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The crystallization history and mechanism of emplacement of the western part of the Galway Granite, Connemara, Western Ireland

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SUMMARY. The Galway Granite often has a highly siliceous aphyric alkali granite at the margin, followed inwards by a K-feldspar phenocrystic adamellite and then a steeply layered granodiorite. This previously puzzling arrangement, which seemed to conflict with the necessity to cool from the periphery and crystallize the most basic granite at the margin, is examined by a traverse of chemically analysed rocks and biotites. The Mg/(Mg+Fe+Mn) values indicate that the granodiorite probably crystallized from the outside inwards. The marginal aphyric granite crystallized from the acid residuum in the nearly solid adamellite. This was drawn out of the adamellite by blocks of country rock falling into the adamellite and creating a zone of rarefaction behind them. This also explains the absence of a chilled margin and the aplitic texture and mineralogy of the aphyric granite. The adamellite largely accumulated by crystal settling with gravity grading but the granodiorite crystallized in vertical layers during upward vertical movements of the magma that tipped up the gravity layering in the adamellite. Scattered microdioritic xenoliths are postulated to be disrupted dykes. Eighteen granite and twenty-seven biotite analyses are tabulated.

RECENT work on the Galway Granite (fig. 1), Western Ireland (Wright, 1964; Aucott, 1966, 1968; Lawrence, 1968; Claxton, 1971; Coats and Wilson, 1971), has shown that the batholith often has a marginal fine grained, aphyric, acidic, biotite-poor granite called the Murvey Granite, which rapidly, over a few metres, passes inwards into a coarse porphyritic granite, the Errisbeg Townland Granite with K-feldspar phenocrysts. In the west, this latter granite also forms the edge of the batholith in places where the Murvey Granite is absent. Passing further into the granite in the west, the Errisbeg Townland type gives way over a 300 m transition zone to the Carna Granite, which is granodioritic and generally lacks K-feldspar phenocrysts. The Carna Granite occupies the centre of the western part of the batholith and contains layers of phenocrystic K-feldspar granites, the principal occurrence being a layer named the Cuilleen Granite (fig. 1).

The outstanding feature of this arrangement is that the batholith in both the east and the west has the most basic granite in the centre with a more acid variety at the edge. This is a puzzling arrangement because the batholith could only have lost heat from the periphery and normally some crystallization would be expected from the margin inwards even if crystal settling on the floor of the batholith took place at the same time.

There are a number of possible explanations for this pattern but these more or less resolve into either a hypothesis based on multiple intrusion in which the Carna, Errisbeg Townland, and Murvey Granites are separate injections of magma that mixed only marginally or a hypothesis of continuous crystallization of one magma from the centre of the batholith towards the edge. As the gradational nature of the contacts

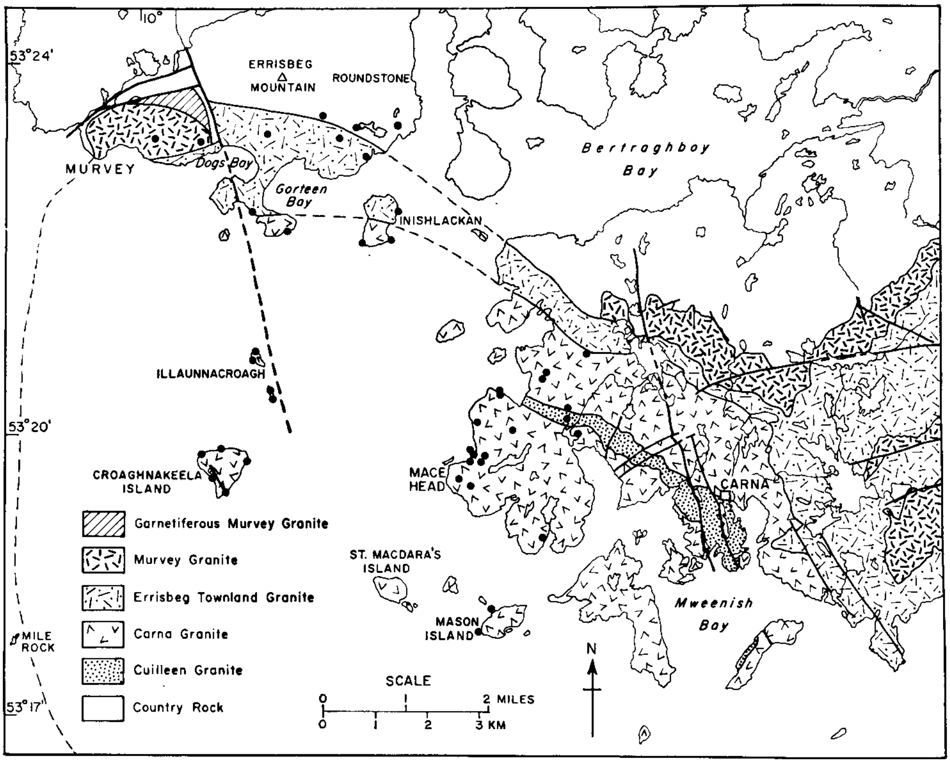


FIG. 1. Geological sketch map of the western part of the Galway Granite. Locations of analysed biotites shown by solid circles.

between the different granite types does not allow unequivocal decision between these two hypotheses, the variation in the rock, feldspar, and biotite compositions across the different granite types in the western part of the Galway batholith was examined to discriminate between the two possibilities. If the granites formed from one magma injection, then systematic chemical trends should occur from the centre of the batholith to the outside, whereas if there were separate magma intrusions distinct breaks would be expected between each pair of granite types, even if blurring of these breaks occurred within the gradational contact zones. Unexpectedly, a complex pattern has emerged, which is interpreted as crystallization from one magma but with both inward and outward crystallization, a previously unsuspected view. Using the discovered pattern of

