Jl geol. Soc. Lond. Vol. **136**, 1979, pp. 29–38, 4 figs., 8 tables. Printed in Northern Ireland.

Ordovician intrusions in the English Lake District

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SUMMARY: Rb–Sr whole rock isochron and K–Ar whole-rock and mineral ages suggest that there were four intrusive episodes in the Lake District in Ordovician times, in addition to the widely recognized end-Silurian event. The Carrock Fell Gabbro has given an age of 468 ± 9 Ma and is probably coeval with the Eycott Volcanic Group. A suite of dioritic lamprophyres, including the Great Cockup 'Picrite', has a preferred age of 458 ± 9 Ma and may be related to the main Borrowdale Volcanic Group. The Eskdale Granite was emplaced around 429 Ma, probably during the Caradoc, and the Ennerdale Granophyre, Carrock Fell Granophyres, and the Harestones Felsite are coeval with the Stockdale Rhyolite (421 Ma) and of Ashgillian age. Muscovites from various facies of the Eskdale Granite show a wide spread of K–Ar ages from 426 to 388 Ma. The implications of these results for the tectonic and mineralogenic history of the area are discussed and previous research is reviewed in their light.

Widely different views have been expressed in the past concerning the age relations of the Lake District intrusions: a summary of published work is given in Table 1. In most cases it is difficult to assign precise ages to the intrusions on stratigraphic evidence alone, hence many workers have used structural relationships to draw conclusions about time of emplacement. Harker (1902) classified them as being older or younger than the main earth movements which he assumed were all end-Silurian. Green (1917), however, was aware that some of the folding was pre-Bala, but still only related the intrusive events to what he considered to be end-Silurian structures. It is now widely recognized that the Lake District area has been subjected to at least five major tectonic episodes (Moseley 1972) and hence the structural relationships deduced for the various intrusive rocks must be viewed with caution.

The first estimates of absolute ages were made by Miller (1961) and Brown *et al.* (1964), who determined K–Ar ages for the main intrusions which suggested that most were emplaced in end-Silurian times. However, a Rb–Sr whole-rock isochron age for the Threlkeld Microgranite (Wadge *et al.* 1974) showed that at least one of the intrusions was of Ordovician age.

The present investigation was directed at the systematic dating of the main intrusions by the Rb–Sr isochron method, and an extension of the earlier K–Ar work, in an attempt to determine a precise time-scale for the magmatic events in the Lake District. This paper presents the results obtained for the Eskdale Granite, Ennerdale Granophyre, Carrock Fell Complex, Embleton 'Diorite' and Great Cockup 'Picrite'.

Summary of geology

Detailed accounts of the geology of the Lake District have been given by Hollingworth (1955) and Mitchell (1956). The oldest rocks in the area are the Skiddaw Slates of Lower Ordovician age and the earliest magmatic episode was the extrusion of the Eycott Volcanic Group which is interbedded with slates of the *Didymograptus bifidus* zone (Downie & Soper 1972). Following unconformably on the Skiddaw Slates, the youngest of which are *D. murchisoni* zone (Wadge *et al.* 1972), is the main Borrowdale Volcanic Group (hereafter BVG). At the close of the volcanic episode the area was again subjected to folding, uplift and erosion (Moseley 1972) before the deposition of the Coniston Limestone Group, which is now thought to be Ashgillian (Ingham & McNamara in press), thus the Borrowdale Volcanic episode probably took place during the Llandeilian (Mitchell 1956).

Interbedded with the Ashgillian rocks is the Stockdale Rhyolite lava which has been dated at 421 ± 3 Ma by the Rb–Sr whole-rock isochron method (Gale *et al.* in press). The Coniston Limestone Group pass conformably upwards into grits and mudstones of the Silurian System. In end-Silurian times the area was subjected to intense compression leading to deformation, uplift and erosion which, in Wright's view (1976), was brought about by final closure of the Iapetus ocean and continental collision. Six main granitic masses intrude the Lower Palaeozoic rocks, together with numerous minor bodies, and their distribution is shown in Fig. 1.

Analytical details

Rb/Sr ratios were determined using a Phillips PW 1450 automatic X-ray fluorescence spectrometer, and Rb and Sr concentrations were calculated using the Mo Compton Scatter peak as a measure of the mass absorption coefficient. Hence Rb and Sr concentrations, which are not used in the age calculations, are approximate values only.

Most of the strontium isotopic compositions were measured with a Micromass 30 solid source mass

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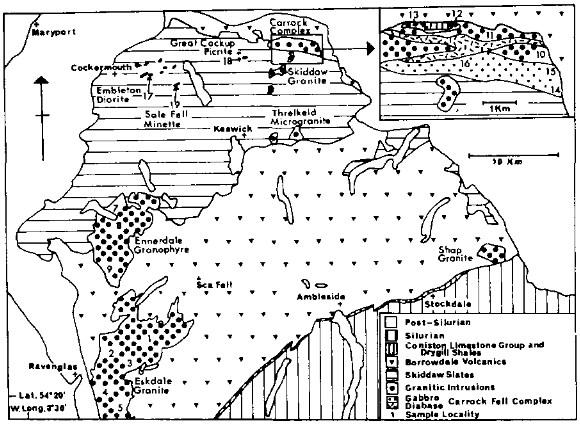

FIG. 1. Geological sketch map to show sample localities

spectrometer with on-line calculator control. Strontium ion beams were produced from a single tantalum filament loaded with a mixture of an aqueous solution of strontium chloride and phosphoric acid. A few samples were analysed using a Thomson THN 206 spectrometer. Several samples were analysed on both machines and no significant difference was detected between the results, although a higher precision was obtained with the MM 30. Replicate analyses of the Eimer and Amend strontium isotope standard gave 87/86 ratios of 0.70803 ± 0.00004 (2 standard errors) for the MM 30 (6 analyses) and 0.70805 ± 0.00011 for the THN 206 (5 analyses).

