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New data on the composition of Caledonian granites

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SUMMARY. New analyses are given of granites from 23 intrusions in Scotland, Ireland, and the Isle of Man. Together with existing analyses, these were used to measure the regional variation in composition of Caledonian granites by means of trend surface analysis. An explanation of the variation is presented that involves the production of magma by melting in the crust, at a depth determined by the geothermal gradient.

THE author has shown (Hall, 1969*a*, *b*) that, in addition to the compositional variation that occurs within individual intrusions, it is possible to recognize more general trends of variation between different granites over the whole area of the Caledonian orogenic belt. In order to obtain more information on the nature of this regional variation, the author has now collected and analysed samples of many of the granites for which no modern analytical data are available. Combined with existing data, the new analyses provide an improved basis for the measurement of the regional variation by trend surface analysis.

New analyses

A number of specimens were collected, some from granites that have not been previously analysed, and some from granites for which only very old and probably unreliable analyses are available. The samples were chosen to be as representative as possible of the main components of their respective intrusions, as judged by field and petrographic examination. Twenty-seven new chemical analyses are given in tables I and II. The granites represented are:

SCOTLAND: *Aberchirder.* The analysed specimen is a medium-grained, grey biotite-granite, conforming to the description given by Read (1923). The granite shows slight granulation of the quartz, a feature also shown by the nearby granite of Longmanhill which has the rather high Rb/Sr isochron age of 501 Myr (Bell, 1968), and both granites may therefore predate the last period of Caledonian movement.

Ardclach. This intrusion is rather variable in composition, and the analysed specimen is a coarse red biotite-granite with large phenocrysts of orthoclase, similar to that described by Horne (1923) from this locality. An early analysis of the Ardclach granite was given by Mackie (1901), along with analyses of the Ben Rinnes and Cairngorm granites.

Bennachie. The Bennachie granite is a relatively homogeneous intrusion, described by Wilson and Hinxman (1890), and two typical specimens were analysed. The rock is a coarse, pink, slightly porphyritic biotite-granite. Specimen 3 contains fewer phenocrysts than specimen 4, and this is reflected in the lower K_2O content.

Ben Rinnes. The analysed rock is a slightly weathered example of the medium-grained, pink biotite-granite that makes up the greater part of this intrusion (Hinxman and Wilson, 1902). The granite resembles those of Aberchirder and Longmanhill in having a slightly cataclastic texture.

Cairngorm. The analysis given in table I represents a specimen of the common type of pink, homogeneous, medium-grained biotite-granite that makes up the principal unit of the Cairngorm granite (Harry, 1965).

Creetown. The Creetown granite is a medium-grained, grey biotite-granite, containing some secondary muscovite and calcite, and the analysis is of a typical specimen from the collection of the Institute of Geological Sciences.

Glen Gairn. The granite of Glen Gairn is poorly exposed and has not yet been mapped in detail. The analysed rock is a fine-grained, pink, homogeneous 'biotite'-granite, showing some unusual features. The rock has a very high SiO_2 content for a granite, and the 'biotite' is unusual in being a pale grey colour in thin section although black in hand specimen. A manganese-rich composition is suggested by the rock analysis, and a detailed study of this mica is in progress.

Grantown. The specimen is of a fine-grained biotite-granite from the north-east margin of the intrusion. Some of the rocks in this area are contaminated by partly digested country rock. The analysed specimen is relatively homogeneous, but may not be representative of the intrusion as a whole. This granite has been described by Hinxman and Anderson (1915).

Helmsdale. The analysed specimens represent the two main varieties of the intrusion distinguished by Read and Phemister (1925): a coarse red porphyritic biotite-granite (no. 10 in table I), and a fine-grained red biotite-granite (no. 11 in table I). Specimen no. 10 contains some hornblende, which is largely pseudomorphed by a mixture of chlorite and calcite, and a CO_2 determination is therefore included. The porphyritic variety has unusually high alkali contents for a granite, reflecting the very high proportion of feldspar phenocrysts in this rock.

Park. This is a small intrusion near Nairn consisting of a coarse porphyritic biotite-granite, and the analysed rock is a typical specimen from the ornamental-granite quarry at Park, described by Horne (1923).

Peterhead. The Peterhead granite is a homogeneous, coarse, red potash-granite, and the analysed specimen is a typical example from the Boddam stone quarries. An early analysis of this granite was given by Phillips (1880).

IRELAND. *Carnsore*. The Caledonian age of this granite has until recently been uncertain, but is indicated by isotopic age determinations (Brindley, 1969; Leutwein, 1970). Petrographically, there is no evidence for an earlier age. The progressive zoning of plagioclases, the absence of chloritization of the biotite, and the preservation of textural relationships similar to those in other Caledonian granites, indicate that the rock has not been metamorphosed. The specimen represented by the analysis in table II is a coarse red biotite-bearing potash granite typical of the intrusion.

Corvock. The analysed specimen is a grey, medium-grained biotite-granite typical of this small intrusion, which has been described briefly by Stanton (1960).

Crossdoney. This is a highly contaminated intrusion containing granodiorites grading into quartz-diorites (Skiba, 1952). Several partial analyses were made of different samples from the relatively less contaminated southern part of the intrusion, and the complete analysis in table II is of the most acid of these, a fine-grained, hornblende-biotite-granodiorite. It has not been used in the trend surface analysis because it has a normative sum (Q+Or+Ab) < 80 %.

Dreenan. The Dreenan granite is one of several granite intrusions that together with basic plutonic and volcanic rocks make up the poorly exposed 'Tyrone Igneous Series'. The granites in this area are believed to be of Caledonian age because of the presence of large inclusions of Ordovician volcanic rocks (Cobbing *et al.*, 1965). Petrographic examination shows no definite evidence of metamorphism, and the textural features of the Dreenan and Pomeroy granites can be matched among other Caledonian 'newer granites', although all the rocks in this area are severely weathered. The analysed sample of the Dreenan granite is a medium-grained, pink biotite-granite that shows extensive chloritization of biotite and sericitization of plagioclase.

