

# Geochemistry of diorites and associated plutonic rocks of SE Jersey, Channel Islands

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## Abstract

The plutonic complex in SE Jersey consists of a late Precambrian gabbro–diorite mass which has been intruded by several granites. The status of the diorites which, like the gabbros, often possess a layered structure, is not clear. New geochemical data, including rare earth and trace element analyses, suggest that acid–basic magma mixing was not responsible for the variety of intermediate rocks. Amphibole-controlled fractional crystallization of hydrous basic magma is also unlikely in view of the *REE* and HFS (high field strength) element distribution. The model which best fits all the available field, petrographic and geochemical evidence is one in which the chemical variation was initially produced by fractional crystallization of anhydrous basic magma and subsequently overprinted by granitic metasomatism. This superimposed calc–alkaline characteristics on the complex and produced hybrid diorites which, because they were above their solidus temperature, recrystallized with textures indicative of a magmatic origin.

KEYWORDS: geochemistry, diorite, Channel Islands.

## Introduction

THE layered diorites of SE Jersey occur in a close and complex association with a layered gabbro and at least two phases of granite which are clearly intrusive towards the basic and intermediate rocks. The origin of the diorites is not clear, but from evidence based on field relationships, petrography and mineral chemistry Bishop and Key (1983) have suggested that they were produced from gabbro by a process of hydrothermal recrystallization and metasomatism caused by the emplacement of the granite, and that the layering is a relict structure inherited from the gabbroic precursor. Topley and Brown (1984) have opposed this view and suggested that the layering is a primary feature produced in magmatic diorite.

Very little of the gabbro remains and petrographically the only remnants of the original mineralogy are pyroxene cores to amphibole crystals and some very rare calcic plagioclase. These rocks have complex textures dominated by replacement minerals, including several generations and species of amphibole together with chlorite, saussurite, epidote, prehnite and calcite. Amphibole is ubiquitous and is the major mafic mineral in both diorite and gabbro. In the latter it is clearly secondary, replacing clinopyroxene, and in

much of the diorite it occurs as large, sieved poikiloblasts of apparently subsolidus origin which overprint the ophitic texture of the gabbro.

Other diorites in the complex, and in particular the coarser grained leucodiorites called appinites (Wells and Bishop, 1955), have a simpler mineralogy consisting mainly of amphibole and sodic plagioclase, and textures with clear grain boundaries characteristic of rocks which have crystallized from a melt. It is the presence of these 'igneous looking' intermediate rocks, some of which are layered, which throws doubt on a completely secondary, metasomatic origin for the diorites.

The problematical origin of some intermediate plutonic rocks is not new. Diorites of Precambrian to Tertiary age are found in a close spatial and temporal relationship with basic and acid plutonic rocks, although genetic relationships between the various members of this 'suite' are commonly obscure or at best tenuous. Field relationships are frequently very complex in detail and often present contradictory evidence. Normally in this association an early basic pluton was intruded by one or more granites, possibly whilst the gabbro was still hot or even incompletely solidified. Intricate contacts between granite and diorite which suggest fluid–fluid interfaces are common.

Intermediate plutonic rocks have been ascribed

to a variety of petrogenetic processes including intrusion of a primary dioritic magma (Busrewil *et al.*, 1975), fractional crystallization of basic magma (Perfit *et al.*, 1980; Snoko *et al.*, 1981; Walsh and Clarke, 1982; Whalen, 1985), liquid immiscibility (Vogel and Wilband, 1977; Bender *et al.*, 1982), and mechanisms which involve mixing and hybridization of acid and basic magmas (Vogel, 1982; Vogel *et al.*, 1984; Whalen and Currie, 1984; Mezger *et al.*, 1985). Nockolds (1934; 1941) employed contamination and reciprocal reaction where a solid basic rock is metasomatically recrystallized by a later fluid granite to the extent that the products attain chemical, mineralogical and possibly textural characteristics intermediate between those of the parent rocks. Bishop and French (1982) invoked this process in their interpretation of the diorites of N Guernsey.

This paper is an extension of previous work on the diorites of SE Jersey (Wells and Bishop, 1955; Bishop, 1963; Key, 1974, 1977, 1985; Bishop and Key, 1983) which concentrated mainly on field relationships and petrography. New geochemical

data, including major, trace and *REE* analyses, are presented and used to put some constraints on the origin of the Jersey diorites in the broad context of the processes referred to above. Published mineral/liquid partitioning data for trace elements are employed to evaluate the rôle of the most abundant constituent, amphibole, in the petrogenesis of these rocks.

### Field relationships

The areal extent of the main rock types is shown in Fig. 1. Diorite and gabbro are grouped together because they cannot easily be distinguished in the field and junctions between the two are almost imperceptibly gradational over a distance of tens of metres. Gabbro, revealed by thin-section petrography, occurs only as isolated patches within the diorite, principally at Le Nez Point, Green Island and Seymour Tower. The age of the gabbro is uncertain, as are its intrusive relationships since these have been obliterated by later granites. The oldest intrusive granite is 580 Ma (Adams, 1976) so

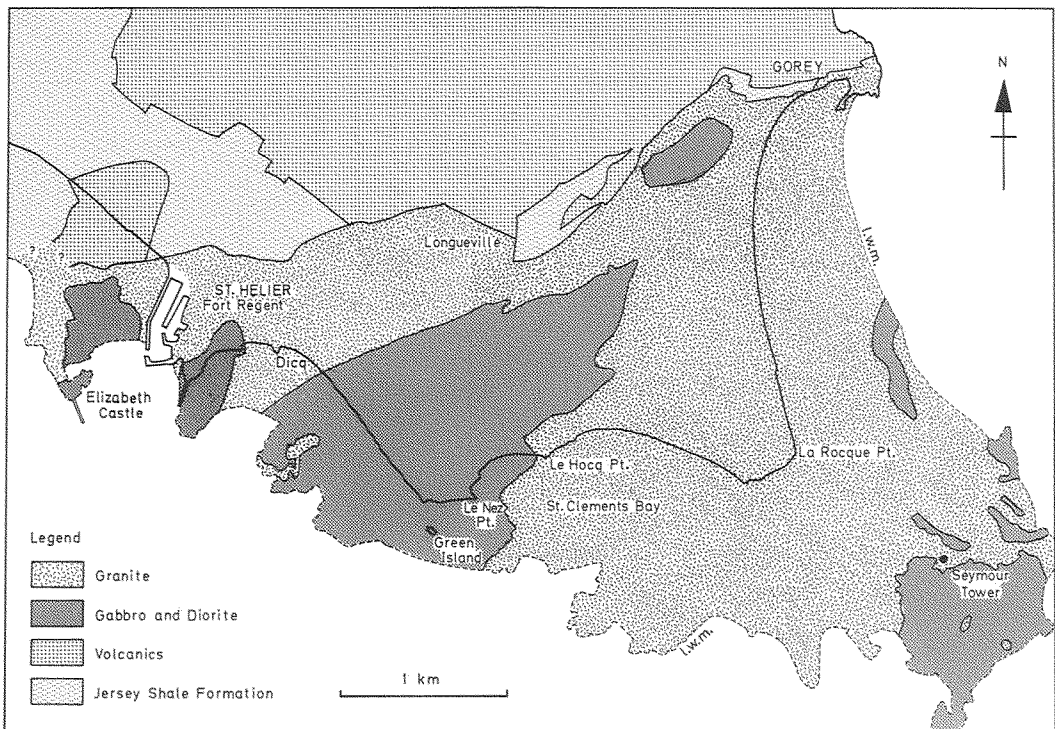


FIG. 1. Geological sketch map of SE Jersey showing the distribution of the major rock types (dykes and other minor intrusions are omitted). Published by permission of the Director, British Geological Survey (Natural Environment Research Council).

