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Relationships between late Caledonian lamprophyric, syenitic, and granitic magmas in a differentiated dyke, southern Scotland

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ABSTRACT. The 2 km × 5 m Newmains Dyke in the Scottish Southern Uplands consists mainly of primitive (mg number > 70), at least partly mantle-derived lamprophyre (vogesite–spessartite, SiO_2 50–60%), with hornblende-pyroxene-rich cumulates ($SiO_2 < 50\%$) and small amounts of quartz syenitic to granite residua (60–73% SiO_2). The lamprophyres and cumulates yield an Rb–Sr whole-rock isochron age of 395 ± 9 Ma (MSWD 2.0), and $(^{87}Sr/^{86}Sr)_i$ 0.70514 ± 5—identical values to the nearby Criffell granitic pluton. After some 65% hornblende + clinopyroxene fractionation of parent lamprophyre magma, a volatile phase separated and metasomatically enriched the country rock greywackes in K, Ba, and Rb. The remaining quartz syenitic liquids became contaminated by ^{87}Sr from these greywackes, which have a mean $(^{87}Sr/^{86}Sr)_{395}$ value of 0.70789 ± 114. Further fractionation of the contaminated syenitic liquids gave the granitic rocks, which have $(^{87}Sr/^{86}Sr)_{395}$ values of 0.7056–64. The dyke appears to demonstrate *in situ* some of the hidden processes previously invoked to explain the evolution of the Criffell pluton itself.

KEYWORDS: lamprophyre, syenite, granite, Caledonian, Newmains Dyke, Scotland.

RECENT isotopic studies (Stephens and Halliday, 1979; Halliday *et al.*, 1980; Halliday and Stephens, 1984) of zoned Caledonian granitoid plutons in the Southern Uplands of Scotland have shown that the dioritic components tend to have low $^{87}Sr/^{86}Sr$ initial ratios consistent with derivation from largely basaltic or mantle sources, while the more silicic, granodioritic and granitic, rocks have isotopic characteristics indicating an increasing proportion of a metasediment-derived component. *In-situ* contamination with crustal Sr from the sedimentary rocks of the aureoles has been judged (Halliday *et al.*, 1980) to be of negligible importance, and the increase in the sedimentary contribution is thought to be related to the mobilization of higher-level melts by upwards movement of magma from deeper levels and the preferential incorporation of these melts into the hot cores of the plutons.

The current study is complementary to work on the plutons. It explores the genetic relationship of silicic rocks to mafic Caledonian dyke rocks, the latter perhaps being nearer to uncontaminated, mantle-derived magmas than any rocks exposed in the plutonic masses. It also provides direct evidence of interactions between silicic magmas and country rocks. The study presents the first published isotopic data for S. Uplands dyke rocks, together with the first trace element and modern major element data for a critical body.

Geological setting

The Newmains dyke (Kennedy and Read, 1936; Reynolds, 1938), 7 km west of Dumfries, is one of a poorly documented regional suite of many thousands of late Caledonian minor intrusions in the Southern Uplands. This suite overlaps the period of emplacement of the major granitoid plutons and both suites are in some way related to events immediately prior to, and following, the closure of the Iapetus Ocean (Watson, 1984; Rock *et al.*, 1986). More specifically, the dyke lies within a 10 km zone, parallel to the regional strike and immediately NW of the assumed Iapetus

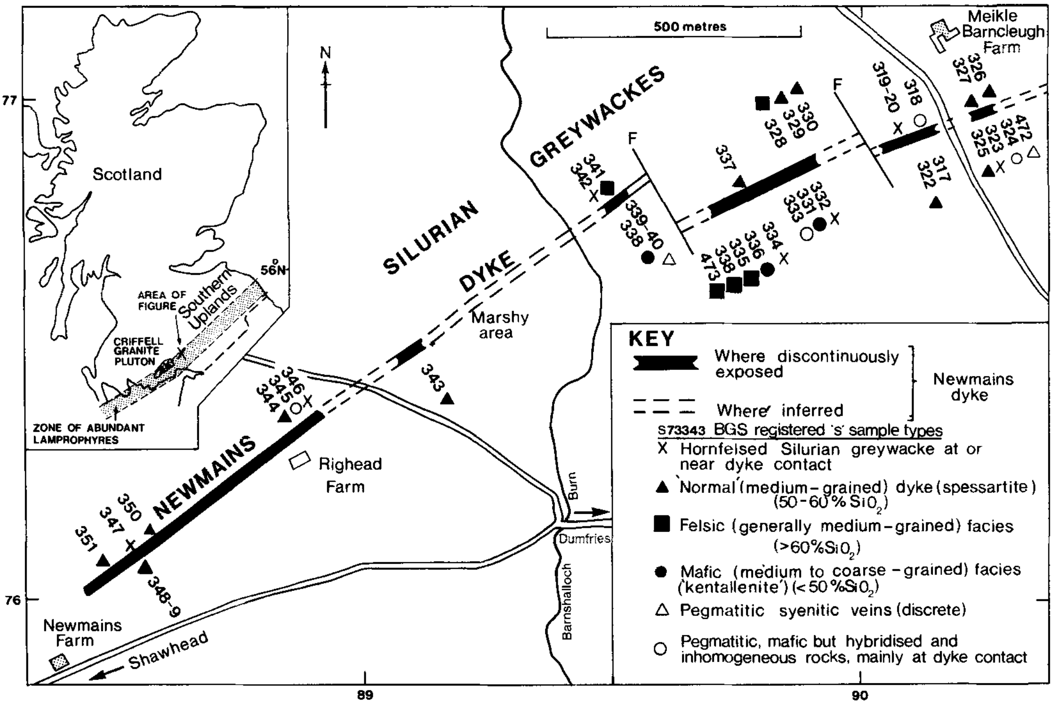

FIG. 1. Locality and sample location map. Marginal ticks are UK National Grid coordinates in 100 km square NX. Based on 1:10 000 mapping. Features such as locally sinuous margins, swelling and small-scale offsets exhibited by the dyke margins cannot be represented at this scale. Other lamprophyre dykes occur in the immediate vicinity but are omitted for clarity. One or two outcrops shown on BGS sheet 10W (Thornhill) as separate dykes are mapped as part of the one Newmains dyke, based on extrapolation of available exposure and petrographical/chemical affinities. Exposure was more continuous in 1984 than shown in Sheet 10W but less so than in Kennedy and Read (1936).

