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## The geochemistry of the Devonian lavas of the northern Lorne Plateau, Scotland

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**SUMMARY.** Chemical analyses of the Lorne volcanic rocks show that the basalts and andesites are a closely related suite of lavas, notably rich in alkalis, especially potassium. The rhyolites of the Lorne area do not appear to form a continuous series with the more basic rocks. The various lava types are compared with the plutonic rocks of the area, and a relationship is suggested between the basic lavas and appinitic intrusions. The acid lavas are not comparable to granites in the area.

The late orogenic igneous activity in this part of the Caledonides therefore appears to involve three generations of magma, produced separately but within a short time of one another. The assumption that all the late Caledonian igneous rocks of the Scottish Highlands are differentiates of a common parent magma is not justified.

THE DEVONIAN lavas of the west of Scotland are an example of the volcanic association described by Turner and Verhoogen (1960) as the basalt-andesite-rhyolite association of orogenic regions. They show a close temporal and spatial relationship to a wide variety of acid and basic, plutonic and hypabyssal igneous rocks, all of which were produced during the latest stages of the Caledonian orogeny. The purpose of this study was to ascertain from chemical evidence whether the Caledonian igneous rocks of this region are consanguineous, as assumed by previous authors (Nockolds and Mitchell, 1948; Bailey, 1958), or whether they represent separate generations of magma, as some current petrogenetic hypotheses would imply.

The geology of the region is shown in fig. 1. Recent papers have described the lavas of Ben Nevis (Haslam, 1968) and Glen Coe (Roberts, 1966), but there has been relatively little work on the more extensive lavas of the Lorne area since their early geological mapping by Kynaston and Hill (1908) and Lee and Bailey (1925). The plutonic rocks of the area are comparatively well known as a result of detailed studies on the intrusions of Ben Nevis (Anderson, 1935; Haslam, 1968), Glen Coe (Bailey and Maufe, 1960), Etive (Anderson, 1937), Ballachulish (Bowes *et al.*, 1964; Bowes and Wright, 1967; Platten, 1966; Westoll and Miller, 1969), and Garabal Hill (Nockolds, 1941).

The Lorne lavas occupy an area of about 300 km<sup>2</sup>, and their present maximum thickness is approximately 800 m. They rest in most places unconformably on Dalradian metamorphic rocks, but locally there are Devonian sediments at the base and

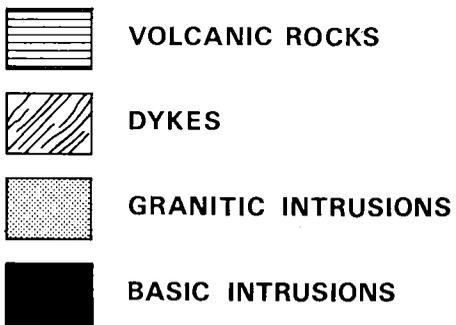
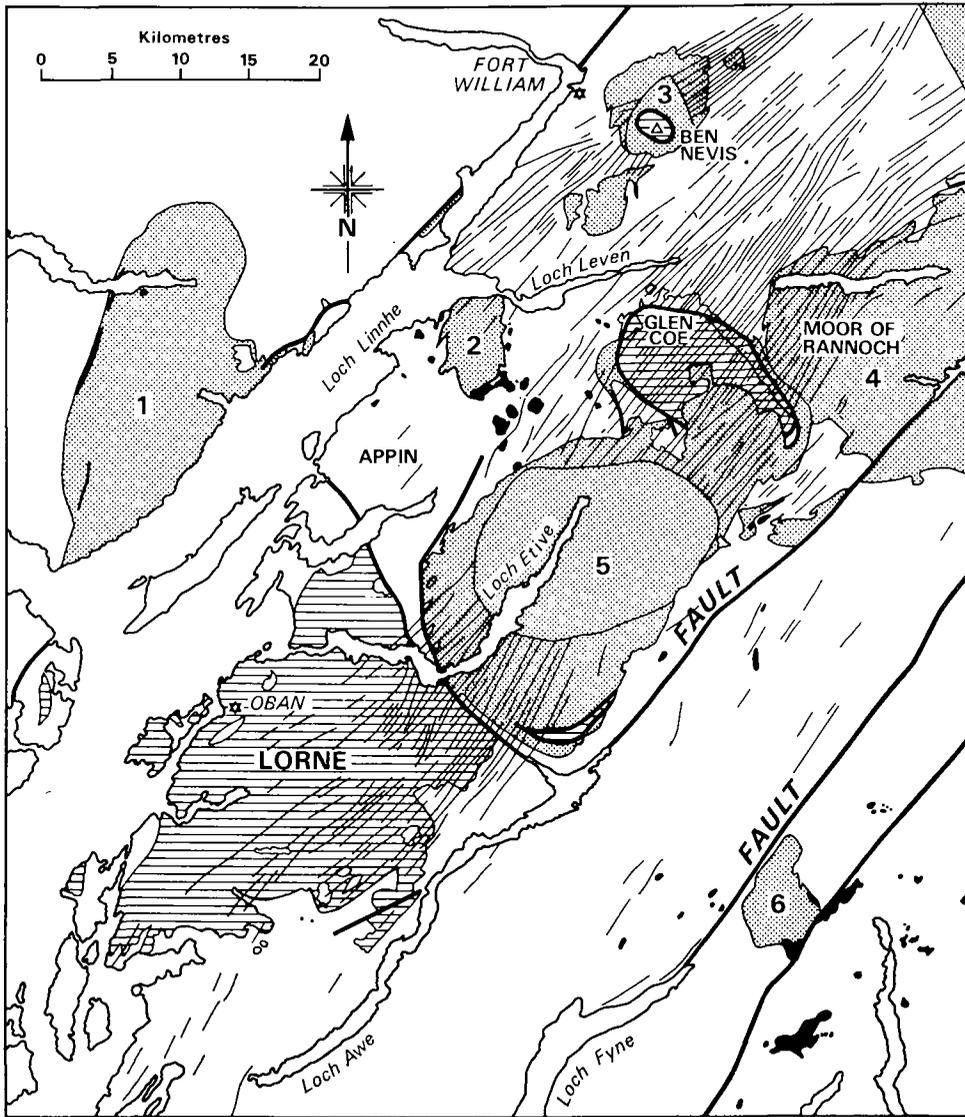


FIG. 1. Geological map of the Lorne area, west of Scotland, showing the distribution of Caledonian igneous rocks.

intercalated in the lava sequence. Individual lava flows range in thickness from less than 5 m to more than 30 m; they can not usually be traced for any distance because of the poor exposure inland, except near the north side of Loch Etive where they form prominent escarpments that can be followed for several kilometres. The predominant rock types are basalts and andesites, often vesicular, with subordinate acid lavas and acid tuffs (ignimbrites). Details of the occurrence and petrography of the rocks are given by Kynaston and Hill (1908).

The method of this study was to determine the range of chemical variation in the Lorne lavas, and to compare their compositions with those of plutonic and hypabyssal rocks in the same area to which they may be genetically related. Samples were collected from all parts of the lava succession in the northern Lorne area (i.e. east of Oban, and north of Loch Etive), and analysed by a combination of classical and instrumental methods. The whole of the lava pile has been severely affected by either deuteric alteration or weathering, and the analysed specimens represent a selection of the least altered material. The degree of alteration has precluded detailed mineralogical study, but a few mineral analyses are included in Tables VI and VII.

#### *Composition of the lavas*

Analyses of the basalts, andesites, and rhyolites are given in Tables I–III respectively. The rocks have been named according to their silica contents: all basic rocks ( $\text{SiO}_2 < 52\%$ ) are referred to as basalt, all intermediate rocks ( $\text{SiO}_2$  52–65%) as andesite (or basaltic andesite at the basic end of this range), and all acid rocks ( $\text{SiO}_2 > 65\%$ ) as rhyolite or dacite. No attempt has been made to identify the acid rocks individually as dacite or rhyolite because the degree of alteration precludes accurate measurement of the modal plagioclase:alkali-feldspar ratio, but the normative feldspar ratios (Table III) indicate both types of acid rock to be present.

