Lamprophyre dykes from Argyll.

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Summary. In the Carboniferous–Permian dyke-suite north of Loch Sunart, Argyll, a complete gradation is displayed from olivine-dolerite to camptonite. The dolerites are more numerous than the camptonites, and dykes of monchiquite are rare. A small number of minettes and allied lamprophyre types of Devonian age are also present. New analyses of biotite and diopside from a minette and of augite and hornblende from a camptonite are presented, with optical data, and the classification of the dykes briefly discussed.

The lamprophyre and dolerite dykes dealt with here occur in an area of some 40 square miles, north of the head of Loch Sunart in Argyll. They cut rocks of the Strontian Granitic Complex, a Newer Caledonian Granite, and precede the Ca–Ba–Pb–Zn mineralization in the area, which gave rise to the Strontian veins. The veins themselves are cut by north–south dolerite dykes of Tertiary type. The lamprophyre dykes are divisible into a small group of minettes and allied types and a later group of monchiquites and camptonites, with which dykes of camptonitic dolerite and olivine-dolerite are associated. Similar lamprophyres have been described from many parts of Scotland. A Devonian period of intrusion is generally accepted for the minettes (Phemister, 1960) and a late Carboniferous or Permian period for the camptonites and monchiquites (Richey, 1939; Leedal, 1951). Carboniferous–Permian volcanicity in the Western Highlands also gave rise to scattered monchiquitic volcanic vents but these do not occur in the present area. In Monar, dolerites have been shown to be closely associated with the camptonites and monchiquites (Ramsay, 1955).

The petrographical characteristics of the dykes are illustrated by means of modal analyses and eight new chemical analyses (made by modified 'rapid' methods). A slightly modified form of the conventional petrographical classification of the lamprophyres, based on the principal mafic mineral and the main constituent of the matrix, has been used in naming the dykes:

Minette	Biotite	Potash feldspar
Kersantite		Plagioclase
Vogesite	Diopside (or diopsidic augite) or common hornblende	Potash feldspar
Spessartite		Plagioclase
Camptonite	Augite (usually titaniferous), or brown hornblende, rarely biotite	
Monchiquite		A glassy base with little or no visible feldspar

Field characteristics.

The six lamprophyre dykes of probable Devonian age trend between N. 60° W. and N. 50° E. and one of the three minettes intrudes the Strontian granite, as do single dykes of spessartite and vogesite. A dyke of kersantite type is associated with Carboniferous–Permian dolerites to the east of the granite. The minette dykes are severely crushed, possibly as a result of renewed movements along fractures initiated prior to their intrusion. One, which contains xenoliths of granite, is veined and impregnated by carbonate. The analysed minette dyke, which averages 7 ft. in width, is the largest of the group and is cut by Carboniferous–Permian dolerites at the north-east edge of the Strontian granite (shown on 1-in. Sheet 53). Coarse marcasite occurs along one contact for several feet in brecciated quartzite. Mineralization of this type is not associated with Carboniferous–Permian intrusives in the area but pockets of iron sulphides occur in pre-granite lamprophyre sheets near Salen, west of Strontian, and pyritized vogesites of post-Cambrian age are known in Assynt (Sabine, 1953, p. 158).

Large numbers of west-north-west dykes of dolerite and lamprophyre occur in the area. They are of later age than the Devonian lamprophyres and earlier than the epigenetic metalliferous mineralization and the subsequent intrusion of north–south dykes of Tertiary type. The entire suite can be assigned to a Carboniferous–Permian period of intrusion. The dykes have an average trend of N. 70° W. and an average width of about 4 ft. although some dolerites are up to 30 ft. thick. About 180 of these dykes were mapped in the area, divisible into monchiquite (6), camptonite (35), camptonitic dolerite (13), and olivine-dolerite (approximately 120 dykes, of which nearly 50 were examined in thin section). Included with the olivine-dolerite dykes are intimately related varieties which are hornblende-bearing or olivine-free. The total width of the dolerite dykes in the suite is about four times that of the true lamprophyre dykes. The intrusive relationships of the lamprophyres and the dolerites are not displayed in the investigated area but at Gortenfern (in eastern Ardnamurchan), camptonite and monchiquite dykes intrude the same hornblende-bearing olivine-dolerite and at Lurga mine (Morvern), xenoliths of olivine-free dolerite occur in a dyke of camptonite type. In addition, the lamprophyres are of later age than the large Carboniferous–Permian quartz-dolerites that occur throughout this part of Argyll. The age-relationships of the quartz-dolerites and dykes of the olivine-dolerite group have not been resolved. In some places, lamprophyre and dolerite dykes intrude the same fissure but are always separated by narrow strips of granite or schist, which are often brecciated. The dykes may themselves be brecciated, pointing to limited post-intrusive movements along the original structures. Small-scale transcurrent displacements are displayed by many dykes intruded across lines of fracture that were subsequently re-opened.