it seems likely that the gabbro is late Precambrian (Cadomian) and was emplaced into Brioverian sediments. The fairly limited extent and essentially two-dimensional nature of the exposure reveal little of the overall form of the intrusions, but gravity and magnetic studies (Briden *et al.*, 1982) indicate that a larger basic mass exists to a depth of 3 km just south of Jersey and that the granites occupy a much greater volume than the present outcrop suggests.

The field relationships between the gabbro and the much more voluminous diorite which surrounds it are rather unclear. Hornblende K–Ar ages from the diorites range from 582 to 527 Ma, almost exactly the same spread as the granite ages, implying that they reflect metamorphic events produced by thermal overprinting. There are no sharp contacts between gabbro and diorite to suggest that one intruded the other, and layered structures in gabbro and diorite have the same attitude where the two occur together (Bishop and Key, 1983). The diorites exhibit a wide variation in both texture and modal mineralogy, but the most dominant lithology is a dark, rather fine grained rock which occupies most of the intertidal reefs between Elizabeth Castle and St. Clement's Bay. None of the diorites are petrographically homogeneous; apart from a layered structure defined by slight variations in colour index, there are abundant layers, streaks and pods of coarser grained, often pegmatitic leucodiorite which has been termed appinite (Wells and Bishop, 1955; Key, 1977). These appinites, which are characterised by euhedral prismatic amphiboles, have a completely random distribution but occur only within diorite where they can often be seen to truncate layering.

The diorites are completely surrounded by granite and are not seen in intrusive contact with any other rocks except a younger dyke swarm which is not shown in Fig. 1. These dykes, which from field evidence can be seen to overlap in age with the sequence of granite intrusions, range in composition from dolerite through lamprophyre to microgranite. Composite dykes which have centres of porphyritic microgranite and margins of dolerite, and in which there is clear evidence of co-mingling, suggest simultaneous availability of both acid and basic magmas.

On the basis of whole-rock Rb–Sr dating Adams (1976) has distinguished between 'older' and 'younger' phases of granite intrusion. The Dicq and Longueville granites give a rather imprecise isochron at about 580 Ma which sets an upper age limit for the gabbro and diorite, while the Fort Regent granophyre and Le Hocq granite are dated at  $520 \pm 4$  Ma. Although there are petrographic differences between these granites there are no field

relationships which show one type intruding the other.

Granite does not occur in direct contact with gabbro, the two always being separated by a zone of diorite towards which the granite is clearly intrusive. The Dicq granite has both sharp and gradational junctions with diorite. The sharp contacts are intricate with a crenulate style indicative of a fluid–fluid relationship (Blake *et al.*, 1965). The gradational junctions exist where diorite contains abundant quartz and K-feldspar and the granite has digested fragments of diorite. This contaminated granite, which has a higher colour index and composition approaching granodiorite, is characterised by the presence of K-feldspar megacrysts mantled by oligoclase.

The commonest type of granite–diorite contact is more consistent with a very fluid acid magma having been injected into brittle diorite. The resulting net-vein breccia has sharp, angular contacts with no obvious effects of reaction between the light and dark rocks. Neither of these two contrasting styles of junction is exclusive to either the 'older' or 'younger' granites. At Elizabeth Castle the Fort Regent granophyre shows both fluid–fluid and brittle fracture contacts with diorite within a distance of a few metres.

These broad aspects of the field relationships, together with petrographic evidence, have been interpreted as resulting from a layered gabbro which was subsequently intruded by several granite pulses which caused hydrothermal, metasomatic recrystallization (Bishop and Key, 1983). The products were diorites which inherited a layered structure from the parental gabbro. In places the diorites attained temperatures above their solidus, due partly to the thermal effects of the granites and possibly aided by residual heat from the gabbro, so that some of these metasomatic rocks eventually developed igneous textures.

Other possible interpretations of these relationships which have not yet been tested are: (i) that the main rock types are separate, unrelated intrusions, implying that the diorite was intruded as a magma; (ii) that the diorites, and possibly even the granitoids, were derived from a basic parental magma by fractional crystallization, either *in situ* or from an unseen source at depth; (iii) that intrusion of granite magma into an incompletely solidified gabbroic magma chamber produced hybrid diorite by magma mixing.

### Petrography

Petrographic detail of some of the members of this complex are given elsewhere (Wells and Bishop, 1955; Bishop, 1963; Key, 1974, 1977, 1985;

Table 1. Major element (wt.% oxides) and trace element (ppm) abundances in gabbros, diorites, appinites and granitoids from SE Jersey