suture trace, in which lamprophyre dykes are particularly abundant (Rock *et al.*, 1986). It is the best exposed and largest of a local concentration of lamprophyric dykes within this zone, covering some 6 km^2 just W. of Dumfries (BGS sheet 9W—Thornhill). This dyke warrants special attention because, as far as we know, the range of differentiation and contamination phenomena which it exhibits is unique among British Caledonian minor intrusions.

The Newmains dyke (fig. 1) runs for just over 2 km, its NE-trending outcrop conforming with the strike of the country-rocks. The width varies along its length but averages 5 m. Exposure is good, except for a marshy central section.

Following Kennedy and Read (1936), we distinguish five broad groups of rocks within the dyke. (1) A *normal facies* comprises medium-grained, vogesite-spessartite lamprophyres. It is defined as having SiO_2 in the range 50–60 wt. %; these limiting values, firstly, correspond to the modal class (50%) and defined upper SiO_2 limit (60%) of such lamprophyres worldwide (Rock, 1984) and, secondly, divide Newmains rocks with 0–10% normative *qz* from those with *hy*+*ol* and those with > 10% *qz* (Table II). (2) A cumulate *mafic facies* (SiO_2 < 50%) is enriched in hornblende+clinopyroxene and may be classified as kentallenite (Kennedy and Read, 1936; Rock, 1984). (3) Rocks of the *felsic facies* (SiO_2 > 60%) are generally medium-grained, forming irregular patches and schlieren within the dyke. Two types of *pegmatitic variants* also occur: (4) discrete quartz syenitic veins up to 15 cm wide; and (5) more mafic, but inhomogeneous pegmatitic hybrid patches confined to the dyke contact or to the vicinity of greywacke rafts within the dyke. These mafic pegmatitic hybrids occur only where felsic rocks form local contacts against country rocks. They represent the first stages of more extensive hybridization (Kennedy and Read, 1936) between igneous and country rocks. Elsewhere, the dyke contact is sharp, although a zone of hornfelses extends outwards for some 2 m.

The mafic, felsic and pegmatitic facies together form only a small percentage of the intrusion (Kennedy and Read, 1936). Rocks of all groups show an irregular distribution across and along the dyke, illustrated diagrammatically by sampling location on fig. 1; most grade into each other.

The Silurian country rocks are a succession of folded greywackes and minor shales. Our sampling has concentrated on hornfelsed greywackes immediately adjacent to the dyke; sample S73320 and analysis 1, Table 1 of Kennedy and Read (1936) represent unmodified greywacke.

Petrography

The petrography of the dyke and country rocks has already been described in great detail (Kennedy and Read, 1936) and we provide here only a brief summary. New probe analyses of major minerals are given in Table I.

Lamprophyres of the *normal facies* have panidiomorphic-granular texture, and consist of abundant, euhedral prisms of amphibole (commonly cored by clinopyroxene) and turbid sodic plagioclase, in a granophyric mesostasis. Quartz forms scattered discrete grains. Apatite and Fe-Ti oxides are

TABLE I. Representative microprobe analyses of minerals in lamprophyric facies of Newmains dyke

	AMPHIBOLES*				CLINOPYROXENES			FELDSPARS			
Sample	S73337	S73345	S73348		S73345	S73348		S73337	S73348		
SiO_2	41.39	45.10	44.18	42.96	52.26	53.27	51.84	65.88	62.97	67.88	64.40
Al_2O_3	11.73	9.35	10.48	10.97	3.22	1.55	2.62	21.86	23.27	20.19	18.35
FeO_t	10.23	13.22	11.96	10.36	6.20	4.49	5.83	0.04	0.19	0.01	0.01
MgO	14.77	14.05	14.41	15.06	16.46	17.66	16.84	0.02	0.09	0.00	0.02
CaO	11.44	11.63	11.36	11.40	21.00	20.49	20.54	2.62	1.63	1.05	0.01
Na_2O	2.37	2.08	2.08	2.28	0.34	0.39	0.33	9.67	8.76	11.18	0.40
K_2O	0.85	0.76	0.74	0.77	-	-	-	1.17	2.06	0.06	16.19
TiO_2	3.28	1.85	1.25	2.76	0.76	0.26	0.57	0.00	0.00	0.00	0.00
MnO	0.15	0.31	0.25	0.15	0.19	0.16	0.22	-	-	-	-
Cr_2O_3	-	-	-	-	0.50	0.87	0.66	-	-	-	-
Total	96.21	98.35	96.71	96.71	100.93	99.14	99.45	101.26	98.97	100.37	99.38
Formula units											
O =	23	23	23	23	6	6	6	32	32	32	32
Si	6.087	6.530	6.440	6.259	1.904	1.959	1.915	11.439	11.262	11.839	11.981
Al	2.035	1.597	1.802	1.885	0.139	0.068	0.114	4.497	4.907	4.153	4.024
Fe^3	0.626	0.608	0.770	0.645	-	-	-	-	-	-	-
Fe^2	0.632	0.992	0.687	0.617	0.190	0.138	0.180	0.007	0.030	0.002	0.003
Mg	3.239	3.034	3.133	3.272	0.894	0.968	0.928	0.007	0.025	0.000	0.006
Ca	1.802	1.804	1.774	1.779	0.820	0.808	0.813	0.491	0.312	0.197	0.003
Na	0.676	0.584	0.588	0.644	0.025	0.028	0.024	3.270	3.036	3.781	0.146
K	0.160	0.140	0.138	0.143	-	-	-	0.262	0.469	0.015	3.844
Ti	0.363	0.201	0.137	0.302	0.021	0.008	0.016	0.000	0.000	0.000	0.000
Mn	0.019	0.038	0.031	0.019	0.007	0.006	0.007	-	-	-	-
Cr	-	-	-	-	0.015	0.026	0.021	-	-	-	-
Total	15.64	15.53	15.50	15.57	4.016	4.007	4.019	20.029	20.042	19.987	20.007
IMA (1978) name (Rock and Leake, 1984)	Titanium magnesio-hastingsite	Edenitic hornblende	Ferrian tschermakitic hornblende	Titanian magnesio-hastingsitic hornblende	%Fe 10	7	10	%Ab 81	80	95	3
					%Mg 47	51	48	%Or 7	12	<1	97
					%Ca 43	42	42	%An 12	8	5	<1

