Some aspects of Tertiary acid magmatism in NE Ireland

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ABSTRACT. Geochemical data (including *REE* determinations) are presented for all five Mourne Mountains granites and three Northern Ireland rhyolites. These confirm (1) the extremely fractionated nature of some of the rocks (Sr and Ba < 10 ppm, Rb > 400 ppm, Eu/Eu* < 0.1, and K/Rb < 100), and (2) a major revision to the outcrops of the E. Mourne granites G1 and G2 in which much of the former is reclassified as G2. Combined petrographic and geochemical studies have also indicated that magmatic pulses were involved in the emplacement of Mourne intrusions G2 (Revised)–G5 inclusive.

The N. Ireland Tertiary acid rocks exhibit general geochemical similarities to their analogues elsewhere in the British Tertiary Igneous Province (in which Sr is generally < 100 ppm and Ce_N/Yb_N generally < 8 with Eu/Eu* often < 0.6), but *as a suite* the Mourne granites are enriched in Rb and some other LIL elements relative to their N. Arran counterparts.

The more fractionated acid magmas of NE Ireland are believed to have evolved from primitive granitic parent liquids by crystal fractionation at depth which involved major and accessory phases (including zircon and allanite). In the Mourne (and County Antrim) areas the primitive acid compositions lie at the ends of basaltic (tholeiitic) differentiation series, and in the Mourne central complex there is a complete geochemical sequence from basic rocks through intermediate members to primitive and ultimately highly evolved, subalkaline, granitic intrusions. It is concluded that the data are consistent with the Mourne granites and Northern Ireland rhyolites being essentially basaltic differentiates, although Sr isotope evidence indicates some (probably minor) crustal involvement.

THIS paper presents some new data and conclusions within the framework of a review of certain important aspects of the Tertiary acid magmatism of NE Ireland, as exemplified by the County Antrim rhyolites and Mourne Mountains granites. It also considers the relevance of this research to the other areas of the British Tertiary Igneous Province (BTIP).

The crustal setting and chemistry of the Irish

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Tertiary igneous rocks indicate that they are of major importance in studying the magmatism of the BTIP *as a whole* (e.g. Meighan, 1979, 1981). Specifically:

(1) The Irish acid magmatism occurred in different environments on the north side of the Iapetus Suture, within a crustal sector which spans the SW geological continuation of the Midland Valley of Scotland and part of the Longford–Down Massif, the equivalent of the Southern Uplands of Scotland. Rhyolites occur in the 'Midland Valley' region but are volumetrically subordinate to the associated Tertiary basaltic lavas, whereas the intrusive central complexes (Mourne Mountains, Slieve Gullion, and Carlingford) are all sited well to the south of this, in the Longford–Down Massif, with granitic rocks predominating superficially in the Mourne area.

(2) The rhyolites include relatively fresh rocks, e.g. the three examples discussed below. Their magmas appear to have been uniquely associated in time with an episode of basaltic quiescence marked by the Interbasaltic Formation (Old, 1975) which separates the Lower and Upper Basalts of County Antrim.

(3) Both the intrusive rocks of the Mourne Mountains and the Co. Antrim extrusives include some of the most extremely fractionated compositions encountered within the BTIP *subalkaline* acid suites, as well as more primitive acid members (i.e. rocks with lower values of the Thornton–Tuttle differentiation index and less fractionated trace element chemistries). Furthermore, *all* the Mourne granites have been less severely affected by meteoric-water–rock interaction than many other intrusions in the BTIP (Meighan, 1979; McCormick *et al.*, 1980; this paper), a factor of some significance in evaluating the chemistry of these rocks.

(4) In contrast to central complexes such as Slieve Gullion and St Kilda, the two Mourne centres do not exhibit large-scale, complex acid–basic field relationships. Thus, considering also (2) above, it is apparent that in Northern Ireland there

are opportunities to study Tertiary acid magmatism in geologically simpler situations than certain other parts of the BTIP; perhaps in the Mourne and County Antrim areas, in contrast to Skye (Thompson, 1980, 1982), recycling of Tertiary acid material was an insignificant factor.

(5) Geochemically and isotopically, the Mourne granites can be usefully compared with their Skye counterparts in the knowledge that there is, as yet, no definite evidence that the Mourne acid magmas originated and evolved within a high-grade gneissose basement (as opposed to a low-grade, Silurian metasedimentary envelope). However the proximity of the Newry Complex (Meighan and Neeson, 1979) dictates that Tertiary remelting at depth of typical Caledonian diorites and granodiorites must be assessed for the Mourne intrusions.

(6) In the Mourne central complex there is *a continuous compositional sequence* from olivine tholeiite through intermediate to acid compositions (Akiman, 1971) and the acid rocks exhibit a continuous range from relatively primitive to highly fractionated members which seem to define a subalkaline acid differentiation series (Hood *et al.*, 1981; Hood, 1981; this paper). The acid volcanics of the Tardree area also lie on trends passing from olivine tholeiitic through intermediate lava compositions (Lyle, 1980; Lyle and Thompson, 1983), but although certain other rhyolites display evidence of much more extreme fractionation (Meighan and Gamble, 1972; Meighan, 1979; this paper), trace element data indicate that the rhyolites as a whole cannot be considered as a single, comagmatic series (Meighan, 1981). Overall, the demonstrations of basic–intermediate–acid sequences are highly significant in assessing the origin of the acid magmas and their strontium isotopic compositions.

(7) Finally, bearing in mind the work of Morrison *et al.*, 1980, it should be noted that in contrast to Skye, Mull, and Arran there is no evidence that Permo-Carboniferous magmatism occurred in the Mourne region, and in this context, given the feasibility of basic parental magmas, it is interesting to observe the high levels of certain LIL elements in the Mourne acid suite as a whole (Tammemagi, 1976; Meighan, 1979, 1981).

The rhyolites

In this paper attention is confined to three acid volcanic rocks from Mid-Antrim—the Sandy Braes porphyritic obsidian (near Tardree Mountain) and Kirkinriola rhyolite (Meighan, 1979) together with the Quarrytown rhyolite which outcrops some 2 km ENE of Kirkinriola in the Ballymena area (the petrography and geochemistry of these individual

occurrences would seem to negate the possibility that they are all parts of a single flow). Although the three rocks represent a relatively less fractionated acid magma (Sandy Braes) and two very evolved biotite rhyolites (the Kirkinriola example being the most fractionated member of the Northern Ireland rhyolite suite; Meighan, 1981), it must be stressed at the outset that they cannot be assumed to be comagmatic *sensu stricto*. Tables I and II contain

TABLE I. Selective geochemical data for 3 peraluminous County Antrim rhyolites

wt.%	S	Q	K
SiO$_2$	75.5	75.7	75.1
TiO$_2$	0.12	0.04	0.03
MgO	0.10	0.07	0.07
CaO	0.88	0.46	0.17
K$_2$O	4.92	4.73	4.35
P$_2$O$_5$	0.025	0.018	0.017
D.I.	92.3	95.4	96.4
Trace elements (ppm)			
Rb	129	428	953
Sr	43	5	<5
Ba	524	<10	<10
Zr	265	123	131
K/Rb	316	92	38

S = Sandy Braes obsidian, K = Kirkinriola rhyolite (Meighan, 1979); Q = Quarrytown rhyolite. D.I. = Thornton–Tuttle differentiation index. All determinations by X.R.F. spectrometry.