Overall reproduceability of sample analyses in this laboratory is estimated to be better than ±1% for the Rb/Sr ratios and ±0.02% for the 87/86 ratios and these values have been used to weight the points when determining the best-fit line to the data points on an isochron diagram, and also to determine the 'goodness of fit' of the points to this line (Brooks *et al.* 1972). Whenever the scatter of points about the line is greater than can be attributed solely to experimental error, as indicated by a value for the calculated parameter MSWD (as defined by Brooks *et al.* 1972) greater than 2.5, the errors on the age and intercept have been enhanced, to incorporate this excess scatter, by multiplying by the square root of the MSWD.

It must be noted that the errors for ages calculated from the isochron slope are based on precision estimates. Hence, since all samples in this study were

TABLE 1: *Summary of previous arguments favouring either end-Silurian or Ordovician ages*

Intrusion	For end-Silurian age	For Ordovician age
Eskdale Granite	1) Post-dates folding in B.V.G. 2) Responsible for post tectonic metamorphism in Skiddaw Slates 3) K-Ar biotite age of 390 Ma	1) Related minor intrusions are pre-cleavage. Secondary mineralisation in B.V.G. is syn-cleavage and temporally related to interstitial muscovite in the granite 2) Stress field causing joints in granite not the same as that producing folding and cleavage in B.V.G. 3) Cut by end-Silurian thrust 4) Pre-Caradoc tilt of B.V.G. due to hidden Ordovician intrusion
Ennerdale Granophyre	4) K-Ar whole-rock age of 377 Ma 5) Cuts folds in B.V.G. which are related to end-Silurian Skiddaw anticline Later than cleavage in Slates	5) Folded with the country rocks 6) Before main Crust movements 7) Similarities with Threlkeld Microgranite 8) Same age as pre-cleavage dyke swarm
Carrock Fell Complex	6) Younger than any of the granites - possibly Tertiary 7) K-Ar date of 362 Ma. Folding in hornfels completed before intrusion 8) Intruded after main folding of Skiddaw Slates. Harestones Felsite related to Skiddaw Granite	9) Baked slate cleaved after heating. Harestones Felsite may be equivalent to Stockdale Rhyolite 10) Chemically related to Eycott Lavas and pre-cleavage 11) Younger than lower Eycotts but older than Skiddaw Granite. Gabbros older than Granophyre
Embleton Diorite'	9) Intruded after cleavage of slates and following the axes of the folds	12) Chemical affinities with Eycott volcanics
Great Cockup 'Picrite'	[illegible]) Related to the diorite suite	13) Older than main earth movements
References	1) Dwerryhouse(1908), Simpson (1933), Trotter et al. (1937) 2) Soper (1970) 3) Miller (1961) 4) and 7) Brown et al. (1964) 5) Eastwood et al. (1931) 6) Harker (1902) 8), 9) and 10) Eastwood et al. (1968)	1) Oliver (1961) 2) Firman (1960) 3), 5) and 9) Green (1917) 4) Mitchell (1956) 6) Rastall (1906) 7) and 10) Soper (in discussion of Wadge et al. 1974) 8) Eastwood et al. (1931) 11) and 12) Firman (in press) 13) Harker (1902)

analysed for Rb–Sr ratios over a short space of time, using the same XRF machine and the same primary standard (GSP–1), these error estimates can be used to determine whether or not the various results are significantly different from one another. However, to compare these results with the currently existing time-scale one must take into account possible systematic errors affecting the overall accuracy of the results, such as inter-laboratory differences in values for the primary XRF standard and errors in the decay constants, where different dating methods have been used. Since these are unlikely to be less than about ±2% at the 95% confidence level it is considered unrealistic to quote Rb–Sr isochron ages with errors less than this, and hence for external comparison a minimum error of ±2% has been adopted for all isochron ages. In this context it must be noted that the Rb–Sr ratios for samples of the Stockdale Rhyolite (Gale *et al.* in press) were determined at the same time and on the same machine as those in this study and hence, in this case, precision errors can be used for comparison (see section on 'Geological implications').

Potassium was determined by flame photometry using a lithium internal standard, and argon was extracted by fusion in vacuum using RF induction heating and analysed by the isotope dilution method with an AEI MS.10 mass spectrometer operated in the static mode. Errors for the K–Ar ages were computed by combining the standard errors determined for the isotope ratio measurements, the spike volume and the potassium determination and represent estimates of the analytical precision only. They do not incorporate errors in the decay constants or errors due to argon loss or extraneous argon. Wherever a result is the mean of replicate determinations the errors have been reduced by the factor (no. of determination)$^{1/2}$.

All errors quoted in this work are twice the standard error and the constants used in the age calculations are those recommended by the IUGS Subcommission for Geochronology (Steiger & Jäger 1977). (λ^{87}Rb = 1.42×10^{-11}/y, $\lambda^{40}K^{\beta} = 4.962\times10^{-10}$/y, $\lambda^{40}K^{e} = 0.581\times10^{-10}$/y, ^{40}K at % = 0.01167). All previous age data quoted here have been recalculated with these values.