*Amphiboles were classified by computer. FeO_t was allocated to $Fe^2 + Fe^3$ (cations) such that Σ Si + Al + Fe + Mg + Ca + Mn + Ti = 13.0 per 23 oxygen formula unit.

accessory, chlorite, carbonate and epidote secondary phases. The amphiboles are hastingsitic hornblende (Rock and Leake, 1984), with moderate but variable Ti contents, and the clinopyroxenes are endiopside (Deer *et al.*, 1963), with notable contents of Cr and Al. EDS scans indicate that the carbonate phase is mainly, or wholly, calcite.

Difficulty was experienced during probe analyses of feldspars, partly due to alteration and partly due to the presence of both granophyric intergrowth and, apparently, myrmekite. Although An contents only range up to 12%, several distinct compositions appear to be present in different grains within single samples: albite-oligoclase (Ab_{88-90}), as already reported (Kennedy and Read, 1936); almost pure orthoclase (Or_{93-97}), almost pure albite (Ab_{95-96}), and alkali feldspars with approximate compositions Ab_{80} and Or_{70}. There is little evidence of zoning, and, for example, potassic feldspar (Or_{72}) occurs as clear overgrowths on sodic feldspar (Or_{20}) in S73348. EDS scans across three probe sections studied indicate the ubiquitous presence of each of these compositions.

These feldspar variations cause problems in the classification of the lamprophyre. Staining cannot reveal the relative proportions of plagioclase and alkali feldspars, due to the alteration, and probe scans tend to overestimate the proportion of orthoclase, which alone tends to form fresh, tabular grains suitable for probing. Streckeisen's (1979) classification only covers lamprophyres with dominant *K-feldspar* or *plagioclase*, and fails to cover those with abundant albite (Rock, 1984). The rock is probably best described as a vogesite-spessartite, but for simplicity, it is termed lamprophyre here.

Two analysed samples of *mafic pegmatitic hybrid* (S73318, S73333) are mineralogically similar to the

TABLE II Selected analyses of dyke rocks and greywackes, Newmains

	Mafic (kentallenite)		Normal (lamprophyric)				Felsic (syenitic-granitic)				Greywackes		
(S73---)	331	338	345‡	333‡	318	344	339‡	328	472	Mix	347	320	319
Major elements (wt %)													
SiO_2	46.5	48.5	51.9	54.3	55.6	58.0	62.8	66.5	73.3	50.6	54.3	59.7	68.3
TiO_2	1.80	1.13	0.71	0.59	0.90	0.88	0.41	0.61	0.09	1.08	0.99	0.96	0.66
Al_2O_3	12.43	12.92	9.46	13.93	14.34	15.22	18.16	15.69	14.07	12.95	18.29	16.23	10.60
Fe_2O_3*	9.07	8.55	6.74	7.10	6.79	6.49	3.71	4.10	1.67	8.31	9.59	7.63	4.41
MnO	0.14	0.17	0.17	0.15	0.14	0.12	0.08	0.12	0.03	0.16	0.13	0.12	0.10
MgO	10.32	10.13	10.28	9.82	8.85	7.79	2.63	3.85	0.54	10.65	7.45	6.48	3.33
CaO	10.35	8.36	10.57	5.06	5.46	4.85	3.39	2.07	0.44	9.12	3.62	5.13	7.55
Na_2O	1.80	1.87	1.22	2.25	2.55	2.75	3.33	3.30	2.77	2.53	0.81	1.30	2.10
K_2O	1.64	2.34	2.28	1.57	2.49	2.72	4.70	2.70	5.11	2.12	2.91	1.18	2.95
P_2O_5	1.01	1.01	0.17	0.32	0.29	0.29	0.40	0.17	0.08	-	0.21	0.21	0.16
mg no.	72.6	73.4	78.0	76.7	75.2	73.7	62.3	68.6	43.0	-	-	-	-
normative quartz	0	0	4.7	8.5	6.1	8.6	14.2	26.2	36.2	-	-	-	-
Trace elements (ppm)													
Ba	737	1655	946	719	1037	995	2410	656	2073	-	528	328	665
Ce	120	341	37	45	41	50	184	70	64	-	80	72	70
Cr	406	408	768	571	460	417	7	171	8	-	173	173	150
Nb	13	21	7	6	7	8	15	8	6	-	14	14	9
Ni	243	240	136	211	172	142	36	70	8	-	104	80	40
Rb	45	56	55	46	59	76	122	74	121	-	84	36	93
Sr	640	884	250	584	452	441	815	415	268	-	305	284	425
Th	7	8	5	7	6	6	17	11	13	-	14	14	11
Y	29	26	17	16	18	19	13	16	12	-	24	26	26
Zr	147	213	100	134	128	142	240	157	186	-	129	156	214