TABLE II. Rare-earth element data (ppm) for the County Antrim rhyolites of Table I

Sample	S	Q	K
La	69	5.4	4.3
Ce	152	20.5	14
Pr	19	2.3	0.71
Nd	65	7.4	n.f.
Sm	17.8	3.3	0.94
Eu	1.69	0.07	0.005
Gd	15	5.2	1.60
Tb	2.2	1.07	0.25
Dy	12.9	7.1	3.07
Ho	2.2	1.6	0.86
Er	8.6	6.4	3.31
Tm	-	0.79	-
Yb	7.0	5.0	7.54
Lu	1.25	0.73	1.44
ΣREE	374	67	38
Ce$_N$/Yb$_N$	5.52	1.04	0.47
Eu/Eu*	0.32	0.052	0.013

Determinations by radiochemical neutron activation analysis at the Universities Research Reactor, Risley : S and K are from Meighan (1979).

selective geochemical data and *REE* analyses for these three peraluminous compositions; petrography, full analyses and norms are contained in

Meighan (1981). Important aspects of the present results are:

(1) Despite the relatively similar SiO_2 levels in the three rocks, there are other significant differences, e.g. CaO, TiO_2, and the Thornton–Tuttle differentiation index (DI) (Table I also illustrates the danger of using SiO_2 content as an index of differentiation in the more siliceous acid suites).

(2) Certain trace elements (e.g. Rb, Sr, Ba, Eu) and the ratios K/Rb, Eu/Eu*, and Ce_N/Yb_N reveal very dramatic compositional variations (Eu* is Eu derived by interpolation between Sm and Gd after chondrite-normalization, and Ce_N and Yb_N are the chondrite-normalized values). The *extremely* low levels of Sr, Ba, and Eu in the Quarrytown and Kirkinriola rhyolites would seem to effectively preclude their *direct* genesis by either total or partial melting of 'normal' crustal rocks such as typical 'greywacke'-Caledonian granodiorite-gneissose basement.

(3) With increasing values of DI and decreasing K/Rb, the chondrite-normalized *REE* patterns (fig. 1) show first, *LREE* enrichment with a relatively small (but none the less significant) negative Eu anomaly (Sandy Braes), then an approximately chondritic pattern with an appreciably smaller value of Eu/Eu* (Quarrytown) and finally *HREE* enrichment with an extremely large negative Eu anomaly (Kirkinriola). The total and most individual *REE* concentrations (especially Eu) decrease in this sequence, but it is important to note that the abundances of the *HREE* Yb and Lu are not particularly different in the Sandy Braes and Kirkinriola rocks.

Thus in terms of the DI values, K/Rb ratios and their remarkable enrichment in Rb with extreme depletion in Sr, Ba, and Eu, the Quarrytown and Kirkinriola rhyolites are highly fractionated compositions, both in an absolute sense and relative to the Sandy Braes rock. It is also observed that the former bear strong geochemical resemblances to the topaz rhyolites documented by Burt *et al.*, 1982, which are a *special* class of non-peralkaline, high silica rhyolite of anorogenic affinity.

Noting that the phenocryst phases in the Sandy Braes rock include quartz, alkali and plagioclase felspar, allanite and zircon, fractional crystallization of the more primitive acid magma(s) appears to be the most feasible explanation for the compositional variation in the rhyolite suite. Given the uncertainty about comagmatism, trace element modelling will not be discussed here, but clearly any
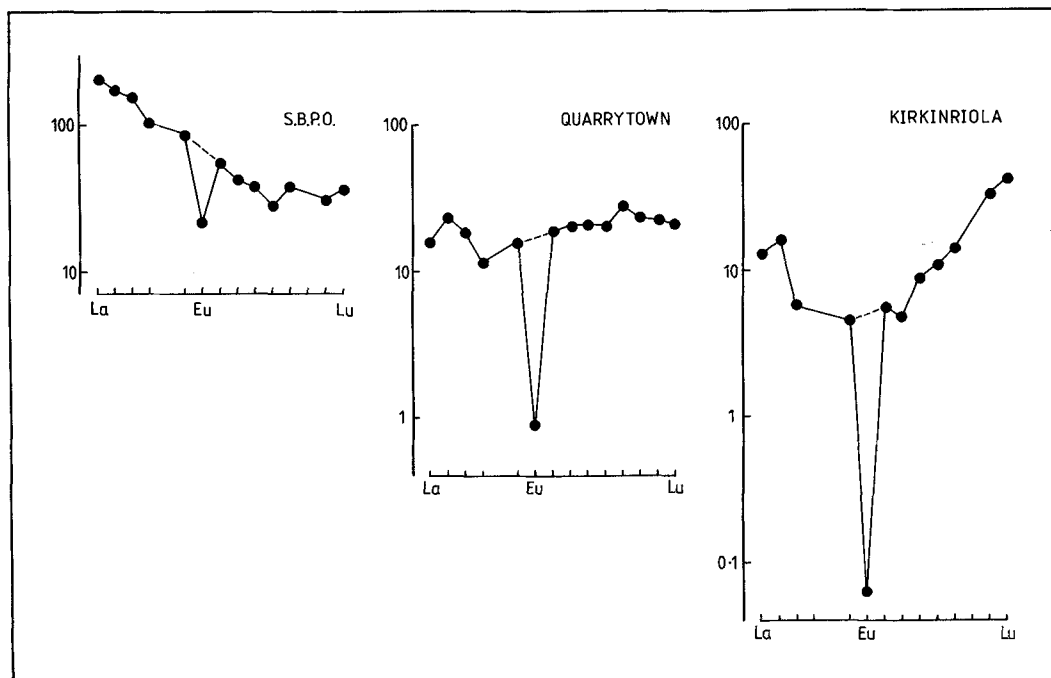

FIG. 1. Chondrite-normalized (Nakamura, 1974) *REE* patterns for the Sandy Braes porphyritic obsidian (SBPO), Quarrytown and Kirkinriola rhyolites, Co. Antrim (Table II) with rock/chondrite (log scale) plotted against atomic number (linear scale).

proposed crystal fractionation assemblage must include two felspars and the accessory minerals zircon and allanite. Essentially, Sr and Eu/Eu* would have been controlled by both felspars and Ba by alkali felspar and biotite, but since neither Zr nor any of the *REE* behaved incompatibly in the rhyolite magmas, *accessory mineral fractionation* must also be invoked. The petrographic evidence for the involvement of allanite here (Meighan, 1979; Brooks *et al.*, 1981) is especially important in the context that this mineral probably exerted a fundamental control on the extreme depletion of La and Ce and the reduction in Ce_N/Yb_N in the two more evolved melts. However, the Kirkinriola and Quarrytown rocks show much more extreme depletion in the *LREE* than the geochemically comparable Mourne granites (Table VI) and the possibility must be considered that an additional (as yet undetected) *REE*-bearing accessory phase(s) contributed to the fractional crystallization process in the rhyolite magmas. In this context it must be noted that Miller and Mittlefehldt (1982) stress the importance of monazite fractionation in certain acid magmas.