	GB1	GB2	GB3	GB4	GB5	GB6	GB7	GB8	GB9	GB10	GB11	GB12	D1	D2	D3	D4	D5	D6	D7
SiO <sub>2</sub>	49.45	49.47	48.66	49.27	49.88	50.18	50.72	49.51	50.75	50.57	49.96	49.31	54.54	54.36	54.24	51.78	54.04	53.15	51.21
TiO <sub>2</sub>	0.80	0.84	0.88	0.66	0.70	0.96	0.91	0.89	0.72	0.66	0.57	0.95	1.08	1.04	1.06	0.97	1.21	1.04	0.96
Al <sub>2</sub> O <sub>3</sub>	13.81	17.21	14.29	16.89	16.75	15.21	16.41	15.30	16.67	18.11	17.81	16.56	18.77	18.71	19.11	19.62	18.43	17.74	16.31
FeO*	9.90	9.29	10.49	7.91	6.65	9.13	8.40	8.37	8.26	6.57	6.96	7.72	8.41	8.91	8.61	8.86	9.13	8.03	9.64
MnO	0.16	0.15	0.18	0.16	0.14	0.16	0.18	0.16	0.20	0.18	0.20	0.20	0.17	0.15	0.15	0.16	0.16	0.16	0.17
MgO	14.70	10.85	12.57	8.36	7.98	7.83	7.85	9.29	8.11	7.44	7.53	7.50	4.33	4.58	4.26	5.27	3.91	5.34	7.59
CaO	7.69	8.16	8.92	13.59	14.65	13.48	11.82	13.18	11.90	12.92	13.32	13.87	6.94	6.79	7.13	7.62	7.16	8.76	10.04
Na <sub>2</sub> O	1.96	2.22	1.77	1.71	1.92	1.85	2.18	1.74	2.13	2.30	2.11	2.14	3.34	3.02	3.47	3.18	3.30	3.64	2.58
K <sub>2</sub> O	0.88	1.45	1.19	1.04	1.07	1.23	1.36	1.17	1.31	0.93	1.24	1.02	1.77	1.86	1.73	1.98	1.78	1.20	1.07
P <sub>2</sub> O <sub>5</sub>	0.18	0.17	0.17	0.13	0.16	0.17	0.19	0.19	0.16	0.18	0.15	0.18	0.29	0.21	0.22	0.21	0.25	0.22	0.19
<b>Total:</b>	<b>99.53</b>	<b>99.81</b>	<b>99.12</b>	<b>99.72</b>	<b>99.90</b>	<b>100.20</b>	<b>100.02</b>	<b>100.80</b>	<b>100.21</b>	<b>99.86</b>	<b>99.85</b>	<b>99.45</b>	<b>99.64</b>	<b>99.63</b>	<b>99.98</b>	<b>99.65</b>	<b>99.37</b>	<b>99.28</b>	<b>99.76</b>
Ba	195	355	341	235	248	264	315	267	274	252	430	323	464	486	454	446	453	286	360
Co	54	49	53	41	34	44	40	44	47	35	36	33	31	33	30	35	30	32	39
Cr	366	285	350	68	56	51	79	53	57	142	95	101	48	59	52	76	42	112	169
Li	33	22	22	29	22	15	25	19	25	25	22	18	30	28	28	30	25	15	21
Nb	2	4	3	2	1	2	7	3	7	10	8	1	26	17	18	18	19	13	4
Ni	234	161	189	74	70	57	59	63	46	78	75	59	27	29	26	33	25	42	93
Sc	25	26	26	44	47	47	48	59	39	40	37	46	25	23	23	21	26	31	28
Sr	284	377	327	429	488	432	507	368	502	510	470	433	499	489	468	476	469	454	419
V	179	192	187	217	237	314	262	339	209	177	182	217	212	198	197	199	223	214	196
Y	18	20	19	14	14	17	18	26	16	17	13	20	38	25	26	21	27	25	23
Zn	197	162	177	137	126	132	146	148	139	124	128	122	107	109	102	114	103	114	135
Zr	70	77	68	35	34	43	51	65	59	55	51	51	135	84	80	80	97	90	95
	DB	D9	D10	D11	D12	A1	A2	A3	A4	A5	A6	A7	GR1	GR2	GR3	GR4	GR5	GR6	GR7
SiO <sub>2</sub>	50.65	50.45	52.73	53.11	51.67	58.88	59.02	56.46	56.82	57.30	59.34	58.05	70.89	76.81	66.66	71.47	75.96	75.45	75.58
TiO <sub>2</sub>	1.08	0.87	1.11	0.62	0.89	1.14	1.20	1.13	1.09	1.26	1.19	1.28	0.44	0.06	0.57	0.35	0.14	0.15	0.15
Al <sub>2</sub> O <sub>3</sub>	16.42	16.54	15.57	17.80	16.29	17.54	18.81	18.28	18.19	18.94	17.97	17.11	15.29	13.65	16.72	15.74	12.74	12.89	12.72
FeO*	10.66	8.33	9.78	7.08	8.54	7.63	7.21	8.23	8.63	7.95	7.23	6.65	2.75	1.11	3.96	2.57	1.40	1.67	1.76
MnO	0.18	0.15	0.15	0.18	0.20	0.13	0.13	0.14	0.15	0.14	0.13	0.14	0.04	0.02	0.07	0.04	0.02	0.02	0.02
MgO	6.21	7.57	5.65	6.70	6.81	3.11	2.51	3.08	3.63	2.39	2.64	3.16	0.56	0.01	1.29	0.36	0.23	0.21	0.22
CaO	11.15	12.40	10.92	11.30	11.27	5.96	4.82	6.47	6.87	6.71	5.68	7.91	1.38	0.40	2.70	1.43	0.88	0.90	0.77
Na <sub>2</sub> O	2.43	2.25	2.76	2.75	2.53	3.44	3.82	3.87	3.16	4.01	3.81	3.95	3.61	3.01	2.96	3.58	3.68	3.87	3.95
K <sub>2</sub> O	1.05	1.09	1.26	1.24	1.31	1.67	1.91	1.52	1.86	1.60	2.20	1.57	4.52	4.42	4.66	3.24	4.70	4.57	4.52
P <sub>2</sub> O <sub>5</sub>	0.20	0.21	0.21	0.17	0.22	0.28	0.41	0.22	0.24	0.48	0.28	0.32	0.11	0.03	0.17	0.10	0.07	0.07	0.07
<b>Total:</b>	<b>100.03</b>	<b>99.86</b>	<b>100.14</b>	<b>100.95</b>	<b>99.73</b>	<b>99.78</b>	<b>99.84</b>	<b>99.40</b>	<b>100.64</b>	<b>100.78</b>	<b>100.47</b>	<b>100.14</b>	<b>99.59</b>	<b>99.64</b>	<b>99.36</b>	<b>98.88</b>	<b>99.82</b>	<b>99.80</b>	<b>99.76</b>
Ba	248	222	282	292	330	411	451	395	453	587	607	424	758	271	500	486	580	473	264
Co	41	39	41	34	38	24	22	24	22	20	21	26	10	4	13	8	5	6	3
Cr	42	95	54	111	59	73	96	40	36	53	40	44	8	2	70	17	8	10	14
Li	19	29	14	25	19	25	23	18	19	22	26	14	15	10	11	32	12	11	14
Nb	6	7	9	10	12	18	25	18	1	33	20	18	28	16	16	16	20	25	21
Ni	50	72	44	65	50	24	22	21	20	21	20	25	16	9	27	11	8	11	9
Sc	31	45	30	37	33	22	20	26	18	20	21	21	8	3	6	5	4	7	6
Sr	471	452	446	559	496	534	484	459	395	624	535	564	239	60	439	92	124	150	192
V	312	257	292	196	184	137	97	209	144	76	136	134	23	2	69	17	20	18	25
Y	21	20	21	16	22	25	28	29	21	35	28	33	28	8	10	29	14	20	23
Zn	125	132	115	125	121	87	82	92	79	85	84	86	35	22	44	48	24	36	49
Zr	66	61	63	76	109	121	165	102	111	176	134	283	329	85	265	205	112	127	94

\*Total Fe as FeO.

Sample numbers: GB = gabbro, D = diorite, A = appinite, GR = granitoids.

Analyst: C H Key

Bishop and Key, 1983). Only the most salient features which are important in the geochemical interpretation are given here.