Devonian minettes.

The minettes are deeply weathered, orange-brown dyke-rocks composed essentially of biotite and clinopyroxene set in potassium feldspar. Carbonate micropseudomorphs after olivine occur in the calcite-veined minette and are relatively numerous in the chilled margins of the dyke. Clinopyroxene is less common (8 %) and feldspar more abundant (46 %) than in the analysed dyke, the mode of which is given in table I. In the third minette, both olivine and clinopyroxene are replaced by carbonate, possibly as a result of deuteric activity since epigenetic calcite is not associated with the dyke.

The analysis in table I of the principal minette, on rock taken from the dyke centre 2 ft. below the weathered surface, is generally similar to published analyses of minette dykes (e.g. Knopf, 1936, p. 1765). Flakes of biotite exhibit 'battlemented' ends and average 0·2 mm in length, rare individuals attaining 1 cm. Minute inclusions are shown in (001) sections. Pleochroism is strong, α pale yellow, $\beta = \gamma$ olive-brown to reddish brown. Interference colours are faintly mottled and tiny opaque oxide grains follow the basal cleavage, probably as a result of the deep weathering of the dyke which may also account for the low potassium content shown by the biotite analysis in table II. The biotite is fairly rich in titanium, some of which has been included in the (Si, Al) grouping in recalculating the analysis.

Small prisms and granular clusters of colourless clinopyroxene are subsidiary to biotite in the analysed rock and from the chemical analysis given in table III appear to be diopside with aluminium substituting for

TABLE I. Chemical and modal analyses of a Devonian minette.

SiO_2	46·1		
Al_2O_3	12·4	Orthoclase	38
Fe_2O_3	3·1	Biotite	32
FeO	6·1	Diopside	17
MgO	9·7	Opaque minerals	4
CaO	11·4	Apatite	4*
Na_2O	0·4	Calcite	4*
K_2O	4·4	Quartz	1
H_2O^+	2·0	* Calculated from chemical analysis	
H_2O^-	0·4		
TiO_2	2·8	Sp. gr.	2·67
P_2O_5	1·93		
MnO	0·11		
CO_2	1·7		
S	0·30		
Total (less 0·08 O for S)	102·76		

Minette dyke, 1700 ft. S. 48° W. of western tip of loch in Coire nan Capull, Sunart.

TABLE II. Chemical analysis of biotite from minette (table I).

	1.	2.		3.	
SiO_2	35·7	36·1	Si	5·22	Z 8·00
Al_2O_3	14·8	15·3	Al	2·61	
			Ti	0·17	
TiO_2	4·9	4·9		0·36	Y 5·701
Fe_2O_3	2·6	1·3	Fe‴	0·14	
FeO	11·4	11·5	Fe″	1·39	
MnO	0·34	0·34	Mn	0·042	
MgO	16·8	17·4	Mg	3·75	
P_2O_5	0·15	0·15	P	0·019	
CaO	3·0	2·8	Ca	0·43	X 1·46
Na_2O	0·5	0·5	Na	0·14	
K_2O	4·7	4·8	K	0·89	
H_2O^+	4·4	4·5	OH	4·35	
H_2O^-	0·4	0·4	Sp. gr.	2·93	
Total	99·69		γ	1·642 (±0·003)	

1. Original analysis.
2. Analysis calculated free of impurities, 3·7 % by weight, of which diopside (analysis in table III) forms 1·4%, orthoclase ($KAlSi_3O_8$) 0·5 %, and magnetite (Fe_3O_4) 1·8 %.
3. Atomic ratios to 24 (O, OH).

silicon to a small extent. Tiny diopside grains fringe small quartzite xenoliths in the rock (fig. 1).

The biotite and diopside are enclosed in a reddish coloured base of partly altered orthoclase, forming ill-defined grains which average $0{\cdot}3 \times 1{\cdot}0$ mm in size. Accessory grains of magnetite (a 8·395±0·005 Å)

TABLE III. Chemical analysis of diopside from minette (table I).