There is to date no firm evidence that any Northern Ireland rhyolite was erupted from a zoned magma body, although most of the outcrops are small with limited exposure. Overall it is not suspected that liquid state differentiation as advocated by Hildreth (1979, 1981) for the Californian Bishop Tuff magma chamber was the principal mechanism which produced the more evolved rhyolites; as stated above, crystal fractionation (Meighan, 1979, 1981) is still favoured as the predominant process. The ultimate origin of the rhyolites is considered later in this paper in conjunction with their Mourne granite counterparts.

The Mourne Mountains granites

Revision of granites G1 and G2. Following Meighan (1976) a major revision of the E. Mourne granites G1 and G2 can be confirmed (with fuller analytical data in terms of sample numbers and elements determined—Meighan, 1981; Hood, 1981). Essentially, on field, petrographic, geochemical and indeed isotopic evidence, a substantial part of the first granite is reclassified as G2 (fig. 2). Specifically this involves the three G1' outcrops in the NW, N. and E. parts of the centre (Richey's 'Outer Felspathic Granite') and the large G1 'wall' outcrop of the east border (part of his 'Inner Felspathic Granite'), some of which is separated from the G1' to the east by a screen of
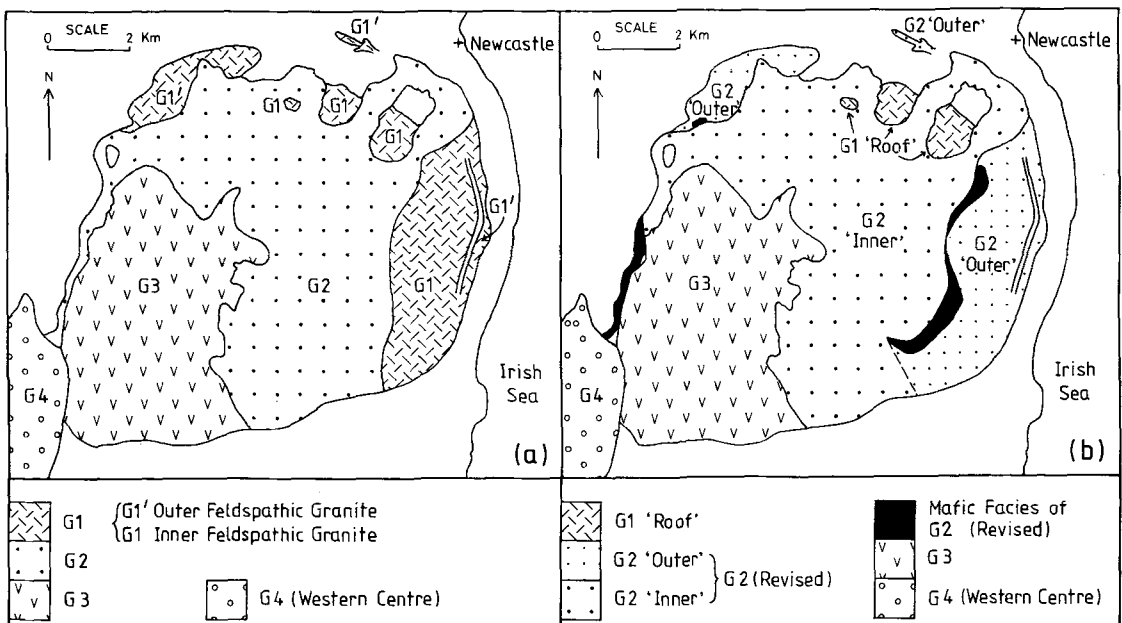

FIG. 2. Simplified geological maps of the E. Mourne Tertiary Centre, Co. Down: (*a*) is after Richey (1928) and (*b*) shows the revisions originally proposed by Meighan (1976) and the 'mafic facies' of G2 (Revised) as mapped by Hood (1981). The country rocks are unshaded and the G1 'Roof' outcrops indicated on (*b*) are from east to west those of Slieves Donard, Commedagh, and Corragh respectively.

Silurian country rocks. Consequently the remaining G1, everywhere underlain by G2 and hence termed G1 'Roof', comprises only three relatively small, separate outcrops of the 'Inner Felspathic Granite' on Slieves Donard, Commedagh, and Corragh, for which an original *ring dyke* form cannot be inferred with any certainty. The entire G2 granite (including the reclassified G1 and G1' outcrops) will subsequently be referred to as G2 (Revised) following Hood (1981), to avoid confusion with Richey's (1928) designation.

The field–petrographic criteria for the revision include differences in colour index values, which are significantly higher in G1 'Roof', and the fact that primary amphibole is virtually confined to this granite. However, geochemical data (Table III)

TABLE III. Selective major, minor and trace element ranges for E Mourne
granites G1 and G2

wt.%	G1 'ROOF'	OTHER G1 + G1' OF RICHEY	G2 (RICHEY)
SiO_2	69.0 – 70.8	74.5 – 79.2	76.1 – 80.6
TiO_2	0.34 – 0.42	0.09 – 0.22	0.05 – 0.19
CaO	1.41 – 1.72	0.28 – 0.77	0.33 – 0.77
D.I.	86.6 – 87.6	92.4 – 95.7	94.1 – 96.0
Trace elements (ppm)			
Rb	213 – 276	290 – 530	339 – 663
Sr	75 – 87	5 – 54	<5 – 32
Ba	779 – 1118	<10 – 425	<10 – 173
Zr	428 – 577	96 – 312	98 – 223
Eu	2.1 – 2.2	0.25 – 0.82	0.15 – 0.60
Sc	7.0 – 11.2	1.6 – 3.8	1.5 – 2.8
Y	80 – 89	59 – 114	53 – 120
Nb	37 – 43	29 – 43	27 – 54
K/Rb	173 – 201	82 – 130	58 – 120
Zr/Y	$\geqslant 5.0$	$\leqslant 3.4$	$\leqslant 2.6$
Zr/Nb	$\geqslant 10.7$	$\leqslant 6.6$	$\leqslant 7.2$
Y/TiO_2	$\leqslant 243$	$\geqslant 326$	$\geqslant 409$

The G1 'Roof' column includes analyses for the outcrops on Slieves Donard, Commedagh and Corragh : data for the mafic facies of G2 (Revised) - see text - have been included in the 'other' G1,G1' (but not the G2) column. For Rb, Sr, Ba and Zr the ranges are for the combined sample populations of Meighan (1981) and Hood (1981) involving 21 specimens of G1 'Roof', 104 of the other G1,G1' and 100 of J.E. Richey's G2. The other data are from Meighan (1981). D.I. = Thornton - Tuttle differentiation index.

All analyses by X.R.F. spectrometry, except those for Eu and Sc which are neutron activation determinations made at the Universities Research Reactor, Risley.

provide especially convincing evidence. Although meteoric-water–rock interaction is probably an insignificant factor in this problem (Meighan, 1979; McCormick *et al.*, 1980; Gibson and Fallick, unpublished data)—whole rock $\delta^{18}O$ values for the granites in question and indeed G1 'Roof'–G5 inclusive are in the range +6.1 to +9.7‰—it

should nevertheless be noted that the immobile elements Ti and Zr (and especially the Zr/Y, Zr/Nb and Y/TiO_2 ratios) amply confirm the revision. Furthermore the *relatively* homogeneous composition of G1 'Roof' and the obvious geochemical hiatus between it and the other (more fractionated) G1/G1' do not support a model in which these are all parts of a single, unhomogenized hybrid intrusion (cf. Brown, 1956). On the contrary, the geochemical similarities between the 'other' G1/G1' and Richey's G2 are striking.