**Gabbro.** The distinction between gabbro and diorite is based on both geochemical and petrographic criteria. Gabbros are those rocks in which  $\text{SiO}_2 < 51.0$  wt.%; previous analytical data (Bishop and Key, 1983; Table 3) which distinguished between ferrous and ferric iron, also showed that these rocks have a significantly lower  $\text{Fe}^{3+}/\text{Fe}^{2+}$  ratio than the diorites, suggesting that recrystallization was accompanied by oxidation. The freshest gabbros contain clinopyroxene ( $\text{en}_{40}\text{wo}_{49}\text{fs}_{11}$ ) and plagioclase ( $\text{An}_{64}$ ) in a simple ophitic relationship with lath-shaped plagioclase producing an igneous lamination parallel to the modal layering. Fe-Ti oxides and apatite occur as minor accessories. All the gabbros are altered, often to the extent that the primary mineralogy has been completely replaced. Plagioclase is saussuritized and pyroxene is progressively replaced by amphibole. The latter is most commonly green magnesiohornblende and brown pargasitic hornblende, but actinolite and cummingtonite also occur as replacements and overgrowths to hornblende. In the most basic gabbros thin layers and clots rich in chlorite and fibrous amphibole probably represent alteration products of olivine-rich segregations since many of the gabbros have a high normative olivine content (Bishop and Key, 1983).

**Diorites.** Adjacent to the outcrops of gabbro the diorites have very complex textures and mineral assemblages. An apparently relict ophitic texture persists between saussuritized plagioclase and amphibole, but the plagioclase has partially recrystallized to give fresh, clear rims of oligoclase, and pargasitic hornblende forms large sieved poikiloblasts which progressively overprint the ophitic texture. Skeletal Fe-Ti oxides are replaced by sphene and leucoxene, and other common accessories include cummingtonite, actinolite, chlorite, epidote and calcite.

The more uniform, even-grained diorites which show evidence of fluidity possess a simpler mineralogy and more obviously igneous texture. Green and brown hornblende form euhedral, subhedral to euhedral grains and fresh interstitial plagioclase is oligoclase to andesine in composition. Small disseminated grains and spicules of Fe-Ti oxides are the commonest accessory.

The appinites are more leucocratic than the average diorites and are characterised by hollow-shell, prismatic crystals of deep brown Ti-rich pargasite or kaersutite in a matrix of oligoclase with minor amounts of biotite, quartz and K-feldspar.

**Granites.** The granitoids are mainly alkali leucogranites which show a wide variation in grain size

and texture. The micrographic texture of the Fort Regent granophyre and megacrystic, rapakivi texture of the Dicq granite make these types easily distinguishable. The Longueville and Le Hocq granites are more variable and include syenitic and adamellitic types with aplitic and rarer pegmatitic facies. Feldspar assemblages range from two-feldspar types containing oligoclase and orthoclase to essentially one-feldspar granites with perthitic alkali feldspar showing weakly developed microcline twinning. Clouding and recrystallization of feldspars together with widely varying structural states in K-feldspars are probably due to reheating by subsequent phases of granite intrusion. Mafic minerals are rare, but the Dicq granite, especially where it is in contact with diorite, has abundant green hornblende and biotite and is relatively depleted in K-feldspar giving a composition approaching granodiorite.

### Geochemistry

Samples were carefully selected on petrographic criteria to ensure that a complete range of compositions was obtained. Major and trace element analyses (by inductively coupled plasma source spectrometry) are given in Table 1, and REE analyses (by instrumental neutron activation) for eight of the samples are given in Table 2. Graphical presentation of data in Figs. 2 and 3 shows oxides (wt.%) and trace elements (ppm) plotted against the Larsen Differentiation Index ( $\frac{2}{3}\text{SiO}_2 + \text{K}_2\text{O} - [\text{FeO} + \text{MgO} + \text{CaO}]$ ). The good correlation between  $\text{SiO}_2$  and D.I. results in very similar patterns when the same data are plotted on Harker type diagrams.

Table 2. Rare Earth element abundances (ppm)

	D1	GB1	GR2	A6	GR3	GB5	GB11	D10
La	22.6	11.0	24.6	21.4	34.3	7.1	9.5	13.4
Ce	49.6	21.5	38.9	41.7	50.7	12.9	17.1	28.5
Nd	29.3	13.7	9.3	22.5	16.0	6.8	7.9	14.7
Sm	6.40	2.83	1.58	4.77	2.32	1.81	1.93	3.40
Eu	1.73	1.12	0.20	1.54	0.93	0.76	0.64	1.25
Gd	4.7	2.0	<2	4.4	<2	<2	<2	3.1
Tb	0.80	0.34	0.20	0.58	0.25	0.24	0.25	0.51
Tm	0.52	0.23	0.19	0.37	0.18	0.15	0.11	0.22
Yb	3.4	1.5	0.95	2.4	1.1	0.95	1.0	1.5
Lu	0.53	0.19	0.16	0.32	0.18	0.13	0.16	0.24
Eu/Eu*	0.93	1.38	0.40	1.02	1.31	1.32	1.05	1.17
$\text{La}_N/\text{Yb}_N$	4.3	4.7	16.7	5.8	20.2	4.8	6.1	5.8