	1.	2.		3.	
SiO_2	49·7	50·3	Si	1·87	Z 2·00 (Si + 0·13 Al)
Al_2O_3	5·7	5·2	Al	0·13	(in Z)
				0·10	WXY 1·981 (Al 0·10 to Mn)
Fe_2O_3	2·0	1·7	Fe‴	0·05	
FeO	4·2	4·0	Fe″	0·12	
MgO	12·7	12·7	Mg	0·70	
CaO	21·6	22·7	Ca	0·90	
Na_2O	0·7	0·7	Na	0·05	
K_2O	0·6	0·3	K	0·01	
TiO_2	1·6	1·4	Ti	0·04	
P_2O_5	0·08	0·08	P	0·003	
MnO	0·27	0·27	Mn	0·008	
H_2O^+	0·5	0·3	Sp. gr.... ...	3·13	
H_2O^-	0·4	0·4	α	1·684	±0·002 (α, β, γ)
Total	100·05		β	1·691	
			γ	1·712	
			$2V_\gamma$	56° (av. for 3 grains)	
			γ:[001] ...	41°	

1. Original analysis.
2. Analysis calculated free of impurities, 4·6 % by weight, of which biotite (analysis in table II) forms 2·9 %, orthoclase ($KAlSi_3O_8$) 1·3 %, and magnetite (Fe_3O_4) 0·4 %.
3. Atomic ratios to 6 oxygen.

and subsidiary pyrite are scattered through the rock. Needles of fluor-apatite (ω 1·635±0·002) up to 0·5 mm in length and irregular patches of calcite (probably deuteric in origin) are fairly common.

Other Devonian lamprophyres.

The three dykes of this group are fine-grained lamprophyres composed of green hornblende and brown biotite in variable proportions set in a matrix of pink plagioclase in the spessartite and kersantite, or of potassium feldspar, which lends an ash-grey colour to the vogesite. In the vogesite, tabular orthoclase grains and minor amounts of quartz and plagioclase surround groups of unorientated biotite and hornblende individuals up to 2·5 mm in diameter. A little biotite is associated with the very abundant hornblende in the spessartite, the general composition of which is very similar to that of foliated spessartite sheets occurring west of the Strontian granite (Guppy and Sabine, 1956, p. 18). Sphene is fairly common in all three dykes with lesser amounts of pyrite. Modal analyses gave:

	Quartz.	Ortho-clase.	Plagio-clase.	Biotite.	Horn-blende.	Acces-sories.
Vogesite	8	43	4	13	23	9
Spessartite	10½	—	23	4	58	4½
Kersantite	8	13	35	22	14	8

FIG. 1. Minette (analysed, table I). Biotite (*bi*) flakes and numerous cross-sections are set in an orthoclase base (*or*, no ornament) with grains of diopside (*di*) and magnetite (*mt*). Also present are scattered patches of calcite (*cc*) and a quartzite xenolith (*qu*) fringed by tiny diopsides.

Carboniferous–Permian dolerites.

A gradual transition from olivine-dolerite to camptonite is displayed within the Carboniferous–Permian dyke-suite but not by individual intrusions of the type described by Ramsay (1955). The dykes are fine-grained, aphanitic rocks, commonly amygdaloidal and altered as a result of later epigenetic mineralization, and chilled edges are well developed.

Most of the true lamprophyres contain ocelli and are darker in colour than the true dolerites but identification of many of the dykes requires the evidence of thin sections.

In the olivine-dolerites (table IV, 2), bowlingite micropseudomorphs after olivine are set amongst laths of labradorite (average length 0·3 mm) and sub-ophitic or intergranular fawn augite. Modal olivine varies from 4 to 23 % in the dykes and olivine-poor varieties are probably transitional to the olivine-free dolerites (table IV, 1), which form a small group in the dyke-suite. Although very highly weathered, the olivine-free dykes appear to be tholeiitic in character. In the analysed olivine-dolerite (table V, 1), length-slow fibres of yellow-green bowlingite are positive with α' 1·554, γ' 1·584 (both $\pm$0·003), forming box-like arrangements within the pseudomorphs, which have an average maximum diameter of about 1 mm. There is a small variation in plagioclase composition (An_{68-76}). The augite is slightly zoned with β 1·678 ($\pm$0·002), $2V_\gamma$ 46–48° (range for 4 grains), corresponding to $Ca_{38}Mg_{53}Fe_9$ (Hess, 1949). Magnetite is the main opaque mineral of the rock, but discrete grains of ilmenite also appear to be present (from X-ray evidence) and trace amounts of pyrite and possibly chalcopyrite were also observed. Apatite and traces of fibrous zeolite are additional accessories.