The basalts and andesites are mineralogically very variable and the majority are porphyritic. The ferromagnesian phenocrysts include olivine, hypersthene, augite, hornblende, and biotite, either alone or in a wide range of combinations, with the exception that hornblende and biotite do not form phenocrysts in the same rocks as olivine and hypersthene. There is no apparent relationship between the occurrence of these phenocrysts and the composition of the rock, each of the minerals being equally likely to occur in a basalt or an andesite. Plagioclase phenocrysts also occur, but are only common or abundant in the andesites, and plagioclase is never the only phenocryst phase. The groundmass in all the rocks consists principally of feldspar with small amounts of ferromagnesian minerals and abundant iron oxide. Olivine and hypersthene phenocrysts are almost invariably pseudomorphed by alteration products, but the other minerals can be found in a fresh condition.

The dacites and rhyolites are of very restricted occurrence. They occur as small flows not more than 2 m in thickness. They are pink or orange in colour and show flow banding. They contain a small proportion of phenocrysts (quartz, sanidine, and oligoclase) in a turbid crystalline groundmass, which in most cases appears to be devitrified glass. Biotite and clinopyroxene occur in small amounts in some of the samples, and all contain granules of iron oxide.

TABLE I. *Analyses of basalts (1-5) and basaltic andesites (6-10) from northern Lorne*

	1	2	3	4	5	6	7	8	9	10
SiO <sub>2</sub>	49.46	49.52	50.16	50.89	51.87	52.02	52.23	52.94	53.20	54.73
TiO <sub>2</sub>	1.51	1.51	1.49	1.15	1.19	1.36	1.25	1.31	1.22	1.31
Al <sub>2</sub> O <sub>3</sub>	16.30	16.94	16.81	15.90	16.09	15.43	16.54	16.50	15.71	15.51
Fe <sub>2</sub> O <sub>3</sub>	5.89	4.82	4.27	5.16	5.38	5.49	5.44	5.55	6.04	6.22
FeO	2.95	3.88	4.04	2.65	2.79	2.51	2.45	1.88	1.86	1.95
MnO	0.12	0.13	0.12	0.10	0.13	0.14	0.12	0.11	0.10	0.10
MgO	5.66	6.35	7.08	6.19	6.63	6.88	5.05	2.55	6.37	4.23
CaO	8.12	7.49	7.12	8.48	7.78	6.60	7.74	8.25	5.43	5.30
Na <sub>2</sub> O	4.04	3.53	3.69	3.44	2.87	3.68	3.59	4.16	4.05	5.50
K <sub>2</sub> O	2.41	2.16	2.19	2.25	1.45	2.41	2.05	2.28	2.30	2.33
H <sub>2</sub> O <sup>+</sup>	2.16	3.14	2.01	2.42	2.70	2.98	2.38	1.69	2.86	1.81
CO <sub>2</sub>	—	—	—	0.88	0.65	—	0.45	1.69	—	—
P <sub>2</sub> O <sub>5</sub>	0.65	0.50	0.43	0.29	0.23	0.42	0.27	0.45	0.39	0.44
	99.27	99.97	99.41	99.80	99.76	99.92	99.56	99.36	99.53	99.43
<i>Trace elements (ppm)</i>										
Co	38	41	41	41	41	35	32	23	41	29
Cr	362	364	347	354	400	292	345	309	433	258
Cu	24	27	25	29	16	18	26	40	33	14
Li	31	23	28	25	25	32	13	15	28	18
Ni	158	167	170	150	174	127	144	111	190	118
Rb	30	29	16	28	20	19	18	25	28	37
Sr	1390	1180	1250	1200	810	1350	1120	1110	1210	850
Zn	130	86	127	86	86	100	95	82	123	105
Zr	127	160	153	120	122	112	110	132	82	165
<i>Norm</i>										
Q	—	—	—	0.99	6.87	0.69	3.74	6.10	2.24	0.16
Or	14.24	12.76	12.94	13.29	8.57	14.24	12.11	13.47	13.59	13.77
Ab	31.53	29.86	31.21	29.09	24.27	31.12	30.36	35.18	34.25	46.52
An	19.23	24.00	22.84	21.30	26.74	18.47	22.97	19.62	17.90	10.76
Ne	1.46	—	—	—	—	—	—	—	—	—
Di	13.08	7.74	7.61	10.35	4.85	8.97	8.42	5.98	5.05	9.85
Hy	—	7.57	5.75	10.61	14.26	12.97	8.67	3.58	13.52	5.96
Ol	5.63	3.89	7.05	—	—	—	—	—	—	—
Mt	5.52	6.99	6.19	5.53	5.97	4.61	4.67	2.62	2.79	2.81
Il	2.87	2.87	2.83	2.18	2.26	2.58	2.37	2.49	2.32	2.49
Ap	1.54	1.19	1.02	0.69	0.55	1.00	0.64	1.07	0.92	1.04
Cc	—	—	—	2.00	1.48	—	1.02	3.84	—	—
Hm	2.08	—	—	1.34	1.26	2.31	2.22	3.74	4.12	4.28
Water	2.16	3.14	2.01	2.42	2.70	2.98	2.38	1.69	2.86	1.81

Localities of the analysed specimens (National Grid references)—

1	NM 957367	5	NM 972355	8	NM 986341
2	NM 957373	6	NM 932367	9	NM 933365
3	NM 948370	7	NM 937375	10	NM 911347
4	NM 919368				

TABLE II. *Analyses of andesites from northern Lorne*

	1	2	3	4	5	6	7	8	9	10	11	12
SiO <sub>2</sub>	55.04	56.20	57.48	57.91	59.81	59.88	59.91	60.83	60.88	61.29	62.35	62.67
TiO <sub>2</sub>	1.23	1.20	0.97	0.92	0.99	0.82	1.13	0.86	0.69	0.83	0.69	0.79
Al <sub>2</sub> O <sub>3</sub>	16.30	16.84	16.45	16.12	16.72	15.82	15.88	16.86	15.58	16.10	15.40	16.19
Fe <sub>2</sub> O <sub>3</sub>	5.12	3.22	4.46	4.00	2.12	2.96	4.37	2.15	3.36	3.44	1.70	2.30
FeO	1.71	3.01	2.07	2.05	2.94	1.95	1.85	2.40	1.98	1.44	2.48	2.35
MnO	0.11	0.13	0.11	0.07	0.11	0.06	0.08	0.05	0.07	0.08	0.06	0.07
MgO	5.01	4.30	3.39	3.99	3.44	3.40	4.79	2.45	3.43	3.80	2.78	2.85
CaO	6.22	4.84	4.51	6.22	5.15	3.13	1.89	4.73	4.21	0.89	3.67	3.44
Na <sub>2</sub> O	4.27	4.50	4.85	4.17	4.40	5.64	4.94	4.09	4.03	6.45	3.06	4.34
K <sub>2</sub> O	2.16	2.68	2.45	2.33	2.50	2.57	1.90	3.06	2.97	2.34	3.83	3.46
H <sub>2</sub> O <sup>+</sup>	2.03	2.13	2.05	1.11	1.37	2.25	2.75	1.46	1.40	2.82	2.17	1.50
CO <sub>2</sub>	0.12	—	0.62	0.72	0.53	0.50	—	—	0.55	—	1.06	—
P <sub>2</sub> O <sub>5</sub>	0.42	0.28	0.37	0.37	0.25	0.35	0.32	0.30	0.27	0.26	0.18	0.25
	99.74	99.33	99.78	99.98	100.33	99.33	99.81	99.24	99.42	99.74	99.43	100.21
<i>Trace elements (ppm)</i>												
Co	26	23	23	23	20	17	29	14	14	19	14	11
Cr	267	169	300	250	150	108	329	117	150	142	145	133
Cu	23	47	53	111	23	15	55	37	25	16	22	66
Li	13	19	31	23	14	31	37	24	27	27	25	25
Ni	101	92	101	101	39	33	101	36	65	49	39	26
Rb	20	22	27	30	39	35	15	60	64	40	67	54
Sr	960	1050	870	990	890	840	1080	950	760	1110	940	1410
Zn	86	73	109	164	86	77	127	105	100	95	77	86
Zr	135	127	132	120	117	115	115	137	115	147	124	107
<i>Norm</i>												
Q	4.50	4.23	7.97	9.68	10.10	7.84	13.64	12.44	14.23	8.01	20.34	12.93
Or	12.76	15.83	14.48	13.77	14.77	15.18	11.23	18.08	17.55	13.83	22.63	20.44
Ab	36.11	38.06	41.02	35.27	37.21	47.70	41.78	34.59	34.08	54.55	25.88	36.71
An	18.94	17.84	15.89	18.39	18.50	10.08	7.29	18.61	15.64	2.72	10.33	14.48
Di	6.55	3.41	0.11	4.27	1.64	—	—	2.30	—	—	—	0.75
Hy	9.44	10.23	8.39	7.95	10.00	8.46	11.93	6.31	8.54	9.46	9.04	7.98
Mt	2.31	4.67	4.22	4.17	3.07	4.10	2.95	3.12	4.61	2.50	2.46	3.33
Il	2.34	2.28	1.84	1.75	1.88	1.56	2.15	1.63	1.31	1.58	1.31	1.50
Ap	1.00	0.66	0.88	0.88	0.59	0.83	0.76	0.71	0.64	0.62	0.43	0.59
C	—	—	—	—	—	0.07	3.03	—	0.01	1.96	2.44	—
Cc	0.27	—	1.41	1.64	1.21	1.14	—	—	1.25	—	2.41	—
Hm	3.53	—	1.55	1.12	—	0.13	2.34	—	0.13	1.72	—	—
Water	2.03	2.13	2.05	1.11	1.37	2.25	2.75	1.46	1.40	2.82	2.17	1.50