During fieldwork, it was found that an immediate distinction could be made between G1 'Roof' and the reclassified G1/G1', the only exception being exposures of a somewhat localized, relatively mafic-rich variant in the latter, now termed the G2 (Revised) mafic facies. However, with care this can be distinguished petrographically from G1 'Roof' and chemically the mafic facies (Table VII) generally lies between the latter and 'normal' G2 (e.g. fig. 4), considerably extending the compositional range of the reclassified G1/G1' (Table III). It is also interesting to note that the facies is geochemically very similar to the relatively mafic-rich microgranitic–granophyric variety of Western Mourne granite G5 (see below), e.g. fig. 4, Table VII.

The G2 (Revised) mafic facies forms an integral part of what might now be termed G2 'Outer' (Hood, 1981) which includes the reclassified G1/G1' outcrops (fig. 2). In the E. and ENE parts of the centre the facies is found exclusively along J. E. Richey's (1928) G1 'wall'–G2 contact, but in the SSE it actually crosses this boundary, thus providing a further indication that his map requires some modification. The mappable junction between the mafic facies and G2 'Inner' (essentially Richey's G2) now appears as an internal contact in G2 (Revised) and would seem to provide evidence that G2 Outer and G2 Inner represent at least two magmatic pulses as defined by Harry and Richey (1963). Hence it is concluded that revision of Richey's pioneer Mourne granite mapping provides new evidence for another of his important contributions, namely the magmatic pulse concept.

Magmatic pulses. The original evidence of Harry and Richey (1963) that G2 (i.e. G2 Inner) was emplaced as two magmatic pulses was based on the distinction of coarse and finer grained varieties of this granite, the latter being confined to the northern and western parts of the mass. Combining this with the conclusions of the last section and the work of Hood (1981), it is now apparent that several magmatic pulses were involved (whose exact number has yet to be determined), and this is also the case for G3, the youngest granite of the eastern centre (Harry and Richey, 1963; Hood, 1981). By
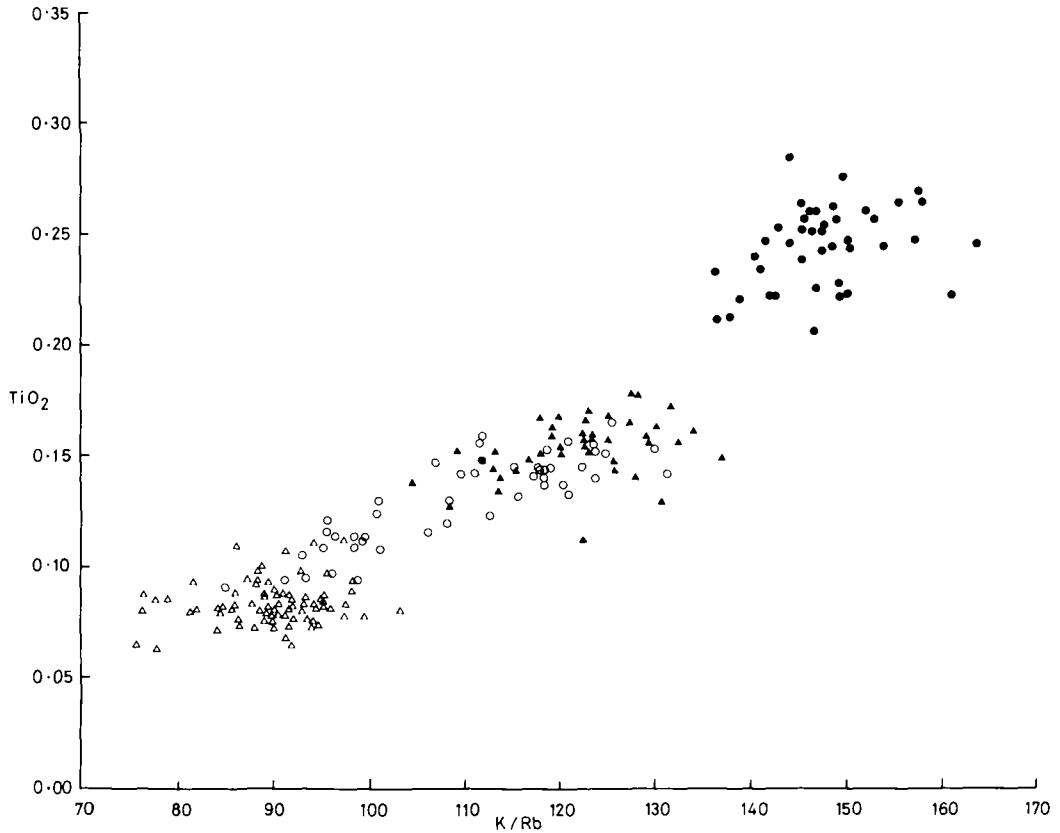
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FIG. 3. Plot of TiO_2 (wt. %) against K/Rb for the major petrographic variants of the W. Mourne granites detailed by D. Gibson. Solid triangles represent coarse grained G4 (43 samples), open triangles finer grained G4 (83 samples): solid circles represent relatively mafic-rich microgranitic·granophyric G5 (45 samples), open circles mafic-poor G5 (47 samples).

contrast the earliest mass, G1 'Roof', appears to have been emplaced as a single pulse.

A new study of the W. centre (Gibson, in prep.) indicates that evidence for magmatic pulses can be recognized within granites G4 and G5 (Emeleus, 1955) both in the field, using texture and mineralogy, and geochemically (fig. 3). Specifically, G4 can be subdivided into a 'coarse-grained' and a somewhat 'finer grained' pulse, whereas G5 seems to have been emplaced as a 'relatively mafic-rich microgranitic-granophyric' pulse and a 'mafic-poor' one. Some of the geochemical evidence is striking, as illustrated by fig. 3 which displays the compositionally distinctive fields within each granite, the latter neatly corresponding to the appropriate textural–mineralogical variant. Indeed, a general conclusion of the recent work in the Mourne Mountains (Hood, 1981; Gibson, in prep.) is that, within G2 (Revised), G3, and G4, the coarser granites tend to have the more primitive (i.e. less

fractionated) compositions which include relatively higher TiO_2, Sr, and Ba levels and higher K/Rb ratios than those of the finer varieties (e.g. fig. 3).

