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The eastern end of the Galway Granite

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(With Plate I)

SUMMARY. An account of the eastern part of the Galway Granite is presented together with the first detailed geological map. An aphyric medium-grained alkali granite occurs at the margin of the pluton followed by a coarse porphyritic granite, which becomes more basic towards the granite centre, consistent with findings in the western and northern parts of the batholith. Westwards the coarse porphyritic granite develops a foliation in which xenoliths, and occasionally potash feldspar phenocrysts, are aligned. Chemical fractionation trends illustrate the consanguinity of the granites and aplites. Field, petrographic, and chemical evidence suggest that most of the xenoliths are cognate.

The zonation of the granite is thought to have resulted from crystallization of a magma in which compositional gradients were set up during the early crystallization period. A temperature gradient, decreasing from the centre of the magma chamber outwards into the country rocks, resulted in the migration of water, accompanied by alkalis and other volatiles, towards the granite margin; also the early-crystallizing minerals displaced the residual magma outwards. Crystallization was followed by shearing in the deeper parts of the pluton to produce the granite foliation. A total of 166 rocks have been chemically analysed for 31 constituents.

THE Galway Granite is a zoned pluton that intrudes the Connemara migmatites on its northern margin (Leake and Leggo, 1963) and the South Connemara Series in the south on the islands of Lettermore and Gorumna (McKie and Burke, 1955). The granite has been dated by the Rb–Sr method as 384 ± 1 Myr (Leggo *et al.*, 1966) using a Rb^{87} half-life of $4{\cdot}7\times10^{10}$ years. Pidgeon (1969) has obtained a U–Pb of 420 ± 20 Myr, closely in agreement with the Rb–Sr age of 407 ± 5 Myr based on a Rb^{87} half-life of $5{\cdot}0\times10^{10}$ years.

About 20 square miles of the granite near Galway, Western Ireland (pl. I) have been mapped on 1:10 560, the area being limited to the north-east by the unconformable Carboniferous limestone and to the south by the sea. Exposure varies from very good along the coast and in the west to poor close to Galway.

The only previous map, sheet 105 on the scale of 1:63 360, was by the Irish Geological Survey (Kinahan, 1869). The migmatites were distinguished from the Galway Granite, within which porphyritic and foliated types were recognized together with an intrusive granite, now regarded as thick porphyry dykes. Cole (1915) described a 'composite gneiss' near Barna, interpreted in the light of this work as the progressive granitization of large xenoliths. Wager (1932) worked in the Roundstone district and recognized two major units within the Galway Granite. Burke (1957) described the general structure of the pluton. Fig. 1 indicates the parts of the Galway Granite that have been studied recently.

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Field relations

Country rocks. The foliation of the migmatitic basic gneisses dips steeply to the north or north-west. They are medium to coarse grained hornblende–plagioclase rocks, veined by quartz–K-feldspar–plagioclase–biotite rocks, especially in the south. The country rock foliation is not deflected at the granite contact and there is only slight contact alteration and no apparent stoping. The granite is clearly transgressive to the country rock, the contact striking roughly north–south, at right angles to the strike of the basic gneisses.

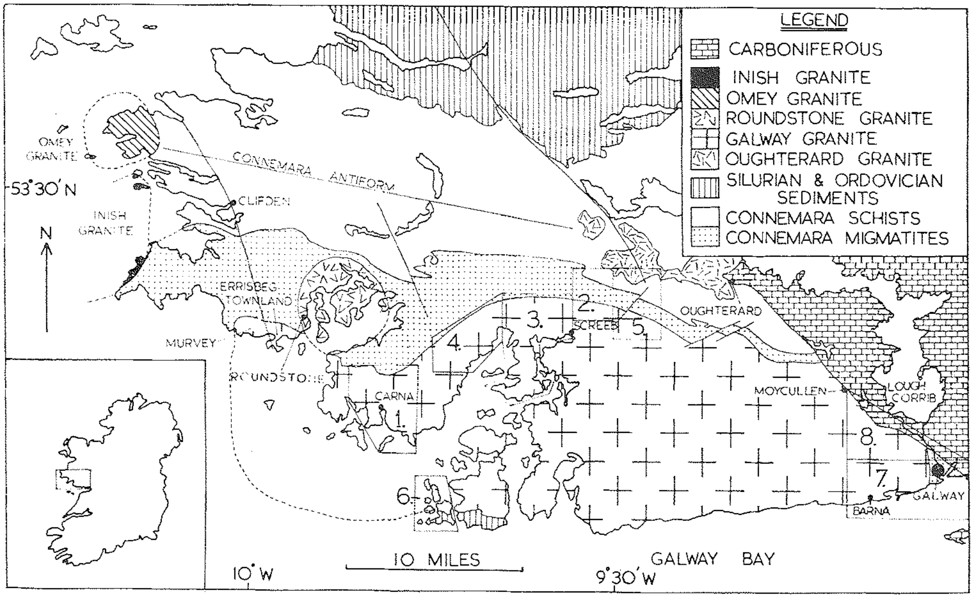

FIG. 1. Location of areas studied, or under study, with respect to the granites of Co. Galway, Ireland. 1. Wright (1961, 1964). 2. Leggo (1963). 3. Claxton (1965). 4. Aucott (1966). 5. Plant (in preparation). 6. Lawrence (1968). 7. Coats (1970). 8. Wilson (1969).