Localities of the analysed specimens (National Grid references)—

1	NM 883313	5	NM 954356	9	NM 874313
2	NM 953357	6	NM 909341	10	NM 903335
3	NM 918371	7	NM 916369	11	NM 973356
4	NM 921369	8	NM 956331	12	NM 982333

The ignimbrites that occur in the Lorne area are of several kinds. Kynaston and Hill (1908) distinguished crystal and lithic tuffs. Twenty-six samples of ignimbrites were analysed chemically. They include compositions similar to those of the rhyolites, but, as Walker (1972) has pointed out, the compositions of ignimbrites are often severely modified by crystal sorting and other processes during and after eruption, and the analyses are here shown only diagrammatically (fig. 9).

TABLE III. *Analyses of dacites and rhyolites from northern Lorne*

	1	2	3	4	5	6	7	8	9	10
SiO <sub>2</sub>	65.58	66.06	66.60	69.40	74.83	75.37	76.66	77.08	77.35	78.64
TiO <sub>2</sub>	0.65	0.71	0.18	0.04	0.11	0.08	0.10	0.06	0.27	0.14
Al <sub>2</sub> O <sub>3</sub>	15.93	16.24	14.54	14.06	14.21	13.51	13.33	13.40	11.13	11.52
Fe <sub>2</sub> O <sub>3</sub>	3.11	2.93	0.99	0.58	0.80	0.08	0.89	0.42	0.59	0.54
FeO	1.12	1.23	1.30	0.51	0.09	0.79	0.19	0.23	0.28	0.06
MnO	0.10	0.04	0.06	0.04	0.02	0.02	0.01	0.00	0.02	0.01
MgO	0.74	1.38	1.16	0.88	0.09	0.40	0.09	0.13	0.17	0.16
CaO	1.43	0.25	2.58	3.78	0.07	0.63	0.13	0.09	0.03	0.04
Na <sub>2</sub> O	3.72	4.38	3.83	3.49	4.06	3.85	4.10	2.47	1.55	3.37
K <sub>2</sub> O	3.34	4.46	3.97	3.04	4.35	2.75	3.61	4.97	7.04	4.54
H <sub>2</sub> O <sup>+</sup>	2.95	1.79	2.19	2.92	1.02	1.34	0.97	1.27	1.08	0.60
CO <sub>2</sub>	0.39	—	1.59	0.57	—	0.39	—	—	—	—
P <sub>2</sub> O <sub>5</sub>	0.31	0.23	0.13	0.04	0.03	0.02	0.02	0.02	0.02	0.02
	99.37	99.70	99.12	99.35	99.68	99.23	100.10	100.14	99.53	99.64
<i>Trace elements (ppm)</i>										
Co	19	*	14	*	*	*	*	*	*	*
Cr	*	83	*	*	*	*	*	*	*	*
Cu	*	29	*	*	*	*	*	*	30	*
Li	8	19	6	8	6	4	4	4	39	15
Ni	27	*	27	23	18	18	18	18	*	*
Rb	101	73	108	98	127	35	80	140	149	95
Sr	260	150	270	520	180	350	100	60	150	50
Zn	70	82	63	63	35	209	25	28	23	30
Zr	210	357	132	140	160	202	350	160	127	137
<i>Norm</i>										
Q	28.95	21.57	25.97	29.78	34.39	41.06	38.66	43.38	41.14	41.41
Or	19.73	26.36	23.46	17.96	25.70	16.25	21.33	29.36	41.59	26.82
Ab	31.46	37.06	32.39	29.52	34.34	32.56	34.68	20.89	13.11	28.50
An	2.61	—	1.90	13.73	0.15	0.53	0.51	0.32	0.02	0.07
Di	—	—	—	0.92	—	—	—	—	—	—
Hy	1.84	3.44	4.27	2.22	0.22	2.29	0.22	0.32	0.42	0.40
Mt	2.05	2.04	1.44	0.84	0.04	0.12	0.36	0.57	0.19	—
Il	1.23	1.35	0.34	0.08	0.21	0.15	0.19	0.11	0.51	0.15
Ap	0.74	0.55	0.31	0.09	0.07	0.05	0.05	0.05	0.05	0.05
C	5.24	4.31	3.25	—	2.77	4.01	2.49	3.84	0.96	1.04
Cc	0.89	—	3.62	1.30	—	0.89	—	—	—	—
Hm	1.69	1.53	—	—	0.77	—	0.65	0.03	0.46	0.54
Water	2.95	1.79	2.19	2.92	1.02	1.34	0.97	1.27	1.08	0.60

\* An asterisk indicates a trace element content below the detection limit (10 ppm for Co, Cu, and Ni; 30 ppm for Cr).

Localities of the analysed specimens (National Grid references)—

1	NM 984304	5	NM 958365	8	NM 928367
2	NM 932319	6	NM 959364	9	NM 914374
3	NM 985305	7	NM 956368	10	NM 933366
4	NM 986342				

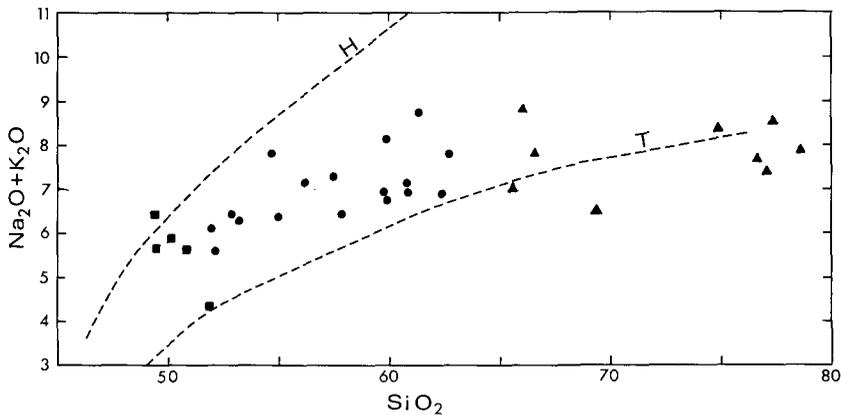
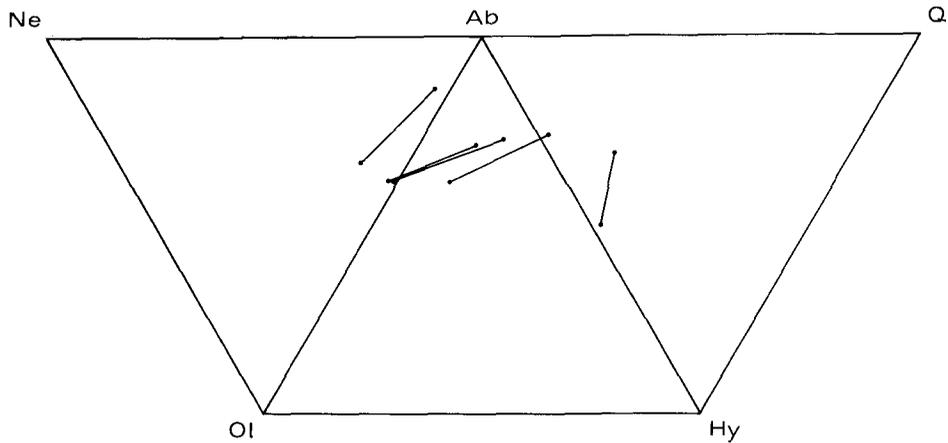
The normative compositions of the most basic Lorne lavas are shown diagrammatically in fig. 2. The basalts include both nepheline-normative and quartz-normative types, even if allowance is made for the effects of oxidation on the normative silica balance. The most distinctive chemical feature of the Lorne basalts is their  $K_2O$  content, which is relatively high compared with other basalts of orogenic areas or island arcs and is unequalled by the basalts of stable continental or oceanic areas.