In all the dolerites, interstitial chlorite and mineraloid are fairly common, amygdales filled with carbonate surrounded by rosette chlorite are generally present, and autobrecciated fragments of chilled edge may occur in central rock. At the centres of thick olivine-dolerites, plagioclase is relatively abundant, olivine pseudomorphs uncommon, and brown hornblende is present in trace amounts. Where accessory amounts of brown hornblende are developed in the olivine-dolerites (table IV, 3), the augite tends to be granular rather than sub-ophitic and is sometimes porphyritic. In one dyke of this type, the augite has β 1·692 ($\pm$0·002), $2V_\gamma$ 50–54° (range for 4 grains), corresponding to $Ca_{43}Mg_{40}Fe_{17}$. The hornblende forms tiny prisms that show marked pleochroism, α orange-yellow, γ dark reddish brown, and have a small extinction angle, γ:[001] 11–13°.

Certain characteristics of the camptonites are developed in a small number of dykes in the suite that are otherwise very similar to the olivine-dolerites. These dykes are characterized by the presence of several per cent of brown hornblende (table IV, 4). Plagioclase is less common and finer-grained than in the true olivine-dolerites, although generally similar in composition. Augite grains (often zoned) are faintly purplish brown in colour and sometimes well shaped, and occur as phenocrysts in many dykes. The brown hornblende forms prisms up to 0·2 mm in length, which in places mantle augite grains, fringe amygdales, or occur together with apatite, carbonate, and traces of analcime in weakly developed ocelli.

TABLE IV. Modal analyses of Carboniferous–Permian lamprophyres and related dolerites.

	1.	2.	3.	4.	5.	6.	7.
No. of modes	8	19	25	13	13	39	9
Plagioclase	29	35	38	29	27	22	1
Altered base	15	—	—	—	4	6	20
Clinopyroxene	29	25	27	28	20	30	42
Olivine	tr.	15	13	14	9	13	12
Hornblende	—	tr.	1½	5½	26	15	8½
Opaque minerals	12	8	8½	9	8	9	9½
Analcime	—	—	—	½	3½*	3*	4*
Biotite	—	—	—	tr.	tr.	tr.	1
Chlorite, carbonate ...	15	17	12	14	2½	2	2
Per cent mafic minerals ...	29	40	41½	47½	55	58	63½

* Including about 1 % apatite and fibrous zeolite.

1, olivine-free dolerite; 2, olivine-dolerite; 3, hornblende-bearing olivine-dolerite; 4, camptonitic dolerite; 5, hornblende-camptonite; 6, augite-camptonite; 7, augite-monchiquite.

Carboniferous–Permian camptonites.

The camptonite dykes show wide variations in mineral composition. Titanaugite is usually the most common constituent, but in a few dykes brown hornblende is the principal mafic mineral (table IV, 5). It may be noted that while camptonites are often defined on the presence of abundant brown hornblende, augite predominates over barkevikite in the mode of the type camptonite (Troger, 1935, p. 163). The camptonite dykes of the present group, which contain relatively small amounts of brown hornblende, form a natural transition with the camptonitic dolerites. Both augite-camptonite and hornblende-camptonite types are sometimes developed within single dykes (cf. Flett, 1900, p. 885). Bowlingite pseudomorphs after olivine are present in very variable numbers in all the dykes but are generally more common in augite-camptonite types (table IV, 6). Biotite is an accessory mineral in a few dykes.

Plagioclase is relatively common in the camptonites where olivine is scarce; examples with 54 and 56 % of plagioclase have 3½ and 1 % of olivine. In two rocks, analcime (20 and 12½ %) was found to exceed plagioclase (9½ and 11 %). Plagioclase is the predominant constituent of the usually numerous ocelli, which average 2–3 mm in diameter in most dykes. Laths are distinctly larger in size in the ocelli than in the general body of the rocks, where the plagioclase is occasionally interstitial and in one instance replaced by fibrous analcime. A chloritised, isotropic base occurs in the ocelli, in places composed of analcime, which may be replaced by calcite (fig. 2). Associated constituents are apatite, fibrous

Fig. 2. Camptonite (analysed, table V, 2). At the centre of the ocellus, about 3 mm in diameter, analcime (*an*) is partly replaced by calcite (*cc*). Large laths of andesine-labradorite (*pl*) occur marginally in an altered, glassy base (*ch*) penetrated by apatite needles (*ap*). Prisms of brown hornblende (*hb*) fringe the ocellus and mantle titan-augite grains (*py*), which with bowlingite pseudomorphs after olivine (*ol*) are more numerous away from the ocellus.

zeolites, and dendritic opaque oxides, which in some instances penetrate plagioclase laths and analcime patches.