TABLE IV. Summary of current information on numbers of magmatic pulses within Mourne granites G1 'Roof' - G5 inclusive

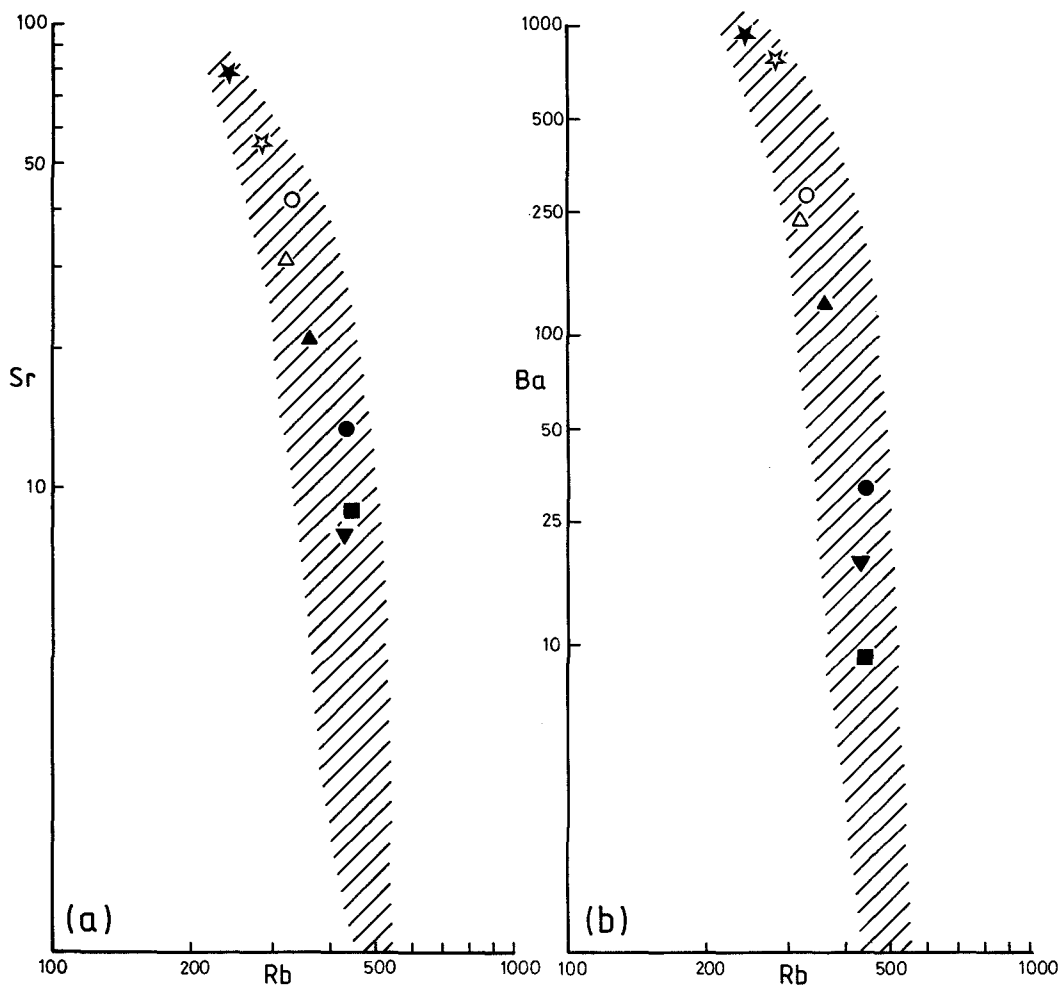| INTRUSION		NO. OF PULSES	SOURCE OF INFORMATION
G1 'Roof'	('roof' outcrops of J.E. Richey's Inner Felspathic Granite)	1	Hood (1981)
G2 (Revised)	G2 Outer (mostly J.E. Richey's G1' and G1 'wall') together with G2 Inner (essentially J.E. Richey's G2)	>2	Harry and Richey (1963); Hood (1981); Meighan (1981)
G3		>2	Harry and Richey (1963); Hood (1981)
G4		2	Gibson, in preparation
G5		2	Gibson, in preparation

FIG. 4. Plots of (a) Sr and (b) Ba contents against Rb content (all data in ppm, logarithmic scales) which illustrate the compositional field of Mourne granites G1 'Roof'-G5 inclusive (excluding highly evolved autointrusions). Mean values are also plotted for G1 'Roof' (solid star), its autointrusions (open star), the mafic facies of G2 (Revised) (open circle), G2 (Revised) excluding the latter (solid circle), G3 (solid square), G4 (solid inverted triangle), G5 (solid triangle), and the relatively mafic-rich microgranitic-granophyric variant of the latter (open triangle).

Table IV summarizes the current position regarding magmatic pulses in the two Mourne centres.

Chemistry. Extensive analytical data have now been acquired for both the E. and W. Mourne centres (Meighan, 1981; Hood, 1981; Gibson, in prep.), and on several plots (e.g. fig. 4) it is apparent that there is virtually complete compositional variation from the most basic intrusion, the (fayalite-) biotite-amphibole granite G1 'Roof', to the younger and considerably more evolved biotite granites G2 (Revised), G3, and G4. Specifically, the relatively narrow compositional fields of the indi-

vidual granites and granitic pulses (*sensu stricto*) are linked and extended by their minor segregations, i.e. autointrusions (including aplites), a feature in itself rather suggestive of a subalkaline fractional crystallization sequence. Furthermore, as with the rhyolites, the extreme depletion of Sr and Ba in the more evolved granites precludes their *direct* genesis by total or partial melting of typical upper crustal sources (including the Sr-rich Newry Complex rocks; Table IX).

Table VI presents complete *REE* analyses for typical samples of G1 'Roof'-G5 inclusive (Table V), noteworthy features of these data being (1) the

TABLE V. Geochemical data for typical samples of Mourne granites G1 'Roof'-
          G5 inclusive

wt.%	G1/17	G2/7	G3/2	G3/B.	G4/R.R.	G5/2
SiO_2	69.3	78.2	77.8	76.9	75.6	75.0
TiO_2	0.40	0.11	0.10	0.05	0.18	0.26
Al_2O_3	14.10	11.83	11.60	12.73	12.34	12.55
Fe_2O_3	1.24	0.25	0.58	1.09*	0.53	0.76
FeO	2.52	1.01	0.53	–	1.06	1.12
MnO	0.094	0.027	0.024	0.027	0.026	0.034
MgO	0.21	0.08	0.07	0.06	0.20	0.13
CaO	1.53	0.63	0.54	0.49	0.70	0.83
Na_2O	3.52	3.49	3.44	4.01	3.34	3.25
K_2O	5.43	4.76	4.78	4.43	5.30	5.41
P_2O_5	0.104	0.018	0.017	0.014	0.028	0.044
D.I.	86.6(M)	94.9(M)	96.1(M)	95.7(P)	93.9(M)	93.1(M)

Trace elements (ppm)

Rb	237	424	440	665	395	307
Sr	84	16	10	<5	17	35
Ba	1052	21	<10	<10	65	233
Zr	501	136	130	164	193	225
K/Rb	190	93	90	55	111	146

* = total Fe as Fe_2O_3. D.I. = Thornton – Tuttle differentiation index :
M = metaluminous, P = peraluminous.

G1/17   = typical G1 'Roof', J 362284.

G2/7   = typical G2, J 318288, now G2 (Revised).

G3/2   = typical (relatively coarse grained) G3, J 313251.

G3/B.   = relatively fine grained, very drusy G3 (probably an autointrusion),
          borehole sample Q.U.B. 141 (Meighan, 1981), J 301243.

G4/R.R. = typical sample of relatively coarse grained C4, Rocky River,
          J 243265.

G5/2   = typical sample of relatively mafic-rich, microgranitic G5,
          J 219239.

All determinations (except FeO) by X.R.F. spectrometry.

