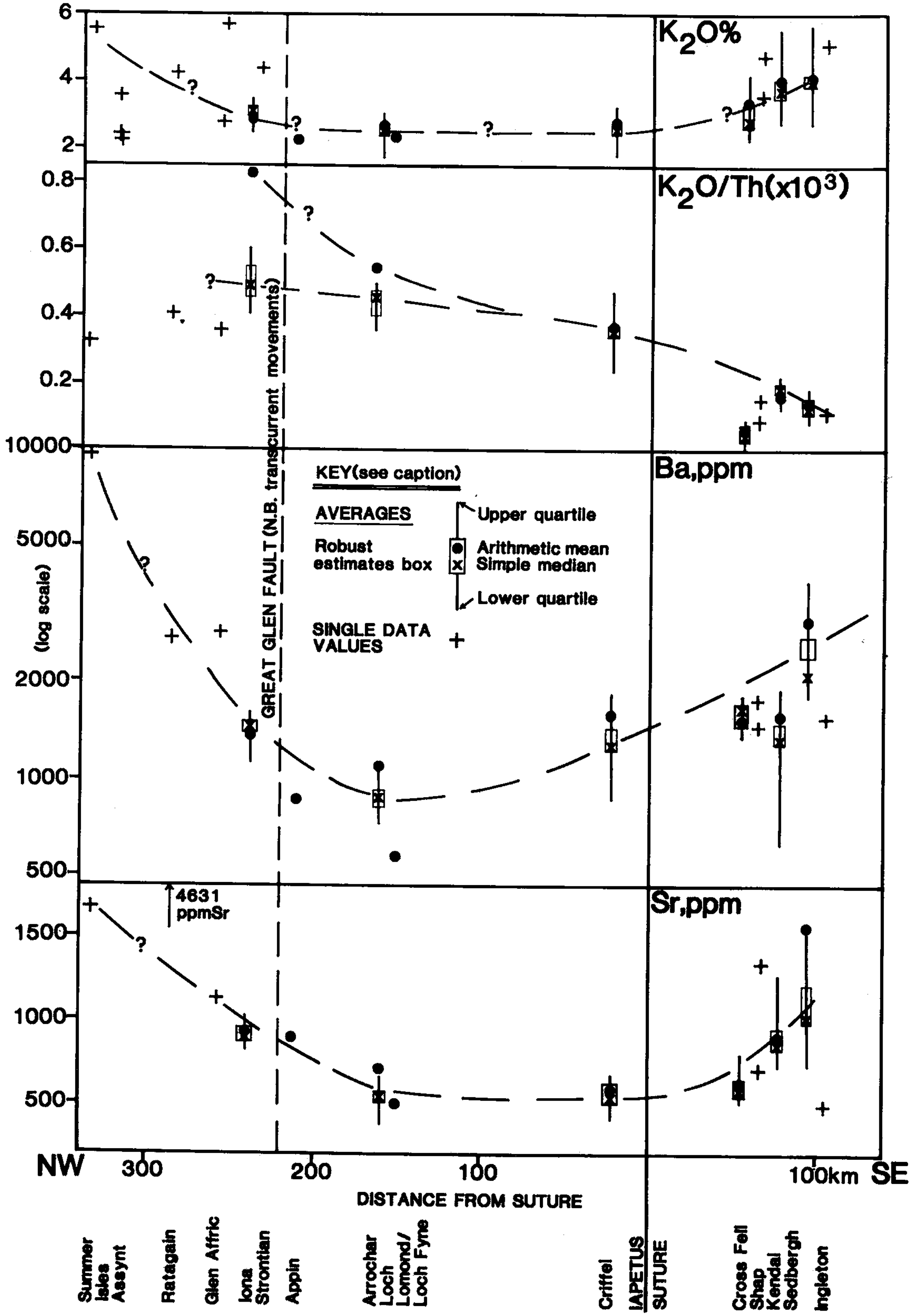
Regional NW–SE variations across the western part of the Caledonian province