The chilled edges of the camptonite dykes usually carry larger and more numerous olivines, lesser amounts of hornblende and plagioclase, and fewer ocelli than central rock. In one exceptional example, however, hornblende forms 47 % in the edge-rock and 19 % at the dyke centre. Olivine and usually some titanaugite are porphyritic and smaller pyroxene grains are invariably mantled by brown hornblende. The

TABLE V. Chemical and modal analyses of Carboniferous–Permian dolerite and lamprophyre dykes.

	1.	2.	3.	A.	B.	C.
SiO_2	46·3	43·9	40·3	47·46	43·3	38·8
Al_2O_3	12·5	12·5	13·8	14·78	12·7	11·7
Fe_2O_3	3·8	4·0	4·1	3·02	4·8	4·7
FeO	7·5	7·1	8·5	8·01	7·1	7·1
MgO	10·7	10·0	10·7	7·28	7·4	10·4
CaO	8·5	10·1	10·8	8·46	10·5	11·9
Na_2O	2·5	3·2	2·1	3·03	3·3	2·5
K_2O	0·7	1·6	1·0	1·13	1·9	1·7
H_2O^+	3·4	2·2	3·3	2·62	3·0	3·3
H_2O^-	1·3	1·0	1·2	0·86		0·8
TiO_2	1·6	2·6	2·5	2·26	2·8	3·0
P_2O_5	0·39	0·31	0·14	0·36	0·7	1·1
MnO	0·24	0·26	0·23	0·16	0·2	0·3
CO_2	0·5	1·9	1·2	0·48	2·0	2·1
&c.	0·02	0·13	1·07	0·09	0·3	0·6
Totals	99·94	100·77	100·68			
Sp. gr.	2·81	2·88	2·96			

	1.	2.	3.	C.I.P.W. norm (1).	
Plagioclase	32	17½	—	or	4·1
Altered base	—	2	19½	ab	21·1
Clinopyroxene	32	21	47	an	20·8
Olivine	22½	13	15	di	12·4
Hornblende	—	25	7½	hy	18·1
Opaque minerals ...	6½	6	10	ol	7·8
Analcime	—	6	tr.	mt	5·5
Zeolite, apatite	tr.	4	tr.	il	3·0
Chlorite, carbonate ...	7	5½	1	py	0·1
				ap	0·9
				cc	1·1

1. Olivine-dolerite, centre of dyke about 3800 ft. S. 78° E. of the summit of Garbh Bheinn, Ardgour. Also found: 0·02 % sulphur (total less 0·01% O for S) and trace of BaO.
2. Hornblende-camptonite, centre of dyke on the south side of vein in Allt Tarsuinn, Corrantee mine, nearly 3 miles N. 14° W. of Strontian, Sunart. Also found: 0·13 % sulphur (total less 0·03 % O for S) and trace of BaO.
3. Augite-monchiquite, centre of dyke in the crags of An Torra Ban, nearly 2½ miles N. 55° E. of Strontian, Sunart. Also found: 1·03 % sulphur (total less 0·26 % O for S), 0·04 % ZrO_2, and trace of BaO.

A. Average Carboniferous–Permian olivine-dolerite, analyses mainly of dykes in Central Scotland (Tomkeieff, 1937, table I, anal. 19).

B. Average of seven analyses of camptonite dykes of the Orkneys and Western Highlands, recalculated to 100 %. Analyses from Guppy and Thomas (1931, anal. 186), Guppy and Sabine (1956, anals. 671–674 inclusive), Ramsay (1955, p. 307, anal. 7), and anal. 2 in this table.

C. Average of seven analyses of monchiquite dykes of the Orkneys and Western Highlands, recalculated to 100 %. Analyses from Guppy and Thomas (1931, anals. 343 and 344), Guppy and Sabine (1956, anals. 714–17 inclusive), and anal. 3 in this table.

mutual boundaries of the pyroxene and hornblende grains are highly irregular, but the free edges of the hornblendes are usually well-shaped. Large, well-shaped prisms of hornblende are concentrated at the edges of ocelli in many camptonites (fig. 2). The order of crystallization in the camptonites was probably as follows: opaque oxide grains, olivine, titanaugite, brown hornblende, biotite, plagioclase, analcime, apatite and fibrous zeolite, dendritic opaque oxides, chlorite and carbonate.

