

The origin of the Kennethmont granite-diorite series, Inch, Aberdeenshire

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SUMMARY. The Inch granite-diorite complex of Aberdeenshire consists of acid and intermediate igneous rocks that are quite distinct from, and younger than, the differentiates of the Inch basic mass.

The main components of the complex include two types of uniform granite (one pink, one grey), and a variety of inhomogeneous dioritic rocks (diorite xenoliths in grey granite matrix, granodiorite with residual mafic inclusions, and more uniform diorite). Full chemical analyses for major and trace elements are presented for sixteen rocks representative of all types, together with initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and rare-earth-element distribution patterns for a selection of samples. The pink granite is not chemically related to the remaining members of the complex. Comparison with chemical data for a range of basic igneous rocks of the Inch and Boganclough basic masses discredits the hypothesis that the diorite rocks were produced by assimilation of any of these in the grey granite magma. A primary diorite magma is recognized as essential to the petrogenesis of the complex.

This study is concerned with a group of acid and intermediate igneous rocks that outcrop over an area of several square miles, mostly in the parish of Kennethmont, five miles west of Inch, Aberdeenshire. The area, which is rather poorly exposed, has previously been studied by Read (1923), Sadashivaiah (1954), and Read and Haq (1965). They have described rock types ranging from homogeneous diorites, through xenolithic rocks and inhomogeneous rocks with a relatively acid matrix, to more uniform granites, locally developing a syenitic facies. These are collectively referred to as the Inch granite-diorite complex and are distinct from the differentiated gabbro-syenite sequence of the Inch basic mass which belongs to the 'Younger' Caledonian igneous suite of north-east Scotland. The broad distribution of the complex and adjacent parts of the Inch basic mass are shown by Read *et al.* (1961), and no major differences were found on remapping by Busrewil (1970).

Sadashivaiah (1954) and Read and Haq (1965) discredited on chemical grounds earlier assumptions that the granitic rocks of the complex could be late fractionation products of the Inch basic mass and suggested that they represented a distinctly younger episode of igneous activity. They further attributed the dioritic and xenolithic rocks to assimilation by the granite magma of already consolidated basic rocks similar to the hypersthene-gabbros of the basic mass. However, the basic rocks of the Inch mass have been more fully investigated since the early work on the Inch granite-diorite complex (Read, Sadashivaiah, and Haq, 1965; Clarke and Wadsworth, 1970), and it is now recognized that two quite distinct types of hypersthene-gabbro are present. One of these is part of the layered cumulate sequence; the other (granular hypersthene-gabbro) is apparently a separate, later intrusion.

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The present study was undertaken in an attempt to clarify the petrogenesis of the granite–diorite complex and its relationship to the main Inch intrusion. It also formed a necessary corollary to an investigation of the Boganclogh area (Busrewil, Pankhurst, and Wadsworth, 1973), which represents a possible extension of the Inch basic mass to the west of the Bogie O.R.S. outlier and comprises a wide range of rock types (peridotite, norite, diorite, and granite), some of which are at least superficially similar to members of the Inch granite–diorite complex.

Petrology

Sadashivaiah (1954) recognized granite and diorite as the principal components of the complex. On this basis his diorite group includes a variety of material ranging from basic ('diorite') xenoliths, through more homogeneous quartz–diorites, to relatively acid rocks containing small, diffuse, mafic inclusions ('xenolithic rocks with granitic matrices'). It was implied that these acid rocks grade into the extreme granitic components of the complex, which occur as discrete masses, as veins and stringers cutting the diorites, and as the host to the diorite xenoliths. For the purpose of this investigation these rocks with dioritic affinities will all be classed as 'inhomogeneous rocks'. Consideration will be given to their geochemistry to test whether they represent the intermediate products of contamination of one class of homogeneous igneous rock (the granitic rocks of the complex) by assimilation of another (the basic rocks of the main Inch and Boganclogh intrusions).

With this in mind, the following nomenclature is proposed for the complex (modal data for the analysed samples is shown in Table I):

I <i>Homogeneous acid rocks</i>	II <i>Homogeneous basic rocks</i>	III <i>Inhomogeneous rocks</i>
(a) grey granite	(a) granular hypersthene-gabbro	(a) diorite xenoliths in granite matrix (of Ia type)
(b) pink granite	(b) ferrogabbros and ferrodiorites	(b) granodiorite with residual xenoliths
	(c) quartz–biotite–norite	(c) relatively homogeneous tonalite

Acid rocks. The *grey granite* (Ia) typically forms the matrix of the most distinctively xenolithic part of the inhomogeneous series (IIIa), and occurs as irregular veins cutting various members of the complex. It normally consists of quartz, microcline, oligoclase, and biotite, but it appears to show all gradations towards the contaminated acid material containing residual xenoliths (IIIb). The *pink granite* (Ib) does not appear to be involved with the inhomogeneous rocks, but forms quite large masses of relatively homogeneous granite (the main Kennethmont granite–syenite areas mapped by Read, Sadashivaiah, and Haq, 1961). It shows much closer resemblance to the principal Newer Granites of the region (e.g. the Bennachie Granite) than to the grey granite. It is rather uniform in appearance, except for slight variations in quartz content and in grain size and is relatively poor in biotite (and ferromagnesian minerals

generally). Its distinctive colour seems to be due to the alkali feldspar (microcline-perthite), which is considerably in excess of plagioclase (oligoclase). A very similar granite outcrops near the western margin of the Boganclogh igneous complex and is grouped with the Kennethmont pink granites for the purposes of this account.