Discussion of results

Eskdale Granite

The majority of authors accept an end-Silurian or Devonian age for this intrusion (Dwerryhouse 1908, Simpson 1934, Oliver 1961, Firman 1960, & in press). Trotter *et al.* (1937) recognized two main types of granite, an earlier biotite-granodiorite in the south and a later pink muscovite-granite in the north. The assumption of a Devonian age appears to have been validated by a K–Ar age of 390 Ma obtained by Miller (1961) for biotite from the granodiorite near Bootle. However, it must be noted that the two samples contained only 3.28 and 2.83% K_2O, indicating a high degree of alteration and the strong possibility of argon loss causing spuriously young ages.

Only Green (1917) suggested an Ordovician age for this intrusion but the comments of several of the earlier workers noted in Table 1 suggest that a Devonian age is by no means proven.

In the present investigation ten samples of the pink granite (localities 1–3, Fig. 1) and twelve from the granodiorite (localities 4 and 5) were collected for Rb–Sr analysis, and three samples of the Devoke Water Greisen (locality 6) for K–Ar dating of micas. The Rb–Sr results are shown in Table 2, and the K–Ar results in Table 6.

When plotted on a Rb–Sr isochron diagram (Fig. 2) the pink granite samples form a linear array yielding an age of 429 ± 4 Ma with an initial ratio of 0.70756 ± 0.00048. The MSWD is low (0.74) indicating that all the points fit the line within the limits of experimental error. A regression of the granodiorite data, however, gives an MSWD of 7.66 indicating a high degree of excess scatter due to disturbance of the Rb–Sr system by geological factors. Calculation of the age, incorporating the error enhancement procedure, yields 429 ± 22 Ma with an intercept of 0.70726 ± 0.00071 The slope of this line is dominated by samples WAB 6 and 7 which are from an aplite vein containing no biotite. If only the true biotite-granodiorite samples are regressed, there is an even higher MSWD (8.86) and the age is 428 ± 71 Ma. When all 22 samples are regressed together the age is identical with that of the pink granite alone (429 ± 4 Ma) but there is a small amount of excess scatter (MSWD = 4.21).

It is concluded from these data that the two varieties of the Eskdale Granite are coeval and consanguineous

TABLE 2: *Rb–Sr results for Eskdale Granite*

map reference		Sample No.	ppm Rb	ppm Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
SD 145 984		BEC 14	357	20	52.811	1.02671
NY 164 004		BEC 15	367	17	63.553	1.10091
"		BEC 16	164	52	9.197	0.76407
"		BEC 17	328	21	47.799	1.00121
"		BEC 18	306	19	48.006	1.00334
"	Pink Granite	BEC 19	38	39	2.758	0.72436
SD 116 991		BEC 20	316	14	67.346	1.11430
"		BEC 21	394	16	52.836	1.02822
"		BEC 24	269	25	32.527	0.90518
"		BEC 25	268	25	31.916	0.90319
SD 138 913		BUC 10	156	221	2.037	0.71915
SD 136 907		BUC 12	133	228	1.679	0.71734
SD 133 907		BUC 13	167	256	1.889	0.71800
SD 113 943		WAB 1	168	206	2.367	0.72215
"		WAB 2	174	206	2.447	0.72181
"		WAB 4	178	246	2.087	0.72053
"	Granodiorite	WAB 5	164	211	2.255	0.72159
"		WAB 6	207	74	8.208	0.75838
"		WAB 7	259	21	36.647	0.92781
"		WAB 8	164	274	1.749	0.71866
"		WAB 9	167	165	2.947	0.72485
"		WAB 10	178	200	2.597	0.72304

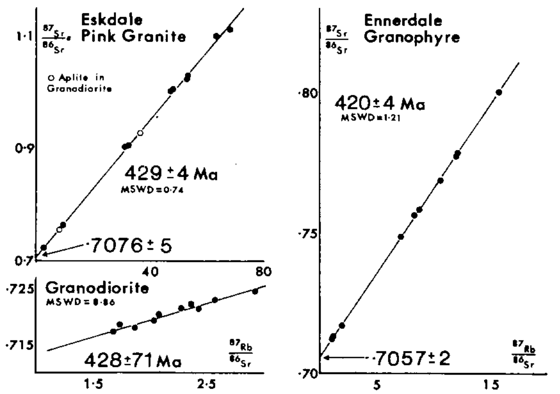

FIG. 2. Rb–Sr isochron diagrams for Eskdale Granite and Ennerdale Granophyre

but that the Rb–Sr systems of the granodiorite have been disturbed by a subsequent event. This disturbance probably affected the biotites only, since the feldspathic aplite phase lies on the pink granite isochron. The best estimate of the age of emplacement of the granite is given by the isochron for the undisturbed pink granite samples and is 429±4 Ma with an initial ratio of 0.70756±0.00048.

The K–Ar results (Table 6) obtained for micas from the whole-rock samples and from the Devoke Water Greisen show a wide spread of ages but two distinct groups can be identified. The three biotites from the granodiorite yield a mean age of 427±8 Ma which is not significantly different from the Rb–Sr isochron age and hence must represent the time of initial post-crystallization cooling below the blocking temperature for argon diffusion. It is interesting to note here that the biotites appear to have retained argon whereas it was inferred above that their Rb–Sr systems have been disturbed.