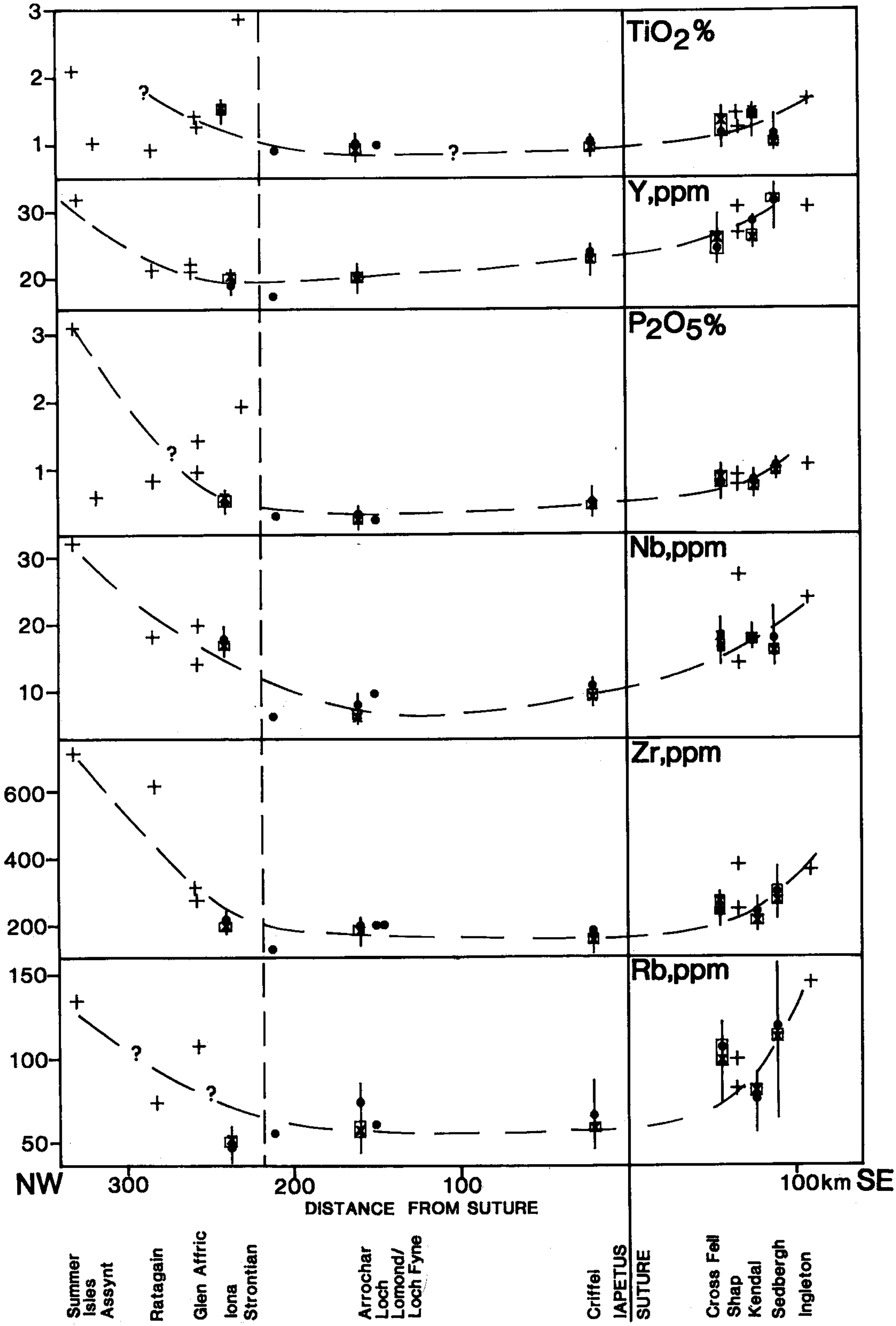
Figure 4 is a preliminary summary of known variations in contemporaneous lamprophyres, *versus* approximate distance from the 'Iapetus Suture' (Fig. 1). To try to highlight tectonically rather than magmatically controlled variations, Figure 4 compiles data for primitive lamprophyres only, defined both petrographically and chemically as in Thirlwall (1981). Figure 4 also restricts compilation to the west and southwest of the province, to minimize uncertainties over distances from the Suture, owing to possible Suture curvature in the North Sea (*e.g.*, Fig. 6 of Thirlwall 1981). Collectively, the more than 200 screened compositions constitute a reasonable 'first attempt' at a chemical traverse normal to the Suture. Although the effect of large-scale transcurrent movements (Watson 1984) should be borne in mind, such movements are unlikely to affect our conclusions because the movements are generally thought to have been parallel or subparallel to the Suture, and would therefore not affect the ordering of areas on the abscissa of Figure 4.