Leinster. The Leinster batholith is the largest mass of granite in the British Isles and was the first to receive detailed geochemical and mineralogical investigation (Haughton, 1856). It consists of several intrusive complexes, which are difficult to distinguish from one another because of the extremely poor exposure. Brindley (1970) has distinguished three main masses. The northern unit is represented by specimens 7 and 8 in table II, both of which are typical coarse muscovite-biotite-granites. The northern unit is probably separated by a band of country rock from the central mass, the Tullow Lowlands granite, represented by specimen 13 in table II, a white medium-grained muscovite-granite. The southern mass is the Blackstairs Mountain granite and is of variable composition; the analysed specimen (no. 1 in table II) is a biotite-muscovite-granite. Several outlying bodies of granite are shown on Geological Survey maps in addition to the three main units, and specimen no. 5 in table II is a medium-grained muscovite-biotite-granite from the Curraghmore intrusion at the south-western end of the batholith. Most of the smaller outlying bodies consist of quartz-porphyry or felsite and are not true granites.

Main Donegal granite. No modern analyses of the Main Donegal granite have yet been published. This intrusion is very heterogeneous (Pitcher *et al.*, 1958), but the analysed specimens (nos. 9 and 10 in table II) represent common granite types of the south-western part of the intrusion. They are both fine-grained biotite granodiorites, and no. 10 is banded.

Pomeroy. The Pomeroy granite is one of the larger granite bodies of the 'Tyrone Igneous Series', and the comments on the Dreenan granite also apply to this intrusion. The analysed sample is a coarse, red biotite-granite, in which the biotite is severely chloritized.

Roundstone. The Roundstone granite is one of the small intrusions west of the Galway batholith. It is a fine-grained grey granodiorite, of which the analysed specimen is a typical example. An analysis of the granite from another locality has recently been

TABLE I. *New analyses of Scottish Caledonian granites*

	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	75·65	73·90	75·07	74·13	75·15	75·50	70·02	77·43	73·29	66·52	72·32	72·84	74·05
TiO_2	0·25	0·48	0·29	0·37	0·28	0·28	0·35	0·07	0·24	0·61	0·47	0·37	0·22
Al_2O_3	12·74	13·64	13·06	13·34	13·03	13·18	15·25	12·32	14·73	15·14	14·23	14·33	12·90
Fe_2O_3	0·06	0·49	0·58	0·46	0·82	0·33	0·07	0·06	0·31	0·82	0·69	0·69	0·78
FeO	1·34	1·23	0·75	0·48	0·41	0·77	1·62	0·62	0·64	1·19	0·68	0·68	0·92
MnO	0·03	0·04	0·05	0·03	0·02	0·04	0·04	0·18	0·06	0·04	0·03	0·03	0·03
MgO	0·10	0·43	0·37	0·29	0·19	0·18	0·92	0·02	0·27	0·66	0·60	0·47	0·21
CaO	0·62	1·25	1·15	0·81	0·89	0·80	2·27	0·46	1·20	2·64	0·83	1·35	0·58
Na_2O	3·02	3·34	3·49	3·31	3·42	3·70	4·44	3·80	3·73	4·40	4·22	4·25	3·67
K_2O	5·11	4·09	4·54	5·70	4·96	4·63	3·06	4·18	4·26	5·34	4·95	4·43	5·14
H_2O^+	0·30	0·58	0·46	0·37	0·36	0·37	0·80	0·65	0·57	0·60	0·46	0·58	0·65
H_2O^-	0·21	0·15	0·13	0·18	0·15	0·12	0·08	0·04	0·23	0·10	0·21	0·05	0·27
P_2O_5	0·03	0·06	0·07	0·05	0·05	0·05	0·08	0·01	0·04	0·21	0·12	0·11	0·05
CO_2	—	—	—	—	—	—	0·72	—	—	1·59	—	—	—
	99·46	99·68	100·01	99·52	99·73	99·95	99·72	99·84	99·57	99·86	99·81	100·18	99·47
Q	36·20	35·15	34·34	31·03	34·22	34·07	27·34	37·74	32·14	18·52	26·49	27·82	31·28
C	1·19	1·59	0·48	0·37	0·54	0·75	2·37	0·73	1·90	1·51	0·71	0·35	0·37
Or	30·20	24·17	26·83	33·69	29·32	27·37	18·09	24·71	25·18	31·56	29·26	26·18	30·38
Ab	25·55	28·26	29·53	28·01	28·94	31·30	37·57	32·15	31·56	37·23	35·70	35·96	31·05
An	2·88	5·81	5·25	3·69	4·09	3·64	6·19	2·22	5·69	1·67	3·33	5·98	2·55
Di	—	—	—	—	—	—	—	—	—	—	—	—	—
Hy	2·30	2·21	1·43	0·72	0·47	1·20	4·70	1·36	1·31	2·22	1·49	1·29	1·26
Mt	0·09	0·71	0·84	0·57	0·58	0·48	0·10	0·09	0·45	1·19	0·93	1·00	1·13
He	—	—	—	0·06	0·42	—	—	—	—	—	0·05	—	—
Il	0·48	0·91	0·55	0·70	0·53	0·53	0·66	0·13	0·46	1·16	0·89	0·70	0·42
Sph	—	—	—	—	—	—	—	—	—	—	—	—	—
Ap	0·07	0·14	0·16	0·12	0·12	0·12	0·19	0·02	0·09	0·50	0·28	0·26	0·12
Cc	—	—	—	—	—	—	1·64	—	—	3·62	—	—	—
Water	0·51	0·73	0·59	0·55	0·51	0·49	0·88	0·69	0·80	0·70	0·67	0·63	0·92