Basic rocks. The basic rocks of the western part of the main Inch intrusion (between the Kennethmont area and the Red Rock Hills) are scarcely exposed. Hitherto they have been mapped as hypersthene-gabbro (Read *et al.*, 1961) and correlated with similar rocks in the eastern part of the intrusion. Undoubted granular hypersthene-gabbros (IIa) occur in this area, but they only form recognizable *in situ* outcrops in the extreme eastern part of it, close to the Red Rock Hills. They are similar to those described by Clarke and Wadsworth (1970), and interpreted as intrusive into the Inch cumulates. Texturally they are rather fine-grained, and are composed of equigranular plagioclase (An₆₅₋₇₀), augite, and orthopyroxene (En₆₀).

In the north-east corner, the rocks of the complex are mainly granite and are in contact with Upper Zone cumulates of the Inch Layered Series (IIb). The latter are predominantly ferrogabbros (Clarke and Wadsworth, 1970) and consist of plagioclase (An₅₀₋₅₅), olivine (Fo₁₀₋₄₀), ferroaugite, and hypersthene, together with minor amounts of apatite, ilmenite, and intercumulus hornblende and biotite. Equivalent rocks, though not clearly layered and with a slightly less calcic plagioclase, form the northern part of the Boganclogh intrusion, where they have been termed ferrodiorites (Busrewil *et al.*, 1973).

The remaining outcrops in the gabbro area south-east of Kennethmont are of a distinctive rock type not previously described from the Inch intrusion, but of considerable importance in the Boganclogh area (Busrewil *et al.*, 1973) and in the Morven-Cabrach (Allan, 1970) and Haddo House (Gribble, 1967) intrusions. This is quartz-biotite-norite (IIc), which is relatively coarse-grained compared with the granular hypersthene-gabbro, and is composed of plagioclase (An₅₆), orthopyroxene (En₅₀), and augite, together with prominent poikilitic crystals of biotite, evenly scattered throughout the rock, minor hornblende (locally replacing pyroxene), and interstitial quartz. The quartz-biotite-norites have been interpreted by Gribble (1967) and Allan (1970) as the products of crystallization of the regionally available basic magma in a water-saturated environment, in contrast with the relatively dry conditions believed to have given rise to the cumulate fractionation sequence of north-east Scotland (Wadsworth, 1970).

The proximity of all three basic rock types to the Granite-Diorite Complex means that any of them would have been available as basic end-members for the inhomogeneous rocks.

Inhomogeneous series. Although this is a very variable group of rocks, it has been possible to distinguish three main rock types (IIIa, b, c), which could be taken to represent stages in the progressive contamination of acid magma with basic material. A relatively early stage (IIIa) is indicated by the occurrence of coherent xenoliths in apparently unmodified grey granite. The xenoliths are typically finer-grained than the acid matrix. They show gradations from a relatively igneous appearance, with occasional relict phenocrysts of plagioclase, to a distinctly granular metamorphic

texture. The xenoliths are dioritic and tend to be very rich in ferromagnesian minerals. Biotite is quantitatively the most important of these, although hornblende is consistently present, becoming particularly prominent at the margins of the inclusions, and pyroxenes are generally visible (mostly clinopyroxene, but some orthopyroxene). Plagioclase (An_{35}) is the principal felsic constituent but small amounts of interstitial quartz occur in certain examples.

An apparently intermediate stage in the contamination series is represented by a more granodioritic type of acid rock, containing small mafic 'clots' (IIIb). The granodiorite itself is distinguished from the grey granite by the dominance of plagioclase over alkali feldspar and the occurrence of hornblende as well as biotite, although the latter always predominates; the accessory minerals are apatite, opaque oxide, sphene (of interstitial to poikilitic habit), and orthite. The mafic 'clots', which are interpreted as residual xenoliths of more basic material, consist of relatively high concentrations of biotite or hornblende (or both).

In certain areas, notably in the vicinity of the Kennethmont railway cutting, there are other rocks of this series that are considerably more homogeneous than IIIa and IIIb, and can generally be classified as tonalites (IIIc). On the granite-gabbro hybridization theory they would have to be interpreted as representing virtually complete assimilation of the basic material by the acid magma, although geochemical evidence presented later suggests that this is not the case. The tonalites show some variation in grain size and in the proportion of ferromagnesian constituents, but the same minerals are generally present. Plagioclase (cores of An_{35} strongly zoned outwards) is often the only feldspar, although minor alkali feldspar occurs in a few cases. Small amounts of pyroxene (both clino- and ortho-pyroxene) are often present, typically showing signs of replacement by amphibole; hornblende and biotite are the principal ferromagnesian phases, and tend to be present in approximately equal quantities. Interstitial quartz is ubiquitous, varying between 5 and 20 %. Minor accessories include apatite, opaque oxide, and sphene.

Ages of the rock types of the complex

Sadashivaiah (1954) showed not only that the granitic rocks of the Kennethmont complex were mineralogically and chemically unlike the syenitic differentiates of the *Insch* basic magma, but also that the pink granite exhibited intrusive relations to the *Insch* ferrogabbros. A significant difference in the emplacement ages of these rocks has since been established by radiometric dating.