The three muscovites from the Devoke Water Greisen also form a close grouping with a mean age of 411±8 Ma. However, this is not significantly different from the biotite age, at the 95% confidence level. The remaining four muscovites from the pink granite show a wide spread in ages ranging from 426±9 Ma to 388±8 Ma. The significance of these ages is discussed later (see section on 'Geological implications').

Ennerdale Granophyre

The bulk of evidence (Table 1) favours an Ordovician age for this intrusion, although the K–Ar whole-rock age of 377 Ma (Brown *et al.* 1964) was taken to suggest a Devonian origin. However these authors did accept the possibility of argon loss from this sample. In view of this, and in the absence of any separable minerals suitable for K–Ar dating, only the Rb–Sr whole-rock method has been used here. Five samples were collected from the area around Ennerdale Water (localities 7 and 8, Fig. 1) and five from crags on the northern side of the Bleng Valley (locality 9). Results of the analyses are shown in Table 3 and Fig. 2. All ten points define a line within the limits of experimental error on the isochron diagram (MSWD = 1.21) which yields an age of 420±4 Ma and an intercept of 0.70568±0.00024.

TABLE 3: *Rb–Sr results for Ennerdale Granophyre*

map reference		Sample No.	ppm Rb	ppm Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
NY 142144	Ennerdale Water	CCR 32	176	48	10.664	0.76857
NY 138143		CCR 33	184	33	16.000	0.80063
NY 157136		CCR 34	128	42	8.801	0.75895
NY 153137		CCR 35	185	45	12.014	0.77836
NY 152137		CCR 36	193	47	12.212	0.77815
NY 124089	River Bleng	CCR 58	83	121	1.999	0.71739
NY 120088		CCR 59	73	165	1.279	0.71325
NY 117087		CCR 60	77	192	1.158	0.71280
NY 116086		CCR 61	168	58	8.439	0.75628
NY 115085		CCR 62	170	69	7.173	0.74892

This age differs from that of the Eskdale Granite by more than four times the standard error, calculated from the analytical data, and hence we can have a high degree of confidence in concluding that the Ennerdale Granophyre is younger than the Eskdale Granite. At present there is no published field evidence to show the age relations of these two bodies. However, a recent visit to the contact zone at the foot of Wast Water confirmed that there is no clear cut evidence either way, due to lack of exposure, but suggested that detailed work may reveal evidence to confirm the conclusion based on the age data. It may be noted that Firman (in press) has suggested that the Ennerdale Granophyre was intruded in pre-Bala times and formed a 'cap-rock' to the later Eskdale Granite magma.

Carrock Fell complex

Mitchell (1956) described the complex as 'consisting of gabbro, granophyre, diabase and felsite forming a group of steeply inclined sheets or lenses'. Eastwood *et al.* (1968) thought that the whole complex was injected as 'one steep-sided plug-like mass' after the main folding of the country rock, but suggested that the gabbros may be older than the granophyres and not genetically related. They noted that hornblendes in the gabbro were of secondary origin, and also suggested that the Harestones Felsite may be chemically allied to the Skiddaw Granite. Other authors, however (Table 1), preferred an Ordovician age for the whole complex.

The granophyres

Six samples from the exposures on the eastern slopes on Carrock Fell (locality 10, Fig. 1) and six from the Rae Crags exposure (locality 11) were analysed (Table 4).

The six samples from the Carrock Fell exposure show a wide scatter about a line on the isochron diagram (Fig. 3) (MSWD = 14.63) and no reliance can be placed on the age derived from the slope. It is obvious that the Rb–Sr systems in these rocks have been severely disturbed by a post-crystallization event, which can most probably be attributed to the emplacement of the Skiddaw Granite. However, the six samples from Rae Crags have produced an isochron (Fig. 3) with MSWD of 1.88 yielding an age of 416 ± 20 Ma and an intercept of 0.70708 ± 0.0016. Unfortunately, because of the low spread of Rb/Sr ratios found in these samples, there are high errors associated with the results.

The gabbros

These have only been dated by the K–Ar method and the results are given in Table 6. Four biotites from exposures of biotite gabbro on the southeastern edge of the complex (locality 14, Fig. 1) have yielded a spread of ages from 439 ± 10 to 468 ± 10 Ma. It is considered that the oldest of these is the most reliable and that the others are due to argon loss during a later event. Two whole-rock analyses of gabbro from further north along the eastern margin of Carrock Fell (locality 15) have yielded ages of 371 Ma and 394 Ma whilst two hornblende samples from the gabbro above Poddy Gill (locality 16) have given 362 and 392 Ma. It is suggested that the older of these ages (392 and 394 Ma) reflect secondary mineral growth during the end-Silurian event (cf. Eastwood *et al.* 1968) and the younger, argon loss from altered material. The oldest biotite date is hence considered to be the best estimate of the age of the gabbro although this too may be only a minimum estimate due to the possibility of argon loss.