Key:
1. Aberchirder granite. Quarry in Quarryhill Wood, 1·2 km S. of Aberchirder, Banffshire.
2. Ardclach granite. Bank of R. Findhorn, 100 m NW. of Ardclach church, Ardclach, Nairnshire.
3. Bennachie granite. 2·5 km ENE. of Keig, SW. side of Bennachie Hill, Aberdeenshire.
4. Bennachie granite. East side of R. Don, 3·5 km N. of Monymusk, Aberdeenshire.
5. Ben Rinnes granite. Meikle Conval Hill, 3 km ENE. of Ben Rinnes, Banffshire.
6. Cairngorm granite. Road cutting on west side of An t-Aonach, Cairngorm, Inverness-shire.
7. Creetown granite. 2 km S. of Creetown, Kircudbrightshire.
8. Glen Gairn granite. 15 m N. of bridge over R. Gairn at Gairnshiel Lodge, Aberdeenshire.
9. Grantown granite. NE. side of Carn Luig, 5 km N. of Grantown-on-Spey, Morayshire.
10. Helmsdale granite. 100 m E. of Torrish farm, Strath of Kildonan, Sutherland.
11. Helmsdale granite. Bed of Allt Cille Pheadair, Kilphedir Bridge, Strath of Kildonan, Sutherland.
12. Park granite. Park quarry, between Park and Raitcastle, 5 km SSE. of Nairn, Nairnshire.
13. Peterhead granite. Boddam quarry, Stirling, Aberdeenshire.

published by Leake (1970), but does not qualify for the trend surface analysis because the normative sum Q+Or+Ab is less than 80 %.

ISLE OF MAN. *Foxdale.* The Foxdale granite is a coarse-grained muscovite-granite. The analysed sample is from the collection of the Institute of Geological Sciences. An analysis of granite from this intrusion has previously been published by Finlayson (1910).

TABLE II. *New analyses of Caledonian granites from Ireland and the Isle of Man*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	74·21	73·53	74·49	68·11	72·46	73·56	72·52	72·53	71·97	71·54	74·76	68·46	74·17	74·09
TiO_2	0·30	0·42	0·29	0·54	0·36	0·58	0·33	0·33	0·32	0·37	0·34	0·59	0·16	0·12
Al_2O_3	14·59	13·28	13·55	16·20	14·98	13·34	15·68	15·12	15·03	15·18	13·34	15·77	14·49	14·78
Fe_2O_3	0·15	0·68	0·38	0·67	0·25	0·84	0·21	0·13	0·15	0·31	0·69	1·24	0·20	0·02
FeO	0·97	0·78	0·86	1·47	1·13	1·13	0·70	0·98	1·16	1·17	0·77	1·41	0·64	0·50
MnO	0·04	0·04	0·04	0·04	0·04	0·05	0·03	0·04	0·02	0·02	0·05	0·07	0·04	0·04
MgO	0·33	0·66	0·46	1·41	0·50	0·66	0·28	0·40	0·45	0·47	0·44	1·09	0·20	0·11
CaO	1·14	0·90	1·60	3·08	0·40	1·89	0·91	0·95	1·62	1·45	1·09	2·38	0·72	0·68
Na_2O	3·56	3·33	3·80	4·14	3·13	3·20	3·84	3·65	3·65	3·80	3·06	3·94	3·31	4·30
K_2O	4·18	5·25	3·37	3·12	4·93	3·62	4·60	4·38	4·47	4·76	4·63	3·96	4·68	3·95
H_2O^+	0·56	0·74	0·61	0·73	1·48	0·96	0·75	0·89	0·49	0·31	0·56	0·66	0·90	0·82
H_2O^-	0·20	0·09	0·15	0·12	0·09	0·28	0·18	0·11	0·11	0·20	0·13	0·23	0·16	0·07
P_2O_5	0·16	0·10	0·05	0·13	0·18	0·06	0·16	0·14	0·08	0·08	0·06	0·18	0·44	0·06
Total	100·39	99·80	99·65	99·76	99·93	100·17	100·19	99·65	99·52	99·66	99·92	99·98	100·11	99·54
Q	34·46	31·32	35·12	23·15	33·67	35·99	30·38	31·74	29·02	27·03	36·24	23·84	36·03	32·15
C	2·52	0·72	0·86	0·72	4·20	0·87	3·11	2·98	1·43	1·33	1·46	1·11	3·73	2·34
Or	24·71	31·03	19·92	18·44	29·14	21·40	27·19	25·89	26·42	28·13	27·37	23·41	27·66	23·35
Ab	30·12	28·18	32·15	35·03	26·48	27·08	32·49	30·88	30·88	32·15	25·89	33·34	28·01	36·38
An	4·61	3·81	7·61	14·43	0·81	8·98	3·47	3·80	7·52	6·67	5·02	10·63	0·70	2·98
Di	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Hy	2·06	1·90	2·01	4·84	2·59	2·16	1·32	2·22	2·64	2·49	1·47	3·44	1·32	1·05
Mt	0·22	0·99	0·55	0·97	0·36	1·22	0·30	0·19	0·22	0·45	1·00	1·80	0·29	0·03
He	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Il	0·57	0·80	0·55	1·02	0·68	1·10	0·63	0·63	0·61	0·70	0·65	1·12	0·30	0·23
Sph	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Ap	0·38	0·24	0·12	0·31	0·42	0·14	0·38	0·33	0·19	0·19	0·14	0·42	1·04	0·14
Water	0·75	0·83	0·76	0·84	1·56	1·24	0·92	0·99	0·60	0·51	0·69	0·88	1·04	0·89

Key: 1. Blackstairs granite. 1 km NW. of Kiltealy, co. Wexford.
2. Carnsore granite. Foreshore, 1 km NNE. of Carnsore Point, co. Wexford.
3. Corvock granite. 1 km NE. of Cregganbaun, co. Mayo.
4. Crossdoney granite. 2 km WNW. of Bellananagh, co. Cavan.
5. Curraghmore granite. East slope of Curraghmore Hill, 1·6 km NW. of Tullagher, co. Kilkenny.
6. Dreenan granite. 1·3 km N. of Coolesher Bridge, NW. of Beragh, co. Tyrone.
7. Leinster granite (northern part). Three Rock Mountain, 1 km WSW. of Sandyford, co. Dublin.
8. Leinster granite (northern part). 500 m ESE. of Lough Bray Upper, Kippure Mt., co. Wicklow.
9. Main Donegal granite. 3·2 km NE. of summit of Cleengort Hill and 0·6 km SE. of R. Gweebarra, co. Donegal.
10. Main Donegal granite. 1·0 km NNW. of bridge over R. Gweebarra at Doochary, co. Donegal.
11. Pomeroy granite. 600 m WSW. of summit of Crockbrack, 3 km NW. of Pomeroy, co. Tyrone.
12. Roundstone granite. Shore of Bertraghboy Bay, Canower, Connemara, co. Galway.
13. Tullow Lowlands granite. Quarry on N. side of Tullow Hill, 1 km E. of Tullow, co. Carlow.
14. Foxdale granite. Granite Mountain, Foxdale, Isle of Man.