TABLE VI. Rare-earth element data (ppm) for the Mourne granites G1 'Roof'-
           G5 of Table V

Sample	G1/17	G2/7	G3/2	G3/B.	G4/R.R.	G5/2
La	72.3	59.2	49.3	30.0	81.4	68.6
Ce	140	131	105	59.7	159	144
Pr	20.0	17.2	11.0	10.6	15.3	14.3
Nd	70	69	43.1	37.0	61.7	52.1
Sm	15.3	14.3	8.8	9.8	9.6	8.9
Eu	2.07	0.29	0.20	0.041	0.33	0.56
Gd	18	12.2	9.8	12.8	8.3	9.0
Tb	2.1	1.73	1.6	2.3	1.39	1.47
Dy	11.9	12.1	12.0	13.1	9.11	8.2
Ho	2.4	2.60	2.1	3.2	1.68	1.49
Er	7.8	7.5	8.1	13.5	5.9	5.6
Tm	–	1.19	1.3	1.7	1.05	0.84
Yb	6.1	7.63	7.3	11.2	6.0	4.6
Lu	0.87	1.12	1.12	1.71	0.91	0.68
ΣREE	369	337	261	207	362	320
Ce_N/Yb_N	5.84	4.37	3.66	1.36	6.74	7.96
Eu/Eu^*	0.44	0.067	0.066	0.011	0.11	0.19

Determinations by radiochemical neutron activation analysis at the
Universities Research Reactor, Risley : data for G1/17 and G2/7 have already
been published (Meighan, 1979), but a revised analysis for the latter is
reported here.

presence of significant negative Eu anomalies in *all* the granites and rather large ones in G2 (Revised)–G5 inclusive, (2) the absence of strong *LREE* enrichment patterns (fig. 5) and (3) the relatively constant levels of the *HREE* Yb and Lu in the analysed samples.

Accepting that fractional crystallization at depth (probably in the upper crust) seems the most reasonable interpretation of the extensive geochemical variation amongst the granites *sensu stricto* (Meighan, 1979, 1981; Hood, 1981; Table V), it is apparent that, as with the rhyolites, this must have involved accessory mineral phases as well as quartz, alkali and plagioclase felspars, and biotite. In particular, the decline in Zr, P, and Ti levels with increasing DI values (Table V) points to fractionation of, respectively, zircon, apatite, and Fe–Ti
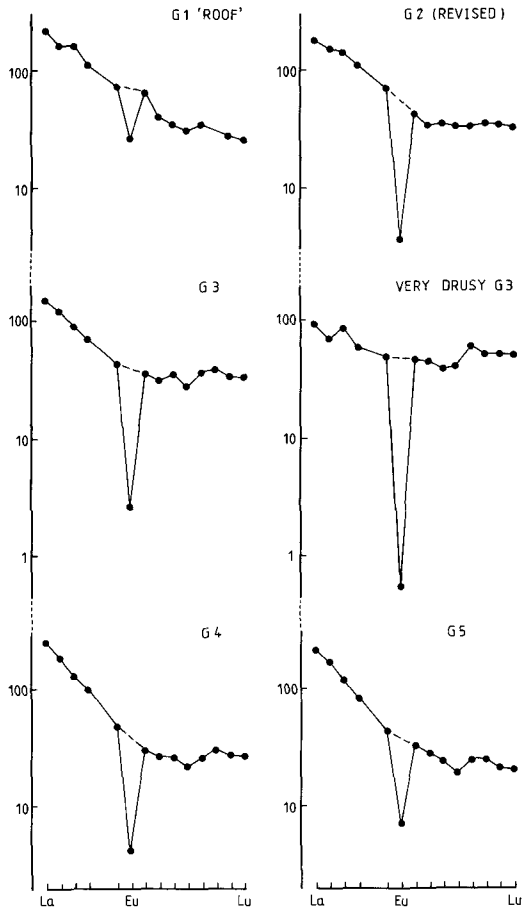

FIG. 5. Chondrite-normalized *REE* patterns (as in fig. 1) for typical samples of Mourne granites G1 'Roof'–G5 inclusive (Table VI). (The very drusy G3 borehole sample probably represents an autointrusion.)

oxides (the latter would have operated in conjunction with biotite to deplete Ti), and indeed the example of rhythmic layering from G1 'Roof' described by Meighan (1979) also suggests their probable involvement together with allanite. The mafic-rich layers in the latter also indicate the likelihood that fayalite, hastingsitic amphibole and clinopyroxene (which has recently been discovered here for the first time in a Mourne granite) functioned in the earlier stages of differentiation. Obviously the large number of phases does not alleviate the difficulty of accurate, quantitative trace element modelling of the fractional crystallization, but the above assemblage does explain the absence of any truly incompatible trace elements amongst those usually determined in current geochemical studies on granitic bodies.

Despite variation in the initial $^{87}Sr/^{86}Sr$ ratios (Hood et al., 1981), on bivariate plots (e.g. fig. 4) G1 'Roof'-G5 and their minor variants seem to define a single, comagmatic, subalkaline (metaluminous-peraluminous) acid differentiation series in which the most fractionated biotite granites, G2 (Revised)-G4 inclusive, are ultimately linked to the more

primitive (older) G1 'Roof' by the latter's auto-intrusions (Hood, 1981). However, with the intrusion of the youngest granite G5, the Mourne acid magma reverted to a more basic composition which, although more evolved than G1 'Roof', exhibits notable geochemical similarities to the mafic facies of G2 (Revised), as described above (Table VII, fig. 4). Since G5 could indicate the beginning of another sequence of acid magmatism in the W. Mourne area, it is vital to determine whether this is comagmatic sensu stricto with G4 and the granites of the E. centre. As already noted, the bivariate plots seem to suggest that G1 'Roof'-G5 inclusive are comagmatic, but REE data (fig. 6) do indicate that irrespective of the degree of fractionation (as measured by Eu/Eu*) the HREE (represented here by Yb) tend to have lower concentrations in G5 than in the other four granites. Consequently caution must be exercised in assuming that the last (exposed) Mourne granite is strictly comagmatic with its predecessors, a conclusion which seems to receive further support from Sr isotope determinations (Gibson, unpubl. data).

Finally, it is interesting to compare some of the geochemical data for the Mourne Mountains with their Arran counterparts in the Northern Granite Complex for which Cs, U, and Th data are also available (Table VIII). Noting that Mourne G1

TABLE VII. Geochemical data for typical samples of the more mafic-rich Mourne granites - G1 'Roof', the 'mafic facies' of G2 (Revised) and the 'relatively mafic-rich micrograniticic/granophyric' pulse of G5

wt.%	G1/17	'G1'/15	G5/2
SiO_2	69.3	74.5	75.0
TiO_2	0.40	0.22	0.26
Al_2O_3	14.10	12.61	12.55
Fe_2O_3	1.24	0.53	0.76
FeO	2.52	1.47	1.12
MnO	0.094	0.041	0.034
MgO	0.21	0.17	0.13
CaO	1.53	0.77	0.83
Na_2O	3.52	3.29	3.25
K_2O	5.43	5.17	5.41
P_2O_5	0.104	0.045	0.044
D.I.*	86.6(M)*	92.4(P)*	93.1(M)*
Trace elements (ppm)			
Rb	237	330	307
Sr	84	45	35
Ba	1052	303	233
Zr	501	243	144
U	6.7	7.0	8.7
Th	23.3	38.3	41.9
Ce	140	145	144
Eu	2.07	0.82	0.56
Yb	6.1	7.8	4.6
Sc	10.2	3.8	3.5
K/Rb	190	130	146
Ce_N/Yb_N	5.84	4.73	7.96
Eu/Eu*	0.44	0.23	0.19