Fe_2O_3* – total Fe as Fe_2O_3 ‡ Pegmatitic facies

Mix = (0.35 x S73339) + (0.60 x average of 10 amphibole analyses) + (0.05 x average of 8 clinopyroxene analyses). Compare with S73338.

mg no. = Mg/(Mg + Fe), mole %, with Fe normalized to $Fe^3/(Fe^2 + Fe^3)$ cation ratio of 0.15.

normal lamprophyres, except that clinopyroxene is absent and the amphibole is notably zoned from a brown variety to pale green edenitic rims (Table I). A feature of the pegmatitic rocks, however, is extensive hydrothermal alteration, especially of plagioclase.

Rocks of the *mafic facies* are similar, but richer in hornblende (up to 70% modally) and clinopyroxene. These mafic phases form either euhedral crystals or aggregated mats of crystals, in association with apatite. The aggregates are rather patchily distributed, even on a hand specimen scale, and we interpret them as the products of synneusis during magma transport.

Rocks of the *felsic facies* are mineralogically similar to the lamprophyres but have less abundant amphibole, plentiful sodic plagioclase and a higher proportion of granophyric ± discrete quartz matrix. They range from syenites to granites, as the proportions of quartz:feldspar and granophyric intergrowth:plagioclase increase. The *pegmatitic syenites* are coarse-grained, pink to white in colour, and carry acicular hornblende crystals over 2 cm long. Their mineralogy is comparable to the syenites of the felsic facies.

Analytical techniques

Major- and trace-element analyses of 19 lamprophyres, 7 felsic rocks, 7 hornfelses, and 1 unmodified greywacke were made in Lancaster by XRF, using a Philips PW 1400 spectrometer. Representative analyses are given in Table II. Major elements were determined on fused glass discs and trace elements on powders. Estimated precisions for trace elements are (1σ): Ba, Ce, Cr, and Ni 2%; Nb and Y 3%; Rb and Th 5%; and Sr and Zr 1%. Also available were analyses of three igneous and two sedimentary samples (Kennedy and Read, 1936), though Na_2O determinations in those old data are systematically too high.

Igneous samples were reanalysed for Rb/Sr ratios at BGS, using an XRF system optimized for this measurement, with a precision (1σ) of 0·5%. International standards run at the same time were within 1% of the accepted value. Comparison of the two Rb/Sr data sets showed a mean deviation of 1·9 ± 5%, the Lancaster ratios having been calculated from less precise concentration measurements, whereas those BGS were calculated directly from intensity ratios for the two elements. Rb/Sr ratios of the greywacke samples were not redetermined at BGS and so an error of ±5% has been assumed. Strontium was extracted from 0·2 g aliquots of the powder by mixed acid digestion and ion exchange column chemistry, and analysed for 87/86 ratios using a VG 354 automatic solid-source, multi-collector mass spectrometer with an average precision of better than ±0.003% (1σ). A value of

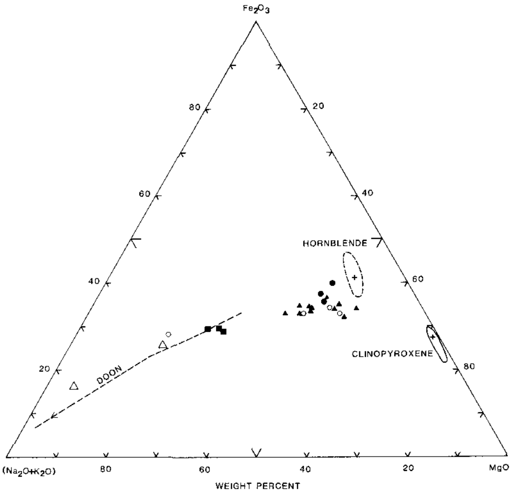

FIG. 2. AFM plot, with trend for Doon pluton (Brown *et al.*, 1979) shown for comparison. Fields of hornblende and clinopyroxene compositions outlined, a cross marking mean compositions. Symbols as in fig. 1. Analyses from Kennedy and Read (1936) not included, because of their anomalously high Na_2O values.

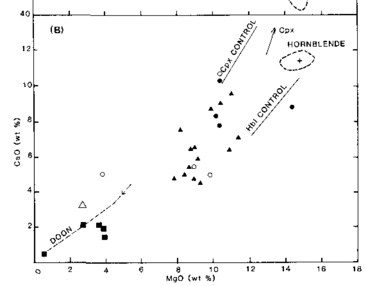

FIG. 3. MgO-variation diagrams. Fields of hornblende and clinopyroxene compositions outlined, a cross marking mean. Hornblende and clinopyroxene control lines chosen arbitrarily. Trend for Doon pluton from Brown *et al.* (1979). Estimated trend of Newmains liquids shown in A. Symbols as in fig. 1. Analyses from Kennedy and Read (1936) included.

0.710224 ± 18 was obtained for replicate analyses of the NBS 987 Sr standard run at the same time. Ages were calculated using a value of 1.42×10^{-11} a^{-1} for the decay constant of Rb. The regression technique was that of York (1969).