TABLE VI. Chemical analysis of hornblende from camptonite (table V, 2).

	1.	2.		3.	
SiO_2	39·4	39·2	Si	5·91	Z 8·00
Al_2O_3	15·4	15·5	Al	2·09	
				0·66	Y 5·244
Fe_2O_3	3·6	3·3	Fe‴	0·38	
FeO	10·9	10·8	Fe″	1·36	
MgO	10·5	10·6	Mg	2·38	
TiO_2	3·6	3·6	Ti	0·41	
P_2O_5	0·13	0·13	P	0·016	
MnO	0·30	0·30	Mn	0·038	
CaO	12·5	12·4	Ca	2·00	X 2·60
Na_2O	1·7	1·7	Na	0·50	
K_2O	1·0	1·0	K	0·19	
H_2O^+	1·0	1·0	OH	1·01	
H_2O^-	0·5	0·5	Sp. gr.	3·22	
Total	100·53		α	1·678	±0·003
			γ	1·700	
			$2V_\alpha$	78° (av. for 5 grains)	

1. Original analysis.
2. Analysis calculated free of impurities, 2·2 % by weight, of which titanaugite (analysis in table VII) forms 1·1 %, plagioclase (An_{54}) 0·3 %, bowlingite (saponite composition), 0·2 % and magnetite (Fe_3O_4) 0·6 %.
3. Atomic ratios to 24 (O, OH).

Prisms and grains of brown hornblende have a characteristically small extinction angle, γ:[001] 11–14°, throughout the dyke-group and show marked pleochroism, α orange-yellow, β brown, γ dark reddish brown. The pyroxene is characteristically purplish brown and weakly pleochroic. Zoning is often developed in phenocrysts but rarely in granular pyroxene. The chemical composition and optical properties of the hornblende and the pyroxene (tables VI and VII) that were separated from the analysed camptonite dyke (table V, 2) agree closely with those of titaniferous hornblende and titanaugite from a Skaergaard camptonite dyke given by Vincent (1953). The associated olivine is completely replaced by fibrous green bowlingite with α' 1·557, γ' 1·582, and sp. gr. 2·36. The X-ray powder spacings of this bowlingite correspond fairly well with A.S.T.M. data for saponite. Partly altered olivine was found in two other dykes in the group.

The plagioclase of the camptonites is generally a sodic labradorite of smaller grain-size than the labradorite of the olivine-dolerites. In the analysed rock, laths of andesine-labradorite, An_{48-60}, measure 0·1 to 1·5 mm in length. Ramsay (1955) has suggested that plagioclase in the ocelli of camptonites is more sodic than in the general body of the rocks,

TABLE VII. Chemical analysis of titanaugite from camptonite (table V, 2).

	1.	2.		3.	
SiO_2	48·0	48·2	Si	1·80	Z 2·00 (Si 1·80, Al 0·20)
Al_2O_3	6·1	5·8	Al	0·20 / 0·06	
Fe_2O_3	2·3	2·1	Fe‴	0·06	WXY 1·998 (Al 0·06 to Mn 0·006)
FeO	6·3	6·1	Fe″	0·19	
MgO	13·0	13·0	Mg	0·72	
CaO	20·1	20·3	Ca	0·81	
Na_2O	0·9	0·8	Na	0·06	
K_2O	0·3	0·3	K	0·01	
TiO_2	2·8	2·8	Ti	0·08	
P_2O_5	0·06	0·06	P	0·002	
MnO	0·18	0·18	Mn	0·006	
H_2O^+	0·3	0·3	Sp. gr.	3·30	
H_2O^-	0·1	0·1	α	1·689	±0·002 (α, β, γ)
Total	100·44		β	1·694	
			γ	1·724	
			$2V_\gamma$	49° (av. for 4 grains)	
			γ:[001]	44°	

1. Original analysis.
2. Analysis calculated free of impurities, 3·5 % by weight, of which hornblende (analysis in table VI) forms 2·6 %, plagioclase (An_{54}) 0·5 %, bowlingite (saponite composition) 0·1 %, and magnetite (Fe_3O_4) 0·3 %.
3. Atomic ratios to 6 oxygen.