TABLE 4: *Rb–Sr results for Carrock Granophyres*

Map reference		Sample No.	ppm Rb	ppm Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
NY 349339	Carrock Fell	CAR 38	139	64	6.282	0.74378
NY 349338		CAR 39	136	74	5.310	0.73605
NY 348338		CAR 41	130	77	4.895	0.73562
NY 346337		CAR 42	133	76	5.058	0.73539
NY 349335		CAR 44	124	83	4.309	0.73333
NY 349336		CAR 45	126	59	6.227	0.74170
NY 334342	Rae Crags	RAE 1	129	59	6.313	0.74487
"		RAE 2	119	66	5.258	0.73749
"		RAE 3	130	60	6.258	0.74375
"		RAE 4	134	69	5.650	0.74063
"		RAE 5	123	89	4.028	0.73119
"		RAE 6	127	54	6.924	0.74832

TABLE 5: *Rb–Sr results for Harestones Felsite*

map reference		Sample No.	ppm Rb	ppm Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
NY 326345	Drygill Beck	HFE 1	162	37	12.792	0.78328
"		HFE 2	168	57	8.641	0.75976
NY 325346		HFE 4	124	87	4.138	0.73241
"		HFE 5	25	113	0.6505	0.71193
NY 326346		HFE 10	85	65	3.754	0.73032
NY 313346	Harestones	HFE 11	185	65	8.319	0.75804
"		HFE 12	195	53	10.599	0.77110
"		HFE 13	213	68	9.153	0.76336
"		HFE 14	197	64	8.985	0.76175
"		HFE 15	215	43	14.781	0.79672

The Harestones Felsite

The results of the analysis (Table 5) of five samples from Drygill Beck (locality 12) and five from Harestones (locality 13) can be seen to define a line on the Rb–Sr isochron diagram (Fig. 3) with an MSWD of 0.73. This line yields an age of 419 ± 4 Ma and intercept of 0.70799 ± 0.00029. Hence it is extremely unlikely that the felsite is related to the Skiddaw Granite as suggested by Eastwood *et al.* (1968).

The age is almost identical with that for the Ennerdale Granophyre but the initial ratio is significantly higher, suggesting that these bodies are coeval but not cogenetic.

The dioritic lamprophyre suite

A group of minor intrusions lying within the Skiddaw Slates outcrop, to the E of Cockermouth, have been classified by Eastwood *et al.* (1968) as a consanguineous group of dioritic lamprophyres. They considered that the basic and acid members were represented by the so-called 'Picrite' at Great Cockup and the Embleton quartz-diorite exposed in Close Quarry, Embleton, and that the Sale Fell Minette was also part of the same group. The majority of these intrusions were thought to be parts of one sill, or a group of closely related sills, intruded after the cleavage of the slates and following the axes of the folds. Harker (1902), however, considered that the Great Cockup 'Picrite' was older than the main earth movements and Green (1917) noted that the quartz dolerites and related rocks do not occur above the Bala unconformity and thought that they were, therefore, Ordovician in age. Firman (in press) also preferred an Ordovician age on the grounds of chemical affinities with the Eycott lavas.

Six samples of the rock exposed in Close Quarry, Embleton (locality 17, Fig. 1) have been dated by both the Rb–Sr and K–Ar whole-rock methods and the results are shown in Table 7 and Fig. 4. Four of the samples were normal medium-grained quartz-diorite and two were from a pink feldspathic aplite vein.

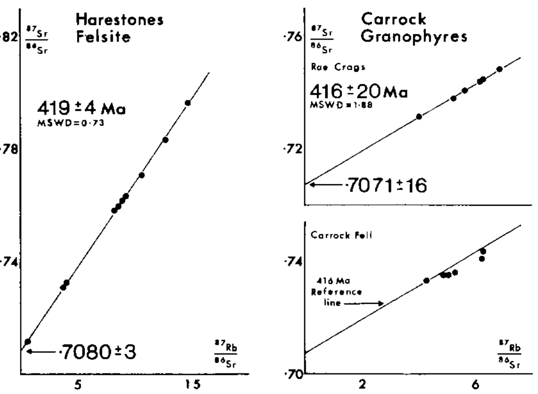

FIG. 3. Rb–Sr isochron diagrams for Harestones Felsite and Carrock Granophyres

Regression of all the Rb–Sr data gives a best fit line with a high MSWD of 6.15. Visual examination suggests that this high value is due mainly to the normal diorite sample CCR 27. Exclusion of the sample reduces the MSWD to 0.94 and the calculated age and initial ratio are 444±24 Ma and 0.70749±0.00036. These results are not significantly different from those obtained when all the samples are regressed (444±54 Ma and 0.70732±0.00072) but are far more precise and hence are the preferred values.

The K–Ar results for these samples show a close cluster of ages for the four normal diorite samples (including sample 27) with a mean of 429±9 Ma which is not significantly different from the Rb–Sr result. The two aplite results, however, although agreeing well with each other are significantly younger at 394±10 Ma. It is concluded from these data that the normal diorite samples have retained most of their argon as well as strontium since initial cooling of the intrusion. However, the fine-grained feldspathic material, although retaining its radiogenic strontium, would appear to have lost all its radiogenic argon

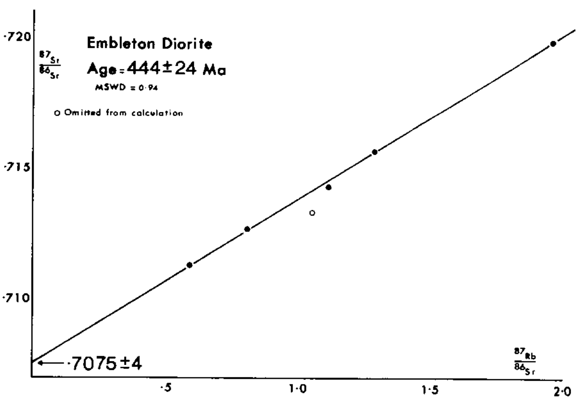

FIG. 4. Rb–Sr isochron diagram for Embleton Diorite

during the end-Silurian event. Three samples of hornblende from the Great Cockup 'Picrite' (locality 18, Fig. 1) have given a mean K–Ar age of 458±9 Ma which is significantly older than the K–Ar age from Embleton but not significantly different from the Rb–Sr age.