Factors tending to obscure any real trends on Figure 4 include: (a) probably inconsistent definitions of 'lamprophyre' in the 11 sources of data (Table 3); (b) interlaboratory analytical differences (especially with trace elements, or between pre-1960 and recent data); (c) the patchy data distribution and inadequate coverage for many areas. Again, the urgent need for a unified, province-wide analytical program is underlined. Despite these obfuscating factors, however, the following hitherto unsuspected variations are still implied by Figure 4: (i) Sr and Ba clearly increase in both directions away from central Scotland; Rb, Ti, Y, Zr, Nb and P show more diffuse, but equivalent trends. (ii) K/Th shows a possible monotonic increase from southeast to northwest, at least as far as the Great Glen; farther northwest, more analytical data are needed. (iii) None of the trends is clearly centered on the inferred position of the Iapetus Suture, although most reach minima not far to its north. (iv) A rather faint trend for K_2O is obscured in the northwest by 'noise' from individual analyses (some of which are suspect — Table 4); unfortunately, no normalization is possible (*cf.* Whitford & Nicholls 1976, who obtained regressed 'K_{55}' values [K_2O at SiO_2 = 55%] on modern subduction-related lavas), because present correlations and regressions between K_2O and SiO_2 are statistically insignificant (based on *F* ratios, Pearson's *r*, Spearman's ρ and Kendall's τ). Note particularly that some of the above trends are obscured if arithmetic means are plotted alone; the mean is not a reliable average for geological datasets which, like these, are far from normally distributed and contain gross outliers (Rock 1988b).

Differences between lamprophyres immediately N and S of the Suture (southernmost S. Uplands and Lake District)

Among analyzed lamprophyres from the Southern Uplands, only 6% have Th > 20 ppm (mean ± s.d. = 10±5), as opposed to 88% of those from the English Lake District (mean Th = 32±11); a discrimination efficiency of about 90% is thus achievable on this one element alone. (Note: respective Th data were obtained on XRF spectrometers at Lancaster and Aston universities, whose mutual analytical comparability has been extensively and specifically confirmed). Two-group linear discriminant analysis increases this remarkable efficiency of classification to 93% using a Th–Sr discriminant function, and to 97% using a 10-element function.


K2O%
K2O/Th(x10^3)
Ba,ppm
(log scale)
Sr,ppm
4631 ppmSr
GREAT GLEN FAULT (N.B. transcurrent movements)
KEY(see caption)
AVERAGES
Robust estimates box
Upper quartile
Arithmetic mean
Simple median
Lower quartile
SINGLE DATA VALUES
NW
SE
300
200
100
100km
DISTANCE FROM SUTURE
Summer Isles
Assynt
Ratagain
Glen Affric
Iona
Strontian
Appin
Arrochar
Loch Lomond/
Loch Fyne
Criffel
IAPETUS
SUTURE
Cross Fell
Shap
Kendal
Sedbergh
Ingleton



TiO_2%
Y,ppm
P_2O_5%
Nb,ppm
Zr,ppm
Rb,ppm
NW
300
200
100
100km
SE
DISTANCE FROM SUTURE
Summer Isles
Assynt
Ratagain
Glen Affric
Iona
Strontian
Arrochar
Loch Lomond/
Loch Fyne
Criffel
IAPETUS SUTURE
Cross Fell
Shap
Kendal
Sedbergh
Ingleton

Comparison of trends for the dykes with those for Late Caledonian plutonic and volcanic rocks in northern Britain