Pankhurst (1970) presented a Rb-Sr whole-rock isochron for the *Insch* Upper Zone of 504 ± 26 Myr (5.0×10^{10} y. half-life). Another isochron, for rocks in the metasomatic thermal aureole of the Haddo House mass, gave 499 ± 23 Myr. It was considered that these data taken together demonstrated essentially simultaneous emplacement of the basic rocks of the 'younger' gabbro suite, including the quartz-biotite-norites of Haddo House and Arnage, 501 ± 17 Myr ago. This age would therefore apply to the three groups of basic rock mentioned above (IIa, IIb, and IIc). Although it has been suggested that the granular hypersthene-gabbros crystallized as a later intrusion separate from the *Insch* Layered Series (Clarke and Wadsworth,

1970), these authors accepted some genetic link between the two. The granular gabbros probably represent a late pulse of magma broadly equivalent in composition to the parent magma of the Inch Layered Series before differentiation and no significant time-lag would be anticipated between these intrusions.

The pink granite of the Kennethmont Complex (*Ib*) has also been dated by the Rb-Sr whole-rock isochron method at 463 ± 4 Myr (Pankhurst, 1974), and seems to be part of a phase of post-tectonic granitic magmatism that affected the whole of north-east Scotland about 465 Myr ago. This demonstrates a very significant time interval between crystallization of the basic and acid rocks (at least 20 Myr, perhaps as much as 60 Myr). The Rb-Sr data for the grey granite (*Ia*) reported in Table II strongly suggest that this was contemporaneous with the pink granite and in view of their disposition in the field it is suggested that this is also the age of formation of the inhomogeneous rock series (*IIIa*, *IIIb*, and *IIC*). The Bennachie granite (together with the Aberdeen and Peterhead granites) was intruded still later, at about 420 Myr ago (Bell, 1968).

Chemistry

Hitherto only six analyses of these variable rocks have been published, and only two include trace-element data (Read, 1923; Sadashivaiah, 1954; Read and Haq, 1965). A further sixteen rocks from the granite-diorite complex and immediately adjacent areas, including a sample of the Bennachie granite, have therefore been analysed for both major and trace elements (Table I). The average composition of the Inch granular hypersthene-gabbros (Busrewil, 1970) and of the Boganclough ferrodiorites (Busrewil *et al.*, 1973), as well as two diorite analyses from Sadashivaiah (1954), are given for comparative purposes. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Table II) and rare-earth-element concentrations (Table III) were also determined on representative samples.

Major- and trace-element variation. The principal feature of this series of rocks is the fairly continuous spectrum of compositions represented, ranging from the gabbroic rocks through the intermediate xenolithic rocks to the granites. Not surprisingly this results in fairly smooth variation of most elements when plotted against differentiation index (fig. 1), with the basic rocks at one end and the grey granites at the other. However, these diagrams show the generally anomalous character of the pink and

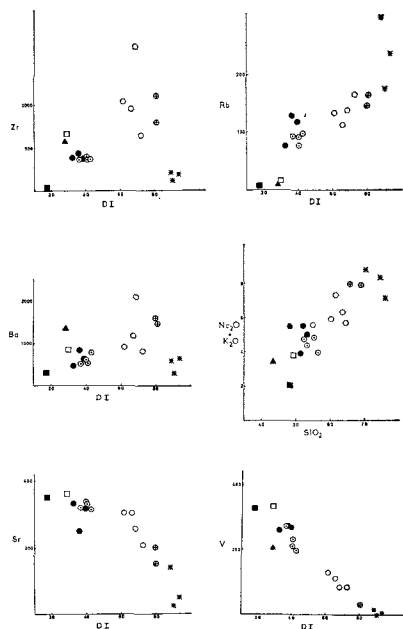


FIG. 1. Variation diagrams for alkalis vs. SiO_2 and selected trace elements vs. differentiation index (Thornton-Tuttle). Key: * pink granite, \oplus grey granite, \circ granodiorite, \odot tonalite, \bullet diorite xenoliths, \square quartz-biotite-norite, \blacksquare hypersthene-gabbro, \blacktriangle ferrodiorite.