Fig. 3 is an alkali-silica diagram for all the Lorne lavas. The trend of variation does not match either of the well-known alkalic or tholeiitic trends of non-orogenic volcanic suites, having a gentler alkali/silica gradient than both, but a very similar trend is found in some other orogenic suites, for example that of the Andean geosyncline in Chile (Vergara, 1972). Although it was thought at one time that alkali-poor, alumina-rich basalt was characteristic of this association (Turner and Verhoogen, 1960), it is now recognized that orogenic lava suites include an even greater range of basalt types than non-orogenic suites. The basic end-members of orogenic suites range from tholeiitic types very poor in alkalis (Katmai, Izu-Hakone), through basalts similar to those of the Lorne area, to shoshonitic types very rich in alkalis (New Guinea Highlands, Exeter Volcanic Series). Where the basalt has a fairly high alkali content, as in Lorne or in the Andean geosyncline, the associated intermediate and acid rocks are not comparably rich in alkalis, thus giving the rather flat alkali-silica trend shown by fig. 3.

Jakeš and White (1972) have reviewed the evidence that the various types of basalt and associated volcanic rocks in orogenic areas vary in composition in a regular way according to their tectonic situation. They distinguished three associations, tholeiitic, calc-alkaline, and shoshonitic, and suggested that in recent island arcs the three associations are developed at successively greater distances from the oceanic side of the arc, corresponding to successively greater depths of the inclined seismic zone underlying the arc. In terms of their classification, the Lorne lavas correspond to the high-K subdivision of the calc-alkaline association.

The well-known relationship between the  $K_2O$  content of lavas and the depth of the inclined seismic zone in island arcs is a reflection of the distribution of the three associations, and can be recognized in the orogenic belts of continental regions as well as in island arcs (Dickinson, 1970). The  $K_2O$  variation in British Ordovician volcanic rocks has already been used to suggest the possible position of a Benioff zone in the Caledonian orogenic belt of southern Britain (Fitton and Hughes, 1970). If interpreted on similar lines, the high-K calc-alkaline association of the Lorne area may be taken to indicate the presence of such a zone during the Devonian at a rather great depth ( $\sim 200$  km) under the Lorne area. The compositions of other Scottish Devonian lavas may provide an indication of the inclination of this zone, but sufficient analyses are not yet available.

Fig. 4 is an AFM diagram for the Lorne lavas. The trend is similar to those of other orogenic lava series, for example those of the Cascade province or the Lesser Antilles (Nockolds and Allen, 1953), and distinct from those of non-orogenic lava series. Despite the similarity of the diagram to those given by other orogenic igneous rocks, it can not be stated with confidence that the lavas of the Lorne area form a continuous



FIGS. 2 and 3: FIG. 2 (top). The compositions of the Lorne basalts (analyses with  $< 52\%$   $\text{SiO}_2$ ) in terms of the normative constituents Ne-Ol-Ab-Hy-Q. The normative silica balance is strongly dependent on the state of oxidation of the rocks, and each analysis is therefore represented by a line joining the actual composition of the rock (Q-rich end) to its composition if all the iron were unoxidized (Q-poor end). The magma composition is presumed to lie between these extremes. FIG. 3 (bottom). Alkali-silica diagram for the Lorne lavas. The Lorne trend is compared with the Hawaiian alkalic trend (H) and the Thingmuli tholeiitic trend (T), from Macdonald and Katsura (1964) and Carmichael (1964). Squares represent basalts, circles andesites, and triangles dacites and rhyolites.

magma series. Only a few analyses lie between the small cluster representing the most acid rhyolites and the larger group of andesite and basalt analyses. The rhyolitic cluster would probably be enlarged if the ignimbrite magmas could be taken into consideration, and the basalt-andesite cluster would be enlarged if the number of analyses were in proportion to the abundance of the different rock types, but inter-

mediate lavas of dacitic or rhyodacitic composition appear to be rare. Furthermore, although there is a continuous gradation in alkali contents, there appears to be a break in magnesia content between the high values of the basic rocks and the low values of the rhyolites.

Variation diagrams of Harker and Thornton-Tuttle type have been plotted by the authors and they show the familiar trends described by Nockolds and Mitchell (1948) for Caledonian igneous rocks as a whole, for example iron and magnesium decrease with increasing silica whereas potassium and rubidium increase. Chayes (1964) and others have questioned the significance of such diagrams, in which apparently smooth trends automatically result from the inverse relationship between mafic and felsic minerals and the constant sum of the percentage constituents. Variation diagrams may, however, be significant if they do not show a smooth trend, and figs. 5 and 6 illustrate some of the constituents of the Lorne lavas for which this is the case.

Apart from any deviations from a putative 'liquid line of descent' due to variations in the amount of suspended phenocrysts, a scatter in these diagrams may reflect the alteration many of the rocks have suffered. The nearest approach to a smooth trend in fig. 5 is shown by  $(\text{FeO} + \text{Fe}_2\text{O}_3)$  for the basalts and andesites. Wilshire (1959) has shown that total iron content is relatively little affected by deuteric alteration of basic lavas, although of course the  $\text{Fe}_2\text{O}_3/\text{FeO}$  ratio is usually increased. The relative smoothness of the total iron curve does show that the Lorne andesites and basalts form a closely related series, and suggests that the scatter in the other constituents is due to alteration effects. On the other hand, the total-iron variation diagram appears to show a definite discontinuity or step at about 66%  $\text{SiO}_2$ , as do those of Ti and Sr, and perhaps also P and Li. This feature, combined with the relative scarcity of compositions between 53 and 74%  $\text{SiO}_2$ , suggests that the acid rocks do not form a continuous differentiation series with the basalts and andesites. A plot of Sr against Ti (fig. 7) shows the lack of continuity between the acid and basic rocks particularly clearly.