The variations in Figure 4 partly mirror, but also significantly extend, previously reported variations in the contemporaneous plutonic and volcanic rocks (Pidgeon & Aftalion 1978, Thirlwall 1981, 1982, Fitton *et al.* 1982): (i) some of the trend minima on Figure 4 seem to correspond to the boundary in central Scotland separating northerly granites (with older, inherited zircon) from southerly granites lacking these features (Pidgeon & Aftalion 1978). Other trends, however, appear to reach minima farther north. (ii) The northwesterly directed trends for Sr, Ba, Ti, P, Nb and K mirror trends in the more primitive lavas, with the Nb trend perhaps rather better defined in the dykes; however, the continuation of these trends, not only southeast of the Southern Uplands Fault (Fig. 1) but even southeast of the Iapetus Suture, is unique to the dykes, and therefore of paramount importance. (Lavas southeast of the Fault, at St. Abbs and Cheviot, do not fit the pattern farther north, and no lavas at all are present southeast of the Suture). (iii) The absence of a clear trend for Th also mirrors the lavas. (iv) The Rb, Zr and Y trends are unique to the dykes; the lavas show no change for Rb or Zr, and Y decreases to the northwest. The dyke chemical trends are intuitively more consistent than those in the lavas, as all *LIL* element concentrations (including Rb) and all high field-strength element concentrations (including Zr, Y) show similar trends.

Arguments for the primary, magmatic origin of the chemical trends on Figure 4

Although these trends must be regarded as tentative, given the patchy data-base, we believe them to reflect primary, province-wide, magmatic variations rather than, say, localized, secondary processes. For example, although the state of alteration and weathering of Caledonian lamprophyres is notoriously variable, six arguments suggest that weathering cannot explain these trends: (1) published data are invariably for the petrographically least altered samples available. (2) The 'robust' estimates used on Figure 4 already eliminate extreme values produced by unusually intense weathering. (3) Trends for CaO, H_2O and CO_2 would be expected, but are absent. (4) Only the trends for 'mobile' elements (K, Rb, Ba, Sr) on Figure 4 could even theoretically have been produced by weathering, and only if this was systematically less intense in the center of the province. (5) Smooth alteration trends from a dozen widespread and independently sampled localities are in practice highly improbable even for one element, and consistent trends for numerous mobile and 'immobile' elements are virtually impossible. (6) The mirroring of chemical trends in the plutonic and volcanic rocks by trends in the dykes must reinforce the geological reality and primary origin of all; the appearance of fortuitous or secondary trends in rocks of such different modes of occurrence is entirely inconceivable.

Like Thirlwall (1981), therefore, we contend that the systematic behavior of mobile and less mobile elements implies that these lamprophyres have not been grossly altered from primary magmatic compositions. By further extension of his arguments, we also consider that the lamprophyre dykes have retained relatively unadulterated chemical fingerprints of their sources and depths of generation compared to the lavas or plutonic rocks, because they are uniformly more 'mantle-like' in chemistry, specifically, more primitive (Rock *et al.* 1986b). They are therefore likely to be more significant in regional tectonic interpretation, to which we finally turn.

FIG. 4. Highly tentative chemical traverse across the western part of northern Britain, illustrating variation in the 'average' composition of primitive Siluro–Devonian lamprophyre dykes, *versus* approximate distance from the 'Iapetus Suture' of Figure 1. Over 25 other elements show no discernible trends. Only 'primitive' dykes are compiled wherever possible, with $SiO_2 < 60\%$, *mg* (mole % $Mg/[Mg+Fe^{2+}]$ with $Fe^{3+}/[Fe^{2+}+Fe^{3+}]$ normalized to 0.3) > 60%, Cr > 200 ppm, and Ni > 75 ppm. (Most analyses have substantially more Cr and Ni than this — up to 1000 ppm Cr, 550 ppm Ni). Only incomplete mean values are available, however, for the Appin and Loch Lomond/Loch Fyne areas (Table 3), so no account can be taken of primitive status or otherwise. 'Robust' averages and variability estimates are used, to eliminate the noise of outlying values caused by suspect earlier analyses or weathering/alteration (or both), to allow for non-normal data distributions, and to make the above cut-offs for the definition of 'primitive' less critical. Averages are indicated by modified box-plots constructed from arithmetic means, medians, interquartile ranges, and ranges for some 15 other robust estimates, including the Gastwirth median, trimean, and various trimmed, skipped and adaptive estimates (Rock 1988b). Note how the arithmetic mean sometimes lies far outside the 'robust box' or even interquartile range, being excessively influenced by outliers. Much less reliance should thus be placed on the single data-values available for one or two localities. Distances to the Suture from Summer Isles to Strontian assume present geography, and are dependent on movements on the Great Glen Fault (Fig. 1). No data are compiled for the many dykes in the east and north of the province (*e.g.*, Borders area in Tables 3, 4), owing not least to uncertainties over the azimuth of the suture in the North Sea (Thirlwall 1981). Data sources detailed in Table 3. Table 4 gives complementary but different mean values for all (rather than just primitive) analyzed lamprophyres.