G1/17 = typical G1 'Roof', J 362284.
'G1'/15 = typical sample of 'mafic facies' of G2 (Revised), J368267.
G5/2 = typical sample of relatively mafic-rich, micrograniticic G5, J 219239.
All analyses by X.R.F. spectrometry, except those for (1) FeO and (2) U; Th, Ce, Eu, Yb and Sc. The latter were determined by neutron activation analysis at the Universities Research Reactor, Risley. *as Table V.
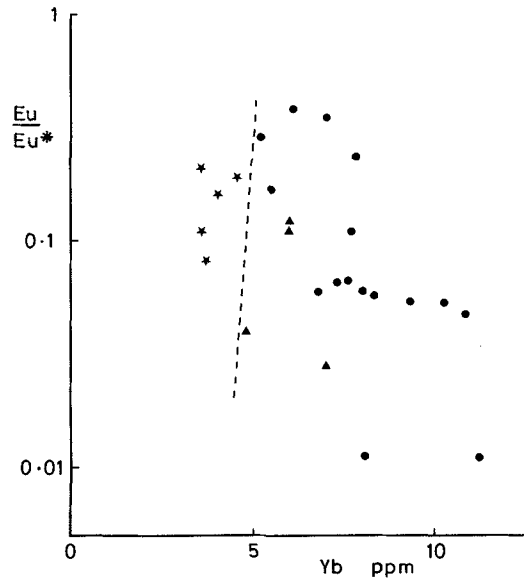

FIG. 6. Plot of Eu/Eu* (log scale) against Yb content (linear scale) for Mourne granites G1 'Roof'-G5 inclusive (autointrusions excluded). Solid circles represent G1 'Roof'-G3 inclusive, solid triangles G4 and solid stars G5.

TABLE VIII.   Selective geochemical data for typical samples of the N Arran

biotite granites and the E Mourne granites G1 'Roof' and G2

(Revised)

wt.%	NORTH ARRAN		E MOURNE MTS	
	Coarse	Fine	G1	G2
SiO$_2$	76.1	77.0	69.3	78.2
K$_2$O	4.93	4.81	5.43	4.76
D.I.	93.5(M)	96.6(P)	86.6(M)	94.9(M)
Trace elements (ppm)				
Rb	165	250	237	424
Sr	57	<5	84	16
Cs	3.1	4.5	7.4	17.2
U	3.8	7.2	6.7	15.0
Th	15.7	23.2	23.3	52.2
K/Rb	248	160	190	93
Eu/Eu*	0.39	0.067	0.44	0.067

D.I. = Thornton – Tuttle differentiation index : M = metaluminous,
           P = peraluminous.

Coarse = typical coarse grained biotite granite, N Arran Centre, sample AR3,
          NR 980416.

Fine   = typical fine grained biotite granite, N Arran Centre, sample
          Q.U.B. 48, NR 952468.

G1   = typical G1 'Roof' granite, E Mourne Centre, J 362284.

G2   = typical G2 (Revised) granite, E Mourne Centre, J 318288.

Cs, U, Th and Eu were determined by neutron activation analysis at the
Universities Research Reactor, Risley and the other elements by X.R.F.
spectrometry.

'Roof' is the most primitive granite with the lowest DI value and assuming that the N. Arran and E. Mourne acid suites are essentially comagmatic *per se*, it is apparent that there are significant geochemical differences between the two central complexes which cannot be explained solely by different degrees of fractionation of the acid magmas. Specifically, the Mourne rocks are enriched in Rb, Cs, U, and Th and have lower K/Rb ratios at any particular stage of fractionation (DI value), yet they have lower initial Sr isotopic ratios (0.708–0.714 at 56 Ma; Hood *et al.*, 1981) than their N. Arran equivalents (0.7145–0.7186) which were studied by Dickin *et al.* (1981). It is suggested that the trace element differences may well reflect the compositions of the basic parental magmas at each central complex (see fig. 7 and below). Consequently one of the variables that should not be overlooked is the Upper Mantle source regions themselves with, in the Mourne case, rather high levels of certain LIL elements in an area beneath which, unlike Arran, there is no evidence for an earlier episode of Permo-Carboniferous basic magma extraction (cf. Morrison *et al.*, 1980). By contrast the Sr isotopic differences *could* largely indicate that beneath N. Arran the Tertiary basic–intermediate magmas were (selectively?) contaminated by more radiogenic upper crustal rocks than in the Mourne area.

Acid magma petrogenesis

Mourne granites. From the previous discussion it follows that petrogenetic attention should be focused on G1 'Roof' as the other Mourne granites seem to have evolved from such a composition and it is very unlikely that the more fractionated members of the suite represent primary magmas formed by melting of typical upper crustal rocks (Meighan, 1979, 1981). Assuming that G1 'Roof'-type composition(s) did yield the other granites by fractional crystallization at depth, it is necessary to consider whether the former might have originated by crustal melting, basaltic differentiation or a more complex process which involved both these mechanisms.

First it must be stressed that, like many other BTIP acid intrusions (Meighan, 1981), G1 'Roof' has certain geochemical attributes generally typical of tholeiitic basaltic differentiates (e.g. Carmichael *et al.*, 1974), including relatively high Zr (in this case around 500 ppm) and low Sr (only about 80 ppm in this relatively basic granite), a moderate *LREE* enrichment pattern (Ce$_N$/Yb$_N$ 5–6) and a distinct negative Eu anomaly (Eu/Eu* approximately 0.4). However, in the Mourne area, combining the data of Akiman (1971) for the minor intrusions with those of the present authors (op. cit.) for all the principal masses, there is further important evidence for a basaltic parentage. There is continuous compositional variation from olivine tholeiites through intermediate members to G1 'Roof' and ultimately the very evolved granites G2 (Revised), G3 and G4, with clear Sr and Ba maxima at the pre-granite stage (figs. 7 and 8). Also, it must be emphasized that there is *no* geochemical hiatus between the acid minor intrusions and the granites; cf. Akiman (1971), whose study included the subsequently revised G1/G1' but not the more basic G1 'Roof' granite.

Table IX, with data for typical samples of Newry granodiorite and G1 'Roof' (on which complete *REE* analyses have been made, e.g. Meighan and Neeson, 1979; Meighan, 1979), negates the possibility that the latter was generated solely by total or partial melting of the Caledonian rocks. Despite relatively similar silica levels, the Mourne compositions have appreciably more Zr and significantly lower Ce$_N$/Yb$_N$ ratios than the high Sr Newry ones, neither of which are geochemical features that can be reconciled with near total or partial melting involving zircon as a likely residual phase. Moreover, bearing in mind the evidence already cited in favour of basaltic differentiation, there is no a priori reason to suggest that the restite-free, generally non-xenolithic G1 'Roof' originated by partial melting of Caledonian diorites, Silurian
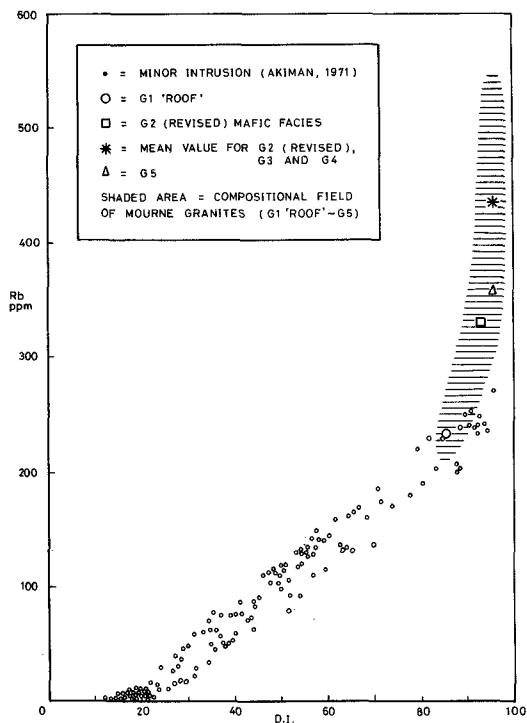
FIG. 7. Plot of Rb content against the Thornton–Tuttle differentiation index (DI) for the basic (tholeiitic) and other E. Mourne minor intrusions (source of data Akiman, 1971) and Mourne granites G1 'Roof'–G5 inclusive (excluding highly evolved autointrusions). Four mean values are plotted for the granites: G1 'Roof'; the mafic facies of G2 (Revised); G2 (Revised), excluding the mafic facies, +G3 +G4; G5. Both scales are linear.