TABLE I. *Chemical*

No.	1	2	3	4	5	6	7	8	9	10	11	12
Rock-type	Ia		Ib			IIa	IIb	IIc	IIIa			
Grid Ref. (NJ)	529292	529292	489283	524267	*	*	*	552252	531292	531292	*	535300
SiO ₂	65.75	68.75	75.45	76.09	70.21	48.58	43.57	49.51	48.56	51.54	51.88	53.33
TiO ₂	0.43	0.36	0.04	—	0.17	1.27	2.87	2.06	1.39	1.46	1.14	1.52
Al ₂ O ₃	19.32	16.24	14.09	15.23	18.46	16.48	18.69	17.39	19.34	16.24	16.24	15.84
Fe ₂ O ₃	1.23	0.71	0.16	0.18	0.64	2.30	3.05	1.92	1.16	3.29	0.95	1.62
FeO	2.73	2.21	0.61	0.66	0.52	8.10	13.28	9.29	7.52	7.66	8.39	6.92
MnO	0.06	0.07	0.02	0.01	0.02	0.19	0.29	0.19	0.19	0.15	0.19	0.15
MgO	0.65	0.60	0.06	0.05	0.32	8.07	3.90	5.34	6.19	6.01	6.84	5.21
CaO	0.49	2.23	0.48	0.39	0.79	11.70	8.60	9.07	8.79	8.66	7.96	8.40
Na ₂ O	2.78	2.82	2.40	2.55	3.37	1.89	2.84	2.66	2.66	2.50	2.76	2.56
K ₂ O	5.11	5.05	5.90	4.12	5.35	0.13	0.67	1.15	2.81	1.28	2.64	2.46
P ₂ O ₅	0.46	0.34	0.31	0.06	0.17	0.23	1.46	0.50	0.50	0.43	0.07	0.49
H ₂ O	1.00	0.66	0.31	0.37	0.37	1.12	0.92	0.93	1.54	0.82	0.78	1.47
Total	100.01	100.4	99.83	99.71	100.39	100.06	100.14	100.01	100.65	100.04	99.84	99.97
<i>C.I.P.W. norms</i>												
Q	25.81	27.04	38.23	44.26	28.36	0.43	—	0.07	—	3.94	—	3.63
Co	7.77	2.90	3.63	6.01	6.10	—	1.15	—	—	—	—	—
Or	30.20	29.84	34.87	24.35	31.61	0.94	3.95	6.80	16.61	7.56	15.60	14.30
Ab	23.52	23.86	20.81	21.58	28.52	15.99	24.02	22.15	19.36	21.15	19.21	21.66
An	3.94	8.84	0.36	1.54	2.81	36.00	33.14	32.11	32.53	29.31	26.33	24.58
Di	—	—	—	—	—	16.70	—	7.94	6.39	8.83	10.42	11.36
Hy	5.02	4.50	1.11	1.21	0.98	21.04	12.87	21.80	—	19.88	18.67	16.55
Ol	—	—	—	—	—	1.59	10.83	—	16.94	—	4.64	—
Mt	1.78	1.03	0.23	0.26	0.93	3.33	4.42	2.78	1.68	4.77	1.38	2.35
Il	0.82	0.68	0.08	—	0.32	2.41	5.45	3.91	2.64	2.77	2.17	2.89
Ap	1.01	0.74	0.68	0.13	0.37	0.51	3.19	1.09	1.09	0.94	0.15	1.07
D.I.†	79.5	80.8	93.9	90.2	88.5	17.4	28.0	29.4	36.0	32.7	34.8	39.6
<i>Modes</i>												
Qtz	29.3	26.8	38.7	36.6	27.2	—	—	1.8	—	—	—	—
Alk. feldspar	54.9	44.3	45.9	57.0	38.1	—	—	—	—	—	—	—
Plag	6.8	26.5	14.4	6.0	33.9	—	—	56.2	—	—	—	—
Cpx	—	—	—	—	—	—	—	12.5	—	—	—	—
Opx	—	—	—	—	—	—	—	12.9	—	—	—	—
Biotite	8.9	8.9	1.0	0.2	0.9	—	—	10.8	—	—	—	—
Hornblende	—	tr	—	—	—	—	—	3.9	—	—	—	—
Accessories	—	—	—	0.2	0.3	—	—	1.6	—	—	—	—
<i>Trace elements (ppm)</i>												
V	32	29	5	—	15	325	207	332	272	258	—	268
Cr	—	—	—	—	—	191	—	—	154	157	—	97
Ni	—	—	—	—	—	8	1	3	24	21	—	10
Rb	148	165	237	177	400	4	12	14	131	77	—	119
Sr	198	150	50	23	144	353	456	364	247	334	—	316
Y	—	—	—	—	—	9	25	32	6	16	—	5
Zr	554	406	83	63	105	19	566	332	193	191	—	189
Ba	1624	1494	326	318	600	295	1379	847	833	471	—	634

* The rock types Ia, Ib, etc. are as described in the text. Samples not given grid references are: 5, Bennachie granite (grid reference 680185); 6, Average granular hypersthene-gabbro from Inch (Busrewil, 1970); 7, Average of four ferrodiorites from Boganclogh (Busrewil et al.,

Bennachie granites relative to the remaining rocks, especially their very low content of Al and many trace elements (e.g. Sr, Ba, P, Zr) despite their high silica contents. Among the basic rocks, the ferrodiorites are distinguished by low Si, high Fe, P (due to cumulus apatite), Sr, Ba, and Zr, and negligible Cr. These features are readily ascribed to extensive fractional crystallization of the regional basic magma by essentially ad-cumulus settling of crystals and have previously been noted in the Upper Zone of the Inch Layered Series. Conversely, the granular hypersthene-gabbros are more basic