Geochemistry, age and origin of the Newmains lamprophyres

All Newmains dyke rocks are silica-over-saturated, *qz* increasing from 0 in the *ol*+*hy*-normative mafic facies to 36% in the most silicic rocks (Table II). On an AFM plot (fig. 2), they apparently define a typical, calc-alkaline trend. The trend is not a simple liquid line of descent, however, because as field, petrographic and previous chemical data already show (Kennedy and Read, 1936), the dyke clearly interacted with its host rocks, with loss of volatiles and formation of hybrids. We discuss the results of these processes by considering the mafic and felsic rocks separately.

Rocks of the mafic and normal facies show a range of compositions from 10.43% to 7.79% MgO. On MgO plots, they show some scatter about a trend which is interpreted as a hornblende ± clinopyroxene control (fig. 3). Rocks displaced from the trend have a high content of mafic aggregates and are relatively enriched in Ni and Cr. We interpret them as slightly accumulitic. High P_2O_5 concentrations in certain specimens (e.g. S73331 and S73338, Table II) confirm petrographic evidence of apatite accumulation also. These specimens also have high abundances of Sr, Ce, and Y, elements known to concentrate in apatite (Irving, 1978; Green, 1981).

Isotopic results are shown on a conventional isochron diagram in fig. 4. The normal and mafic lamprophyres define a 395 ± 9 Ma isochron, with an initial ratio of 0.70514 ± 5. Both age and initial ratio are statistically identical with values for the Criffell mass (397 ± 2 Ma; Halliday *et al.*, 1980) confirming a close relationship between the dyke and its plutonic neighbour. Pegmatitic mafic hybrid S73345 has an unusually low Sr content and thus high Rb/Sr ratio (Table II). Any loss of Sr invoked to explain this feature must have taken

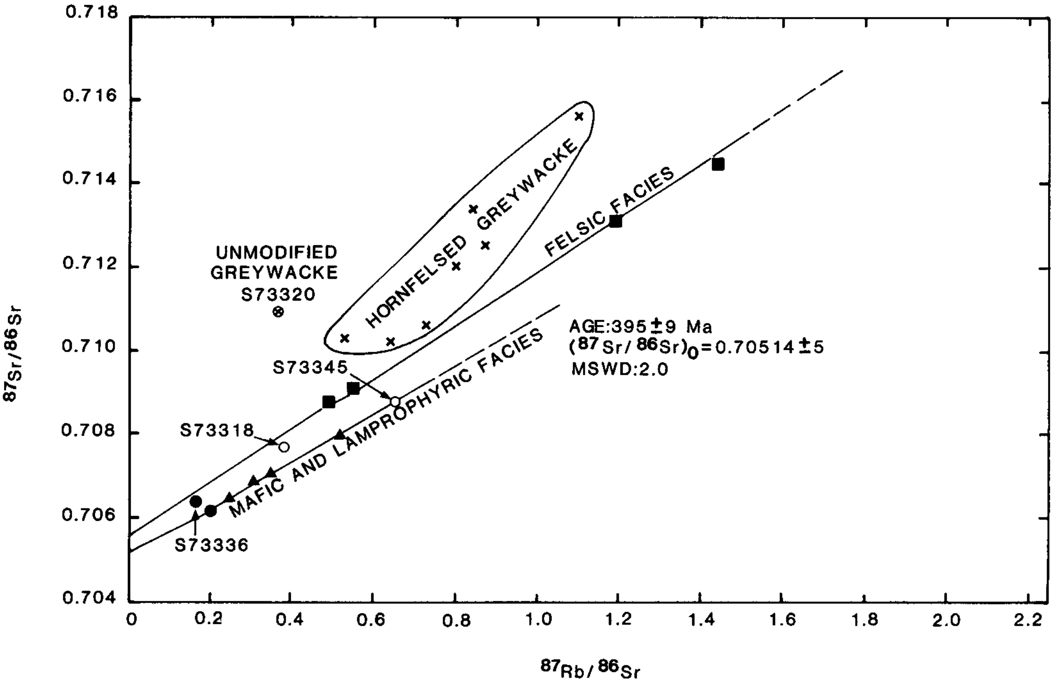

FIG. 4. Rb–Sr isochron diagram for Newmains dyke and country-rock greywackes. Symbols and sampling sites as on fig. 1. The 395 ± 9 Ma age is based on the six normal and mafic facies samples (SiO_2 < 60%) plus the pegmatitic mafic hybrid facies S73345, but excluding the most obvious outlier of this group, S73336. It is considered more precise, but not significantly different from, an age of 380 ± 27 Ma (MSWD 11.5) obtained using all 7 of these more basic samples. The same 7 samples yield a true isochron age of 381 ± 23 Ma (MSWD 1.1), with identical intercept of 0.70524 ± 12, if an error of 0.01% is assumed for the Sr isotope ratio measurements, instead of the recently attainable error of 0.003%.