TABLE I. *Representative chemical analyses*

	BL3490	2748	434	3243	3242	3220	3470	3471	3275
SiO_2	74·73	74·61	75·71	75·37	73·29	72·58	70·41	72·51	69·42
Al_2O_3	14·00	14·10	13·04	13·55	14·46	13·51	14·69	14·08	14·38
TiO_2	0·03	0·16	0·12	0·10	0·12	0·24	0·28	0·18	0·35
Fe_2O_3	0·01	0·42	0·45	0·32	0·41	0·72	0·61	0·03	1·14
FeO	0·57	0·66	0·60	0·13	0·56	1·08	1·54	1·40	1·72
MgO	0·03	0·40	0·36	0·08	0·25	0·77	0·95	0·63	1·22
CaO	0·12	0·59	0·83	0·88	1·22	1·56	1·90	1·55	2·03
Na_2O	4·56	4·05	3·74	4·16	5·41	4·16	3·85	3·88	4·45
K_2O	4·95	4·52	4·88	4·84	3·48	4·27	4·40	4·40	4·60
MnO	0·45	0·04	0·04	0·55	0·07	0·08	0·07	0·05	0·08
P_2O_5	0·01	0·04	0·06	0·02	0·05	0·08	0·15	0·13	0·16
H_2O	0·20	0·27	0·53	0·21	0·72	0·67	0·64	0·56	0·70
Total	99·66	99·86	100·56	100·21	100·04	99·72	99·49	99·40	100·25
si	443	434	453	444	396	381	344	388	315
al	48·9	48·2	46·0	47·1	46·1	41·8	42·3	44·4	38·4
fm	5·4	8·7	8·4	5·5	6·4	13·9	15·7	11·6	18·9
c	0·8	3·7	5·3	5·7	7·1	8·8	9·9	8·9	9·9
alk	44·9	39·4	40·3	41·8	40·2	35·4	32·0	35·1	32·8
ti	0·14	0·70	0·54	0·35	0·49	0·94	1·00	0·72	1·19
p	0·02	0·10	0·15	0·00	0·10	0·17	0·31	0·29	0·31
k	0·42	0·42	0·46	0·43	0·30	0·40	0·43	0·43	0·40
mg	0·05	0·40	0·38	0·13	0·31	0·43	0·44	0·43	0·43

Locations and rock types given in Table II.

variation it is possible to suggest where Carna Granite, isolated on islands (fig. 1), probably belongs in the succession.

The rock analyses are by a combination of X-ray fluorescence techniques using the method of Leake *et al.* (1969) and wet methods. Representative analyses for each of the granite types are given in Table I. It is unnecessary to give these data in full in view of the analyses already given by Wright (1964) and Claxton (1971), who have also supplied full petrographic descriptions of the granites. Coats and Wilson (1971) have studied both major and trace elements of the Galway Granite near Galway and trace element determinations are not quoted here although generally available. Sample BL3659 of Carna Granite with 1013 ppm Ba, 151 Rb, 343 Sr, 21 Yt, 87 Zr, 54 Ce, 18 Ga, 64 Zn, 27 Cu, 17 Ni, and 250 ppm S is typical.

The biotite analyses are by electron-probe analysis using analysed biotites as standards. On the whole, even allowing for undetermined H_2O and Fe_2O_3, the totals are rather low but as all the results have been obtained by reference to the same standards by the same procedures it is probable that variation between the different samples is not significantly influenced by this systematic error, which is believed to lie mostly in the SiO_2 and Al_2O_3. Each oxide given in Table II is the average analysis of at least three and usually five biotite flakes, each flake being analysed in at least ten different parts with one spectrometer always monitoring either K or Ti to ensure that slightly chloritized biotite was avoided. Thus each oxide quoted is usually the average *and Niggli numbers of Galway Granites*

3659	3652	3651	3648	3677	3679	3705	3683	3311	
67·78	69·91	70·03	69·91	69·67	68·89	70·71	69·18	69·27	SiO_2
15·13	14·59	14·71	15·31	14·94	14·88	14·86	14·92	14·97	Al_2O_3
0·39	0·36	0·34	0·23	0·44	0·35	0·20	0·32	0·39	TiO_2
0·86	0·66	0·77	0·52	0·66	0·61	0·39	0·93	1·29	Fe_2O_3
2·20	1·94	1·74	1·52	2·12	2·19	1·45	1·70	1·78	FeO
1·25	0·99	0·98	0·68	0·98	1·18	0·40	0·93	1·28	MgO
3·00	2·15	2·10	2·15	2·70	3·45	1·68	2·41	2·57	CaO
4·04	3·61	3·58	3·97	4·12	3·87	3·78	4·02	3·97	Na_2O
3·79	4·21	3·95	3·64	2·94	2·73	4·00	4·10	3·80	K_2O
0·07	0·07	0·07	0·06	0·07	0·07	0·05	0·07	0·08	MnO
0·24	0·10	0·18	0·14	0·14	0·17	0·10	0·17	0·17	P_2O_5
0·68	0·94	0·76	1·21	1·26	1·26	1·60	0·84	0·72	H_2O
99·42	99·53	99·21	99·34	99·31	99·55	99·22	99·59	100·29	Total
296	337	342	349	327	312	374	322	311	si
39·0	41·4	42·4	44·5	40·6	39·7	46·3	41·0	39·6	al
19·3	17·6	17·4	13·5	17·9	18·6	11·3	16·6	19·9	fm
14·0	11·1	11·0	11·4	13·7	16·7	9·5	12·0	12·4	c
27·7	29·8	29·3	30·6	27·8	24·9	32·8	30·4	28·1	alk
1·25	1·30	1·25	0·86	1·11	1·19	0·80	1·12	1·30	ti
0·44	0·20	0·37	0·29	0·28	0·33	0·22	0·34	0·32	p
0·38	0·43	0·42	0·38	0·32	0·32	0·41	0·40	0·39	k
0·42	0·40	0·41	0·37	0·39	0·43	0·28	0·39	0·43	mg

of fifty individual determinations. Only a selection of the results obtained are listed in Table II but the locations of all the forty-five analysed biotites are listed in the explanation to that table.

The feldspar compositions in the same rocks as the analysed biotites were also determined by electron probe analysis using analysed feldspars as standards, but because of the zoned nature of the crystals, the presence of albite rims, microperthite exsolution in the K-feldspar, and extensive and intensive sericitization of the plagioclase, it has not been possible to obtain the full range of the feldspar compositions nor the average compositions and so these analyses are not listed and a brief summary of the results is given in the text.

Results

Because of the irregular distribution of land and sea, and the unsuitability of referring the samples to distance from the margin of the batholith because the Murvey Granite is not always the peripheral granite, it is convenient to relate the sample positions to the outer edges of the Cuilleen Granite and the Carna Granite, using the former as a datum position and assuming that the nearly constant observed width of the Carna Granite lying peripheral to the Cuilleen Granite is continued towards Errisbeg (fig. 1).