and modal analyses

13	14	15	16	17	18	19	20	21	No.
IIIb				IIIc					Rock-type
529292	529292	528289	552252	544294	524267	*	548287	529293	Grid Ref. (NJ)
60.60	61.88	63.62	64.74	52.59	53.40	55.14	55.38	56.82	SiO ₂
1.19	0.81	0.90	0.78	1.38	1.61	1.48	1.22	1.23	TiO ₂
16.24	18.50	19.19	16.37	19.64	18.12	18.33	17.85	16.05	Al ₂ O ₃
1.63	1.49	2.06	1.20	1.41	1.56	2.21	1.12	1.08	Fe ₂ O ₃
6.23	4.34	3.51	3.91	7.00	7.15	7.24	6.47	6.73	FeO
0.14	0.12	0.11	0.07	0.15	0.16	0.17	0.14	0.14	MnO
1.74	1.23	1.29	1.68	4.97	4.77	2.83	4.59	4.92	MgO
4.13	3.18	1.55	3.63	6.32	8.10	6.06	6.94	7.48	CaO
3.16	3.02	2.97	2.82	2.87	2.97	3.34	2.83	2.38	Na ₂ O
2.72	4.34	3.33	2.82	1.81	1.37	2.25	1.97	1.53	K ₂ O
0.61	0.42	0.41	0.49	0.51	0.41	0.08	0.54	0.52	P ₂ O ₅
1.01	0.86	1.21	1.31	1.43	1.03	1.02	1.27	1.15	H ₂ O
99.40	100.19	100.15	99.82	100.08	100.65	100.15	100.32	100.03	Total
<i>C.I.P.W. norms</i>									
18.27	17.68	28.06	26.35	4.97	3.87	6.12	7.16	11.78	Q
2.05	4.06	9.58	3.25	2.67	—	—	—	—	Co
16.07	25.65	19.68	16.66	10.81	8.10	13.30	11.64	9.04	Or
26.74	25.55	25.13	23.86	24.29	25.13	28.26	23.95	20.14	Ab
16.50	13.03	5.01	14.81	28.02	32.06	28.38	30.18	28.59	An
—	—	—	—	—	5.82	0.97	0.59	4.74	Di
12.72	8.69	6.48	9.22	22.07	18.96	15.90	20.34	19.62	Hy
—	—	—	—	—	—	—	—	—	Ol
2.36	2.16	2.99	1.74	2.04	2.26	3.20	1.62	1.57	Mt
2.26	1.54	1.71	1.48	1.48	3.06	2.81	2.32	2.34	Il
1.33	0.92	0.90	1.07	1.07	0.35	0.18	1.18	0.92	Ap
61.1	68.9	72.9	66.9	40.1	37.1	47.7	42.8	41.0	D.I.†
<i>Modes</i>									
22.7	24.8	26.7	38.1	6.1	10.0	—	12.6	19.0	Qtz
—	26.3	24.2	1.1	—	1.7	—	1.5	0.3	Alk. feldspar
48.7	32.2	31.3	42.2	49.3	49.4	—	43.9	45.6	Plag
—	—	—	—	—	3.0	—	0.3	—	Cpx
—	—	—	—	—	0.7	—	—	—	Opx
22.5	10.6	3.9	16.6	20.3	18.4	—	21.0	21.6	Biotite
4.2	6.2	tr	1.1	23.7	15.5	—	20.5	12.7	Hornblende
0.6	—	—	—	0.5	1.1	—	0.2	0.9	Accessories
<i>Trace elements (ppm)</i>									
129	83	83	—	209	273	—	196	231	V
8	—	9	—	24	42	—	63	131	Cr
4	—	—	—	13	9	—	8	18	Ni
133	138	165	—	89	93	—	96	77	Rb
303	256	204	—	337	320	—	314	331	Sr
10	10	10	—	12	9	—	17	11	Y
509	841	312	—	216	176	—	167	176	Zr
918	2109	810	—	603	515	—	783	549	Ba

1973); 11, Diorite Xenolith and 19, Quartz-diorite (Sadashivaiah, 1954). Major elements were determined by wet chemistry, trace elements by XRF. (Analyst: M. T. Busrewil.) † Differentiation index (Thornton-Tuttle).

in character, being high in Mg, Ca, and Cr and low in alkalis, Rb, Ba, and Zr. As a consequence, the hypersthene-gabbros fit the linear trends more closely than either the ferrodiorites or the quartz-biotite-norites.

However, the uniform trends shown by the inhomogeneous rocks in the variation diagrams cannot be taken as evidence that they formed by mixing between the acid and basic end members any more than they can imply a continuous differentiation series. The latter is ruled out, together with liquid-liquid hybridization, by the

difference in age between the basic rocks and the granites previously noted. At first sight the chemical data would appear to be consistent with a process of reaction between already solidified basic rocks and the grey granite magma as proposed for the generation of dioritic rocks in general by Nockolds (1934). Regarded as such a contamination product the silica and trace-element contents of the tonalites (IIIc) would represent complete digestion by the granite of twice its own mass of basic rock. Even allowing for the selective movement of silica, alkalis, and volatile trace elements,

TABLE II. *Strontium isotope data*

Sample No.	Rock type	Rb/Sr	$^{87}\text{Sr}/^{86}\text{Sr}$	$(^{87}\text{Sr}/^{86}\text{Sr})_0^*$	Sample no.	Rock-type	Rb/Sr	$^{87}\text{Sr}/^{86}\text{Sr}$	$(^{87}\text{Sr}/^{86}\text{Sr})_0^*$	
1 } 2 }	Ia	{ 0.701 1.075	{ 0.7244 0.7314	{ 0.7112 ± 0.0004 0.7112 ± 0.0005	9	IIIa	0.342	0.7165	0.7101 ± 0.0003	
†	Ib	—	—	0.7145 ± 0.0013	13 14 15	IIIb	{ 0.412 0.485 0.760	{ 0.7207 0.7205 0.7289	{ 0.7130 ± 0.0003 0.7114 ± 0.0003 0.7147 ± 0.0004	
R } S } U } V } 75 }	IIa	{ 0.013 0.009 0.018 0.004 0.005	{ 0.7103 0.7079 0.7088 0.7056 0.7094	{ 0.7100 ± 0.0001 0.7078 ± 0.0001 0.7095 ± 0.0001 0.7055 ± 0.0001 0.7093 ± 0.0001	18 20 21		IIIc	{ 0.280 0.269 0.221	{ 0.7144 0.7159 0.7144	{ 0.7091 ± 0.0003 0.7108 ± 0.0003 0.7103 ± 0.0003
‡		IIb	—	—	$0.7109 - 0.7116$			22 23	{ 0.149 0.123	{ 0.7120 0.7111
‡		IIc	—	—	$0.7072 - 0.7114$	1022		{ 0.352	{ 0.7176	0.7109 ± 0.0003