Trend surface analysis

Trend surface analysis was used to measure the regional variation in composition, as described by Hall (1969*b*). A more rigorous sampling plan has been adopted, the details of which are given in Hall (1971). The main features are that the target population was limited to unmetamorphosed intrusive granites representing substantial bodies of magma, and with normative compositions showing Q+Or+Ab $\geqslant$ 80 %. The sample consisted of all analyses of Caledonian granites published since 1920, analyses of each intrusion being averaged.

TABLE III. *Geographical parameters and compositions of Caledonian granites* (Q, Or, *and* Ab *recalculated to total 100 %*)

No.	E	N	Q	Or	Ab	No.	E	N	Q	Or	Ab
1	3·6	8·5	39·4	32·8	27·8	33	3·7	9·9	25·2	34·0	40·8
2	0·2	5·9	26·0	23·2	50·9	34	3·7	8·1	30·8	36·4	32·9
3	3·0	8·5	40·1	27·6	32·3	35	−1·4	4·3	34·1	27·0	38·9
4	2·0	7·6	20·3	32·3	47·4	36	1·1	3·7	34·8	29·7	35·4
5	0·2	5·5	38·0	24·7	37·4	37	−1·2	4·4	40·2	22·0	37·8
6	3·7	8·2	35·6	33·0	31·4	38	3·2	10·0	26·4	20·1	53·5
7	2·2	7·7	22·5	29·4	48·1	39	2·4	5·9	33·8	30·7	35·5
8	3·3	8·4	37·0	31·7	31·3	40	3·2	7·9	29·6	32·8	37·6
9	0·7	3·1	38·6	27·7	33·7	41	3·7	8·6	34·8	35·2	30·0
10	3·0	8·0	36·7	29·5	33·8	42	0·4	6·1	32·3	31·5	36·3
11	2·6	6·0	28·4	34·4	37·2	43	3·7	7·9	34·6	30·8	34·5
12	2·6	5·7	40·2	29·2	30·6	44	2·8	8·4	37·6	29·9	32·5
13	1·0	2·7	34·6	34·3	31·1	45	1·2	4·8	32·9	21·5	45·6
14	2·8	8·9	22·2	19·4	58·4	46	−1·4	4·4	35·4	28·6	35·9
15	−1·1	4·5	40·3	22·8	36·9	47	−0·9	4·2	36·5	24·0	39·5
16	2·5	5·6	32·9	21·8	45·3	48	2·9	8·6	30·9	29·1	40·0
17	3·5	8·0	30·7	27·9	41·4	49	4·1	8·4	33·7	32·8	33·5
18	0·6	3·0	37·7	32·6	29·7	50	0·8	5·4	40·5	30·6	28·9
19	0·7	5·3	42·6	25·3	32·1	51	2·1	5·3	20·9	31·6	47·6
20	3·1	5·0	39·6	31·6	28·8	52	3·3	9·8	28·0	25·8	46·2
21	2·1	7·4	31·1	31·4	37·5	53	2·0	8·0	35·1	31·1	33·8
22	2·3	4·8	35·0	25·4	39·6	54	0·2	6·1	32·3	30·5	37·2
23	2·6	8·2	30·8	30·8	38·3	55	−1·2	4·2	29·6	29·0	41·4
24	−1·2	4·1	32·7	30·0	37·2	56	3·5	5·1	26·1	41·6	32·3
25	2·2	7·2	32·3	21·2	46·4	57	3·3	5·3	35·2	33·8	31·0
26	3·4	7·7	28·1	31·5	40·4	58	3·9	8·6	33·3	35·8	30·8
27	2·5	9·0	32·7	27·2	40·2	59	2·4	8·3	28·2	27·1	44·7
28	3·3	8·0	39·9	26·1	34·0	60	−1·0	5·3	34·0	28·6	37·4
29	2·8	8·6	32·6	31·7	35·7	61	0·2	6·0	33·0	29·6	37·4
30	2·9	7·8	27·8	29·1	43·1	62	0·8	3·4	39·3	30·2	30·5
31	0·2	6·2	26·7	33·7	39·6	63	4·0	5·4	34·0	33·8	32·2
32	3·0	8·3	36·2	28·3	35·5						