Many plots of chemical parameters have been made from the biotite, feldspar, and

TABLE II. *Chemical analyses of*

Position	2·20 BL3490	2·12 3242	2·12 3220	1·90 2748	1·83 434	1·54 3470	1·52 3471	1·48 3274	1·00 3275	0·83 3668	0·75 3670	0·66 3278	0·55 3284	0·50 3318
SiO_2	33·64	37·90	37·56	36·55	36·13	37·16	37·62	37·03	36·80	36·97	36·90	36·80	36·61	36·99
Al_2O_3	17·41	13·79	12·72	15·94	15·27	13·20	13·05	13·38	13·78	13·86	13·94	13·95	13·62	13·60
TiO_2	3·38	3·24	2·80	2·70	2·67	3·45	3·18	3·43	3·19	2·69	3·34	3·55	3·59	3·69
FeO*	24·55	17·43	16·59	20·65	20·73	17·50	16·56	17·63	17·23	17·42	18·22	16·82	17·59	17·69
MgO	4·08	10·63	13·22	7·13	7·58	13·46	13·35	13·40	13·01	13·30	12·59	13·49	13·29	12·98
CaO	0·00	0·02	0·01	0·01	0·01	0·05	0·02	0·03	0·02	0·04	0·01	0·05	0·03	0·01
Na_2O		0·10	0·08	0·13	0·10	0·14	0·16	0·11	0·13	0·11	0·11	0·12	0·12	0·11
K_2O	8·90	9·45	9·49	9·35	9·00	9·29	9·29	9·24	9·42	9·29	9·32	9·14	9·35	9·41
MnO	0·72	1·44	1·13	1·70	1·39	0·78	0·78	0·67	0·62	0·55	0·54	0·68	0·48	0·55
F		1·35	1·35	1·05	1·13	0·68	0·74	0·76	0·66	0·60	0·58	0·62	0·66	0·57
		95·35	94·95	95·21	94·01	95·71	94·75	95·48	94·86	94·83	95·55	95·22	95·27	95·52
O ≡ F		0·57	0·57	0·44	0·48	0·29	0·31	0·32	0·28	0·25	0·24	0·26	0·28	0·24
Total	92·68	94·78	94·38	94·77	93·53	95·42	94·44	95·16	94·58	94·58	95·31	94·96	94·99	95·28
mg	0·22	0·50	0·57	0·36	0·38	0·57	0·58	·057	0·56	0·57	0·54	0·58	0·57	0·56
$\frac{100Mn}{Mn+Fe}$	3·1	7·7	6·4	7·7	6·3	4·3	4·5	3·7	3·5	3·1	2·9	3·9	2·7	3·05

* Total iron as FeO.

KEY TO TABLES I and II. Asterisked samples are biotite analyses not reproduced in Table II. Position is measured in miles positively from the top of the Cuilleen Granite to the margin of the batholith, negatively inwards from the top of the Cuilleen Granite. All measurements are in Imperial units as none of the maps available has a metric scale. All sheets referred to are 6 in. sheets Co. Galway.

BL434	Murvey Granite, 780 yards ESE. of Murvey Lodge on sheet 62.
BL2748	Murvey Granite, 600 yards S. of the *Y* of *Murvey* Townland.
BL3220	Errisbeg Townland Granite vein in country rock 90 yards WSW. of the western point of Cregduff Lough, sheet 63.
BL3242	Murvey-type Granite, western part of the same vein, 1020 yards W. of BM 49.5 on sheet 63.
BL3243	Garnetiferous aplite with muscovite, western end of the above vein, sheet 63.
BL3274	Errisbeg Townland Granite, 30 yards NW. of Spot ht. 87, roadside, Errisbeg West, sheet 63.
BL3275	Transition between Errisbeg Townland and Carna Granites on Inishlackan, 240 yards S. of the *R* of *Pier* on sheet 63.
BL3278	Carna Granite, 425 yards S. of the *K* of *Inishlackan* on sheet 63.
BL3284	Carna Granite, 300 yards WSW. of the 52 triangulation pt. on Inishlackan, sheet 63.
BL3311*	Carna Granite, Deer Island, 100 yards NE. of the *D* of *Croaghnakeela Island*, sheet 76.
BL3316*	Carna Granite, Deer Island, 600 yards S. of the *L* of *Croaghnakeela*, sheet 76.
BL3318	Carna Granite, 270 yards SW. of 55 triangulation pt., Gorteen, sheet 63.
BL3323*	Carna Granite, 210 yards N. of the *B* of *Illaunnacroagh Beg*, sheet 63.
BL3325*	Carna Granite, 120 yards SSW. of the 70 triangulation pt., Illaunnacroagh More, sheet 63.
BL3327*	Carna Granite, 300 yards SSE. of the last *G* of *Illaunnacroagh Beg*, sheet 63.
BL3331*	Carna Granite, 100 yards N. of the 70 triangulation pt., Illaunnacroagh More, sheet 63.
BL3333*	Carna Granite, 370 yards N. of the first *E* in *Croaghnakeela Island*, sheet 76.
BL3334*	Carna Granite, 360 yards WNW. of the 221 triangulation pt., Croaghnakeela Island, sheet 76.
BL3335*	Carna Granite, 390 yards SSW. of the 211 triangulation pt., Croaghnakeela Island, sheet 76.
BL3341*	Transition between Errisbeg Townland and Carna Granites, 750 yards WSW. from the *G* of *Gorteen Bay*, sheet 63.
BL3470	Errisbeg Townland Granite, 65 yards ESE. of Spot ht. 25, Errisbeg East, sheet 63.
BL3471	Errisbeg Townland Granite, 270 yards S. of the first *A* of *Ervallagh*, sheet 63.
BL3490	Garnetiferous aplite in country rock. Location in Leake (1968). K_2O is low and there is probably substantial Fe_2O_3.

biotites in the Western Galway Granite

0·32	0·00	−0·28	−0·50	−0·63	−0·95	−1·00	−1·10	−1·33	−1·58	−1·58	−2·58	−2·90	Position
3659	3652	3671	3658	3677	3689	3700	3680	3687	3705	3705A	3682	3683	
37·08	36·95	37·39	37·66	37·47	36·58	36·94	36·96	36·38	36·07	35·90	36·09	37·22	SiO_2
14·08	14·00	13·33	13·93	13·88	14·53	14·70	13·95	15·98	16·19	16·32	16·28	14·52	Al_2O_3
3·17	3·02	3·60	3·49	3·39	3·42	3·79	3·48	3·12	3·00	3·04	3·16	3·72	TiO_2
16·90	17·52	17·89	17·85	18·13	17·83	18·46	19·04	18·42	18·60	18·76	18·42	18·83	FeO*
13·80	12·99	12·84	12·39	11·99	11·95	10·98	12·03	11·28	10·24	10·33	10·48	11·38	MgO
0·01	0·01	0·02	0·01	0·02	0·02	0·03	0·01	0·01	0·05	0·03	0·01	0·02	CaO
0·07	0·12	0·11	0·12	0·12	0·19	0·12	0·11	0·16	0·12	0·12	0·12	0·11	Na_2O
9·30	9·39	9·40	9·25	9·44	9·35	9·11	9·36	9·41	9·41	9·36	9·48	9·36	K_2O
0·52	0·58	0·56	0·78	0·71	0·54	0·50	0·70	0·52	0·61	0·66	0·63	0·63	MnO
0·66	0·67	0·50	0·76	0·57	0·58	0·36	0·53	0·58	0·65	0·57	0·67	0·54	F
95·59	95·25	95·64	96·24	95·72	94·99	94·99	96·17	95·86	94·92	95·09	95·34	96·33	
0·28	0·28	0·21	0·32	0·24	0·24	0·15	0·22	0·24	0·27	0·24	0·28	0·23	O ≡ F
95·31	94·97	95·43	95·92	95·48	94·73	94·84	95·95	95·62	94·65	94·85	95·06	96·10	Total
0·58	0·56	0·55	0·54	0·53	0·54	0·51	0·52	0·51	0·49	0·49	0·49	0·51	mg
3·0	3·2	3·1	4·2	3·8	3·0	2·7	3·6	2·8	3·2	3·4	3·3	3·3	$\frac{100Mn}{Mn+Fe}$