* Initial $^{87}\text{Sr}/^{86}\text{Sr}$ 465 Myr ago. 2σ errors include analytical errors in both $^{87}\text{Sr}/^{86}\text{Sr}$ and Rb/Sr. Rb/Sr ratios determined in Oxford ($\pm 2\%$ 2σ) may differ somewhat from those calculated from Rb and Sr contents in Table I. Grid references for samples not listed in Table I: R (700257), S (665277), U (652272), V (719305), 75 (643282), 22 (527275), 23 (540276), 1022 (542294).

† From Pankhurst (1974).

‡ From Busrewil *et al.* (1973).

which may be transferred in a fluid medium, such an effect is very difficult to envisage except on a local scale, for example, at the margins of the intrusion. The contaminated grey granite (IIIa) and the granodiorite with mafic 'clots' (IIIb) have clearly not achieved the same degree of intimate mixing, despite the fact that in these cases the acid component in the mixing model exceeds the basic component by a factor of two to one. This again requires extreme variation in the degree of digestion on a local scale. On the other hand, there is no evidence that the tonalites are a small-scale marginal phenomenon. Indeed their very uniform chemical composition (Table I) argues against such an interpretation. The xenoliths (IIIa) have higher Si and K, together with lower Fe, than any of the type II basic rocks, which could also be ascribed to local metasomatic effects resulting from immersion in the granite magma; but against this their chemistry matches that of the tonalites very closely—a fact which will be referred to in later discussion.

Thus the remaining chemical evidence from Sr-isotopes and rare-earth-element distribution patterns may be approached with some reservations about the idea that the inhomogeneous rocks represent a sequence of progressive contamination involving the basic igneous rocks of the area.

Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. Sr-isotope analysis proved to be of little use in elucidating the petrogenesis of this suite of rocks, in that the range of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios 465 Myr ago (Table II) is very restricted. The primary reason for this is that the 500 Myr-old basic

rocks, although derived from a presumed upper mantle source region with an $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.703 or less, underwent isotopic exchange with Sr in the Dalradian rocks surrounding the intrusion during crystallization (Pankhurst, 1969). This resulted in the unusually high value of 0.7117 ± 0.0003 in the basic magma by the time the Upper Zone rocks of the Inch mass were formed. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the Boganclogh ferrodiorites confirm their equivalence to the Inch Upper Zone (Busrewil *et al.*, 1973). The values reported here for the hypersthene-gabbros (0.7056 to 0.7100) show a similar but more restricted degree of isotope exchange, which is consistent with their limited degree of chemical differentiation and presumably reflects the more rapid crystallization responsible for their granular textures. Variable contamination is also observed in the quartz-biotite-norites, which were probably derived from part of the regional gabbro magma developing a water-saturated trend of differentiation (Gribble, 1967; Busrewil *et al.*, 1973).

Consequently it is barely possible to distinguish the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the basic rocks 465 Myr ago from those of the granites. In addition, the determination of the latter is subject to rather large errors due to the high Rb/Sr ratios and uncertainty in the age correction. However, it seems that both the grey granite and the granodiorite (IIIb) have initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios somewhat in excess of 0.711, approaching the value of 0.7145 ± 0.0033 for the Kennethmont pink granite (Pankhurst, 1974).

Because of this very small difference between the acid and basic rocks, the intermediate values obtained for the tonalites (0.7089 to 0.7109) cannot be used to distinguish or resolve possible mixing models. On the other hand, such a relatively small range might not be expected if the granites had assimilated appreciable amounts of either quartz-biotite-norite or granular hypersthene-gabbro, both of which would extend the range to lower values. The one diorite xenolith in grey granite matrix (IIIa) that was analysed gives a value in the middle of the observed range for the tonalites (0.7109).

Rare-earth-element distribution. Eight rare-earth elements were determined by mass-spectrometric isotope dilution, using the method described by O'Nions and Clarke (1972). The results are given in Table III and are plotted as distribution patterns in fig. 2.

The granular hypersthene-gabbro (fig. 2a, sample S) has an unfractionated pattern with low overall abundances (four to eight times chondrite) and even a slight light-end depletion (to six times chondrite for cerium). This would be a typical pattern for a primitive tholeiite basalt except for the marked positive europium anomaly (twelve times). Similar anomalies have been observed in the chill zones of the Stillwater and Bushveld intrusions (Frey *et al.*, 1968) and may be due to a slight concentration of plagioclase relative to the respective parent magma composition (unlike the other rare earths, Eu has a divalent state, which readily substitutes for Ca^{2+} in plagioclase). The ferrodiorite (BG 14) has a strongly fractionated pattern with enrichment of the light rare-earths (up to ninety-five times chondrite) relative to the heavy rare-earths (nine times). There is also a marked positive europium anomaly in this rock, consistent with a concentration of cumulus plagioclase (this group of rocks also has the highest Sr content in the complex). There are, however, considerable difficulties in deriving

both the hypersthene-gabbro and the ferrodiorite from a common parent magma solely by crystal fractionation processes. The ten- to-fifteenfold increase in the light-rare-earth contents requires removal of crystals representing at least 95 % of the