Several of the trace elements are of special petrogenetic interest. Taylor *et al.* (1969, 1971) have attached considerable significance to the distribution of Co, Cr, and Ni in andesites. They believe that fractional crystallization of basalt will not account for the distribution of these elements in andesites, and consider that low Cr and Ni and low Ni/Co ratios are primary features of andesite magma. They also exclude the

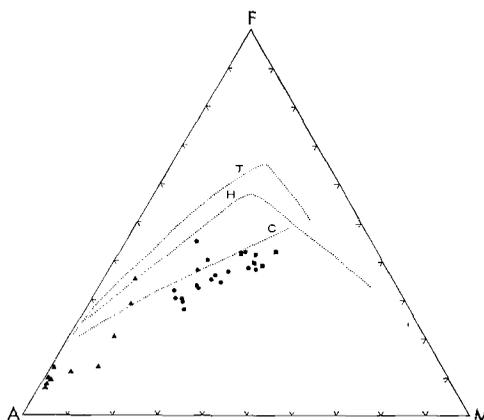
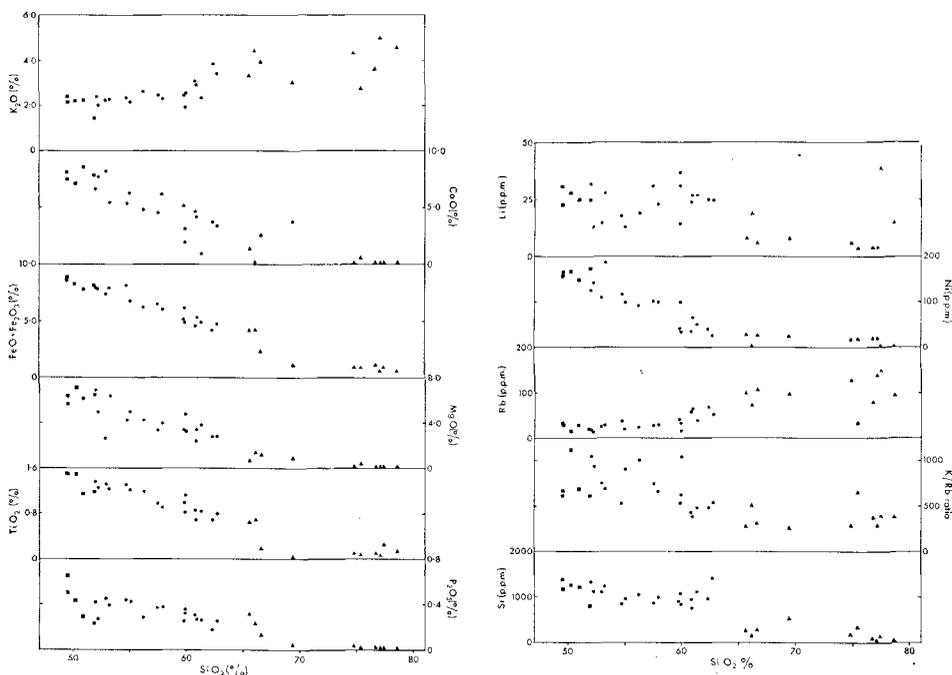


FIG. 4. AFM diagram for the Lorne lavas. The Hawaiian alkalic (H), Thingmuli tholeiitic (T) and Cascades calc-alkaline (C) trends are shown for comparison. The Hawaiian trend is from Macdonald and Katsura (1964) and the Thingmuli and Cascades trends are from Carmichael (1964). A =  $\text{Na}_2\text{O} + \text{K}_2\text{O}$ ; F =  $\text{Fe}_2\text{O}_3 + \text{FeO}$ ; M = MgO. Squares represent basalts, circles andesites, and triangles dacites and rhyolites.

possibility of obtaining andesite by melting of undifferentiated mantle because such a process would give higher Co and Ni contents than they observed. However, the Cr and Ni contents and Ni/Co ratios of the Lorne andesites are much higher than the average values quoted by Taylor and co-workers, and indicate the need for more data to be obtained before any conclusions can be drawn. Although Taylor *et al.* (1969)



FIGS. 5 and 6: FIG. 5 (left). Harker variation diagram for some of the major constituents in the Lorne lavas. Squares represent basalts, circles andesites, and triangles dacites and rhyolites. FIG. 6 (right). Harker variation diagram for some trace elements in the Lorne lavas. Squares represent basalts, circles andesites, and triangles dacites and rhyolites.

quote an average of only 3 ppm of both Cr and Ni in high K-andesites, the Lorne andesites, which are high in potassium, contain an average of 188 ppm Cr and 65 ppm Ni.

In the Lorne basalts and andesites, the Rb content rises and the K/Rb ratio falls with increasing SiO<sub>2</sub> content (fig. 6). The large apparent scatter of the K/Rb ratios in fig. 6 is probably not significant, since the Rb contents were determined near the detection limit and the precision is therefore low. The K/Rb ratios of the Lorne basalts are rather high for basalts with such a high K<sub>2</sub>O content. Usually such K/Rb ratios are typical of tholeiitic rocks (Jakeš and White, 1972). The slightly lower K/Rb ratios of the Lorne andesites compared with the basalts is probably not attributable to fractionation of olivine or pyroxene, which are essentially free of K and Rb, nor to fractionation of biotite, which would have the opposite effect. Fractionation of

hornblende is a possible explanation, since hornblendes in basic rocks have been found to have K/Rb ratios rather higher than the Lorne basalts (Jakeš and White, 1970), although the absolute amounts of K and Rb in hornblende may not be sufficient to exert much influence on their distribution in the magmas. The variation in K/Rb ratio is more likely to have arisen in the magmatic source region or to be due to crustal contamination than to be the result of high-level fractionation.

Whereas the high K/Rb ratios of the Lorne basalts are a feature that Jakeš and White (1972) consider characteristic of alkali-poor (tholeiitic) basalts, the high Sr content is a feature they consider characteristic of alkali-rich (shoshonitic) basalts. This lack of correspondence between the chemical features of the Lorne lavas and those of other orogenic areas indicates the need to avoid generalizations about the detailed geochemistry of any particular volcanic association. The Lorne lavas may owe their high Sr content to a regional high abundance of this element in the crust and mantle, rather than to any particular petrogenetic mechanism. It is known that Sr shows marked regional variations in its abundance (Turekian and Kulp, 1956), and all Caledonian igneous rocks appear to have high Sr contents, whether acid or basic in composition (Nockolds and Mitchell, 1948).

The Lorne basalts are richer in Li than basalts from other areas, the average being 26 ppm, compared with a mean of 11 ppm for all basalts (Prinz, 1968). Li is incorporated most readily into biotite, and the high Li content might be taken as indicating the melting of biotite in the magmatic source region. However, the K<sub>2</sub>O contents and K/Rb ratios of the basalts imply that the rocks of the source region contain a potassic phase with a high K/Rb ratio, and biotite is not a suitable candidate because it preferentially incorporates Rb and thus has low K/Rb ratios. Whereas the basic Lorne lavas are relatively rich in Li, the acid lavas are relatively poor, with an average of only 11 ppm, compared with an average for granitic rocks of 32 ppm (Turekian and Wedepohl, 1961). This again suggests that the acid and basic Lorne lavas are derived from different sources.

The average Cu content of Lorne basalts (24 ppm) is very low compared with estimates of the average content for all basaltic rocks, which range from 72 to 123 ppm (Prinz, 1968). However, the Lorne andesites are richer in Cu than the basalts, and have values comparable to the average of 40 ppm quoted by Taylor (1969) for high-K

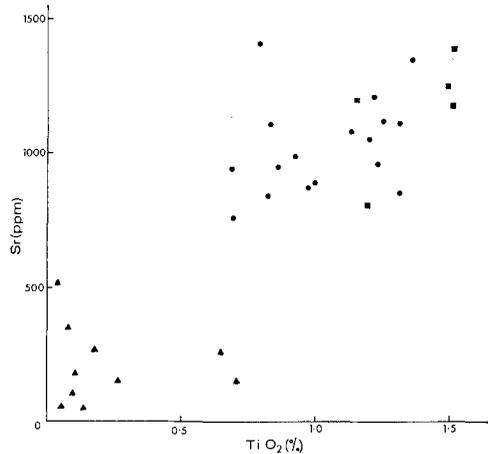


FIG. 7. The relationship between the strontium and titanium contents of the Lorne lavas, showing the hiatus between the basalts (squares) and andesites (circles) on the one hand, and the dacites and rhyolites (triangles) on the other hand.

andesites. There is no obvious explanation of the Lorne andesites being richer in Cu than either the associated basalts or rhyolites. The Lorne lavas are not particularly rich or poor in Zn or Zr compared with those of other areas (cf. Rosman, 1972; Prinz, 1968), and they show similar trends of variation, i.e. Zn decreases with increasing SiO<sub>2</sub> and Zr increases.

*Comparison between the lavas and the plutonic rocks of the area*

The plutonic and hypabyssal rocks of this region fall into three groups: the large granite intrusions of Etive, Glen Coe, Ballachulish, Ben Nevis, etc., the small basic intrusions of the appinite suite, and the porphyrite dykes such as those of the Etive swarm. The granites must obviously be compared with the rhyolitic lavas and ignimbrites, while the more basic plutonic rocks may be compared with the basalts and andesites.