BL3648* Fine 120-yard-thick granite dyke crossing Cuilleen and Carna Granite, 300 yards E. of the triple townland junction, Moyrus, Cuilleen and Ard West, in Mill Lough, sheet 76.

BL3651* Cuilleen Granite, 370 yards N. of the triple townland junction in Mill Lough, sheet 76.

BL3652 Cuilleen Granite, 30 yards E. of the *P* of *F.P.* about 300 yards E. of Forest View House, sheet 63.

BL3658 Fine-grained Carna Granite, 150 yards SE. of the 117 triangulation point Dooyeher, sheet 76.

BL3659 Carna Granite, 60 yards SE. of Spot ht. 43 on sheet 63 near Old Moyrus church.

BL3668 Carna Granite, traces of K-feldspar phenocrysts appearing at transition to Cuilleen Granite, 35 yards SSE. of Spot ht. 43 on sheet 63.

BL3670 Fine-grained Carna Granite, 35 yards SW. of the triangulation point 200 yards SW. of Lough Knockboy, sheet 63.

BL3671 Cuilleen Granite on shore 930 yards W. of Spot ht. 32 on Moyrus beach, sheet 63.

BL3762* Biotite-rich layer in Carna Granite, 10 yards N. of BL3671.

BL3675* Carna Granite, 210 yards at 350° from the *D* of *Dooyeher*, sheet 76.

BL3677 Carna Granite, 600 yards W. of BM 72.5 on shore in Dooyeher, sheet 76.

BL3678* Contacts of fine- and coarse-grained Carna Granite, on shore, 100 yards W. of the *Q* of *Quay* in SW. Dooyeher, sheet 76.

BL3679* Fine-grained rather K-feldspar-poor Carna Granite, 90 yards N. of the *M* of *H.W.M.* in Half Mace, sheet 76.

BL3680 K-feldspar-rich Carna Granite, 60 yards S. of the *H* of *H.W.M.* in Half Mace, sheet 76.

BL3682 Carna Granite with large biotites, 210 yards N. of the *Y* of *Quay* on north Mason Island, sheet 76.

BL3683 Carna Granite, 200 yards SW. of the *M* of *Mason Island*, sheet 76.

BL3687 Fine-grained Carna Granite with large biotites, 210 yards E. of the 93 triangulation pt., Half Mace, sheet 76.

BL3689 Carna Granite K-feldspar-poor, 140 yards S. of BM 33.7, Dooyeher, sheet 76.

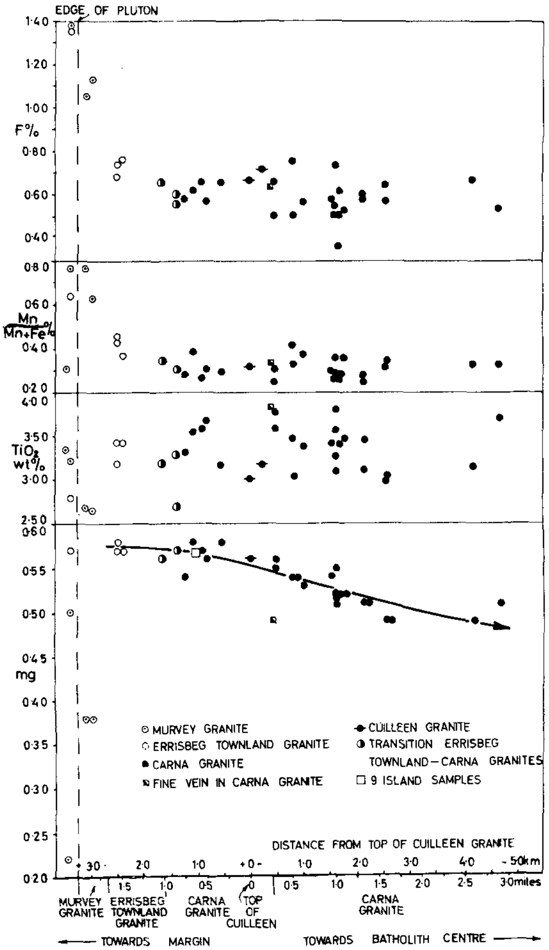
BL3692* K-feldspar-rich layer in Carna Granite, 20 yards ESE. of Spot ht. 23 near the Dooyeher–Half Mace boundary, in a stream, sheet 76.

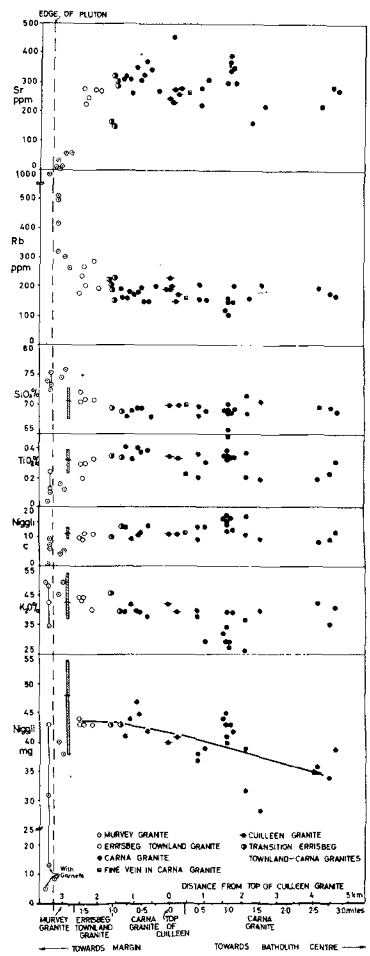
BL3694* Fine biotite-rich edge to fine aplitic-like Carna Granite, 30 yards E. of the first *A* of *Half Mace*, sheet 76.