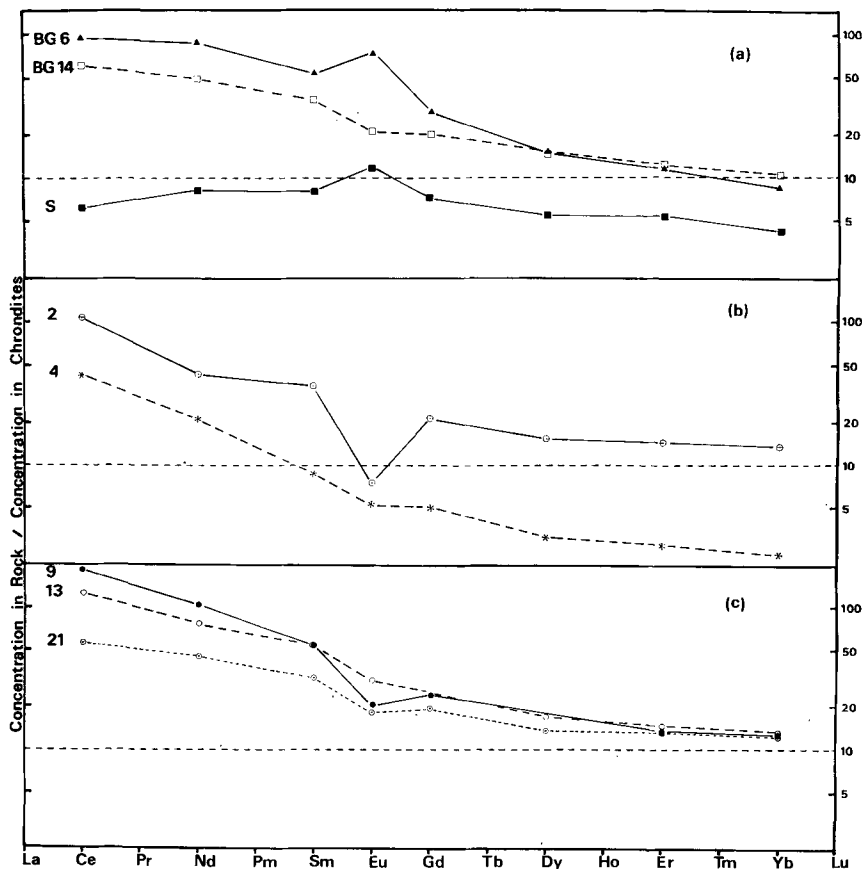


FIG. 2. Chondrite-normalized rare-earth-element distribution patterns for (a) basic rocks, (b) acid rocks, and (c) inhomogeneous rocks. The dotted line in each case is at ten times chondritic abundances. Key as in fig. 1.

original liquid before the ferrodiorite crystallized. Although the observed volume relationships at Inch make this a reasonable possibility, and the K_2O content shows a parallel sixfold enrichment from 0.13 % to 0.87 % for these samples, the removal of large amounts of cumulus plagioclase would significantly reduce the positive Eu anomaly. Differing amounts of partial melting of a common source region would seem to be an equally valid explanation for the differences in rare-earth patterns of these two rocks. This supports the suggestion of Clarke and Wadsworth (1970) that

the granular hypersthene-gabbros are not directly involved in the differentiation of the Inch Layered Series. The quartz-biotite-norite (BG6) also has a relatively fractionated pattern, but without the positive Eu anomaly (in fact a very slight negative one). This could be due to oxidation of Eu to the trivalent state in the water-saturated magma, in which case it would partition between plagioclase and liquid in the same way as the other rare-earth elements.

TABLE III. *Rare-earth-element concentrations*

Sample	Rock-type	Ce	Nd	Sm	Eu	Gd	Dy	Er	Yb
2	Ia	96	26	6.6	0.52	5.3	5.2	2.9	2.7
4	Ib	38	13	1.6	0.37	1.3	1.1	0.56	0.47
S	IIa	5.6	5.0	1.5	0.84	1.8	1.9	1.1	0.84
BG6	IIb	84	52	9.6	5.1	7.3	5.0	2.3	1.7
BG14	IIc	54	29	6.4	1.5	5.0	5.1	2.5	2.1
9	IIIa	160	62	9.9	1.4	6.1	—	2.7	2.6
13	IIIb	110	47	9.5	2.1	6.6	5.9	3.0	2.7
21	IIIc	49	27	5.8	1.3	4.9	4.7	2.7	2.5
Chondritic meteorites*		0.88	0.60	0.181	0.069	0.249	0.34	0.200	0.200

All data in ppm, accuracy $\pm 5\%$ (2σ)

* Mostly from Haskin *et al.* (1966)

Grid references for samples not listed in Table 1: S (665277), BG6 (467292), BG14 (448253). Full chemical analyses of the BG samples appear in Busrewil *et al.* (1973).