These data suggest that the Embleton Quartz Diorite and the Great Cockup 'Picrite' are indeed coeval but that the Embleton samples have most probably lost a small amount of argon from non-retentive sites. The K–Ar whole-rock ages and the Rb–Sr results certainly show that the diorite was emplaced during the Ordovician, before the end-Silurian cleavage and folding. However, in view of the high errors attached to the Rb–Sr result and the possibility of argon loss reducing the K–Ar whole-rock ages, it is suggested that the K–Ar result for the hornblendes from Great Cockup (458±9 Ma) be taken as the best estimate of the age of the whole dioritic lamprophyre suite.

Re-examination of the field evidence at Embleton and Great Cockup has shown that although the Embleton mass does cut a large fold that trends 080°, there is no cleavage developed in the slates adjacent to the intrusion, suggesting that the slates were already hardened and protected by the igneous rock before the cleavage episode. Also, at Great Cockup, penetrative cleavage in the slates becomes fracture cleavage as the margin of the 'picrite' is approached and a thin section shows spotting, with micas parallel to cleavage, moulded around the spots, suggesting intrusion before cleavage (N. J. Soper, *pers. comm.*). Thus a pre-(end-Silurian) cleavage age can be supported by the field evidence.

TABLE 6: *K–Ar results for Eskdale Granite and Carrock Gabbro*

Map reference		Sample No.	Material analysed	%K	nl/g Rg ^{40}Ar	Age (Ma)
SD 133907	Granodiorite	BUC 13	Biotite	3.698	69.66	429 ± 13
SD 113943		WAB 1	"	6.172	116.60	430 ± 13
"		WAB 10	"	5.330	98.75	423 ± 13
NY 164004	Pink Granite	BEC 16	Muscovite	5.776	100.85	402 ± 8
"		BEC 18	"	6.532	116.41	409 ± 9
SD 116991		BEC 20	"	6.597	123.02	426 ± 9
"		BEC 21	"	7.468	125-43	388 ± 8
SD 150968	Greisen	DW 1	Muscovite	8.426	151.61	412 ± 13
"		DW 2	"	8.640	153.40	407 ± 13
"		DW 3	"	8.697	157.39	414 ± 13
NY 349339	Carrock Fell Gabbro	CCR 37	Whole rock	0.999	15.954	371 ± 13
NY 348338		CCR 40	Whole rock	1.242	21.215	394 ± 13
NY 355325		Di 13 A	Biotite	6.539	126.51	439 ± 10
"		Di 13 B	"	5.838	121.38	468 ± 10
"		Di 13 H	"	3.754	73.434	444 ± 14
"		Di 13 I	"	6.507	127.91	446 ± 14
NY 314343		Di 13 K	Hornblende	0.614	9.542	362 ± 11
"		Di 13 L	"	0.685	11.965	392 ± 12

One sample of biotite from the Sale Fell Minette (locality 19, Fig. 1) has yielded a K–Ar age of 402±9 Ma. This age, together with its granitic mineralogy, may indicate affinities with the end-Silurian Skiddaw Granite rather than the diorite suite.

Geological implications

The results discussed above suggest four periods of intrusive activity in the Lake District prior to the widely recognized end-Silurian event (Soper & Roberts 1971, Shepherd *et al.* 1976, Boulter & Soper 1973, Wadge *et al.* in press).

The c.468 Ma event

Within the Carrock Fell Gabbro, Eastwood *et al.* (1968) recognized many xenoliths of Eycott type lavas in various stages of assimilation, and Soper (in discussion of Wadge *et al.* 1974) suggested a chemical similarity between the Carrock rocks and the Eycott lavas. Hence, pending geochemical confirmation, it may be tentatively suggested that the Carrock Gabbros are related to the Eycott Volcanic Group and that a minimum age for this group, and hence of the *Didymograptus bifidus* zone of the Ordovician (Downie & Soper 1972), is 468±10 Ma.

The c.458 Ma event

Rocks of the diorite suite intrude slates of *D. extensus* and *D. hirundo* zones only, and also the Great Cockup hornblende age is not significantly different from that deduced here for the Eycott Volcanic Group. Hence, the diorite suite could also be related to the Eycott lavas. However, the known higher retentivity for radiogenic argon of hornblende, compared to biotite, might suggest that the biotite from the Carrock Gabbro is indeed older than the Great Cockup hornblende, and the dioritic composition of this suite might suggest affinities with the andesitic BVG rather than the Eycotts. Also, it is clear from the field evidence at Embleton quarry, that the diorites were emplaced after the development of a major fold in the Skiddaw Slates, whereas the Eycott lavas are conformably interbedded with the Skiddaw Slates sequence. Hence, despite the suggestion by Firman (in press) that geochemical data support a relationship between the diorites and the Eycott Group, it is suggested here that the preferred age for the diorite suite (458±9 Ma) be also taken as an estimate of the age of the main Borrowdale Volcanic Group.