BL3700* Carna Granite, south end of Mweenish Island, 350 yards N. of the triangulation pt., sheet 76.

BL3705 Carna Granite, 90 yards WNW. of Ard West Pier on sheet 76.

BL3705A As BL3705.





FIGS. 2 and 3: FIG. 2 (left). Plot of analysed biotites against distance from the outer edge of the Cuilleen Granite, distances towards the country rock being positive and those towards the centre of the batholith being negative. The position of nine samples from Croaghnakeela and the Illaunnacroagh Islands cannot be measured due to the isolation of these islands. The most probable position of these samples in the sequence is obtained by fitting their small mg range (0·56 to 0·57) to the differentiation line and suggests these islands lie near the outer edge of the Carna Granite. FIG. 3 (right). Plot of analysed granites against distance from the outer edge of the Cuilleen Granite, distances towards the country rock being positive and those towards the centre of the batholith being negative. Three samples from Croaghnakeela Island plotted using the position derived from fig. 2. The vertical line shows the range, and the horizontal cross-line the average, of thirteen analyses of Errisbeg Townland Granite by Claxton (1971) from Rosmuc, east of the present area. The geographical position of this vertical line has no significance and these data are plotted to indicate the compositional range of the Errisbeg Townland Granite.

rock analyses but most plots show no consistent trends of increase or decrease across the granite. It is considered highly significant that $Mg/(Mg+Fe^{2+}+Fe^{3+}+Mn)$, i.e. Niggli's *mg*, shows an over-all decline in both the rocks and the biotites from the Errisbeg Townland Granite to the innermost sample studied (figs. 2 and 3). Because the variation is small, and the amounts of MgO, Fe_2O_3, and MnO in the rocks are small, all the rock samples were re-analysed for each of these three oxides, as well as CaO and TiO_2, in single runs for each oxide by atomic absorption (CaO, MgO, and MnO) and colorimetry (total iron oxide) so that all these determinations are directly comparable. The biotites have been entirely independently determined by a different procedure (microprobe analysis) so that it is believed that the inward decline in mg across the Carna Granite, although small, is real. It is therefore apparent that mg falls both inwards across the Carna Granite and outwards from the Errisbeg Townland Granite through the albite-bearing Murvey Granite (fig. 2) to the marginal variety of the Murvey Granite that is found mostly at Murvey itself (fig. 1), a garnetiferous albite aplogranite that is identical to garnetiferous aplite veins in the country rock fringing the Errisbeg Townland Granite.

As decline in *mg* is one of the most reliable parameters in igneous rock variation that can be unequivocally linked to falling temperature of crystallization, these results show that the Carna Granite did not crystallize from the inside towards the slightly more siliceous and potassic Errisbeg Townland and then to the Murvey Granite but most probably from the *inner* border of the Errisbeg Townland Granite inwards.

This picture is broadly confirmed by the decline in Ti in the rocks from the outer edge of the Carna Granite, against the Errisbeg Townland Granite (fig. 3) inwards, for Ti falls in granitic rocks with increasing differentiation. The Ti content of the biotites does not reveal any reliable trend but although most of the biotites are unzoned a few show Ti-richer cores and Ti-poorer margins (e.g. BL3683, centre 3·97, edge 3·55% TiO_2), in agreement with a fall in Ti with falling temperature of crystallization.

The plagioclase in the Errisbeg and Carna Granites is usually normally zoned from about $Or_{1-2}\,Ab_{64-58}\,An_{35-40}$ to about $Or_{1-2}\,Ab_{84-83}\,An_{15}$ whereas the Murvey Granite ranges from about $Or_2\,Ab_{83}\,An_{15}$ (cores) to $Or_2\,Ab_{96}\,An_2$ (edges). The K-feldspars in the Carna and Errisbeg Townland Granites have compositions in the centres of about $Or_{85}\,Ab_{15}\,An_{0\cdot2}$ varying to $Or_{95-7}\,Ab_{5-3}\,An_{0\cdot1}$ at the edges whereas the Murvey Granite ranges only from $Or_{92-8}\,Ab_{8-2}\,An_{0\cdot1}$.

Layering in the batholith

The Carna Granite is banded with nearly vertical layers up to 300 m thick of K-feldspar-richer, biotite- and hornblende-poorer layers interbanded with more mafic K-feldspar-poor layers. The best developed K-feldspar-rich layer is the Cuilleen Granite but there are other layers not shown in the generalized geology of fig. 1 (e.g. NE. of Mace Head). These layers appear to have formed during the crystallization and they dip very steeply (*c.* 80°) outwards. It is extremely unlikely that they formed by settling in a subhorizontal position and were later made vertical because they lack settling textures and moreover it is difficult to manipulate the whole of the exposed granite so that all the banding became vertical from an originally flat position. These layers are believed to be the result of vertical movements in the magma giving 'flow sorting' (Wilshire, 1969) during the crystallization from the peripheral part of the Carna Granite inwards. Some of the thin layers could have formed by continuance of these vertical movements when the crystallization was nearly complete and the last crystallizing fraction of the magma, which would be rich in K-feldspar-forming constituents and silica, might be concentrated in zones of movement and then crystallized slowly in the hot Carna Granite, the more mafic material being left in zones on either side that crystallized to K-feldspar-poor granite. The layering as a whole is therefore believed to be generally consistent with a model of crystallization in steep zones from the edge of the Carna Granite inwards, during movements in the granite.

On a smaller scale both the Errisbeg Townland and Carna Granites contain biotite-rich layers (10 cm to 2 m thick) that usually strike E.–W. to ESE.–WSW. and dip outwards towards the edge of the pluton between 50 and 85°. These layers are interpreted as being formed by shearing of the almost solid granite, and overlap and are later than the major banding already described, sometimes crossing this banding. Adjoining many of the biotite-rich layers are layers of K-feldspar-rich, biotite-poor granite, obviously representing the felsic portion complementary to the mafic biotite-rich layer. There was probably a continuous transition from the last-formed major layering to the first-formed biotite-rich layering during which the same processes of movement in the granite were continuous and acted on progressively more consolidated granite. In some instances, the shearing was even later and the felsic matter adjoining the biotite-rich zones formed aplitic veins and patches, and last of all were biotite layers and aplite veins that flagrantly cross the generally ESE.-striking major banding (e.g. NE.-striking biotite layers 200 m north of Mace Head).