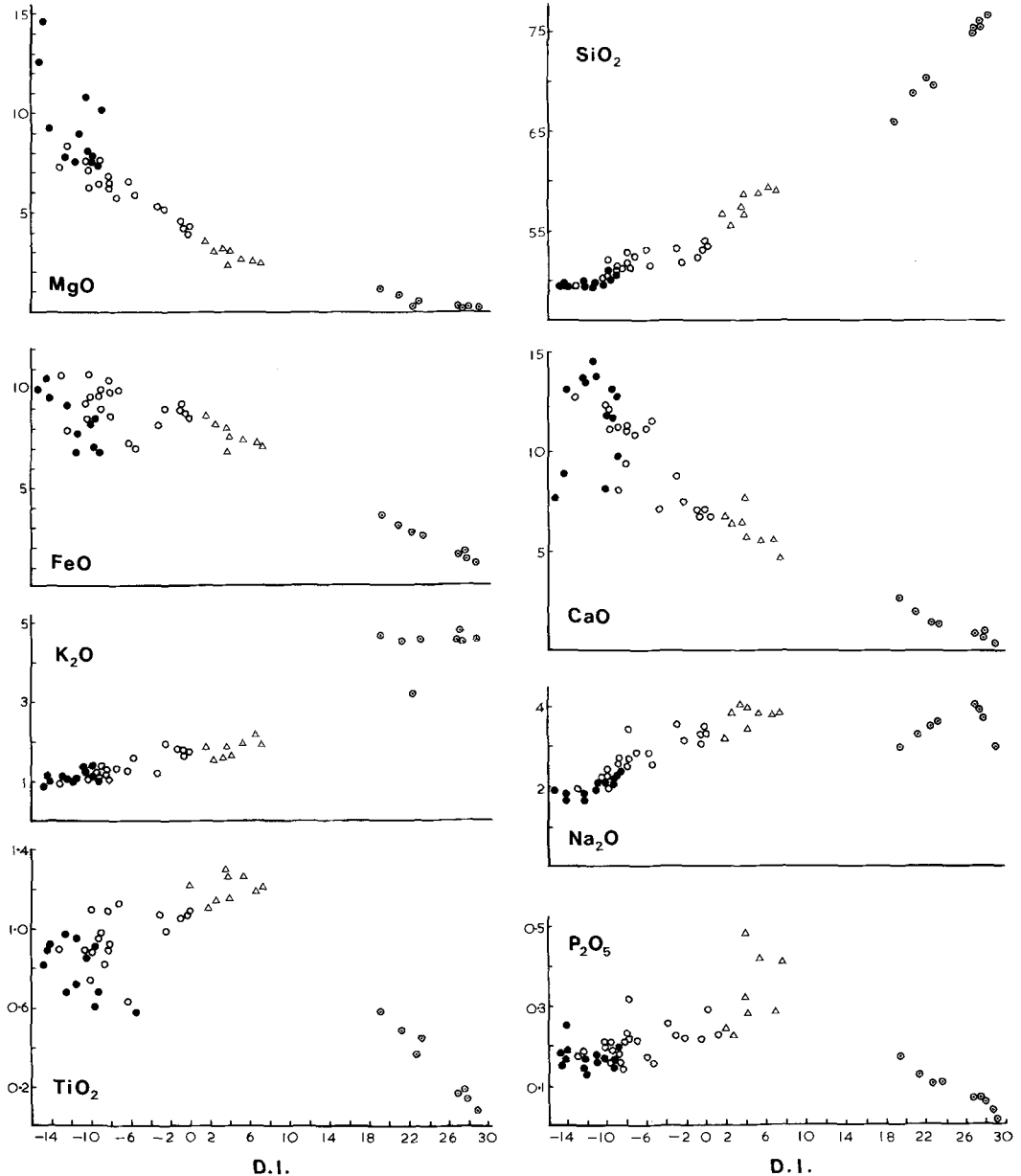


FIG. 2. Major elements (wt. % oxides) plotted against differentiation index (D.I.)  $\frac{1}{3}\text{SiO}_2 + \text{K}_2\text{O} - [\text{FeO} + \text{MgO} + \text{CaO}]$ . Gabbros—filled circles, diorites—open circles, appinites—triangles, granitoids—circled dots.

*Major elements.* With increasing D.I. there is an increase in  $\text{SiO}_2$ ,  $\text{K}_2\text{O}$  and  $\text{Na}_2\text{O}$  balanced by a decrease in  $\text{MgO}$ ,  $\text{FeO}$  and  $\text{CaO}$ . With the exception of  $\text{Na}_2\text{O}$ , which has similar values in the appinites and granitoids, these trends are smooth and near linear throughout most of the range. The

greater spread of plots in the most basic compositions is consistent with these gabbros being cumulates which display a degree of crystal sorting, but the extensive recrystallization makes this impossible to prove from modal mineralogy. The appinites form a separate, although not distinct,

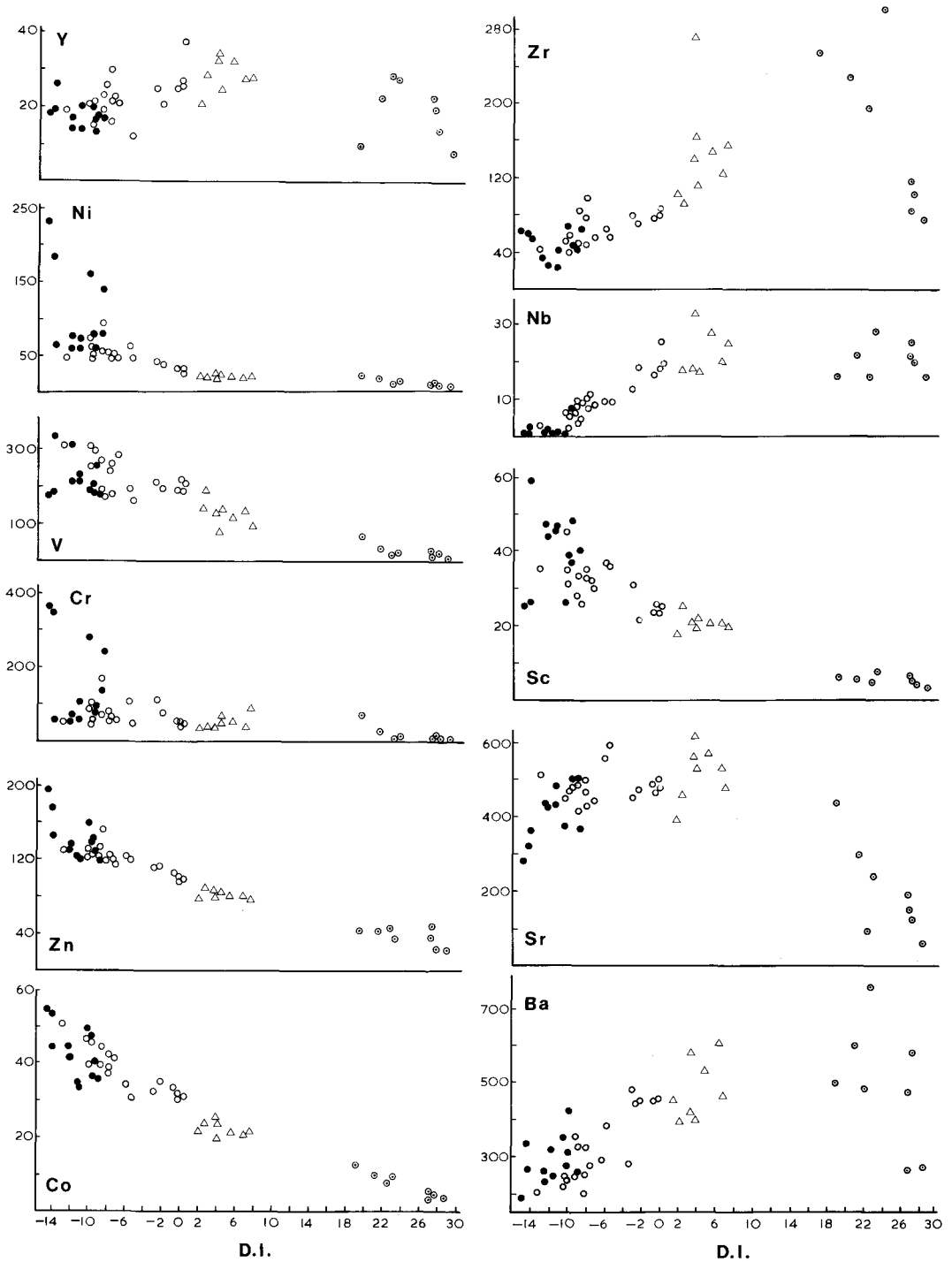


FIG. 3. Trace elements (ppm) plotted against differentiation index (D.I.). Symbols as in Fig. 2.

group intermediate between the gabbros and diorites. A distinct compositional gap in the region 59–66 wt. %  $\text{SiO}_2$  and D.I. 7–19 probably represents a real absence of rocks in this compositional range.