The *Porphyrites*. These were considered by Kynaston and Hill (1908) to be 'the dyke phase of an andesite magma'. There has hitherto been very little information on the composition of the porphyrite dykes and analyses have therefore been made of a range of dyke rocks, which are given in Table IV. Most of the porphyrites consist of large phenocrysts of plagioclase (oligoclase-andesine), hornblende, and biotite in a finely crystalline matrix. Phenocrysts of quartz, orthoclase, or pyroxene occur in a few samples. The rocks are variable in colour, but generally pinkish, and like the lavas they show much alteration, especially of biotite and pyroxene.

It is clear from the new analyses that the porphyrites do not span the same compositional range as the lavas. Their silica contents are restricted to between 63 and 70 %, a range that is relatively poorly represented among the lavas, while the most basic and acid lavas have no equivalents among the porphyrites. No connection is known to exist between any single lava flow and any dyke, and in view of the chemical evidence it may be concluded that the dykes were not the feeders for the volcanic rocks. Nevertheless, their compositions are remarkably complementary. If plotted on the AFM diagram (fig. 4) the porphyrites would fill the sparsely populated area between the more acid and more basic lava types. In all types of variation diagram (AFM, alkali-silica, Harker, Thornton-Tuttle) the porphyrites lie on the same trend as the lavas.

*Appinites*. The appinitic intrusions are the most probable feeders (now seen at depth) for the basic Lorne lavas. They contain rocks of basaltic composition but with high alkali contents, similar to the basic lavas, and they are almost identical to the lavas in isotopic age and initial <sup>87</sup>Sr/<sup>86</sup>Sr ratio (J. F. Brown, pers. comm.).

Appinites (*sensu lato*) are mafic and ultramafic rocks characterized by an abundance of hydrous minerals (hornblende, biotite), generally occurring in small stocks. The type area, Appin, lies immediately to the north of the Lorne plateau (Bailey and Maufe, 1960). Appinitic rocks have compositions indicative of crystal accumulation from hydrous basaltic magma (Hall, 1967). The abundance of hornblende and biotite in the Lorne lavas, and the evidence of explosive activity and extensive deuteric alteration, testify to the hydrous nature of the magmas from which the lavas were

TABLE IV. *Analyses of porphyrites from northern Lorne*

	1	2	3	4	5	6	7	8	9	10
SiO <sub>2</sub>	63.67	64.47	64.66	65.34	65.36	66.63	66.72	66.89	68.11	69.53
TiO <sub>2</sub>	0.69	0.33	0.35	0.40	0.49	0.52	0.36	0.28	0.53	0.39
Al <sub>2</sub> O <sub>3</sub>	15.24	15.83	16.70	16.52	15.63	14.75	15.41	14.91	14.08	13.90
Fe <sub>2</sub> O <sub>3</sub>	1.52	1.33	1.39	1.22	0.60	0.54*	0.69	1.26	1.72	1.09
FeO	2.65	1.63	1.12	1.40	2.74	2.51	2.36	1.12	1.21	1.12
MnO	0.06	0.04	0.05	0.04	0.04	0.04	0.05	0.04	0.04	0.04
MgO	2.68	1.59	0.81	1.00	0.70	1.73	1.53	1.00	1.31	0.88
CaO	2.20	2.47	2.79	2.03	2.29	2.72	1.88	2.44	2.16	1.51
Na <sub>2</sub> O	4.32	3.73	3.68	4.48	4.11	4.42	5.07	3.75	3.83	4.25
K <sub>2</sub> O	3.61	4.28	4.02	4.03	4.09	3.33	3.31	4.09	3.85	3.87
H <sub>2</sub> O <sup>+</sup>	2.12	2.22	2.23	1.48	2.10	1.58	1.44	1.85	1.64	1.49
CO <sub>2</sub>	0.75	1.11	1.19	1.13	1.07	0.50	0.25	1.85	0.79	1.29
P <sub>2</sub> O <sub>5</sub>	0.24	0.17	0.19	0.14	0.20	0.18	0.16	0.12	0.19	0.12
	99.75	99.20	99.18	99.21	99.42	99.45	99.23	99.60	99.46	99.48
<i>Trace elements (ppm)</i>										
Co	11	10	10	*	10	*	10	*	*	*
Cr	75	76	57	38	95	83	38	57	75	83
Cu	14	*	*	*	*	19	16	*	11	*
Li	36	23	21	14	21	23	19	14	21	15
Ni	19	36	32	27	36	16	19	14	25	15
Rb	82	116	104	110	90	75	76	113	112	101
Sr	540	540	440	420	640	640	540	410	420	380
Zn	95	57	73	60	60	73	158	47	50	59
Zr	180	130	145	250	165	140	160	172	180	160
<i>Norm</i>										
Q	17.59	21.61	24.30	21.07	21.63	20.13	17.93	27.83	27.23	29.06
Or	21.33	25.29	23.75	23.81	24.16	19.67	19.56	24.16	22.75	22.86
Ab	36.54	31.55	31.12	37.89	34.76	37.38	42.88	31.72	32.39	35.95
An	4.61	4.13	5.08	2.01	3.29	9.16	6.70	—	4.48	—
Di	—	—	—	—	—	—	—	—	—	—
Hy	9.25	5.38	2.44	3.47	5.54	7.69	7.07	3.12	3.26	2.78
Mt	2.20	1.93	2.02	1.77	0.87	0.78	1.00	1.83	2.49	1.58
Il	1.31	0.63	0.66	0.76	0.93	0.99	0.68	0.53	1.01	0.74
Ap	0.57	0.40	0.45	0.33	0.47	0.43	0.38	0.28	0.45	0.28
C	2.54	3.55	4.44	4.05	3.24	0.52	1.03	4.45	1.97	3.25
Cc	1.71	2.52	2.71	2.57	2.43	1.14	0.57	4.21	1.80	2.93
Water	2.12	2.22	2.23	1.48	2.10	1.58	1.44	1.85	1.64	1.49

\* An asterisk indicates a trace element content below the detection limit (10 ppm for Co and Cu).

Localities of analysed specimens (National Grid references)—

1	NN 009305	5	NM 986336	8	NN 008306
2	NM 988341	6	NN 006313	9	NN 012306
3	NN 007313	7	NN 005313	10	NN 002275
4	NM 995295				

derived, and it is reasonable to suspect the Lorne appinites of being possible cumulates from these magmas.

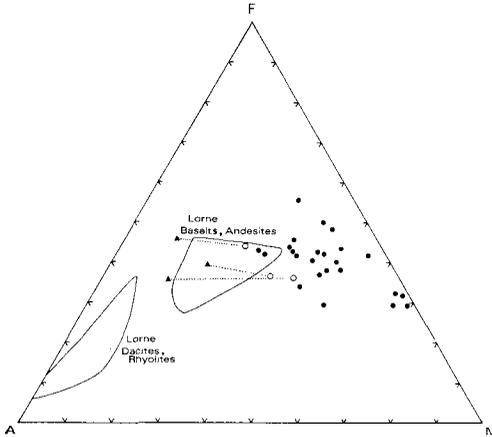


FIG. 8. AFM diagram for the appinitic rocks of the Lorne area. Dots represent previously analysed appinitic rocks (from Bailey, 1958, and Bowes *et al.*, 1964). Open circles represent the newly analysed porphyritic appinitic rocks from Table V, and dotted lines connect these rocks to the calculated compositions of their groundmasses, shown by triangles.

A =  $\text{Na}_2\text{O} + \text{K}_2\text{O}$ ; F =  $\text{Fe}_2\text{O}_3 + \text{FeO}$ ; M = MgO.  
Continuous lines enclose the compositional ranges of the Lorne lavas (from fig. 4).

equilibrium with hydrous basaltic magma. Crystallization in appinitic feeder intrusions may therefore be responsible for the presence of phenocrysts in the lavas, although it is not necessarily responsible for the whole compositional variation in the lava series. The calculated compositions of the groundmasses in the porphyritic appinites are richer in  $\text{K}_2\text{O}$  and  $\text{Al}_2\text{O}_3$  than any of the lavas (or estimated groundmass compositions of the porphyritic lavas). Thus, although the appinite intrusions may represent the vents from which the lavas were extruded, the crystal fractionation they show is not the cause of the variation in the lava series. On the other hand, if the appinite bodies are the feeder intrusions, the composition of the lavas may have been severely modified between generation and extrusion.