A somewhat similar biotite layering is found in the Errisbeg Townland Granite where this is perfectly exposed on the coast, especially on the north shore of Dogs Bay (fig. 4). This layering dips with a much lower inclination, usually between 20 and 45°, but again always northwards to the margin of the granite. Sometimes this gently dipping layering contains right-way-up current bedding and distinct right-way-up graded bedding with biotite-rich bottoms grading upwards into biotite-poorer granite, which is immediately followed by a coarse K-feldspar-rich granite. There is no doubt that this gently inclined layering is the result of crystal settling under the influence of gravity sometimes accompanied by magmatic currents. Similar layering, generally dipping out towards the granite margin, has been described by Claxton (1968) and Aucott (1965) in the Errisbeg Townland Granite east of the present ground and by Emeleus (1963) and Ferguson and Pulvertaft (1963) in syenites and granites in south Greenland. All these authors attribute this layering to gravity settling. The rarity of this gently inclined layering with evidence of gravity settling in the Carna Granite compared with the Errisbeg Townland Granite is indicative of the different conditions of crystallization of the two granites. While it is possible that some of this layering has been formed by mobilization of the granite in zones of shear in the largely consolidated granite, i.e. by a mechanism similar to that which gave the more steeply dipping layers, but accompanied by crystal settling, it is quite clear, e.g. on Dogs and Gorteen Bays, that in general this is a primary igneous layering of the granite accompanying crystallization. This layering is not associated with aplitic felsic matter nor does it cross any pre-existing banding and is either dipping off the Carna Granite or has been tipped up by the rise of the Carna Granite. Such layering indicates upward and outward crystallization differentiation as shown by Sr, Rb, Ti, and SiO_2 in fig. 3.

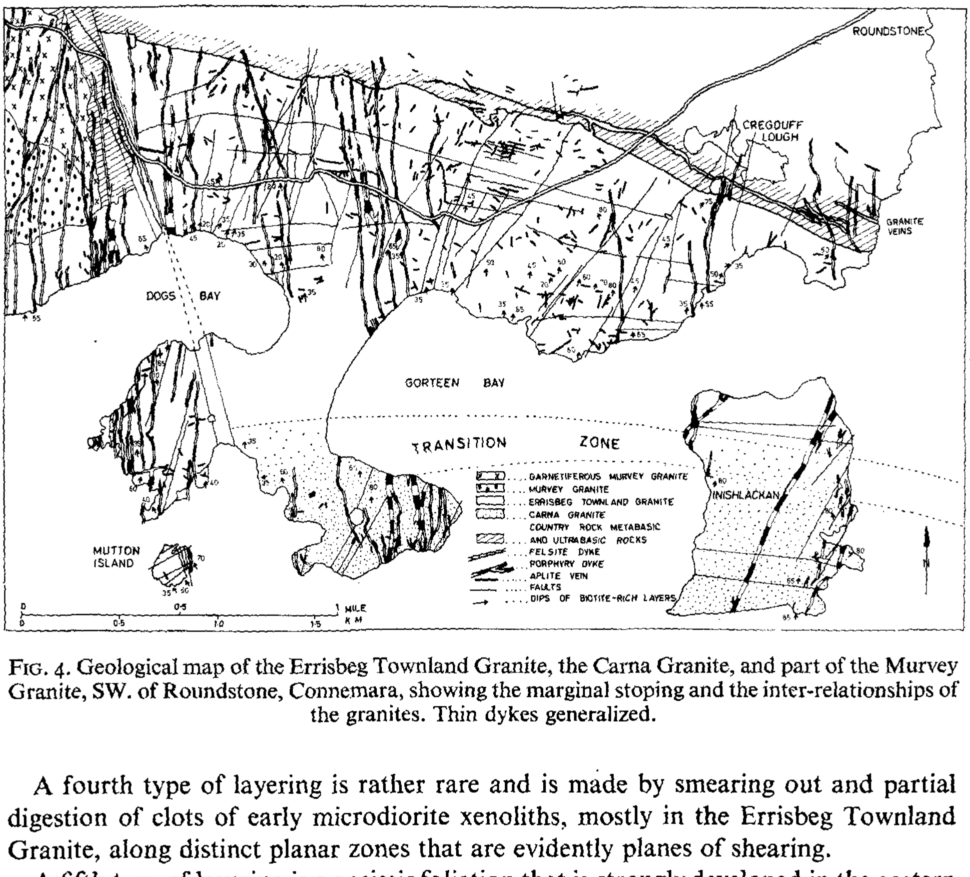


Fig. 4. Geological map of the Errisbeg Townland Granite, the Carna Granite, and part of the Murvey Granite, SW. of Roundstone, Connemara, showing the marginal stoping and the inter-relationships of the granites. Thin dykes generalized.

A fourth type of layering is rather rare and is made by smearing out and partial digestion of clots of early microdiorite xenoliths, mostly in the Errisbeg Townland Granite, along distinct planar zones that are evidently planes of shearing.

A fifth type of layering is a gneissic foliation that is strongly developed in the eastern and north-eastern parts of the batholith but is totally absent in the west. Its absence in the ground dealt with in this account shows that the western part of the Galway batholith was not sheared by post-consolidation penetrative movements. Late movements in the west have produced faults and joints only.

Xenoliths

Xenoliths occur as small 2 cm to 2 m rounded lumps in the Errisbeg and Carna Granites but not in the Murvey Granite. They are microdiorites, being fine grained (0·5 mm) and composed of andesine with clots of hornblende, iron ore, and biotite, but they are variably feldspathized, silicified, and dissipated into the enclosing granite.

Usually such xenoliths are considered to be cognate as an early crystallization from the magma. They are certainly not derived from the country rock, the composition and texture of which is totally different. Moreover there are rare country rock xenoliths and they are quite distinct in appearance and mineralogy and are little modified in the granite. Coats and Wilson (1971) have shown that the cognate xenoliths are chemically more basic than any of the granite masses so far described in the Galway pluton and they plot at the beginning of the differentiation trends of the various Galway Granite types. However, this fine-grained texture seems to exclude an origin by slow crystallization and possibly the xenoliths are torn-off pieces of early chilled Galway Granite magma, crystallized against the edge. More probably they might be completely disrupted dykes injected into partly crystallized granite and cooled relatively quickly because the crystallization temperature of more basic magma would be higher than the enclosing granite. If subsequent turbulent upheaval of the granite and its dykes occurred the dykes could be broken up and distributed as xenoliths in the newly mobilized granite with partial remelting of both the granite and the dyke-xenoliths taking place under the influence of reduced pressure, without heating, due to the restricted water content of the magma, the little available water having been locked in hornblende and biotite. Disrupted dykes converted into xenoliths are magnificently displayed on the east shore of Croaghnakeela Island so the above proposal is not entirely hypothetical and would accord with the general hypothesis of this paper that the granite records a long history of progressive upward emplacement.