On an AFM diagram (Fig. 4) the gabbros, diorites and appinites plot as three separate but continuous groups, and although the compositional gap between appinites and granitoids is still evident, the diorite to granite sequence is typically calc-alkaline. The relative MgO enrichment of the gabbros and broader scatter of data points compared to a volcanic suite is in accord with other calc-alkaline plutonic associations in which the more basic members represent cumulates rather than liquids (Atherton *et al.*, 1979; Perfit *et al.*, 1980; Snoke *et al.*, 1981; Fourcade and Allegre, 1981).

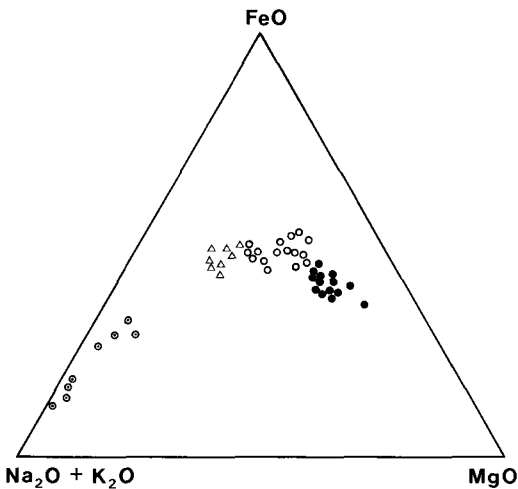


FIG. 4. AFM plot of gabbros, diorites, appinites and granitoids from SE Jersey (F = total Fe as FeO). Symbols as in Fig. 2.

$\text{TiO}_2$  and  $\text{P}_2\text{O}_5$  both show similar trends which differ markedly from other oxides in that they initially increase with increasing D.I. to a maximum in the appinites and then become depleted in the granitoids. Although this type of pattern is common in rock suites produced by anhydrous fractional crystallization of basic magma controlled by  $\text{cpx} + \text{plag} \pm \text{ol}$  removal, it is inconsistent, at least for  $\text{TiO}_2$ , in a rock series in which amphibole is a major component. If the even-grained diorites and appinites approximate to liquid compositions, their rock and mineral chemistry (Bishop and Key, 1983) suggest a distribution coefficient  $D[\text{Ti}]_{\text{amph/liq}} \approx 3.0\text{--}5.5$ , which is in the range of

other published values (Pearce and Norry, 1979; Villemant *et al.*, 1981). This much more compatible nature of Ti in a hydrated system makes derivation of appinitic liquids from a diorite magma implausible if, as textural evidence suggests, amphibole was the main liquidus phase. Brown *et al.* (1980) have shown that amphibole-controlled fractionation can be used to explain the geochemical variation in the diorites and associated rocks of Chouet, NW Guernsey, and that  $\text{TiO}_2$  decreases progressively with increasing  $\text{SiO}_2$ .

Although most of the major oxides show near linear trends, the highest values of  $\text{TiO}_2$  and  $\text{P}_2\text{O}_5$  in the intermediate compositions also argues strongly against an origin for these rocks by acid-basic magma mixing. Both elements have a high field strength (HFS) as a result of their high charge/radius ratio, and are considered to be relatively immobile (Pearce and Norry, 1979). It is difficult, therefore, to envisage any process which could enrich the products of mixing in elements in which the parental liquids were deficient. Where magma mixing has been established, for example in the Marscoite suite of Skye (Vogel *et al.*, 1984),  $\text{TiO}_2$  and  $\text{P}_2\text{O}_5$  show a simple linear variation consistent with that process. However, Vogel (1982) has also suggested magma mixing to account for the net-vein complex of Ardnamurchan in which  $\text{TiO}_2$  and  $\text{P}_2\text{O}_5$  do have maximum concentrations in the intermediate compositions. Marshall and Sparks (1984) explained this apparent anomaly by suggesting that fractional crystallization was initially responsible for producing the chemical variation, followed by more limited magma mixing in a compositionally zoned magma chamber.

The major element chemistry of the Jersey rocks provides neither conclusive proof nor rejection of either a magma mixing or fractional crystallization model for the observed compositional variation, but  $\text{TiO}_2$  distribution implies invariability of amphibole-controlled fractionation. Corroborative evidence for this comes from the amphibole compositions which show progressively higher-temperature chemical characteristics (increasing Ti, Na and Aliv) with increasing D.I. in presumably more 'evolved' rocks (Bishop and Key, 1983).

*Trace elements.* The transition metals Sc, V, Cr, Co, Ni and Zn all behave in a similar way in showing a progressive decrease with increasing D.I. Although there is a greater spread of data points in the most basic compositions, these trends are near linear except for Ni and Cr for which four of the gabbros show considerably higher values. These rocks are intensively altered to chlorite and fibrous amphibole and their high Ni and Cr contents, combined with high MgO, almost certainly results from original olivine- and clinopyroxene-rich



lithologies. The relative rates of decrease in the transition metals is roughly in accordance with the octahedral site preference energy (OSPE) for their most likely valence states (Henderson, 1982; Walsh and Clarke, 1982), a feature consistent with variation produced by fractional crystallization.

As with Ti and P, the other HFS elements Y, Zr and Nb all increase with D.I. to a maximum in the appinites and then become depleted in the granitoids, although for Zr the Fort Regent granophyre and the three contaminated granodiorites have values similar to the appinites. Mineral/liquid distribution coefficients for these elements are relatively sparse, but from the data collected by Pearce and Norry (1979) it is clear that  $D[X]_{\text{amph/liq}} > D[X]_{\text{cpx/liq}}$  for Y, Zr and Nb, and that for each of these elements  $D[X]_{\text{amph/liq}}$  increases markedly with increasing  $\text{SiO}_2$  from values close to unity at 50 wt. %  $\text{SiO}_2$ . Whilst this makes plausible the derivation of diorite from more basic liquids by cpx + plag removal, and possibly even acid derivatives by subsequent amph + plag fractionation, it cannot account for the increasingly incompatible behaviour of Y, Zr and Nb in the diorite to appinite range if amphibole was a primary mineral.

The possibility that amphibole was not a primary cumulus phase is strengthened by the lack of correlation between modal amphibole and Zr

content. Since  $D[\text{Zr}]_{\text{amph/liq}} \approx 1$  for intermediate compositions, and is much higher than for any other major mineral in these rocks, the whole-rock Zr content should correlate reasonably well with the amount of primary amphibole. Fig. 5 is a plot of volume % amphibole against Zr for eleven diorites and appinites which have similar values of D.I., and also two rocks which are chemically gabbros but which contain a very high proportion of amphibole. The diorites, which all come from a similar horizon in the layered sequence at Le Nez Point, do not show any correlation between Zr (52–135 ppm) and amphibole content (36–61 vol. %). The three appinites, which are closely associated with these diorites, have higher Zr values (134–283 ppm) but contain less amphibole (11–23 vol. %). The two amphibole-rich gabbros have Zr values as low as the diorites, producing a very weak negative correlation overall between Zr and modal amphibole. Even allowing for the fact that these rocks might represent orthocumulates in which some of the amphibole crystallized from interstitial liquid, a better positive correlation between total modal amphibole and Zr could be expected. The alternatives are that either the gabbro–diorite–appinite sequence is not genetically related by fractional crystallization, or that the fractionation process was controlled by minerals other than amphibole which must, therefore, have a secondary origin.