TABLE III Rb-Sr isotopic data for the Newmains dyke

BGS Sample	$^{87}Rb/^{86}Sr^*$	$^{87}Sr/^{86}Sr^{\#}$	%SiO_2	Initial $^{87}Sr/^{86}Sr$ (395 Ma)
(a)	Normal and mafic facies (SiO_2 < 60%) [yielding 395Ma isochron]			
S73322	0.3430±17	0.70702±2	56.5	0.70514
S73329	0.2465±12	0.70658	51.0	
S73331	0.1910±10	0.70619	46.5	
S73336 ‡	0.1616±8	0.70624	49.0	
S73344	0.5168±26	0.70806	58.0	
S73345 **	0.6472±32	0.70877	51.9	
S73351	0.3022±15	0.70682	55.6	
(b)	Felsic facies (SiO_2>60%), except S73318			
S73318 **	0.3738±19	0.70766±2	55.6	0.70556
S73324	1.1983±60	0.71311	60.6	0.70639
S73328	0.5439±27	0.70908	66.5	0.70603
S73339 †	0.4313±22	0.70797	62.3	0.70555
S73341	0.4838±24	0.70870	66.8	0.70599
S73472	1.4336±72	0.71448	73.3	0.70644
(c)		Greywackes		
S73347	0.7990±43	0.71201±2	54.3	0.70753
S73346	0.5166	0.71036	54.1	0.70746
S73342	1.0931	0.71571	56.2	0.70958
S73332	0.7284	0.71061	65.9	0.70653
S73323	0.8246	0.71342	58.7	0.70879
S73320	0.3670	0.71096	59.7	0.70890
S73319	0.6352	0.71026	68.3	0.70670
S73317	0.8697	0.71249	65.5	0.70761
			Mean	0.70789±114

* ± figures assume errors of 0.5%

\# ± figures assume errors of 0.003%

** pegmatitic mafic rocks near margins of dyke

† Pegmatitic syenite vein

‡ Outlier on 395Ma isochron

place at, or before, 395 ± 9 Ma, since this specimen also lies on the isochron.

The initial ratio from the lamprophyre isochron (0.7051) is low enough to preclude the origin of these rocks by wholesale involvement of acidic crustal materials. It is not, however, low enough to preclude crustal involvement altogether, not least because (i) lamprophyres exclusively of mantle origin, which have risen fast enough to retain mantle xenolith assemblages, show even lower Sr ratios mostly of 0.703-0.704 (Rock, 1986); (ii) the adjacent country rocks show sufficiently low ($^{87}Sr/^{86}Sr)_{395}$ ratios (Table III) to suggest that *minor* contamination from either country rocks or deeper crustal materials through which the lamprophyres passed would scarcely affect their Sr ratios. *Mg* numbers and Cr contents of the lamprophyres are broadly in the range considered characteristic of 'primary', mantle-derived magmas (Rhodes, 1981), but again, Ni contents tend to be slightly low.

MORB-normalized patterns of the normal facies lamprophyres are similar to those for Caledonian lamprophyres of N. England (fig. 5), though lower in the high-field-strength (HFS) elements. Such patterns, with enrichment in large ion lithophile (LIL) elements relative to those of high ionic potential (HFS elements + *REE*), and strong negative Nb-anomalies, are most closely matched by relatively potassic magmas of subduction zones. It is likely (cf. Pearce, 1982) that such compositional characteristics are derived either from a two-stage origin, or from two magma sources. For example, abundances of such elements as Ti, Y, and the *HREE* in the N. English lamprophyres suggest

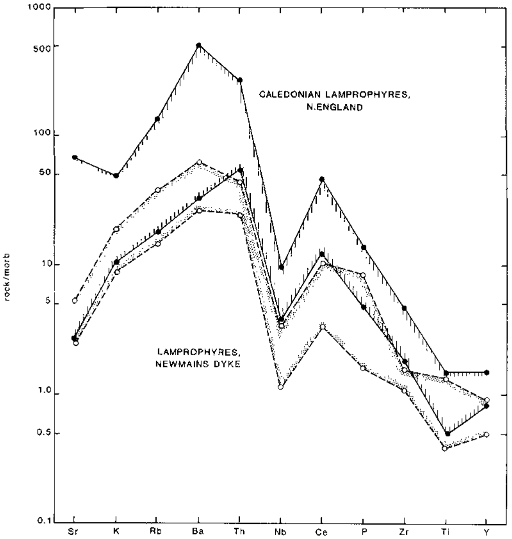

FIG. 5. Geochemical patterns for normal facies lamprophyres. Patterns for Caledonian lamprophyres of northern England (Macdonald *et al.*, 1985) shown for comparison. MORB normalizing values and ordering of elements from Pearce (1982).

mantle sources of 'depleted' type (Macdonald *et al.*, 1985). The enrichment in the LIL elements may represent a subduction zone component, possibly a result of metasomatism of the mantle sources by aqueous fluids driven from subducted oceanic crust.

On the basis of chemical similarity, we suggest that the parental lamprophyres of the Newmains dyke also had a complex, possibly multi-source origin (cf. Rock, 1984, 1986; Thompson *et al.*, 1984; Macdonald *et al.*, 1985), to which crustal contamination was a possible, but minor, contributor.

Derivation of the syenitic residua by lamprophyre fractionation

Quantitative modelling of the suggestion (Kennedy and Read, 1936) that the felsic rocks formed by fractional crystallization of the lamprophyres, is precluded by non-correspondence between rock and liquid compositions. This is seen in the K_2O data. On an MgO-K_2O plot (fig. 6), the felsic rocks split into two groups. A higher-K group plots close to, or above, the trends for the Criffell and Doon plutons, and close to extrapolated hornblende–lamprophyre trends. These high-K felsic rocks are typical of the high-K, British Caledonian granite province (Stephens and Halliday, 1984). A second group has considerably lower K_2O abundances, comparable to those in the lamprophyres. We suggest below that they have lost K to the country rocks.

The hypothesis that the higher-K rocks represent residual liquids from the lamprophyres is tested in Table II. The composition of pegmatitic quartz syenite vein S73339 can be modelled rather closely by the removal of a 12:1 mix of hornblende and clinopyroxene from the enclosing lamprophyre S73338. The percentage of crystallization is 65%, consistent with enrichments of 2–3 for such trace elements as Rb and Th which might be expected to have behaved incompatibly.