The strontium isotope results of Leggo *et al.* (1966) on the Murvey and Errisbeg Townland Granites show that no detectable contamination of the granite by the assimilation of country rock has occurred. Even the marginal Garnetiferous Murvey Granite is totally uncontaminated and as it contains only 3 to 8 ppm Sr whereas the country rocks have several hundred ppm Sr, any contamination would be easily detected. Quite clearly any stoped country rock fell through the magma as undissolved blocks, a deduction in agreement with the unaltered condition of the rare country-rock xenoliths seen. The country rock is basic and ultrabasic rock previously regionally metamorphosed, with a melting-point of over 900 °C, and is rather dense, so that xenoliths of this type would be expected to sink rapidly and with little melting in the granite magma.

The origin of the Murvey Granite

The rock analyses for Si, Rb, Sr, Ti, Ca, K, and mg all show that the Murvey Granite is much more acidic and differentiated than the Errisbeg Townland Granite. The explanation of this possible transition to acidic rocks at the edge of the batholith has been particularly difficult. Coats and Wilson (1971) tentatively suggested that water diffused to the cooler parts of the batholith, lowering the liquidus temperature at the granite margin and transporting alkalis and other volatiles to the granite periphery. There are difficulties with this hypothesis. First, the marginal granites, both Murvey and Garnetiferous Murvey Granite, are the least hydrous, not the most hydrous of the granite suite and secondly, increase of water pressure in the granite system displaces the thermal minimum away from silica-rich compositions such as the Murvey Granite possesses, not towards such compositions.

In view of the gravity-settled layers in the Errisbeg Townland Granite it is an obvious deduction that the Murvey Granite crystallized as a layer on top of the Errisbeg Townland Granite as a last differentiate from that upward crystallization magma.

This is consistent with the transitional contact of the Murvey Granite and the Errisbeg Townland Granite on the shore at Murvey where biotite layers dip 5 to 50° to the north, some of which have right-way-up graded bedding plunging towards the Murvey Granite, which therefore crystallized on top of, at the side of, and after the Errisbeg Townland Granite. It is also supported by the mineralogy, for the Murvey Granite lacks hornblende and has plagioclase ranging from An_2 to An_{15} whereas the Errisbeg Townland Granite has hornblende and lacks albite, and ranges from acid oligoclase to An_{35-40} in the centres of zoned crystals. The biotites in the Murvey Granite are more iron-rich than those in the Errisbeg Townland Granite and spessartine–almandine garnets (analyses in Wright, 1964; Leake, 1968) eventually develop in the aplitic-textured Garnetiferous Murvey Granite. This is foreshadowed in the main Murvey Granite by the occurrence of garnets in aplite veins. There is also a gradual decline in the size of the K-feldspar phenocrysts in the Errisbeg Townland Granite from its base near the Carna Granite where the longest dimension averages 2·2 mm (max. 3 mm) to 1 mm (max. 2 mm) near to the country rock or Murvey Granite. The occurrence of Murvey Granite in a flat sheet capping low hills east of Carna (fig. 1) as mapped by Wright (1964), suggests that the Murvey Granite magma collected in suitable pockets as residual magma on top of the Errisbeg Townland Granite while its absence along parts of the granite periphery shows that it was not present as a uniform sheet on top of and at the edge of the Errisbeg Townland Granite.

However, simple magmatic differentiation due to crystal settling is certainly inadequate to explain all the evidence. Firstly because no chilled marginal magma is known and this would be expected against the walls of the magma chamber. Secondly because there is a very marked break in composition, both chemically and mineralogically, between the Murvey and Errisbeg Townland Granites. Thirdly because there is an equally pronounced textural change when the K-feldspar phenocrysts, in the Errisbeg Townland Granite, although smaller near to the Murvey Granite than further south, abruptly disappear over the contact between the two granites. Finally, the Murvey Granite has a distinct association with marginal situations where the granite appears to corrode into the country rock further than the Errisbeg Townland Granite does (fig. 1).

Furthermore, the Errisbeg Townland Granite injects the country rock south-west of Roundstone (fig. 4) and here a granite vein was arrested in the process of stoping the meta-basic to ultrabasic country rock. This vein has a complete transition from Errisbeg Townland Granite at its root in that granite to Murvey Granite along the length of the vein and to a fine grained aplite with garnet, topaz, and tourmaline in the centre of the vein near its end. Texturally and chemically (specimens BL3220, 3242, 3243; Table I) this transition reproduces in one vertical vein the sequence from Errisbeg Townland Granite through Murvey Granite to marginal aplitic Garnetiferous Murvey Granite. Clearly this vein was formed neither by separate magma injections nor from residual magma at the top of the magma chamber but is an integral part of the crystallization sequence at the margin of the batholith.

A clue to the origin of the Murvey Granite is provided by the aphyric or even *aplitic* texture, mineralogy, and chemical composition of the Murvey Granite. Aplites within granites probably form as a result of dilation during the very last stages of solidification of a granite when the granite is sufficiently solid to crack but still contains a modicum of residual magma. Into the crack flows or distils this residual interstitial liquid to crystallize immediately in the typical fine, even-grained granite texture of aplites. The albitic plagioclase, the nearly pure orthoclase (*c.* Or_{95}) and the general paucity of mafic minerals and their Fe and Mn rich compositions agree with aplites as residual differentiates. The observation in the Errisbeg Townland and Carna Granites that the thickest aplites are the earliest ones and these are crossed by later thinner aplites accords with a picture of diminishing available residual magma with progressively complete rigidity of the granite. The aplites outside the granite, which are well developed along ESE.–WNW. cracks in the country rock at Errisbeg Townland, are formed by rapid egress of the residual magma out of the batholith into a marginal dilational crack. All these cracks, both inside and outside the granite, are believed to form by deep-rooted pushing by underlying magma and possibly by gravitational rising of the lighter granitic material in the crust compared with the country basic and ultrabasic rocks.

The aplites in the Carna and Errisbeg Townland Granites are not so differentiated as those in the Murvey Granite. Thus a typical Carna Granite aplite has An_{6-18} normally zoned plagioclase with Or_{91-96} K-feldspar whereas the aplites containing garnet in the Murvey Granite contain An_{1-9} and Or_{94-97}, values identical with the Garnetiferous Murvey Granite and the garnetiferous aplites outside the granite in the country rock.