Previous evidence of the age of the BVG was provided by a Rb–Sr age for the Threlkeld Microgranite (Wadge *et al.* 1974). This intrusion bakes and spots the lowest part of the BVG and was considered by Wadge *et al.* to be chemically related to the topmost lavas. Recalculation of their data to conform with other results in this work, gives an age of 459±25 Ma with an initial ratio of 0.70556±0.0019 (MSWD=0.66). This age is almost identical with that determined here for the diorite suite and hence adds support to the suggested correlation of the diorites with the BVG.

TABLE 7: *K–Ar and Rb–Sr results from Dioritic Lamprophyre suite*

Map reference		Sample No.	Material analysed	%K	nl/g Rg ^{40}Ar	Age (Ma)
NY 175309	Embleton	CCR 24	Whole rock diorite	0.582	11.084	435 ± 19
"		CCR 25	" " "	0.764	14.266	426 ± 20
"		CCR 26	" " "	0.968	18.384	432 ± 19
"		CCR 27	" " "	0.991	18.491	425 ± 17
"		CCR 28	" " aplite	2.693	45.811	392 ± 14
"		CCR 29	" " "	1.778	30.533	395 ± 15
NY 271324	Great Cockup	12 A	Hornblende	0.425	8.524	453 ± 15
"		12 C	"	0.500	10.389	468 ± 15
"		12 D	"	0.394	7.921	454 ± 15
NY 194296	Sale Fell	CR Di 14	Biotite	5.606	98.468	402 ± 9

map reference	Sample No.	ppm Rb	ppm Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
NY 175308	CCR 24	20	95	0.5963	0.71126
"	CCR 25	26	92	0.8084	0.71272
"	CCR 26	34	87	1.1136	0.71432
"	CCR 27	33	92	1.0567	0.71336
"	CCR 28	90	133	1.9565	0.71987
"	CCR 29	59	134	1.2821	0.71570

The c.429 Ma event

A recent revision of the Lower Palaeozoic time-scale based on a Rb–Sr age for the Stockdale Rhyolite (Gale *et al.* in press) suggests an age of 421±3 Ma for the Cautleyan Stage of the Ashgillian. The age determined here for the Eskdale Granite (429±4 Ma) is significantly older than this, but younger than that derived for the Borrowdale Volcanic Group (458±9 Ma). Trotter *et al.* (1937) believed that 'although the (Eskdale) granite was intruded after the main (end-Silurian) earth-movements, the two phenomena were intimately connected and that they were separated by a comparatively short time interval'. It is clear from the age data discussed above that the earth-movements concerned could not have been those of the end-Silurian event. Hence it is suggested that the granite was emplaced during the Caradocian compressive phase and thus this event took place around 429 Ma.

The initial $Sr^{87/86}$ ratio for the granite is consistent with an origin from a mixture of oceanic and continental crustal material which might be expected above a descending crustal plate. An Ordovician age for the Eskdale Granite resolves several of the problems discussed by previous workers. For example, the stress field which produced the joint and fault patterns, which Firman (1960) believed were formed at an early stage in the emplacement of the granite, was of Ordovician age, whereas that producing cleavage in the BVG was end-Silurian, and the pre-cleavage minor intrusions (cf. Oliver 1961) can be related to the granite, whereas the post-cleavage secondary mineral growth in the BVG and the Skiddaw Slates (Oliver 1961, Soper 1970) must be due to the Shap and Skiddaw magmatic episode and not to the Eskdale Granite.

In this context the K–Ar mineral data provide useful information. Sample BEC 20 which contains little hematite in thin section, has given a muscovite age which is not significantly different from the intrusive age calculated from the whole-rock Rb–Sr data (429 Ma), whereas sample BEC 21, which, both in thin section and hand specimen can be seen to contain much free haematite occupying late fractures in the rock, has given a muscovite age which is not significantly different from that of the Shap and Skiddaw granites (*c*.395 Ma, Wadge *et al.* in press, Shepherd *et al.* 1976). The difference in muscovite ages shown by the haematized and non-haematized granite provides support to the suggestions of Shepherd (1973) concerning the multistage genesis of the haematite ores throughout the Lake District, the *c*.395 Ma event corresponding well with his intermediate stage of pre-concentration in the granite prior to later remobilization in late Carboniferous and early Permian times. The other muscovite samples from the pink granite have given intermediate ages presumably reflecting partial overprinting during the end-Silurian event. However, the close cluster of ages given by the Devoke Water Greisen muscovites (411±8 Ma) may be significant and may possibly reflect an intermediate phase of activity.

Bott (1974), in an interpretation of gravity data, suggested that the Eskdale Granite was connected at depth to the Shap and Skiddaw granites and formed part of the Lake District batholith. It would appear from the above data that in fact the Eskdale Granite was a separate and much earlier intrusion and that the main batholithic granite was emplaced in end-Silurian times beneath the Eskdale mass.