Importance of the Dykes for Tectonic Modelling of Caledonian Magmatism

The Caledonian magmatic province is commonly related to closure of the Iapetus Ocean, in which Lower Paleozoic subduction of oceanic lithosphere, both northward and southward, was accompanied by extensive transcurrent movement (overviews in Thirlwall 1981, Brown *et al.* 1985). The 'Iapetus Suture' (Fig. 1) probably came into being in late Ordovician time, with final closure merging the southern (Celtic; now England) and northern (Laurentian; now Scotland) plates in late Silurian time. Geophysical, structural and sedimentological evidence for a palaeosuture along the present Solway Firth is increasing (*e.g.*, Hall *et al.* 1984). There are numerous problems with this model, however: Brown *et al.* (1985) were not even prepared to display the 'Iapetus Suture' on their compilation map of the province. Interpretation of the Southern Uplands of Scotland as a fore-arc accretionary prism leads in particular to numerous problems and paradoxes (Rock *et al.* 1986b, Barnes *et al.* 1986).

The chemical trends in the dykes, in relation to those of the lavas, have the following implications, some of which are mutually exclusive alternatives whose assessment will require new data:

(1) The contrasts between lamprophyres north and south of the Suture may support inferred differences in the underlying basement, Southern Uplands basement being Archaean–Proterozoic granulite, but the Lake District basement probably comprising accretionary arc-complexes no older than *ca.* 800 Ma (summary in Brown *et al.* 1985).

(2) K, Rb, Sr and Ba increase in modern calc-alkaline lavas with increasing depth to the subduction zone (*e.g.*, Jakes & White 1972). The mirrored trends on Figure 4 may therefore provide the first chemical support for the simultaneous, northward and southward subduction implied by the sum of existing tectonic interpretations for the Caledonian province (see overview in Thirlwall 1981, especially his tables 1,2). However, two notable problems (Rock *et al.* 1986b) remain: of (a) generation of large numbers of dykes (amounting to significant crustal extension) in a compressional regime; and (b) generation of K-rich (lamprophyre) dykes immediately adjacent to the Iapetus Suture in both southern Scotland *and* northern England.

(3) Alternatively to (2), the K/Th trend (Fig. 4) may support the suggestion (Barnes *et al.* 1986) that all the dykes are related to northward subduction along a suture substantially to the south of the area covered by Figures 1 or 2. K-rich character is then no longer a problem, for the dykes become excellent analogs for K-rich rocks well behind some modern arcs (*e.g.*, Java: Whitford & Nicholls 1976). The Southern Uplands area may thus have been in a back-arc rather than fore-arc setting at the time of dyke emplacement.

(4) These mutually exclusive conclusions (2) and (3) might possibly be reconcilable via the petrogenetic model of Macdonald *et al.* (1985) for the Lake District lamprophyres. These authors invoked metasomatism of supra-Iapetus oceanic lithosphere by fluids from two different sources, the resulting trace-element make-up being tripartite: (i) Ti, Yb *etc.* from mantle similar to the source material for MORB (probably, mantle overlying the subducting plate); (ii) Sr, K, Rb, Ba, Th, *LREE* and P from aqueous fluids driven from subducted oceanic crust; (iii) Zr, Hf, Nb, and Ta from CO_2-rich fluids related to degassing from sublithospheric sources. In terms of this multi-source model, the trends on Figure 4 could be interpreted in terms of increasing metasomatic enrichment of mantle sources away from central Scotland (rather than increasing depth to subduction zones), and could therefore be fitted into the overall model (3) of northward subduction.

(5) The relative timing of the two metasomatic events in Macdonald's model (4) could not be determined. Figure 4 may imply not only that component (i) was constant across the province (given the lack of Ti trends), but also that these metasomatic events were contiguous (to explain the parallel trends of components ii & iii).