The possibility of the diorites and appinites having been produced by magma mixing seems unlikely from the distribution patterns of Y, Zr and Nb for the same reason as that advanced in relation to Ti and P distribution; their immobility resulting from HFS characteristics precludes secondary concentration of these elements in the products of magma mixing.

Of the remaining trace elements, Ba and Sr show a greater spread of values, especially in the granitoid rocks, but their overall pattern is similar to the HFS elements with some of the highest contents in the appinites. Ferry (1985) has shown that Sr underwent considerable migration during hydrothermal alteration of the Skye gabbros, and in the Jersey rocks both Sr and Ba were probably highly mobile where plagioclase suffered extensive recrystallization. Li variation, which is not plotted in Fig. 3, is extremely random but may in part be due to low values (12–33 ppm) and analytical error with the method used.

*Rare earth elements.* Chondrite-normalised REE patterns for eight of the samples are shown on the conventional Masuda-Coryell diagram (Fig. 6). Total REE concentrations are fairly low (37–135 ppm) but show an overall increase with increasing D.I. (Fig. 7), although the granitoids have total REE similar to the diorites and appinites.

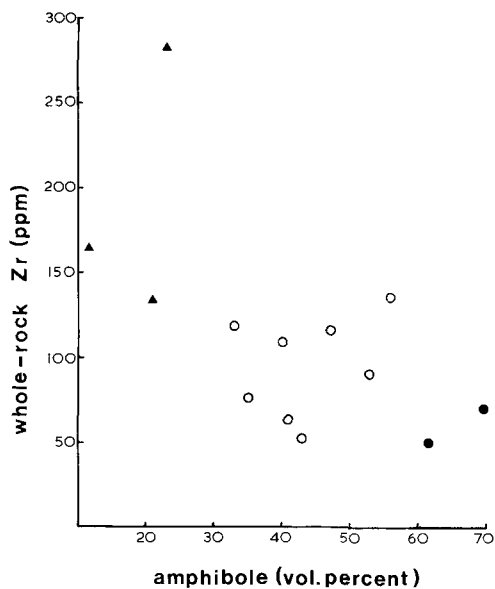


FIG. 5. Modal amphibole (vol. %) plotted against whole-rock Zr (ppm) for selected gabbros, diorites and appinites. Symbols as in Fig. 2.

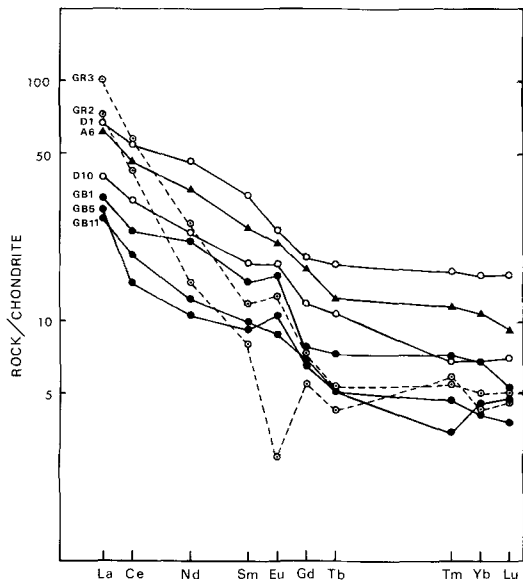


FIG. 6. Chondrite-normalised *REE* abundances in selected gabbros, diorites, appinite and granitoids. Normalising values from Wakita *et al.*, (1971). Symbols as in Fig. 2.

Gabbros, diorites and appinites have very similar patterns with a relatively low *LREE* enrichment ( $La_N/Yb_N = 4-6$ ). Two of the gabbros and one diorite possess positive Eu anomalies ( $Eu/Eu^* = 1.17-1.38$ ) consistent with these rocks being cumulates.

The two granitoids differ from the other rocks in showing much stronger *LREE* enrichment ( $La_N/Yb_N = 16-20$ ), and have almost parallel patterns except for Eu. The Le Hocq granite (GR2) has a marked negative Eu anomaly ( $Eu/Eu^* = 0.4$ ) which tentatively implies that plagioclase fractionation might have been involved in its formation, whilst the positive Eu anomaly in the granodiorite may be due to contamination by a plagioclase rich gabbroic cumulate.

The very close similarity in *REE* patterns of gabbros, diorites and appinites strongly suggests some genetic relationship between them, and also puts some constraints on the possible mechanisms involved. The increase in total *REE* from gabbro to diorite is consistent with fractional crystallization controlled by  $cpx + plag \pm ol$  removal because the distribution coefficient  $D[REE]_{min/liq}$  is much less than unity for those minerals in basic magmas (Irving, 1978; Nicholls and Harris, 1980). The fact that the total *REE* content and pattern of the appinite overlaps with those of the diorites is also significant because in intermediate liquids

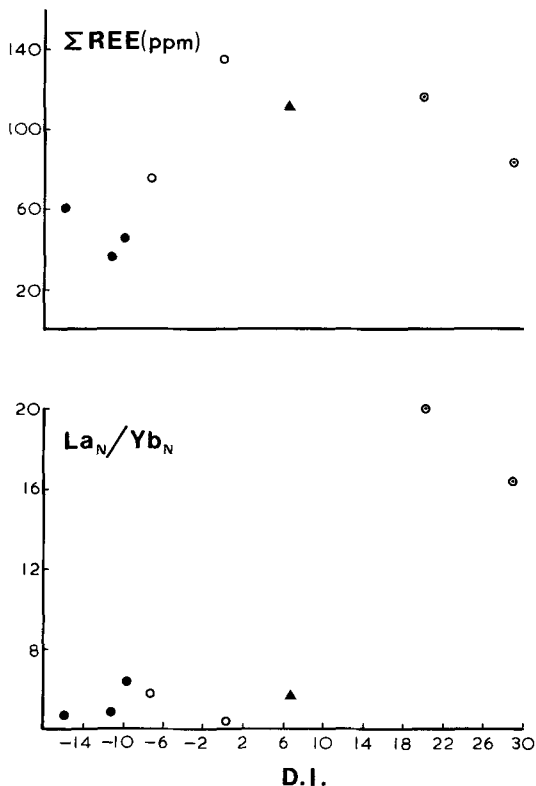


FIG. 7. Plots of total *REE* and chondrite-normalised  $La/Yb$  against differentiation index (D.I.). Symbols as in Fig. 2.