Further information about the history of the Eskdale Granite can be drawn from the marked differences between the two varieties. Trotter *et al.* (1937) described the junction as, in part, a fault and stated that there was no evidence of passage from one rock into the other. They believed that they represent two distinct but cognate intrusions but that the granodiorite was the earlier. Within the limits of experimental error no evidence for this difference can be seen in the ages. It seems more likely that the differences between the two varieties are due to different structural levels and that their present adjacent position was brought about by subsequent faulting. A possible model which would explain the available isotopic data is as follows: after initial emplacement of the granodiorite magma there was a build up of late-stage fluids in the upper portions of the intrusion with the result that early formed biotite was made over to muscovite, and iron ore was finely disseminated to give the pink muscovite-granite. Subsequent cooling of the whole mass is recorded by the Rb–Sr whole-rock age, and the K–Ar ages for the biotites and oldest muscovite. Faulting, presumably during the Caradocian movements, then brought the two varieties adjacent to one another. In end-Silurian times hydrothermal circulations set up by emplacement of the main batholithic granite (represented by the Shap and Skiddaw Granites), caused secondary mineral growth, including concentration of haematite in cracks and fissures, in the pink granite and immediately surrounding rocks. The Rb–Sr systems of the pink granite do not seem to have been disturbed during this event but local re-heating or re-crystallization of muscovites is reflected in the younger K–Ar ages. This suggests that the passage of fluids was restricted to narrow channelways in the pink granite. The Rb–Sr systems of the granodiorite, however, have been disturbed whereas the K–Ar system of the biotites have not. This would suggest that the passage of fluids, below about 300°C, was more general throughout the rock, and may be explained by the more marginal position of the granodiorite phase relative to the main batholithic granite, as shown by the gravity anomalies (Bott 1974).

The *c*.420 Ma event

During Ashgillian times a minor outburst of volcanic activity produced the Stockdale Rhyolite. From the results discussed above it would appear that a significant amount of intrusive activity also occurred at this time. The ages for both the Ennerdale Granophyre (420±4 Ma) and the Harestones Felsite (419±4 Ma) are almost identical with that for the Stockdale Rhyolite (421±3 Ma). The felsite also has an identical initial ratio, within errors, and a similar stratigraphic position, being in contact with the Drygill Shales, of Caradocian age. Hence it would appear that the Stockdale Rhyolite and Harestones Felsite are coeval and consanguineous and that the felsite is Ashgillian in age and not related to the Skiddaw Granite as suggested by Eastwood *et al.* (1968). The Ennerdale Granophyre is the same age, within errors, but has a significantly lower initial ratio than the Stockdale Rhyolite and Harestones Felsite, which presumably reflects a higher proportion of oceanic material in the parent magma.

An Ordovician age for the Ennerdale Granophyre once again confirms the suggestions of some of the earliest workers (Table 1) and suggests that the folds in the BVG which are cut by the intrusion are indeed of pre-Bala age and not end-Silurian as suggested by

Eastwood *et al.* (1931). The whole-rock K–Ar age quoted by Brown *et al.* (1964) is, they suggested, shown to be too young due to argon loss, but the suggestion by Soper of a similar age to the Threlkeld Microgranite cannot be confirmed. However, it must be noted that the initial ratios of these two bodies are not significantly different, with a mean value of 0.7056, whereas the mean for all the other Lake District Granites, including Shap (Wadge *et al.* in press) and Skiddaw (Rundle, unpubl. data) is 0.7076. This may suggest a similar source region for the Ennerdale Granophyre and Threlkeld Microgranite, distinct from the source of the other granites.

The position of the Carrock Fell Granophyres in the sequence of magmatic activity is difficult to decide in view of the high errors associated with the Rb–Sr age (416±20 Ma).

This age cannot be resolved, at the 95% confidence level, from that of the end-Silurian granites, but at an only slightly lower level of confidence it would appear to be older. It is certainly younger than that suggested for the Carrock Fell Gabbros (468±10 Ma) and hence it would appear that the gabbros and granophyres are indeed of different ages as suggested by Eastwood *et al.* (1968) and Firman (in press). The only other granophyre in the Lake District (Ennerdale) belongs to the Ashgillian suite and hence it is suggested that the Carrock Fell Granophyres are also assigned to this suite.

TABLE 8: *Suggested sequence of magmatic events in the Lake District*

Event	Age (Ma)	Magmatic Activity	Tectonic Activity	Stratigraphic position
5	C. 395	Shap Granite Skiddaw Granite Sale Fell Minette.		L. Devonian
			Main end-Silurian cleavage and folding	
4	421 ± 8	Stockdale Rhyolite Ennerdale Granophyre Carrock Granophyre Harestones Felsite		Ashgill
3	429 ± 9	Eskdale Granite	Pre-Ashgillian compression	Caradoc
2	458 ± 9	Great Cockup 'Picrite' Embleton Diorite Borrowdale Volcanics Threlkeld Microgranite		Llandeilo
			Pre-Borrowdale folding	
1	468 ± 10	Carrock Gabbro Eycott Lavas		Llanvirn (D.bifidus Zone)

Conclusions

Radiometric dating of rocks from the English Lake District suggests that there were at least four major magmatic episodes during the Ordovician in addition to the widely recognized end-Silurian event. The sequence of magmatic events and their relationship to tectonism are summarized in Table 8. Information used in compiling this table is derived from this work and from others referred to in the text.

In addition to the age data there is evidence to show that strontium has been retained in K-feldspars whilst argon was outgassed, and conversely that argon has been retained by biotites whilst strontium was removed.

ACKNOWLEDGEMENTS. Thanks are due to all my colleagues in the isotope geology unit for much helpful discussion. In particular to R. D. Beckinsale for initial help, advice and instruction in sample collection and preparation and T. J. Shepherd for help and advice at later stages of the work. Thanks are due also to Mrs J. Robinson for assisting with mineral separation and to N. J. Soper and A. J. Wadge for two stimulating days in the field and for many helpful comments. This paper is published with the permission of the Director, Institute of Geological Sciences, London.

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Received 20 February 1978; revised typescript received 25 April 1978.

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