Key: (1) Aberchirder—new anal. in table I. (2) Ardara—mean of 9 anals. with $Q+Or+Ab \geqslant 80$ % in table I of Hall (1966*b*). (3) Ardclach—new anal. in Table I. (4) Ballachulish—anal. 7 on p. 184 of Muir (1953). (5) Barnesmore—mean of 2 anals. in table I of Walker and Leedal (1954). (6) Bennachie—mean of 2 new anals. in table I. (7) Ben Nevis—mean of anals. 16–19 in table I of Haslam (1968). (8) Ben Rinnes—new anal. in table I. (9) Blackstairs Mr.—new anal. in Table II. (10) Cairngorm—new anal. in Table I. (11) Cairnsmore of Carsphairn—mean of anals. 1 and 2 in Deer (1935). (12) Cairnsmore of Fleet—mean of 2 anals. on p. 293 of Gardiner and Reynolds (1937) and 4 anals. on p. 95 of Parslow (1968). (13) Carnsore—new anal. in table II. (14) Cluanie—anal. 1 on p. 46 of Leedal (1953). (15) Corvock—new anal. in table II. (16) Creetown—new anal. in table I. (17) Cromar—mean of no. 1 in Hall (1969*b*) and no. 1 on p. 349 of Read (1927). (18) Curraghmore—new anal. in table II. (19) Dreenan—new anal. in table II. (20) Eskdale—mean of anal. I on p. 128 of Trotter *et al.* (1937) and anal. of specimen 77164 on p. 400 of Oliver (1961). (21) Etive—anal. 1 in table 3 of Anderson (1937). (22) Foxdale—new anal. in table II. (23) Foyers—mean of anals. 17, 18, 20, and 21 in Marston (1971). (24) Galway—average of 5 averages in table 4 of Wright (1964). (25) Garabal Hill—anal. 30 in table 7 of Nockolds (1941). (26) Glen Clova—anal. 120 in table 1 of Harry (1958). (27) Glenelg-Ratagain—mean of anals. 1 and 11 in table 2 of Nicholls (1951). (28) Glen Gairn—new anal. in table I. (29) Glen Loy—anal. 1680 on p. 61 of Harvey and Wilson (1956). (30) Glen Tilt—average of anals. of biotite granite and muscovite granite in Deer (1938). (31) Goia—mean of 20 anals. with Q+Or+Ab ⩾ 80 % in table I of Mercy (1960). (32) Grantown—new anal. in Table I. (33) Helmsdale—mean of 2 new anals. in table I. (34) Hill of Fare—mean of anal. 1 on p. 87 of Bisset (1934) and anal. A in Table 1 of Anderson (1939). (35) Inish—mean of 4 anals. of the Inish and Inishturk adamellites in table 5 of Townend (1966). (36) Leinster (northern part)—mean of 2 new anals. in table II. (37) Letterfrack—mean of anals L12 and L13 in table 5 of Townend (1966). (38) L. Coire—mean of nos. 72–4 in table 3 of Brown (1967). (39) Loch Doon—mean of anal. 1 on p. 10 of Gardiner and Reynolds (1932) and anal. L on p. 173 of Higazy (1954). (40) Lochnagar—anal. 3 (erroneously described as Glen Gairn granite) in table 1 of Hall (1969*b*). (41) Longmanhill—anal. 4 in table 1 of Hall (1969*b*). (42) Main Donegal—mean of 2 new anals. in table II. (43) Mt. Battock—anal. 5 in table 1 of Hall (1969*b*). (44) Moy—anal. 2 on p. 574 of Nockolds and Mitchell (1948). (45) Newry—anal. 4 in table 1 of Reynolds (1944). (46) Omey—mean of 8 anals. of the Omey and Island types on p. 183 of Townend (1966). (47) Oughterard—mean of 60 anals. represented by columns A, C, and D of table 4 in Bradshaw *et al.* (1969). (48) Park—new anal. in table I. (49) Peterhead—new anal. in table I. (50). Pomeroy—new anal. in table II. (51) Portencorkie—anal. on p. 192 of Holgate (1943). (52) Rogart—anal. 3 on p. 454 of Soper (1963). (53) Ross of Mull—anal. 6 on p. 468 of Hall (1969*b*). (54) Rosses—mean of anals. 4–6 in table I of Hall (1967). (55) Roundstone—new anal. in table II. (56) Shap—mean of anals. 1 and 2 on p. 311 of Grantham (1928). (57) Skiddaw—mean of anals. 1 and 2 in table 1 of Hitchen (1934). (58) Strichen—mean of anals. 7 and 8 in table 1 of Hall (1969*b*). (59) Strontian—anal. 1 on p. 22 of Sabine (1963). (60) Termon Hill (Blacksod)—anal. 2 in table 1 of Hall (1969*b*). (61) Trawenagh Bay—mean of anals. 9–11 in table 1 of Hall (1969*b*). (62) Tullow Lowlands—new anal. in table II. (63) Weardale—mean of anals. A and B in table 1 of Dunham *et al.* (1965).

The data used for the trend surface analysis are given in table III; this list includes the new analyses given in this paper and new analyses published elsewhere (Bradshaw *et al.*, 1969; Marston, 1971; Parslow, 1968), together with the existing data revised in accordance with the modified sampling scheme. The number of intrusions represented by the data has been raised from 40 to 63, and nearly all the large Caledonian intrusions containing rocks of appropriate composition are now included. The modifications to the data used previously (Hall, 1969*b*) are as follows: the Ardara, Glenelg-Ratagain, Gola, and Shap granites are now represented by the average of all analyses with ⩾ 80 % Q+Or+Ab, not just the analyses with the highest total (Q+Or+Ab); previously overlooked analyses of the Eskdale, Glen Loy, and Portencorkie granites have been included; the analysis of the Leinster granite quoted by Charlesworth (1963) has been omitted in favour of the new analyses given here because it is not clear from the stated locality which of the units of the Leinster batholith it represents; analyses have been omitted of a dyke-rock from Strontian and a granite with < 80 % Q+Or+Ab from Letterfrack; the Maryculter granite has been omitted because it is now believed to be one of the 'Older Granites' (i.e. metamorphosed or non-intrusive or both); the Ballater and Coull granites are now grouped as the 'Cromar granite' because there is no evidence that they form separate intrusions; an analysis previously described incorrectly as belonging to the Glen Gairn granite has been relabelled as 'Lochnagar granite' and the Blacksod granite is now described as the 'Termon Hill granite', to conform to the recent usage of the Irish Geological Survey. The geographical parameters quoted in the table (E and N) are based on the 100 km squares of the National Grid, allowance having been made for movement of major post-Caledonian faults. The normative constituents, Q, Or, and Ab have been recalculated to total 100 %.