and this appears to be the most probable cause of the fairly wide compositional variation in the present case. Opaque mineral grains, usually less than 0·2 mm in diameter, are common outside the ocelli of the camptonites. Magnetite, possibly with subsidiary ilmenite, occurs in the analysed rock with traces of sulphide. Associated apatite prisms have ω 1·643 (±0·002) indicating a fluor-hydroxyl variety. Fibrous, biaxial zeolite is present in the ocelli of many camptonites. Analcime occurs mainly in the ocelli where it is often replaced by chlorite (fig. 2) but it is also present in amygdales and as an interstitial mineral. Amygdaloidal analcime may show weak birefringence and rudimentary twinning. In a few dykes, both ocelli and amygdales are composed entirely of analcime. Small flakes of brown biotite were found at the edges of ocelli in three dykes. Granules of what may be epidote occur around some of the ocelli in the analysed camptonite. In the ocelli of several dykes, fibrous green chlorite has altered from a turbid, isotropic base. Calcite may replace plagioclase, chlorite, or analcime in the ocelli. Both carbonate and chlorite occur in amygdales, which are usually less common than in the olivine-dolerites. The well-defined rims of the amygdales are readily distinguishable from the poorly formed edges of the ocelli. In one dyke, amygdales appear to have developed on the sites of original ocelli.

Although there is considerable variation in mineralogical composition among the seven camptonite dykes of the Orkneys and Western Highlands for which chemical analyses are available (table V, B), chemical differences are comparatively small. The close chemical affinities between Carboniferous–Permian olivine-dolerite and camptonite dykes in the Western Highlands noted by Ramsay (1955) are also shown by the new analyses. The camptonite contains less silica and larger amounts of sodium, potassium, and titanium.

Certain unusual characteristics are shown by four dykes that may be camptonites. In one dyke, which intrudes appinite, phenocrysts of plagioclase and bowlingite are set in a matrix of plagioclase and altered pyroxene with subsidiary biotite and brown hornblende; a little analcime occurs in weakly developed ocelli and amygdales filled with chalcedonic silica and carbonate are abundant at the dyke centre. The central parts of a second dyke, 18 ft. in width and deeply weathered, are composed of augite-plagioclase lamprophyre with subsidiary orthoclase and biotite, suggesting affinities with lamprophyres of spessartite-vogesite type; however, the edge-rocks consist of plagioclase, titanaugite, altered olivine, and brown hornblende, with accessory biotite and orthoclase, an assemblage more akin to camptonite although ocelli are not developed. One isolated dyke in Ardgour is largely composed of closely aligned prisms of brown hornblende, which occur with a little altered olivine in a tabular base of sodic plagioclase; very similar rocks have been described as hornblende-spessartites (Phillips, 1956). The main vein at Lurga mine, south of Loch Sunart in Morvern, follows a narrow dyke of very variable composition; orthoclase is a major constituent of parts of the weathered dyke while elsewhere analcime equals plagioclase in amount and biotite is more common than brown hornblende; the augite is sometimes porphyritic and titaniferous.

Carboniferous–Permian monchiquites.

Clinopyroxene is the major constituent of each of the eight dykes examined (including two from eastern Ardnamurchan), but it is seldom porphyritic (average 4 % in the modal analyses). It is similar to the titanaugite of the camptonites, although much of the granular clinopyroxene in the monchiquites shows zoning. In one dyke, titanaugite phenocrysts include pieces of a greenish-coloured clinopyroxene with a small extinction angle. The hornblende of the monchiquites, unlike that of the camptonites, seldom mantles granular titanaugite and is never associated with titanaugite phenocrysts. Bowlingite pseudomorphs after olivine are usually more abundant than brown hornblende (table IV, 7). In the analysed monchiquite (table V, 3), partly altered olivine has γ 1·694 ($\pm$0·002) and 2V about 90°, indicating a forsterite-rich composition. The modal proportion of brown hornblende in the dykes varies between 2 and 17 %, occurring mainly as slender prisms set in a glassy, partly devitrified base, which forms the ocelli. The outlines of accessory plagioclase grains are sometimes discernible in this base. The ocelli are developed to a lesser degree than in the camptonites and are usually smaller in size (below 1 mm in diameter). Small flakes of brown biotite, often fringed by tiny opaque oxide grains, usually occur at the edges of ocelli. Biotite was found in only three of the dykes but it predominates over hornblende in one of these, forming about 6 %. Analcime may be developed as irregular patches throughout the rocks and also in amygdales (rimmed by hornblende prisms) as well as in the ocelli.

The mafic minerals of the monchiquites are mainly well shaped and occur in a structureless, isotropic base partly altered to flecks of chlorite and a little carbonate. Small grains and specks of iron-titanium oxides are common in most of the dykes and tiny specks of sulphide are numerous in the analysed rock. Minute prisms of apatite and possibly some zeolite are profuse in the altered base of the monchiquites. Calcite and chlorite occur in amygdales. A corroded quartz–feldspar xenolith was found in one dyke and a quartz aggregate, rimmed by granular titanaugite, in another.