The distribution patterns for the acid rocks (fig. 2*b*) are very different. The pink granite has a very unusual pattern, with very depleted heavy-rare-earths (down to twice chondrite); this heavy depletion probably indicates equilibration at some stage with garnet, this being the only common mineral that has a partition coefficient significantly greater than one for the heavy rare-earths (Schnetzler and Philpotts, 1970). Such equilibration could have occurred during the partial melting episode—Sr isotope evidence suggests derivation of the late- and post-tectonic granites of north-east Scotland from a deep crustal layer of Precambrian metamorphic rocks (Bell, 1968; Pankhurst, 1974). This certainly rules out participation of the pink granite in any mixing models since none of the other rocks have low heavy-rare-earth contents. The fractionated pattern of the grey granite is more normal. The distinctive feature here is the large negative europium anomaly, which indicates either removal of plagioclase from the liquid or, more likely, that plagioclase was a stable phase in the source region. The rare-earth patterns provide no evidence for a genetic relationship between these two types of granite.

The inhomogeneous rocks of the complex (fig. 2*c*) all have fractionated rare-earth patterns (up to 150 times chondrite at the light end), with slight negative Eu anomalies. In fact the very high light-rare-earth contents of the diorite xenolith (sample 9) and the granodiorite (sample 13) are difficult to explain on the basis of any mixing model since they exceed the light-rare-earth contents of all the possible homogeneous end

members, both acid and basic. Such models can only be further pursued if it is assumed that there is considerable local variation in abundances within each class and that the concentration data obtained on these few samples are not adequately representative (although the main features of the distribution patterns are unlikely to vary to any great extent). Thus it might be argued that the *average* abundance levels in the grey granite (sample 4) could be rather higher than in the analysed sample. Even if this is supposed to be the case, however, the very large Eu anomaly of this rock-type remains a bar to specific mixing models with this as the acid end-member. Incorporation of small amounts of either granular hypersthene-gabbro or quartz-biotite-norite by the grey granite would result in a mixture that would still have a very substantial negative Eu anomaly—certainly much greater than that shown by the granodiorite or the tonalite. This feature of the grey granite pattern would only be lost by assimilation of much greater volumes of basic rock. As in the case of the major and trace element distribution discussed above, the tonalites would have to represent approximately 1 part grey granite to 2 parts hypersthene-gabbro. This would, however, also reduce the heavy-rare-earth contents of the resulting rocks to below ten times chondritic abundances—an effect that is clearly not supported by the data of fig. 2c. If the basic end member were the quartz-biotite-norite, then the problem of relative proportions is even more severe, since the distribution pattern for this rock type is almost exactly matched by that of the tonalite and both have only small Eu anomalies. The proportion of grey granite allowed in this particular mixture would be impossibly small. Among the basic rocks, only the ferrodiorite, with its high rare-earth contents *and* positive Eu anomaly, can be considered a viable contaminant for the grey granite. Assimilation of as little as 40 % of its own volume of ferrodiorite by a grey granite with a pattern essentially the same as the analysed sample, but with higher over-all abundances as explained above, could account for the observed pattern of the granodiorite. However, extension of this process to produce the tonalites by further assimilation is not possible since they should then have less negative (or even positive) Eu anomalies. Moreover, the diorite xenoliths (IIIa) are certainly not related to the ferrodiorites in terms of rare-earth-element patterns. Objections to the ferrodiorite as an end member can also be made on the grounds of other trace elements (especially Ba).

Finally, it may be noted that the *shape* of the distribution patterns for the diorite xenolith and the tonalite are generally very similar—the only difference being the higher light rare earth contents of the former.

Discussion and conclusions

The chemical evidence presented in this paper virtually excludes the initial precept, based on field observations, that the inhomogeneous rocks of the complex represent a contamination series involving assimilation of any of the homogeneous basic rocks by granite magma. Trace-element contents eliminate the pink granite as a possible acid end-member and the ferrodiorite (or *Insch* ferrogabbro) as a possible basic end-member. The rare-earth-element distribution patterns not only support these

findings, but further eliminate both the granular hypersthene-gabbro and the quartz-biotite-norite from the models. In addition, the amount of assimilation required to achieve the composition of the relatively homogeneous tonalites is extremely high. A more reasonable alternative is to postulate a primary magma of tonalitic composition.

The dioritic xenoliths in undoubted grey granite matrix (IIIa) are chemically unlike any of the homogeneous basic igneous rocks. On the other hand, they are very similar in both major- and trace-element composition to the more homogeneous tonalites (IIIc). They also have comparable initial Sr-isotope ratios and their rare-earth distribution patterns have the same major features except that that of the xenolith is somewhat enriched at the light-element end. It is therefore suggested that such xenoliths are in fact derived from consolidated tonalite but that they are largely unmodified chemically by immersion in the granite matrix. The comparative mineralogy is also in accord with this suggestion. If this is so then the mafic 'clots' in the granodiorite are almost certainly of similar origin. The major-element chemistry of the latter could be interpreted in terms of incorporation of relatively small amounts of tonalite into the grey granite, and this would adequately account for much of the trace-element data as well.

Thus the most probable model for the formation of rocks of the inhomogeneous series is the late (465 Myr ago) intrusion of a dioritic or tonalitic magma, which consolidated and was broken up by the grey granite magma. These two magmas may have been of independent origin although all the chemical evidence presented here would allow high-level differentiation of the tonalite to generate the grey granite, which was then emplaced into early crystallizates. The older basic rocks of the 'younger' gabbro suite were not directly involved in this 'event'.

As stated previously, no genetic association can be found to link the pink granite (Ib) to any of the other rock types. It seems to be the last member of the complex to be intruded, and has been dated at 463 ± 4 Myr.

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