$D[REE]_{cpx/liq} \approx 1$  and further pyroxene crystallization might be expected to buffer *REE* fractionation in more acid liquids. This is demonstrated very well in the *REE* distribution in the gabbro to granite suite of the Beinn Chaigle centre in Mull (Walsh and Clarke, 1982).

From published amphibole/liquid distribution data for *REE* (for example Irving, 1978; Nicholls and Harris, 1980), it is evident that amphibole-controlled fractional crystallization will produce trends different to those where anhydrous minerals are liquidus phases.  $D[REE]_{amph/liq} \approx 1$  for basaltic liquids but increases rapidly with increasing  $SiO_2$ , and has markedly higher values for *MREE* at all  $SiO_2$  contents. Amphibole removal from basic magma would therefore produce fractionated liquids with initially buffered total *REE* and then moderate to strong total *REE* depletion in more acid derivatives, with concomitant relative *MREE* depletion. Arth *et al.* (1978) have demonstrated the validity of this model in the gabbro-diorite-tonalite-trondhjemite suite

of SW Finland, and Brown *et al.* (1980) similarly ascribe the *REE* patterns of the dioritic suite of NW Guernsey to amphibole fractionation.

The *REE* patterns of the SE Jersey rocks are not consistent with an origin by fractional crystallization in which amphibole, the most abundant mafic mineral, played a major role. The absence of *MREE* enrichment in the layered diorites also argues against these rocks being primary amphibole cumulates. An alternative explanation for the *REE* patterns, and one which also accounts for the distribution of other trace elements, is fractional crystallization of basic magma and cumulate formation dominated by  $\text{cpx} + \text{plag} \pm \text{ol}$  crystallization.

### Summary and conclusions

Field relationships show that a varied suite of rocks ranging from gabbro through diorite to appinitic leucodiorite were intruded by granite on at least two occasions, and petrography reveals complex disequilibrium mineral assemblages, especially the presence of several generations and species of amphibole, which could be the result of hydrothermal recrystallization caused by the granites. If the basic pluton had not completely solidified when the first granite was emplaced, there is the possibility that magma mixing might have contributed to the formation of the dioritic rocks.

There are several problems inherent in the interpretation of the geochemistry of plutonic rocks. It is not always clear whether they represent liquids or crystal accumulations, and in the latter case to what extent they are orthocumulates or adcumulates. Even in 'young' intrusions of Tertiary age it has been demonstrated that hydrothermal alteration caused by circulating meteoric water can significantly affect both mineralogy and bulk chemistry. In rocks of Precambrian age which are intimately pervaded by granite and have suffered metasomatism to varying degrees, a geochemical interpretation becomes even more tenuous, and there is little basis for rigorous, quantitative geochemical modelling of processes in which the original components are not precisely known.

The coherent geochemical variation between gabbros, diorites and appinites does, however, suggest some form of genetic relationship. Most major oxides ( $\text{SiO}_2$ ,  $\text{FeO}$ ,  $\text{MgO}$ ,  $\text{CaO}$  and  $\text{K}_2\text{O}$ ) and the transition metal trace elements ( $\text{Sc}$ ,  $\text{V}$ ,  $\text{Cr}$ ,  $\text{Co}$ ,  $\text{Ni}$  and  $\text{Zn}$ ) vary systematically with D.I. and fall on smooth linear trends which are extended to the granitoids. Although such trends could result from acid-basic magma mixing this is ruled out as the predominant petrogenetic process by the distribution of the HFS elements ( $\text{Ti}$ ,  $\text{P}$ ,  $\text{Y}$ ,  $\text{Zr}$  and

$\text{Nb}$ ) which have maximum concentrations in the intermediate rocks. Because these elements are considered to be relatively immobile, it is unlikely that they could attain higher concentrations in the products of mixing than in either of the parental liquids. The absence of compositions in the 59–66 wt. %  $\text{SiO}_2$  range also shows that complete mixing and homogenization of two contrasting liquids did not occur.

It is therefore assumed that the distribution of HFS elements is a result of some other process which occurred prior to granite emplacement, and that this process was fractional crystallization of basic magma. The progressive enrichment in HFS elements with increasing D.I. is consistent with fractionation controlled by  $\text{cpx} + \text{plag} \pm \text{ol}$  since those elements behave incompatibly in such a system. Although amphibole is the main, or only, mafic mineral in these rocks its precipitation and removal could not produce the same trends because distribution coefficient values for HFS elements in amphiboles exceed unity and increase significantly with increasing  $\text{SiO}_2$ . The compatibility of HFS elements in an amphibole-rich assemblage is unlikely to be significantly subdued by the simultaneous crystallization of plagioclase because of the suppression of plagioclase liquidus temperatures in a hydrated system. This is reflected in the textures of the diorites where plagioclase is always interstitial towards euhedral amphibole.

The *REE* patterns for gabbros, diorites and appinites, which are very similar but show total *REE* content increasing with D.I., give further support to the secondary status of amphibole. The absence of *MREE* depletion in diorites and appinites suggests that amphibole was not a primary liquidus during fractionation, and the lack of *MREE* enrichment in the layered diorites precludes an origin as primary amphibole-rich cumulates.

The alternative model proposed here is that the observed chemical variation, especially of *RE* and HFS elements, was in a large part developed during fractional crystallization of basic magma to form a sequence of gabbroic cumulates with an essentially  $\text{cpx} + \text{plag} \pm \text{ol}$  mineralogy. This gabbro was intruded by granite shortly before or after its complete solidification, which had the metasomatic effect of introducing  $\text{SiO}_2$ ,  $\text{K}_2\text{O}$  and  $\text{Na}_2\text{O}$  dissolved in infiltrating hydrothermal fluids. The main results of this were threefold:

- (1) The primary gabbroic mineralogy was randomly converted to an amphibole-rich assemblage, essentially by subsolidus recrystallization.
- (2) Granitic metasomatism accentuated some of

the 'evolved' chemical trends (increasing SiO<sub>2</sub>, K<sub>2</sub>O and Na<sub>2</sub>O) and superimposed a broadly calc-alkaline chemistry on the complex.

- (3) These mineralogical and chemical changes resulted in a lowering of the solidus temperatures of these metasomatic diorites to below the ambient temperature, and although melting was insufficient to destroy the relict layered structure it caused the diorites in places to recrystallize as rocks with igneous textures.

Although this model is complex it is the one which best fits the equally complex field relationships and petrographic detail, and might be more widely applicable to other diorites in calc-alkaline complexes where early gabbro is intimately associated with later granites.

The limited amount of geochemical data presented here for the granites does not suggest an obvious petrogenetic link with the basic rocks, although the marked Eu anomaly in the Le Hocq granite may be the result of plagioclase fractionation of a more basic parental magma. The presence of large volumes of basic rocks at depth as revealed by gravity and magnetic studies, and the proximity of Pentevrian basement, make both fractional crystallization and crustal melting viable processes for the production of granite magmas. It might be anticipated that future isotope studies will reveal that both processes have contributed to the origin of the Jersey granites.

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