FIG. 8. Plot of (a) Sr content and (b) Ba content against DI for the Mourne Central Complex as in fig. 7 (including minor intrusion data from Akiman, 1971).

turbidites or less certain, deeper crustal components in this region, i.e. gneissose basement rocks.

Accepting that the geochemistry presented so far points towards differentiation of tholeiitic basalt for the genesis of G1 'Roof', it is evident that the first Mourne intrusion was not mainly an inhomogeneous melt of the country rocks in contrast to its counterparts in the earliest centres on Mull and Skye (Thompson, 1982). Nevertheless strontium isotope data (Hood et al., 1981) indicate that there is a crustal component in all the Mourne granites whose mode(s) of incorporation in some respects now typifies the BTIP 'granite problem' and must be assessed in terms of several possibilities. These are (1) meteoric-water–rock interaction; (2) acid (crustally contaminated or uncontaminated basaltic differentiate)–acid (crustal melt) hybridization involving substantial volumes of each component; (3) such hybridization together with recycling of the

magmas; (4) contamination of the parental basaltic magma(s) involving some bulk crustal assimilation and selective isotopic effects but no large-scale crustal anatexis. The first (Taylor and Forester, 1971) can be rejected on account of the lack of evidence for extreme meteoric-water–rock interaction within the Mourne centres (McCormick et al., 1980; this paper) and the demonstrations that this phenomenon generally did not seem to produce significant changes in the Sr isotopic compositions of BTIP rocks (Pankhurst et al., 1978; Walsh et al., 1979; Dickin et al., 1980). A simple 'acid–acid' hybridization model suffers from the defects that no evidence for (inhomogeneous) crustal anatectic melts or unhomogenized acid–acid hybrids has been identified in the Mourne central complex. Indeed, on the currently available data it is difficult to accept that there are any major bodies in the BTIP which represent 'pure' crustal melts without a basaltic differentiate component (Meighan, 1979, 1981), which should be considered in assessing the overall viability of the 'acid–acid' hybridization model in the Hebridean central complexes. It is possible, however, that in some cases direct evidence for the latter process has been 'clouded' by recycling

TABLE IX. Selective geochemical data for typical samples of E Mourne granite G1 'Roof' and Newry Complex granodiorites

	MOURNE G1 'ROOF'		NEWRY GRANODIORITES		
wt.%	1	2	3	4	5
SiO_2	69.3	70.7	65.2	67.6	66.9
K_2O	5.43	5.66	2.87	2.54	2.95
Trace elements (ppm)					
Rb	237	254	116	97	102
Sr	84	83	547	436	430
Ba	1052	996	725	645	551
Zr	501	440	134	127	161
U	6.7	6.8	1.6	2.9	2.7
Th	23.3	22.1	10.7	9.2	12.4
Ce	140	158	50	59.1	77.6
Yb	6.1	7.0	0.73	1.03	1.86
Ce_N/Yb_N	5.84	5.74	17.4	14.6	10.6

1 = E Mourne granite G1 'Roof', sample G1/17, J 362284.

2 = E Mourne granite G1 'Roof', sample G1/50, J 356284.

3 = Newry granodiorite,NE pluton, sample Q.U.B. 127*, J 303396.

4 = Newry granodiorite, NE pluton, sample Q.U.B. 148*, J 204354.

5 = Newry granodiorite, central pluton, sample Q.U.B. 269, J 122291.

U, Th, Ce and Yb were determined by neutron activation analysis at the Universities Research Reactor, Risley and the other elements by X.R.F. spectrometry. * = sample analysed by Meighan and Neeson (1979).

of the magmas (Thompson, 1980, 1982), but in the absence of large-scale, complex acid-basic field relationships, this is rather difficult to argue for the two Mourne centres. On the contrary, the fourth mechanism, namely contamination of basaltic liquids without the generation of substantial, exogenous granite magma bodies by crustal anatexis, seems the most reasonable one for the Mourne area.

Northern Ireland rhyolites. The general field relationships of the acid volcanics favour an essentially basaltic differentiation origin in that the eruptions were uniquely associated with the major interval of basaltic quiescence marked by the Interbasaltic Formation, during which it seems inevitable that some subvolcanic basic magma bodies would eventually have fractionally crystallized to more siliceous, residual magmas (Meighan, 1979, 1981).

As for the Mourne granites, some rhyolites have very highly fractionated compositions which cannot be viewed as serious contenders for primary magma status, i.e. only the more primitive members really need to be petrogenetically assessed in terms of the ultimate source(s) of the acid magmas. The Sandy Braes porphyritic obsidian (Tables I and II) belongs to the latter category and, like the geochemically similar porphyritic rhyolite of nearby Tardree

Mountain, lies on trends passing from olivine tholeiitic through intermediate compositions (Lyle, 1980; Lyle and Thompson, 1983). As with the Mourne granite G1 'Roof', its low Sr content (approximately 40 ppm), moderate Ce_N/Yb_N ratio (5-6) and distinct negative Eu anomaly (Eu/Eu* approximately 0.3) are by no means at variance with derivation principally from a basic (tholeiitic) parent. However, Sr isotope data (A. G. McCormick, pers. comm.) again indicate that there is a crustal component and so apparently the Northern Ireland rhyolites, like all the major BTIP acid bodies (Meighan, 1979, 1981), cannot be isotopically uncontaminated (closed system) basaltic differentiates. In the absence of direct evidence for 'acid–acid' hybridization and recycling, it seems reasonable to propose that the rhyolites are petrogenetically similar to their Mourne Mountains counterparts, i.e. *contaminated* basaltic differentiates.

Thus, although some of the intrusive and extrusive Tertiary acid rocks of NE Ireland exhibit evidence of extreme fractionation, the less evolved members seem to match the general geochemical characteristics of most BTIP granitic compositions, namely low Sr contents (normally < 100 ppm), slight–moderate *LREE* enrichment patterns with distinct negative Eu anomalies (Ce_N/Yb_N generally < 8 and Eu/Eu* often < 0.6), and in some cases high Zr levels (> 400 ppm) which are in excess of those in the potential crustal source rocks (Meighan, 1979, 1981). It is being increasingly argued that, for at least some of these granites (e.g. Walsh and Clarke, 1982), the best petrogenetic overview is one of basaltic differentiation with minor crustal contamination.

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