We therefore suggest that, after emplacement, *in situ* fractionation of parental lamprophyre magma produced volatile-rich quartz syenitic residua having *c.*60% SiO_2. These residua separated from the lamprophyres, one fraction being directly emplaced as the syenitic veins, another evolving further but quite separately.

Sr-isotopic evidence of dyke–greywacke interactions

The felsic rocks + pegmatitic mafic hybrid S73318 do not define an isochron (MSWD = 50) but the best fit line to the data (fig. 4) has a steeper slope than for the more basic rocks. The higher ratios of these samples are probably related in some way to interaction with the greywackes, which plot well

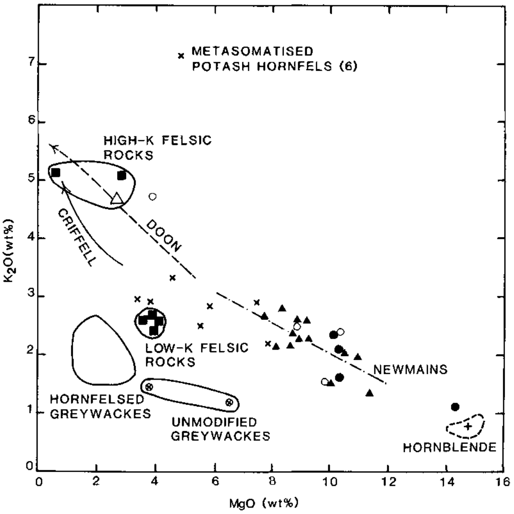

FIG. 6. MgO–K_2O plot. Field of hornblende compositions outlined, a cross marking mean. Symbols as in fig. 1, with the addition of circled crosses—unmodified greywacke compositions. Analysis of very potassic hornfels from Kennedy and Read (1936). Trends for Doon (Brown *et al.*, 1979) and Criffell (Stephens and Halliday, 1985) plutons shown for comparison. Greywacke field based on data in Pettijohn (1975, p. 228).

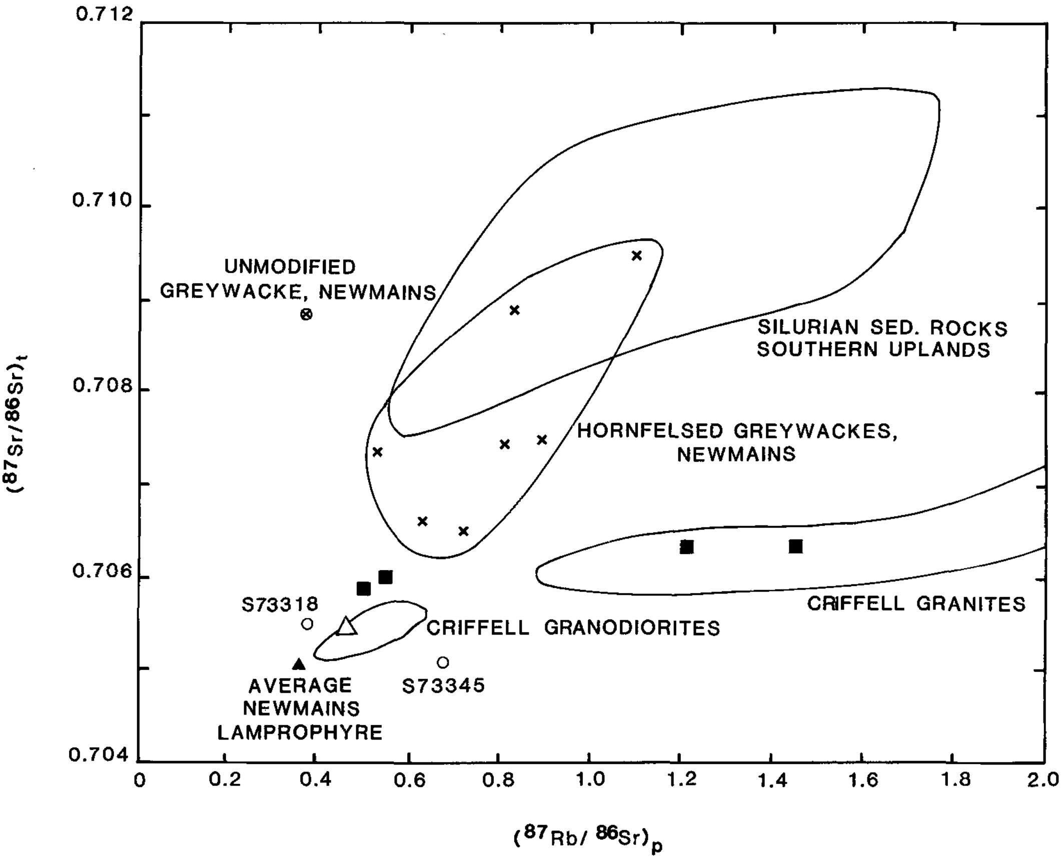

FIG. 7. Plot of $(^{87}Sr/^{86}Sr)_t$ against present day $^{87}Rb/^{86}Sr$. Symbols as in fig. 1, with addition of circled cross—unmodified greywacke composition. Fields of Criffell rocks and S. Uplands sedimentary rocks from Halliday *et al.* (1980). Newmains lamprophyres shown as average only.

above the lamprophyre regression line. Interpretation of the relationships is conveniently made by comparison with data for the Criffell mass and Lower Palaeozoic metasediments (fig. 7).