Trend surfaces of up to the sixth order were calculated for each of the recalculated normative constituents Q, Or, and Ab, and the significance of the calculated surfaces

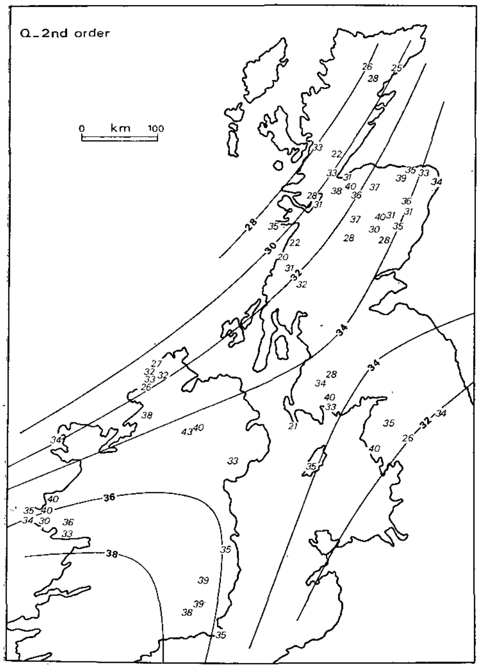
TABLE IV. *Analysis of variance for trend components of successive orders*

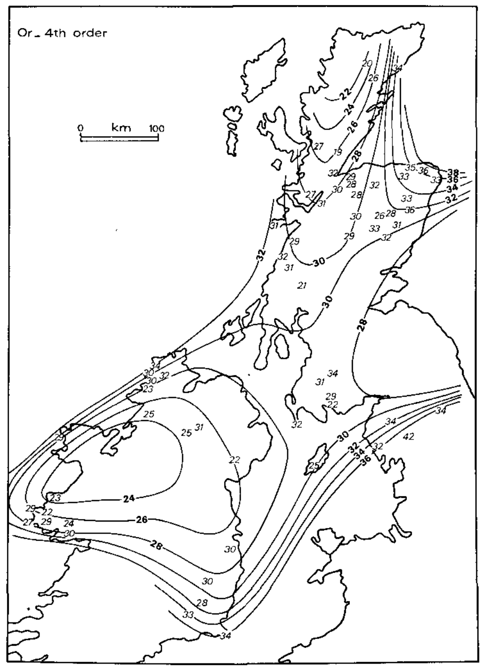
	% of variation	D.F.	Mean Square	F	Confidence level
Quartz					
Accounted for by 1st order surface	11·0	2	5·50	3·72	~97 %
Residuals	89·0	60	1·48		
Accounted for by 2nd order trend components	8·1	3	2·70	1·90	~80 %
Residuals	80·9	57	1·42		
Accounted for by 3rd order trend components	1·3	4	0·32	0·21	very low
Residuals	79·6	53	1·50		
Orthoclase					
Accounted for by 1st order surface	20·0	2	10·00	7·52	>99 %
Residuals	80·0	60	1·33		
Accounted for by 2nd order trend components	5·1	3	1·70	1·29	~70 %
Residuals	75·0	57	1·32		
Accounted for by 3rd order trend components	16·3	4	4·08	3·68	~99 %
Residuals	58·7	53	1·11		
Accounted for by 4th order trend components	15·1	5	3·02	3·32	~98 %
Residuals	43·6	48	0·91		
Accounted for by 5th order trend components	5·3	6	0·88	0·97	very low
Residuals	38·3	42	0·91		
Albite					
Accounted for by 1st order surface	17·7	2	8·85	6·46	> 99 %
Residuals	82·3	60	1·37		
Accounted for by 2nd order trend components	8·8	3	2·93	2·27	~91 %
Residuals	73·5	57	1·29		
Accounted for by 3rd order trend components	12·2	4	3·05	2·63	~95 %
Residuals	61·3	53	1·16		
Accounted for by 4th order trend components	3·5	5	0·70	0·58	very low
Residuals	57·8	48	1·20		

D.F. = degrees of freedom associated with trend surface or components and with residuals.
F = variance ratio.

was estimated by means of analysis of variance (Snedecor and Cochran, 1967), as shown in table IV.

The high confidence levels associated with the first order trend surfaces confirm the existence of a regional variation in the content of each normative constituent. The significance of higher order trend surfaces is less firmly established. Because of the unavoidably uneven distribution of sampling points, and the possibility of uneven variance of the compositional variables over the area studied, analysis of variance is not a completely satisfactory method of assessing the significance of the trends. The regressions appear to contain significant components of up to 2nd order for Q, 4th order for Or, and 3rd order for Ab, but the corresponding surfaces (shown in figs. 1 to 3), may include both genuine detail in areas of good sample coverage and spurious detail elsewhere. If more was known about the origin of the regional variation it might be possible to predict whether variation was to be expected on a small scale, best represented by a high-order surface with much local flexure, or on a large scale, best represented by a low-order surface showing broad undulations, but this knowledge is lacking.





FIGS. 1 and 2: FIG. 1 (left). Second order trend surface for normative quartz in Caledonian granites. Actual normative quartz contents are indicated at the localities of the individual intrusions. FIG. 2 (right). Fourth order trend surface for normative orthoclase in Caledonian granites. Actual normative orthoclase contents are indicated at the localities of the individual intrusions.

The second-order quartz surface is shown in fig. 1. The Q contents are highest along a NE.–SW. ridge from SW. Ireland to the east of Scotland, and fall away to the north-west and to the south-east. The fall to the north-west is apparent from the individual Q values, but the fall to the south-east is based on a rather small number of sampling points.

The fourth-order orthoclase surface is shown in fig. 2. As a higher order surface, it shows more convolutions than the quartz surface in fig. 1. The mean Or content of Caledonian granites is 29·4 %, and the surface is lower than this in the north of Scotland and over much of Ireland. High values are concentrated in NE. Scotland, northern England, and SE. Ireland.

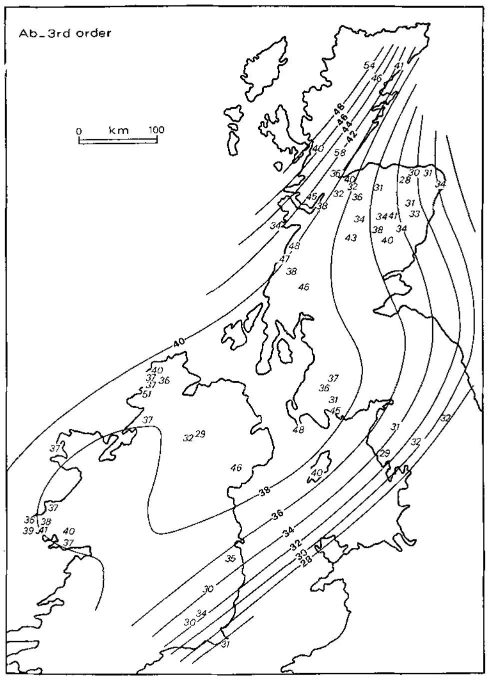


FIG. 3. Third order trend surface for normative albite in Caledonian granites. Actual normative albite contents are indicated at the localities of the individual intrusions.