Various experimental studies have shown that all the main compositions represented by the Lorne lavas could be produced directly by melting under appropriate conditions, either from peridotite in the mantle under hydrous conditions (Kushiro, 1972), or from the basalt in subducted oceanic crust under either hydrous conditions (Holloway and Burnham, 1972) or anhydrous conditions (Green and Ringwood, 1968). No high-level fractionation is necessarily required to provide any of the observed lava types, although the evidence of the appinites is that some fractionation has occurred. The appinitic cumulates should probably be regarded as minor by-

Chemical analyses of the appinites in this part of Scotland have been published by Walker (1927), Nockolds (1941), Bailey and Maufe (1960), and Bowes *et al.* (1964), and are represented in fig. 8. New analyses are given in Table V of some porphyritic varieties of appinite from the chilled margins of appinitic intrusions. Their phenocrysts have also been analysed (Tables VI and VII) in order to compare the compositions of the suspended crystals with those in the lavas.

The phenocryst compositions of the basic lavas and the appinites are very similar, the clinopyroxenes having a nearly identical range of Al, Ti, Ca, and alkali contents, while the amphibole in both is a variety poor in Si and rich in tetrahedral Al, intermediate between pargasite and tschermakite. The phenocrysts in both types of rock are almost identical to those crystallized by Holloway and Burnham (1972) in

products of local fractionation rather than as volumetrically important complementary differentiates.

*Granites.* The relationship between the acid lavas and the granites in this area is more difficult to determine. Fig. 9 includes a comparison between the compositions of

TABLE V. *Analyses of porphyritic appinitic rocks (1-3) and the calculated compositions of their respective groundmasses (1G-3G)*

	1	2	3	1G	2G	3G
SiO <sub>2</sub>	52.33	53.71	49.79	53.23	57.98	52.65
TiO <sub>2</sub>	0.68	1.34	0.70	0.78	0.90	0.89
Al <sub>2</sub> O <sub>3</sub>	14.55	16.38	13.19	18.95	17.40	20.64
Fe <sub>2</sub> O <sub>3</sub>	2.69	1.81	3.09	2.98	1.07	3.79
FeO	5.39	6.43	5.89	5.27	6.17	3.07
MnO	0.15	0.16	0.16	0.15	0.17	0.12
MgO	8.02	5.00	10.22	4.51	1.83	2.83
CaO	8.36	6.27	8.97	4.44	4.54	3.73
Na <sub>2</sub> O	3.20	3.65	2.69	4.35	4.44	4.36
K <sub>2</sub> O	2.87	1.82	2.98	3.97	2.31	5.15
H <sub>2</sub> O <sup>+</sup>	0.59	2.53	1.21	0.82	2.65	2.11
P <sub>2</sub> O <sub>5</sub>	0.40	0.40	0.35	0.55	0.53	0.61
	99.23	99.50	99.24	100.00	99.99	99.95
<i>Norm</i>						
Q	—	3.13	—	—	8.12	—
Or	16.96	10.76	17.61	23.46	13.65	30.43
Ab	27.06	30.89	18.72	36.79	37.57	34.51
An	16.87	22.94	15.12	18.44	19.06	14.52
Ne	—	—	2.19	0.01	—	1.29
Di	17.63	4.53	21.64	—	—	—
Hy	2.90	18.63	—	—	13.83	—
Ol	11.11	—	16.14	12.66	—	5.91
Mt	3.90	2.62	4.48	4.32	1.55	5.50
Il	1.29	2.54	1.33	1.48	1.71	1.69
Ap	0.95	0.94	0.83	1.30	1.25	1.44
C	—	—	—	0.74	0.61	2.57
Water	0.59	2.53	1.21	0.82	2.65	2.11

The appinitic rocks are from: 1—Dalnatrat intrusion, Duror of Appin; 2—Beinn Ghlas intrusion, Glen Falloch; 3—Barnamuc intrusion, Glen Creran. Groundmass compositions were calculated from the analyses of the rocks, their separated phenocrysts (in Tables VI and VII), modal analyses, and specific-gravity measurements.

the rhyolites and published analyses of the neighbouring granites. The volcanic and plutonic rocks are obviously different, although the scatter of rhyolite compositions is more than might be expected for a series of related lavas, and the influence of post-magmatic alteration must be suspected. It may be noticed that the more acid porphyrites fall in the same region of the Q-Or-Ab diagram as the granites but not the rhyolites, supporting the conclusion that they are unrelated to the lavas.

TABLE VI. *Analyses of clinopyroxenes from the Lorne lavas and from neighbouring appinites*

	1	2	3	4	5	6	7	8
SiO <sub>2</sub>	52.07	52.09	52.17	50.19	49.42	49.71	51.46	49.43
TiO <sub>2</sub>	0.59	0.71	0.95	1.13	1.55	1.73	0.47	0.65
Al <sub>2</sub> O <sub>3</sub>	1.74	2.52	3.60	4.26	4.77	5.33	3.27	4.51
Fe <sub>2</sub> O <sub>3</sub>	0.99	1.31	1.95	1.49	2.67	2.70	2.00	2.52
FeO	8.04	6.18	4.99	5.33	5.03	5.17	5.87	4.98
MnO	0.24	0.17	0.15	0.12	0.14	0.14	0.18	0.15
MgO	15.12	15.32	15.41	15.07	14.53	14.11	17.61	14.43
CaO	20.31	21.00	19.96	21.52	20.70	20.47	19.07	22.00
Na <sub>2</sub> O	0.31	0.37	0.33	0.60	0.30	0.33	0.25	0.63
K <sub>2</sub> O	0.04	0.04	0.07	0.07	0.03	0.03	0.05	0.13
Total	99.45	99.71	99.58	99.78	99.14	99.72	100.23	99.43
<i>Atomic proportions on the basis of 6 oxygens</i>								
Si	1.943	1.927	1.916	1.858	1.841	1.838	1.886	1.845
Al <sup>iv</sup>	0.057	0.073	0.084	0.142	0.159	0.162	0.114	0.155
Al <sup>vi</sup>	0.020	0.036	0.072	0.041	0.050	0.071	0.028	0.044
Ti	0.017	0.020	0.026	0.031	0.043	0.043	0.013	0.019
Fe <sup>3+</sup>	0.028	0.036	0.054	0.041	0.075	0.075	0.055	0.071
Fe <sup>2+</sup>	0.251	0.191	0.153	0.165	0.157	0.160	0.180	0.156
Mn	0.008	0.005	0.005	0.004	0.004	0.004	0.006	0.005
Mg	0.841	0.845	0.844	0.832	0.807	0.778	0.962	0.803
Ca	0.812	0.833	0.786	0.854	0.826	0.811	0.749	0.880
Na	0.022	0.027	0.023	0.043	0.021	0.024	0.018	0.046
K	0.002	0.002	0.003	0.003	0.001	0.001	0.002	0.006
Si + Al <sup>iv</sup>	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Others	2.001	1.995	1.966	2.014	1.984	1.967	2.013	2.030
<i>Trace elements (ppm)</i>								
Co	33	—	30	30	36	32	38	30
Cr	187	—	362	286	309	286	590	286
Cu	234	—	270	119	473	191	169	120
Li	29	—	18	27	37	31	18	10
Ni	94	—	153	117	135	131	235	131
Zn	221	—	205	123	359	186	180	345

The rocks from which these pyroxenes were separated were:

1. Andesite (analysis 12 in Table II)
2. Andesite (analysis 4 in Table II)
3. Basaltic andesite (locality NM 924342)
4. Basaltic andesite (analysis 6 in Table I)
5. Basalt (analysis 3 in Table I)
6. Basalt (locality NM 951372)
7. Appinite (analysis 1 in Table V)
8. Appinite (analysis 3 in Table V)