(6) The contemporaneous, compositionally gradational, K-rich lamprophyric magmatism on both sides of the Iapetus Suture implies closer links between the orthotectonic and paratectonic Caledonides than assumed by most recent reviews (which have tended to emphasize only the differences between the granites, and the quite distinct ages and styles of volcanism, between Scotland and England). Emplacement of the earlier, sheared or foliated lamprophyres (at > 420 Ma, Table 1a), in contrast to both the granites and volcanic rocks, clearly predated the end of Silurian sedimentation and final closure of Iapetus by a significant interval, and yet it occurred on both sides of the Suture.

(7) Lamprophyres represent the only syn- to late-tectonic magmatism showing compositional and temporal continuity across the Suture.

We hope that the critical position of the lamprophyres in Caledonian magmatism is now therefore clear, and emphasize that complete and correct regional models cannot be achieved if dyke rocks continue to be ignored. Our continuing studies are directed at improving both the petrographical and chemical data-bases for these important, abundant, and undeservedly neglected rocks.

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REFERENCES

ARTHURTON, R.S. & WADGE, A.J. (1981): Geology of the country around Penrith. *Mem. Brit. Geol. Surv.* (sheet **24**).

BAILEY, E.B. (1960): Geology of Ben Nevis and Glen Coe. *Mem. Geol. Surv. G. Brit.* (sheet **53**).

BARNES, R.P., ROCK, N.M.S. & GASKARTH, J.W. (1986): Late Caledonian dyke-swarms in southern Scotland: new field, petrological and geochemical data from the Wigtown Peninsula, Galloway. *Geol. J.* **21**, 101-125.

BARROW, G., WILSON, J.S.G. & CRAIG, E.H.C. (1905): The geology of the country round Blair Atholl. *Mem. Geol. Surv. Scotland* (sheet **55**).

BECKINSALE, R.D. & OBRADOVICH, J. (1973): Potassium-argon ages for minerals from the Ross of Mull, Argyllshire, Scotland. *Scott. J. Geol.* **9**, 147-156.

BOWES, D.R. (1962): Kentallenite-lamprophyre-granite age relations at Kentallen, Argyll. *Geol. Mag.* **99**, 119-122.

BROWN, G.C., FRANCIS, E.H., KENNAN, P. & STILLMAN, C.J. (1985): Caledonian igneous rocks of Britain and Ireland. *Mem. Geol. Soc. London* **9**, 1-17.

BURGESS, I.C. & HOLLIDAY, D.W. (1979): The geology of the area around Brough-under-Stainmore. *Mem. Brit. Geol. Surv.* (sheet **31**).

CAMERON, I.B. & STEPHENSON, D. (1985): *British Regional Geology: The Midland Valley.* H.M.S.O. (London) for Brit. Geol. Surv.

CARMICHAEL, I.S.E., TURNER, F.J. & VERHOOGEN, J. (1974): *Igneous Petrology.* Wiley, New York.

FETTES, D.J., MENDUM, J.R., SMITH, D.I., MACDONALD, R., ROCK, N.M.S. & MYKURA, W. (1988): The geology of the Outer Hebrides. *Mem. Brit. Geol. Surv.* (in press).

FITTON, J.G., THIRLWALL, M.F. & HUGHES, D.J. (1982): Volcanism in the Caledonian orogenic belt of Britain. *In* Andesites (R.S. Thorpe, ed.). Wiley, New York.

GALLAGHER, M.J. (1963): Lamprophyre dykes from Argyll. *Mineral. Mag.* **33**, 415-430.

GASKARTH, J.W., THORPE, R.S. & MACDONALD, R. (1988): Caledonian magmatic processes deduced from petrology and geochemistry of minor intrusions in northern England. *J. Geol. Soc. Lond.* (in press).

GRANT, N.K. (1966): The Caledonian dykes associated with the northeast end of the Newry complex, County Down, Northern Ireland. *Geol. Mag.* **103**, 44-50.

HALL, A. (1967): The chemistry of appinitic rocks associated with the Ardara pluton, Ireland. *Contr. Mineral. Petrology* **16**, 156-171.

HALL, J., BREWER, J.A., MATTHEWS, D.H. & WARNER, M.R. (1984): Crustal structure across the Caledonides from the "WINCH" seismic reflection profiles. *Trans. Roy. Soc. Edinburgh, Earth Sci.* **75**, 97-112.