It is therefore proposed that the Murvey Granite was formed from residual magma drawn out of the almost crystallized Errisbeg Townland Granite due to stoping of the margin of the granite. As the blocks fell into the granite, as they would because the contact everywhere dips outwards (35–85°), they created a region of rarefaction into which the residual magma in the Errisbeg Townland Granite was drawn. This is why the ends of the Errisbeg Townland Granite, vein-stoping the country rock (fig. 4), contain Murvey and thin aplitic granite. The Garnetiferous Murvey Granite would have formed by a similar drawing of the last crystallizing liquid out of the Murvey Granite giving an aplogranite devoid of aplite veins. This explains why the aplites in the Murvey Granite have identical mineralogy, including sometimes the presence of garnet, and identical texture to the Garnetiferous Murvey Granite. They formed from the same residual magma by a similar rapid crystallization, thus explaining the absence of K-feldspar phenocrysts, which are a characteristic feature of the Errisbeg Townland Granite.

This theory also explains the absence of chilled margins to the granite against the country rock. The original chilled margins have been stoped away. The country rock would have been heated near to the granite and when the pieces of margin fell off they would expose heated country rock against which the granite could not chill.

As the country rock is meta-basic and ultrabasic rock with a melting temperature several hundred degrees above the temperature of granite magma, little or no melting of the country rock would occur and it would fall as dense, largely unmodified blocks through the granite magma.

The paucity in hydrous minerals in the aplogranite, the rarity of topaz, tourmaline, and biotite in the granite vein described and the F enrichment of the biotite in the Murvey Granite (presumably at the expense of the OH constituent) indicates that the last crystallizing liquid was not water-rich but water-poor, a deduction in agreement with the almost complete lack of pegmatities in the Galway Granite. The northern margin of the Murvey and Garnetiferous Murvey Granite at Murvey, against the country rock, has in places a few metres of pegmatitic quartz and K-feldspar crystallized at the periphery and these two minerals form very rare pegmatites elsewhere (e.g. north shore of Croaghnakeela Island, north of the *n* in *Island* on 6 in. sheet 76) but these rare pegmatites, although sometimes with a little muscovite (Wright, 1964), are not rich in hydrous minerals.

The proposed origin of the Murvey Granite implies that where there is Errisbeg Townland Granite against the edge of the batholith, the last block of country rock to fall into the granite fell when the Errisbeg Townland Granite was still largely magma and so this magma filled the space with little or no segregational separation from the bulk of the magma. Alternatively, the magma may have pushed upwards the marginal blocks of country rock without creating a dilational space and occupied the vacated space *en masse*.

The evidence of an unpublished gravity survey (Farah, 1960), of extensive drilling of the Murvey Granite undertaken for molybdenite exploration, and of field observations of the granite margin, all show that the edge of the Murvey Granite dips outwards under the country rock at lower angles (about 60°) than the contact of the Errisbeg Townland Granite and the country rock, which is nearer to vertical. A steep contact would be least favourable for prising away blocks that would fall into the magma and so the inclination of the contact could have been an influencing factor in the location of the Murvey Granite.

The biotite layers at the contact of the Murvey and Errisbeg Townland Granites would have formed by settling of the biotite out of the disturbed marginal Errisbeg Townland Granite.

The Murvey Granite east of Carna is presumably lying just under the now eroded roof of the granite but this falls outside the area mapped by the author and fuller details can be found in Wright (1964).

Errisbeg Townland, Carna, and Cuilleen Granites

The mg value of the Errisbeg Townland Granite is very similar to that of the marginal Carna Granite and chemically most of the plots (figs. 2 and 3) show the very close affinity of the compositions of the two granites. This mg value is consistent with crystallization from the inner margin of the Errisbeg Townland Granite inwards. The tendency in the area considered for the Errisbeg Townland Granite to have a little more SiO_2 K_2O, and Rb and slightly lower CaO and TiO_2 is not found in the Errisbeg

Townland Granite further east where it is several miles in outcrop width (Claxton, 1971) and this is shown diagrammatically on fig. 2. Accordingly it is reasonable to suppose that the weak chemical tendencies mentioned are connected with the occurrence in the present area of the Errisbeg Townland Granite in a narrow marginal layer. If stoping of the country rock occurred early in the crystallization of this granite when it was still partly liquid then the preferential migration of the siliceous alkali-feldspar-rich material to the margin plus upward differentiation might explain these muted chemical features. An aplitic texture would not be expected from early stoping as slow crystallization would still be possible for liquids not at a eutectic.

The presence of K-feldspar phenocrysts, which certainly in their later stages of growth replaced plagioclase, is indicative of a long period of relatively undisturbed crystallization, consistent with the well-developed gravity layering. The smaller size of the phenocrysts near to the margin of the granite suggests repeated disturbances of the magma that prevented the growth of large phenocrysts. The gradual increase in size of the phenocrysts towards the Carna Granite expresses a less disturbed regime. The disappearance of the phenocrysts, but without diminution of their size, in passing through the 300 m transition zone to the vertically layered Carna Granite suggests that the Carna Granite formed from a vertical zone of magma that moved sufficiently late to prevent the static uniformly distributed growth of K-feldspar phenocrysts, this movement occurring in pulses as the granite solidified from the margin inwards. This would accord with the vertical layering and small-scale banding described in the Carna Granite. A pause evidently occurred while the Cuilleen Granite formed. The chemical plots (figs. 2 and 3) demonstrate that the Cuilleen Granite is purely a texturally different layer, not a compositionally distinct rock.

Whereas crystallization in the Errisbeg Townland Granite was partly by crystal settling, crystallization in the Carna and Cuilleen Granites was from the walls inward, often during vertical movements, some of which caused late steep remobilization in the Errisbeg Townland Granite giving the steep biotite-rich layers. These presumably upward movements in the Carna Granite tipped up the flat gravity-settled layers in the Errisbeg Townland Granite and caused them to dip outwards. At the southern edge of the Galway Granite on Gorumna Island the layering in the Errisbeg Townland Granite dips southwards, with Carna Granite lying north of the Errisbeg Townland Granite (Laurence, 1968). On Croaghnakeela Island steep layering strikes north–south and dips westwards. This pattern of outward-dipping gravity layering and concordant-to-the-margin steep layering is only consistent with upward vertical movement in the steep layering. At a late stage these movements disrupted dykes that had been intruded during a period of quiescence on Croaghnakeela Island.

Further east there is good evidence that the Errisbeg Townland Granite crystallized by gravity settling from the centre of the batholith with a marginal granite that is a mixture of both a late sheared Murvey-type granite and a more basic granite that probably crystallized from the edge of the batholith inwards.

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