TABLE VII. *Analyses of hornblendes, biotite, and olivine*

	Hornblendes		Biotite 3	Olivine 4
	1	2		
SiO <sub>2</sub>	41.32	41.52	40.26	38.91
TiO <sub>2</sub>	3.49	2.72	4.71	0.08
Al <sub>2</sub> O <sub>3</sub>	11.49	13.53	13.31	0.00
Fe <sub>2</sub> O <sub>3</sub>	4.37	4.06	1.76	1.40
FeO	7.88	7.30	5.35	22.10
MnO	0.14	0.14	0.07	0.50
MgO	15.67	14.60	21.10	35.50
CaO	10.06	11.55	1.59	1.30
Na <sub>2</sub> O	2.38	1.35	0.69	0.06
K <sub>2</sub> O	1.04	0.39	8.37	0.00
H <sub>2</sub> O <sup>+</sup>	2.10	2.21	3.15	n.d.
Total	99.94	99.37	100.36	99.85

*Atomic proportions on the basis of 24 oxygens (hornblende and mica) or 4 oxygens (olivine)*

Si	6.048	6.042	5.773	1.019
Al <sup>iv</sup>	1.952	1.958	2.227	0.000
Al <sup>vi</sup>	0.030	0.363	0.017	0.000
Ti	0.384	0.297	0.516	0.002
Fe <sup>3+</sup>	0.482	0.444	0.190	0.027
Fe <sup>2+</sup>	0.965	0.888	0.642	0.484
Mn	0.018	0.018	0.009	0.011
Mg	3.418	3.166	4.509	1.386
Ca	1.578	1.801	0.245	0.036
Na	0.676	0.381	0.191	0.003
K	0.194	0.072	1.532	0.000

*Trace elements (ppm)*

Co	—	47	37	89
Cr	—	508	419	1410
Cu	—	144	349	119
Li	—	<2	35	<2
Ni	—	215	174	496
Zn	—	151	161	247

1. Hornblende from andesite (locality NM 928368)
2. Hornblende from appinitic rock (analysis 2 in Table V)
3. Biotite from basalt (analysis 4 in Table I)
4. Olivine from appinitic rock (analysis 3 in Table V)

The compositions of the analysed Lorne ignimbrites are also shown in fig. 9. Two vertical sections through a crystal ignimbrite cooling unit show a fractionation of normative quartz and feldspar attributable to crystal sorting, while a vertical section through a lithic ignimbrite showed a large variation in normative albite:orthoclase ratio possibly attributable to alkali ion exchange.

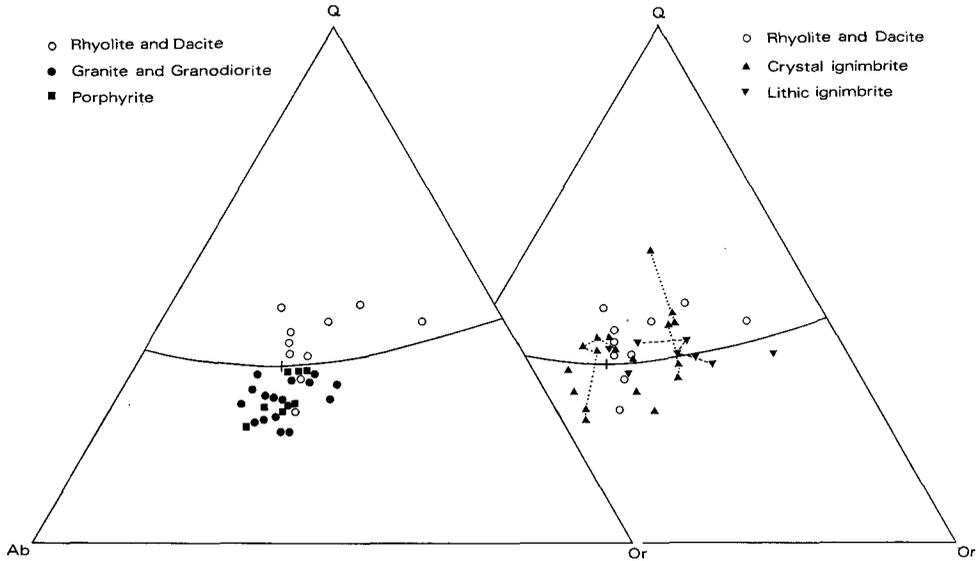


FIG. 9. The compositions of the acid igneous rocks of the Lorne area in relation to the system Q-Or-Ab-H<sub>2</sub>O. The minimum in the system is shown for a water pressure of 2000 bars (Tuttle and Bowen, 1958). The analyses of rhyolites and dacites and of porphyrites are from Tables III and IV respectively. Analyses of granites and granodiorites are from Bailey (1958) and Haslam (1968). Rocks with less than 65 % SiO<sub>2</sub> have not been plotted. The right-hand side of the diagram compares the analyses of 26 Lorne ignimbrites from Groome (1972) with the rhyolites and dacites. Each of the three sets of analyses joined by a dotted line represents a vertical section through an ignimbrite cooling unit at a particular locality.

### Discussion

Previous accounts of the igneous activity in this region have described the rocks in terms of an 'igneous cycle', in which volcanic, hypabyssal, and plutonic rocks are assumed to be closely related and extruded or intruded in a definite sequence (Hatch *et al.*, 1972). The apparently close association between volcanic and plutonic rocks of roughly the same age in the same area has led previous authors (Nockolds and Mitchell, 1948; Bailey, 1958) to interpret the chemical variation of Caledonian igneous rocks in terms of a genetically related co-magmatic series. A more general assumption of a common origin for the basalts, andesites, rhyolites, and associated plutonic rocks in this type of association is inherent in the title and content of Green and Ringwood's recent paper on 'Genesis of the calc-alkaline igneous rock suite' (1968).

Such a viewpoint presents several difficulties. The detailed field relationships in the west of Scotland show that the members of the 'igneous cycle' are not exactly contemporaneous, and it is difficult to find an explanation for the difference in age between the supposedly genetically related magmas. Furthermore, recent petrogenetic studies of Caledonian granites have concluded that their magmas probably originated by melting in the crust (Hall, 1966; Bell, 1968; Hall, 1972; Pitcher and Berger, 1972), an origin which would not be acceptable for the more basic Caledonian igneous rocks.

The evidence of this paper is that the dacites and rhyolites of the Lorne area are not differentiates of the basalt or andesite magmas, nor did they form from the same magma as the granites. The sequence of intrusion and extrusion, together with the chemical information, suggests the following grouping of magma types: (1) eruption of basalts and andesites and intrusion of appinitic stocks, all genetically related, together with (2) overlapping or simultaneous eruption of acid lavas and ignimbrites chemically unrelated to the basic rocks; followed by (3) later intrusion of the granitic plutons and porphyrite dykes.

The recognition of three separate generations of magma in this area (basic, acid volcanic, acid plutonic) is a radical departure from the rather simple interpretation of earlier authors, but analogies with other petrographic provinces in the British Isles provide some support for this conclusion. In south-west England, the lavas of the Exeter volcanic series have compositions (Cosgrove, 1972) that are entirely dissimilar to those of the plutonic rocks (granites) in the area, despite being almost identical in age (Miller and Mohr, 1964); the lavas and granites are not linked by any rocks of intermediate composition, and clearly represent separate generations of acid and basic magma in a late orogenic setting. In the non-orogenic Tertiary volcanic province, contemporaneous basic and acid magmas are also not connected by intermediate compositions, and the acid magmas are believed to have resulted from the melting of crustal rocks by the large volume of basic magmas passing through them (Moorbath and Bell, 1965).

The early phase of igneous activity in the Lorne area is therefore considered to consist of basic magmas (basalts and andesites) derived from a sub-crustal source, together with a small amount of acid magma (rhyolites and ignimbrites) locally produced in the crust during their uprise. The later phase of igneous activity consists of acid magmas (granites) considered to have been produced by more extensive crustal melting, perhaps due to a more widespread increase in the geothermal gradient (Hall, 1972).

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