The Newmains greywackes have $(^{87}Sr/^{86}Sr)_t$ ratios which overlap those of Silurian greywackes collected over a wider area of the Southern Uplands (Halliday *et al.*, 1980), although the *average* Newmains $(^{87}Sr/^{86}Sr)_{395}$ ratio of 0.70789 ± 114 (Table III) is lower than the average of $(^{87}Sr/^{86}Sr)_{392}$ = 0.70977 ± 11 for five samples (Halliday *et al.*, 1980, Table 5, nos. 3-7). Our data confirm the comment (Halliday *et al.*, 1980) that the greywackes generally had low $^{87}Sr/^{86}Sr$ ratios at the time of granite–dyke emplacement.

The felsic rocks can be discussed as two sets, those showing lower and higher Rb/Sr ratios respectively. Rocks with lower Rb/Sr ratios are slightly more radiogenic than the Criffell granodiorites. Their transitional position to the greywackes (fig. 6) clearly implies contamination with radiogenic Sr from the country rocks. The pegmatitic mafic hybrid, S73318, which has a high $(^{87}Sr/^{86}Sr)_{395}$ ratio but a 'normal' Rb/Sr ratio (figs. 4, 7), must also have suffered contamination by radiogenic Sr.

That the Newmains greywackes have contributed radiogenic Sr to the dyke at least partly explains their slightly low $(^{87}Sr/^{86}Sr)_{395}$ ratios in fig. 7 compared to Silurian greywackes in Halliday *et al.* (1980). A contact hornfels S73319 has an $(^{87}Sr/^{86}Sr)_{395}$ ratio of 0.70670, whereas an unmodified greywacke, S73320, 0.5 m from the contact at the same locality has 0.70890 (Table II). This lowering of the apparent ratio could be related to (1) much later Rb–Sr exchange, (2) Sr migration from the magma into the greywackes, or (3) some form of disequilibrium partial melting of the greywackes.

We note below the evidence for metasomatism of the country rocks broadly contemporaneous with dyke emplacement and suggest that (2) is the most likely explanation for the lower ratios.

Evidence for volatile loss from the Newmains dyke to the greywackes

In an earlier section, two groups of felsic rocks were distinguished (fig. 6), a higher-K group thought to be close to magmatic compositions, and a lower-K group with K_2O levels even lower than the host greywackes. The greywackes were subdivided in fig. 6 into hornfelses (Kennedy and Read, 1936), and apparently unmodified rocks removed from the contact.

The non-hornfelsed greywackes have the relatively low K_2O (and high Na_2O/K_2O ratios) characteristic of these rocks (Pettijohn, 1975), while the hornfelsed varieties have $K_2O > Na_2O$. The data seem to confirm the finding (Kennedy and Read, 1936) that K has been expelled from the dyke into the greywackes. Similar analysis of MgO-trace element plots indicates that Rb and Ba were also predictably transferred from magma to greywackes. We further suggest that the loss of these elements was patchy; those local batches of felsic magma which lost a volatile phase crystallized as the medium grained rocks, while some batches which retained volatiles crystallized pegmatitic hybrid rocks such as S73345, with the relatively high Rb/Sr ratio (figs. 4, 7).

All the above effects are well illustrated by two greywackes from the same locality (fig. 1).

	Distance from dyke contact (m)	K_2O	K_2O/Na_2O	Rb	Ba	$(^{87}Sr/^{86}Sr)_{395}$
S73319 (hornfels)	0	2.95	1.40	93	665	0.70670
S73320 (unmodified)	0.5	1.18	0.91	36	328	0.70890

Evolution of the Newmains dyke and its significance

We envisage the evolution of the dyke as follows:

(i) A lamprophyric parent magma was generated by partial melting of upper mantle rocks, followed by minor modification by sediment assimilation and/or volatile enrichment in the crust.

(ii) The parental magma fractionated by separation of hornblende ± clinopyroxene.

(iii) The differentiated column of magma migrated to its current level of exposure. During ascent, mafic phases + apatite were aggregated into mats, to provide patches of magma slightly enriched in these cumulate minerals.

(iv) After about 65% crystallization, a volatile-rich quartz syenitic residual fluid separated. The syenitic residuum metasomatically enriched the contact-hornfelsed metasediments in K, Ba, and Rb, and was itself contaminated by radiogenic Sr from the country rocks. The syenitic liquids locally crystallized within the dyke as discrete pegmatitic veins. Megascopic hybridization between felsic liquids, mafic cumulates and greywackes took place locally along the dyke margin. This produced igneous-looking, pegmatitic mafic hybrids, some enriched in ^{87}Sr from the greywackes and some in Rb from the volatile phase.

(v) Continued fractionation of those portions of the contaminated syenitic liquid which had retained the volatile phase produced small amounts of granodioritic to granitic residua.

The Newmains dyke appears, in miniature, to carry petrogenetic implications widely applicable to the British Caledonian Granites. The outstanding overall characteristics of these granites are high K, Sr, and Ba, and most of the dioritic to granodioritic rocks are considered (Stephens and Halliday, 1979, 1984; Halliday *et al.*, 1980; Halliday and Stephens, 1984; Harmon *et al.*, 1984) to have developed from unspecified high Mg, high Ni, mantle-derived magmas which had been affected to varying degrees by crustal contamination before emplacement. All these characteristics are shown by the Newmains lamprophyres which, moreover, have identical ages and initial ratios to the nearby Criffell pluton. We therefore identify the lamprophyres as these unspecified mafic precursors and infer that similar rocks underlie many, if not all, of the major Caledonian plutons. This model will be developed in subsequent papers on S. Uplands dykes. At present, we merely stress that this model does not even pose a volume problem, if dyke-rocks constitute as much as 10–15% of the volume of late Caledonian magmatism (Watson, 1984; Rock *et al.*, in press), and if silicic rocks form as much by partial melting of country rocks as by fractionation of lamprophyric parent magmas.

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