HARMON, R.S., HALLIDAY, A.N., CLAYBURN, J.A.P. & STEPHENS, W.E. (1984): Chemical and isotopic systematics of the Caledonian intrusions of Scotland and Northern England: a guide to magma source regions and magma-crust interaction. *Philos. Trans. Roy. Soc. London Ser. A,* **310**, 709-742.

HILL, J.B., PEACH, B.N., CLOUGH, C.T. & KYNASTON, H. (1905): The geology of mid-Argyll. *Mem. Geol. Surv. Scotland* (sheet **37**).

JAKES, P. & WHITE, A.J.R. (1972): Major and trace element abundances in volcanic rocks of orogenic areas. *Bull. Geol. Soc. Amer.* **83**, 29-40.

KUSHIRO, I. (1972): Effect of water on the compositions of magmas formed at high pressures. *J. Petrology* **13**, 311-334.

LAGIOS, E. & HIPKIN, R.G. (1979): The Tweedale granite – a newly discovered batholith in the Southern Uplands. *Nature* **280**, 672-675.

LEAKE, R.C. & COOPER, C. (1983): The Black Stockarton Moor subvolcanic complex, Galloway, *J. Geol. Soc. London* **140**, 665-676.

MACDONALD, R., ROCK, N.M.S., RUNDLE, C.C. & RUSSELL, O.J. (1986): Relationships between Caledonian lamprophyric and acidic magmas in a differentiated dyke, SW Scotland. *Mineral. Mag.* **50**, 547-557.

———, THORPE, R.S., GASKARTH, J.W. & GRINDROD, A.R. (1985): Multi-source origin of lamprophyres of nothern England. *Mineral. Mag.* **49**, 485-494.

McArdle, P. (1974): A Caledonian lamprophyre swarm in SE Ireland. *Sci. Proc. Roy. Soc. Dublin Ser. A*, **5**, 117-122.

McNeil, A.M. & Kerrich, R. (1986): Archean lamprophyre dykes and gold mineralization, Matheson, Ontario: the conjunction of LILE-enriched magmas, deep crustal structures and Au concentration. *Can. J. Earth Sci.* **23**, 324-343.

Morse, S.A. (1980): *Basalts and Phase diagrams.* Springer-Verlag, Berlin.

Nixon, P.H., Rex, D.C. & Condliffe, E. (1984): A note on the age and petrogenesis of lamprophyre dykes of the Cautley area, Yorkshire Dales National Park. *Proc. Leeds Geol. Assoc.* **10(4)**, 40-52.

Pankhurst, R.J. & Sutherland, D.S. (1982): The Caledonian granites and diorites of Scotland and Ireland. *In* Igneous Rocks of the British Isles (D.S. Sutherland, ed.). Wiley, New York.

Pidgeon, R.T. & Aftalion, M. (1978): Cogenetic and inherited zircon U–Pb systems in granites of Scotland and England. *In* Crustal Evolution in Northwestern Britain and Adjacent Regions (D.R. Bowes & B.E. Leake, eds.). *Geol. J. Spec. Issue* **10**, 183-220.

Pitcher, W.S. & Berger, A.R. (1972): The appinite suite: basic rocks genetically associated with granite. *In* Geology of Donegal (W.A. Pitcher & G. Berger, eds.). Wiley, New York.

Read, H.H. and 9 others. (1926): Geology of Strath Oykell and Lower Loch Shin. *Mem. Geol. Surv. Scotland.*

Richey, J.E. (1939): The dykes of Scotland. *Trans. Edinburgh Geol. Soc.* **13**, 343-435.

Rock, N.M.S. (1984): Nature and origin of calc-alkaline lamprophyres: minettes, vogesites, kersantites and spessartites. *Trans. Roy. Soc. Edinburgh: Earth Sci.* **74**, 193-227.

______ (1987a): The nature and origin of lamprophyres. *In* Alkaline Igneous Rocks (J.G. Fitton & B.G.J. Upton, eds.). *Spec. Publ. Geol. Soc. London* **30**, 191-226.

______ (1987b): Comment on paper by J.K. Leggett. *J. Geol. Soc. London* **144**, 751-752.

______ (1988a): Kimberlites as varieties of lamprophyres. *Proc. 4th Int. Kimberlite Conference, Perth, W. Aust.* (in press).