The third-order albite surface is shown in fig. 3. This surface is simpler in form than the other two, and indicates a progressive decrease in Ab content towards the south-east in general and towards the east in Scotland. The third order Ab surface calculated previously (Hall, 1969*b*) showed bilateral symmetry in the Ab distribution in Ireland, but this symmetry is not confirmed by the newly calculated surface, which is based on a much larger number of samples in this region.

Interpretation of the regional variation in composition

The explanation advanced by Hall (1969*a*, *b*) for the regional variation was that the magma compositions represented the products of magma development under different pressures of water. The compositions of the granites studied are shown in fig. 4 in relation to the system Q–Or–Ab–H_2O. Liquid compositions during fractional crystallization or partial melting at relatively low pressures lie along the cotectic line in this system, and increasing water pressure is reflected by decreasing Q in the melt. At higher water-pressures the minimum in the system has the character of a eutectic point (Tuttle and Bowen, 1958; Luth, Jahns, and Tuttle, 1964), and residual or initial liquid compositions lie close to this point, which moves towards Ab with increasing water pressure. On this basis, granites formed under the highest water pressures would be rich in Ab and low in Q, while those formed under the lowest water pressures would be rich in Q but not necessarily low in Ab.

A comparison of the over-all compositional range of Caledonian granites with those of Variscan granites in western and central Europe has shown that the latter fall near liquidus minima in the system Q–Or–Ab–H_2O for relatively lower water-pressures (Hall, 1971). This relationship may be correlated with generally higher geothermal gradients in the Variscan orogenic belt deduced from metamorphic facies series, and the author has inferred from this that the granites in the two orogenic belts originated by melting at depths (and consequently at water pressures) determined by the geothermal gradient.

It may be possible to interpret the regional variation in composition of Caledonian granites along similar lines. Compositions rich in normative Q are shown by the granites of the east of Scotland and the south and west of Ireland (fig. 1), and correspond to those of melts formed under low water pressures such as would be produced by melting in a high geothermal gradient (Hall, 1971). High geothermal gradients relative to the rest of the Caledonides are in fact indicated by low-pressure regional metamorphic mineral assemblages in the east of Scotland (Read, 1952; Miyashiro, 1961), and probably also in the west of Ireland (Leake, 1970, p. 225); further south in Ireland the grade of regional metamorphism is too low to give any indication of the geothermal gradient.

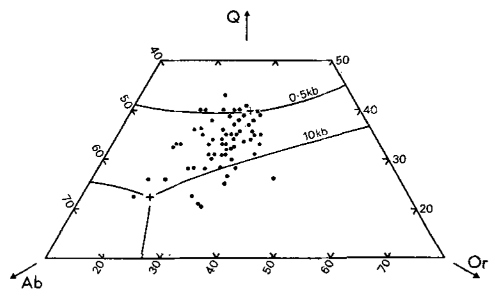


FIG. 4. The compositions of Caledonian granites in relation to the system Q–Or–Ab–H_2O. Minima in this system are shown for water pressures of 0·5 and 10 kb (after Tuttle and Bowen 1958; Luth, Jahns, and Tuttle, 1964).

Magma formation in relation to the geothermal gradient

Some implications of the above hypothesis may now be examined. An uneven distribution of radioactive heat-producing elements in the crust is an obvious cause of regional variations in the geothermal gradient. A correlation between present-day heat flow and radioactive heat production has been observed in other orogenic regions (Birch *et al.*, 1968; Lachenbruch, 1968; Roy *et al.*, 1968), although little is known about the distribution of heat-producing elements in the British Caledonides. However, a high geothermal gradient due to radioactive heat production cannot by itself be sufficient to give rise to granitic magma by crustal melting, since granite formation is restricted to the limited period of an orogenic episode. An episode of melting can only be brought about by a temporary increase in the geothermal gradient.

Stratigraphical and other geological studies have shown that the Caledonian orogenic belt is an elongated region that underwent a long period of sedimentation followed by deformation, uplift, and erosion. Fluctuations in the geothermal gradient at any particular location are a normal result of such a cycle. Rapid deposition of sediment at near-surface temperatures depresses the level of isotherms, which restore themselves to their original position relatively slowly compared with the rate of sedimentation. Uplift and removal by erosion of cold material from the top of the crust bring up the isotherms to a higher-than-normal level, and restoration of the original thermal equilibrium is again slower than the process of uplift and erosion. The whole cycle of geosynclinal and orogenic development involves changes in geothermal gradient in the crust from normal to lower-than-normal to normal to higher-than-normal to normal, as shown in fig. 5.