The monchiquite analyses summarized in table V (C) differ considerably from one another, mainly as a result of the very variable proportions of mafic minerals which the rocks contain. Compared with the camptonites, the monchiquites contain less silica and usually more calcium and magnesium.

A note on lamprophyre classification.

In Scotland, the spatial distribution of the minette, spessartite, vogesite, and kersantite lamprophyres points to a close connexion with the Newer Caledonian Granites. In recent years, however, certain spessartite lamprophyres in which the hornblende is usually a brown, alkali-iron variety, have been described as possible derivatives of basic magmas (Phillips, 1956; Watson, 1957; Chatterjee, 1959), contrary to the tenets of the Rosenbusch inheritance concept. This concept is certainly inadequate when applied to the genesis and classification of the camptonite and monchiquite lamprophyres, as the work of a number of authors, particularly Knopf (1936) and Vincent (1953), has clearly shown. In the Western Highlands, previous evidence of the close relationship between these lamprophyres and dykes of undoubted basaltic parentage (Ramsay, 1955) is supported by the present study of the Carboniferous–Permian dykes in Argyll.

The distinction between spessartite containing brown hornblende as the principal mafic mineral and camptonite in which ocelli are not well developed is a difficult one, although a useful set of criteria for the two lamprophyre types has been given by Richey (1939, p. 418). It may be necessary to distinguish two groups of spessartites based upon the character of the hornblende present.

The distinction between camptonite and monchiquite can usually be made on the relative proportions of plagioclase and glassy base; analcime is not a definitive constituent since it may be conspicuously developed in the camptonites without forming the main element of the matrix. The Argyllshire monchiquites also differ from the associated camptonites by a higher content of titanaugite (see table IV) and in a contrasting hornblende fabric.

There may be some advantage in defining specific lamprophyre types more closely by the use of mineral prefixes (cf. Knopf, 1936, p. 1748). Thus the camptonite and the monchiquite in table V (2 and 3) may be termed hornblende-augite-olivine-camptonite and augite-olivine-hornblende-monchiquite (plagioclase and glassy base are unambiguous definitive constituents in the respective rocks). In this way, the established lamprophyre classes could be extended to cover many of the very rare lamprophyre types listed by Tröger (1935). For example, fourchite, ouachitite, giumarrite, and rizzonite could be included in the monchiquites with due reference to the presence of biotite and feldspathoidal minerals in the individual rock names. In the case of lamprophyres that are of unusual character or highly altered, it may be more useful to list the minerals present rather than assign the rocks to one of the lamprophyre classes.

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References.

CHATTERJEE (N. D.), 1959. Nachr. Akad. Wiss. Göttingen, ser. 2, no. 1.
FLETT (J. S.), 1900. Trans. Roy. Soc. Edinb., vol. 39, p. 865.
GUPPY (E. M.) and SABINE (P. A.), 1956. Chemical analyses of igneous rocks, metamorphic rocks and minerals. Mem. Geol. Surv. Gt. Britain.
—— and THOMAS (H. H.), 1931. Ibid.
HESS (H. H.), 1949. Amer. Min., vol. 34, p. 621.
KNOPF (A.), 1936. Bull. Geol. Soc. Amer., vol. 47, p. 1727.
LEEDAL (G. P.), 1961. Geol. Mag., vol. 88, p. 60.
PHEMISTER (J.), 1960. Scotland. The Northern Highlands. Geol. Surv. British Regional Geology, 3rd edn.
PHILLIPS (W. J.), 1956. Proc. Geol. Ass. London, vol. 67, p. 103.
RAMSAY (J. G.), 1955. Geol. Mag., vol. 92, p. 297.
RICHEY (J. E.), 1959. Trans. Edinb. Geol. Soc., vol. 13, p. 393.
SABINE (P. A.), 1953. Quart. Journ. Geol. Soc., vol. 109, p. 137.
TOMKEIEFF (S. I.), 1937. Bull. Volcanol., ser. 2, tome 1, p. 59.
TRÖGER (E.), 1935. Spezielle Petrographie der Eruptivgesteine. Berlin.
VINCENT (E. A.), 1953. Quart. Journ. Geol. Soc., vol. 109, p. 21.
WATSON (K. D.), 1957. Canadian Min., vol. 6, p. 15 [M.A. **13**-526].