______ (1988b): Estimating averages in geology: a study of the performance of robust estimates. *J. Math. Geol.* (in press).

______, Cooper, C. & Gaskarth, J.W. (1986a): Late Caledonian subvolcanic vents and associated dykes in the Kirkcudbright area, Galloway, SW Scotland. *Proc. Yorks. Geol. Soc.* **46**, 29-38.

______, Duller, P., Haszeldine, R.S & Groves, D.I. (1987): Lamprophyres as potential gold exploration targets. *Univ. Western Aust. Geol. Dep. Extension Publ.* **11**, 271-286.

______, Gaskarth, J.W. & Rundle, C.C. (1986b): Late Caledonian dyke-swarms in southern Scotland: a regional zone of primitive K-rich lamprophyres and associated vents. *J. Geol.* **94**, 505-522.

______ & Hunter, R.H. (1987): Late Caledonian dyke-swarms of northern Britain: spatial and temporal intimacy between lamprophyric and granitic magmatism around the Ross of Mull pluton, Inner Hebrides. *Geol. Rundsch.* **76**, 805-826.

______ & Rundle, C.C. (1986): Lower Devonian age for the 'Great (basal) Conglomerate' of the Scottish Borders. *Scott. J. Geol.* **22**, 285-288.

Sabine, P.A. (1953): The petrography and geological significance of the post-Cambrian minor intrusions of Assynt. *Quart. J. Geol. Soc. London* **109**, 137-171.

______ (1963): The Strontian granite complex, Argyllshire. *Bull. Geol. Surv. G. Brit.* **20**, 6-42.

Smith, D.I. (1979): Caledonian minor intrusions of the N Highlands of Scotland. *In* Caledonides of the British Isles - Reviewed (A.L. Harris *et al.*, eds.). *Spec. Publ. Geol. Soc. London* **8**, 683-698.

Stone, P., Floyd, J.D., Barnes, R.P. & Lintern, B.C. (1987): A sequential back-arc and foreland basin thrust duplex model for the Southern Uplands of Scotland. *J. Soc. Geol. London* **144**, 753-764.

Thirlwall, M.F. (1981): Implications for Caledonian plate tectonic models of chemical data from volcanic rocks of the British Old Red Sandstone. *J. Geol. Soc. London* **138**, 123-138.

______ (1982): Systematic variation in chemistry and Nd–Sr isotopes across a Caledonian calc-alkaline volcanic arc: implications for source materials. *Earth Plan. Sci. Lett.* **58**, 27-50.

______, Morrison, M.A., Hendry, G.L. & Parry, S.J. (1984): An assessment of the relative roles of crustal and mantle in magma genesis, an elemental approach. *Roy. Soc. London Phil. Trans., Ser. A.* **310**, 549-590.

Thompson, R.N. & Fowler, M.B. (1986): Subduction-related shoshonitic and ultrapotassic magmatism: a study of Siluro–Ordovician syenites from the Scottish Caledonides. *Contr. Mineral. Petrology* **74**, 507-522.

WATSON, J.V. (1984): The ending of the Caledonian orogeny in Scotland. *J. Geol. Soc. London* **141**, 193-214.

WENDLANDT, R.F. & HARRISON, W.J. (1979): *REE* partitioning between immiscible carbonate and silicate liquids and CO_2 vapour: results and implications for the formation of *LREE* enriched rocks. *Contr. Mineral. Petrology* **69**, 409-419.

WHITFORD, D.J. & NICHOLLS, I.A. (1976): Potassium variation in lavas across the Sunda arc in Java and Bali. *In* Volcanism in Australasia (R.W. Johnson, ed.). Elsevier, Amsterdam.

WRIGHT, A.E. & BOWES, D.R. (1979): Geochemistry of the appinite suite. *In* The Caledonides of the British Isles — Reviewed (B.E. Leake *et al.*, eds.). *Spec. Publ. Geol. Soc. London* **8**, 699-704.

WYLLIE, P.J. (1978): Magmas and volatile components. *Amer. Mineral.* **64**, 469-500.

______ (1979): Mantle fluid compositions buffered in peridotite–CO_2–H_2O by carbonates, amphibole and phlogopite. *J. Geol.* **86**, 687-713.

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