The effects of these changes on melting relationships in the crust are shown in fig. 6. The actual composition of the material at the depth of potential melting is not very well known. The continental crust is conventionally divided into an upper 'granitic' layer (with overlying sediments), and a lower 'basaltic' layer (Gutenberg, 1955, 1959; Press, 1961; Subbotin *et al.*, 1965; Pakiser and Robinson, 1966; Belousov, 1966). The upper 'granitic' layer is believed to consist of rock types similar to those exposed in the basement complexes of stable continental regions, i.e. a mixture of granites and metamorphic rock types, most of which could give rise to granitic magma on melting (Winkler, 1967). The nature of the lower 'basaltic' layer, and the extent of the discontinuity between the layers, are more uncertain. A basaltic composition has been questioned by many geophysicists (James and Steinhart, 1966), and the mineralogical composition of this layer is probably not basaltic even if its composition is (Ringwood and Green, 1966*a*). The most probable constituents of the 'basaltic' layer are considered by Ringwood and Green (1966*b*) to be either felsic rocks of anhydrous mineralogy (acid and intermediate rocks in the eclogite facies of metamorphism), or mafic rocks of hydrous mineralogy (amphibolites). Neither of these alternatives is a suitable source of granitic magma on melting, the former because too high a temperature would be required, and the latter because the composition is wrong. Some constituents of the 'basaltic' layer may in fact be melting residues from previous orogenic episodes. The upper 'granitic' layer of the crust is therefore the most probable source of granitic magma if the latter originates in the crust, and an origin at this level is consistent with the observed petrological relationships of many individual granite complexes (Hall, 1966*a*; Bateman and Eaton, 1967). The detailed crustal structure of the actual Caledonian region is not yet certain. The 'basaltic' crust is rather thin in the southern part of the area (Blundell and Parks, 1969; Collette *et al.*, 1970), but may be thicker in the northern part (Agger and Carpenter, 1965, Jacob, 1969). In fig. 6 the upper 'granitic' crust and overlying sediments are shown as having an initial thickness of 23 km, which is the mean value of those reported by Kosminskaya *et al.* (1969) for 11 different tectonic regions of the continental U.S.S.R. After geosynclinal sedimentation the thickness of this layer in an orogenic belt would be much greater, and a value of 35 km is arbitrarily indicated in fig. 6B.

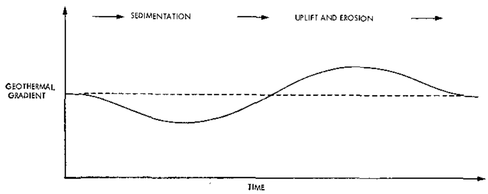


FIG. 5. Diagrammatic representation of the changes in geothermal gradient which take place during the development of an orogenic belt.

In crust of normal thickness, under a realistic geothermal gradient of 30 °C/km, no melting is likely to occur in the 'granitic' crust (fig. 6A). Melting is also unlikely to occur during the period of sedimentation, because although the crustal thickness is increased, the geothermal gradient is lowered (fig. 6B). It may be noted that if sedimentation were infinitely more rapid than heat conduction, the temperature–depth curve would be displaced to the right in fig. 6 by an amount corresponding to the increase in crustal thickness, whereas if conduction were infinitely more rapid than sedimentation, the temperature–depth curve would not be displaced at all (neglecting differences in thermal conductivity of the rocks involved). The curvature of the temperature–depth curve in fig. 6B represents an arbitrary compromise, since the relative rates of sedimentation and conduction are unknown. As sedimentation ceases, the geothermal gradient starts to return to normal, and during subsequent uplift and erosion the conditions for melting become most favourable. The geothermal gradient increases to an above-average value, particularly if erosion is rapid, while the crustal thickness is reduced to approach its original value (fig. 6C). In practice, the crustal thickness is probably rather high for some time after an orogenic episode, and conditions for melting would be even more favourable than those shown in fig. 6C. Eventually, the geothermal gradient returns to normal (fig. 6D) and magma production ceases. This sequence of changes is probably the explanation of the relatively late formation of granitic intrusions during the structural development of the orogenic belt.

There are thus two reasons why different parts of an orogenic belt should have developed under different geothermal gradients and hence contain granites of different composition. One is regional variation in the content of radioactive elements in the crust throughout the period of orogeny. The other is differential rates of uplift and erosion in the later stages of the orogeny. In areas of high radioactive content or most rapid uplift, melting would be most extensive; not only would melting commence at a relatively low P_{total}, but it would proceed furthest into the shaded region of fig. 6, where P_{H_2O} is less than P_{total}. Areas of high normative quartz in granites would therefore

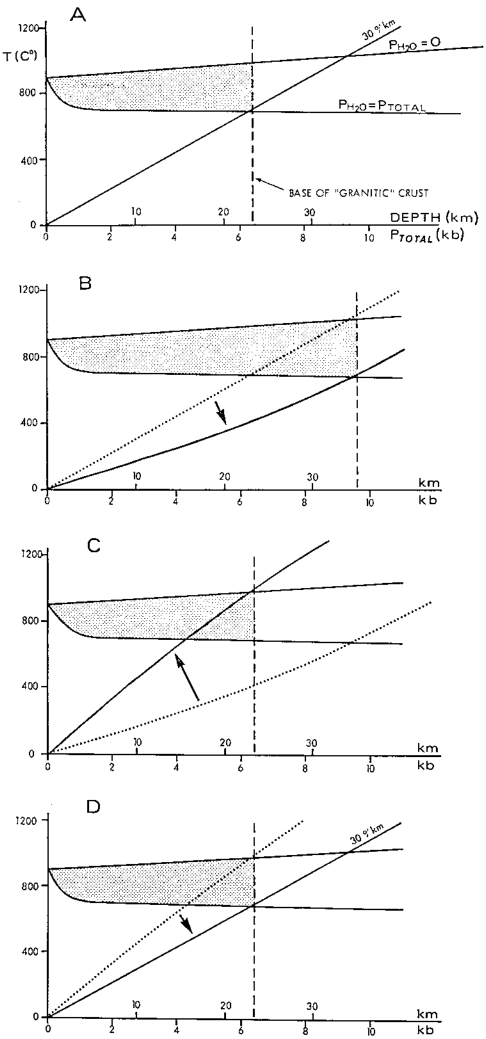


FIG. 6. Possible melting relationships in the crust in relation to variations in geothermal gradient during an orogeny. The shaded area in each diagram represents the conditions for undersaturated melting of the minimum-melting constituents of granite; it lies between the saturated melting curve (P_{H_2O} = P_{total}) and the dry melting curve (P_{H_2O} = zero).

correspond either to regions of rapid late-orogenic uplift and erosion or to regions of high crustal radioactivity. Evidence for the former is provided by the pattern of K/Ar dates in Scotland. Dewey and Pankhurst (1970) suggest that these dates are determined mainly by geothermal gradient and rate of uplift, the accumulation of argon being started by uplift through a critical isotherm for argon retention. Rapid uplift in the eastern Grampians is thus reflected by higher K/Ar ages in this region than in other parts of the Grampian Highlands.

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