The biotite-poor aphyric granite is pink weathering and has a grain size of 2–3 mm, outcropping in a strip adjacent to the country rock. Along the coast south of the coarse porphyritic granite it becomes finer grained (1–2 mm) and is aplitic in character. Three patches of this aplitic variety occur near Corcullen, 4 miles north-west of Galway City. The biotite-poor aphyric granite is comparable to the Murvey Granite found near Roundstone (Wager, 1932) and Carna (Wright, 1964). A characteristic of the Galway Granite is the frequent occurrence of a Murvey-type granite at the margin of the pluton.

The coarse porphyritic granite possesses characteristic pink K-feldspar and occasional plagioclase phenocrysts in a quartz–oligoclase–K-feldspar–biotite groundmass that averages 5 mm in grain size. Westwards this granite becomes more basic, with biotite increasing and quartz decreasing and $2\frac{1}{2}$ miles from the country rock hornblende comes in. The poorly exposed contact of the coarse porphyritic granite and the biotite-poor aphyric granite is thought to be gradational over a few feet, and the former loses its large K-feldspar phenocrysts.

The coarse porphyritic granite is cut by a series of aplites, ranging from early, coarse-grained (1–0·5 mm), broad irregular ones to later, fine-grained (0·5–0·02 mm), narrow ones with constant strike, which may contain small, well-formed garnets. Pegmatites of quartz and K-feldspar occur as pods rarely exceeding four metres in length and as veins up to one metre thick.

The coarse porphyritic granite is similar to that occurring at Errisbeg Townland (Wager, 1932) and Carna (Wright, 1964) but it differs slightly in having a wider variation in grain size.

The coarse porphyritic foliated granite. In the west of the area, the coarse porphyritic granite becomes foliated, defined by the alignment of sheared quartz and biotite and occasional alignment of K-feldspar phenocrysts. In the south the contact of this coarse porphyritic foliated granite with the coarse porphyritic granite and the biotite-poor aphric granite is a 150° trending fault, the Barna fault. Near Barna the foliation strikes at 100° dipping northwards at about 70°, swinging round northwards until it strikes north–south at Corboley, dipping to the east at about 80° (see pl. I). The coarse porphyritic foliated granite has not been described before in the Galway Granite, though a similar granite occurs (see fig. 1) near Shannowona (Plant, pers. comm).

Within the coarse porphyritic foliated granite are irregular bands, up to 250 m wide, of K-feldspar-rich granite, with no hornblende, less biotite, and more K-feldspar and quartz than its host. The foliation of this K-feldspar-rich granite is poorly defined because of the lesser amount of biotite and lack of large aligned K-feldspar phenocrysts. Contacts between the two granites can be sharp but are generally gradational over a few centimetres. Aplites are very common in this granite.

Cutting both the coarse porphyritic foliated granite and the K-feldspar-rich granite are bands of finer foliated granite, which have a similar mineralogy to the former but an average grain size of 1 mm and only rare K-feldspar phenocrysts up to $2 \times 2 \times 1$ cm. The foliation affects this granite as well as its host, with which it has sharp, unchilled contacts, dipping to the north and east. The period of aplite formation overlaps the intrusion of this granite.

Xenoliths are sparsely distributed in the coarse porphyritic granite and are not seen in the biotite-poor aphyric granite. They are grey-weathering, medium-grained plagioclase–biotite–hornblende assemblages with occasional porphyroblastic plagioclase and K-feldspar, and are well rounded with a diameter of up to 60 cm. Xenoliths are abundant in the coarse porphyritic foliated granite, where they are discoid in shape and platy in the foliation plane, varying in size from small biotite clots 1 cm in length up to the largest, measuring 200×50 m. One xenolith, 20×10 m, of semipelitic appearance and with relict foliation oblique to that of the host granite, was observed west of Lough Inch but this was the only xenolith that could be matched with any of the country rocks.

Biotite layers. Mineral layering is a feature of the Galway Granite, having been described by Aucott (1966) in the Crook Moithan area and by Claxton (1968) in the Screeb–Invermore–Rosmuc area.

Biotite-rich layers or bands, cut by aplites, occur in the coarse porphyritic granite, dipping steeply to the north-west and being traceable for up to 200 m. Some of these biotite layers have associated felsic bands. Their maximum thickness is 3 m and the contacts are sharp with the surrounding granite, which is not depleted in biotite. Layers of this type are thought to have resulted from early shear movement along restricted zones, which produced a melt that differentiated to give the layered effect, all the biotite having separated from the now-felsic part of the layer. Other biotite-rich layers have a sharp base and grade up into normal granite, the biotite flakes being roughly orientated in the layer. Potash feldspar phenocrysts can occur in these layers, which may represent original magmatic cumulates. In the coarse porphyritic foliated granite all the biotite layers are in the foliation plane and appear to be of shear origin.

Dykes. A major feature of the eastern part of the Galway Granite is the presence of abundant porphyry dykes. These form a continuous sequence from dark plagioclase porphyries, through grey plagioclase–quartz porphyries and grey or pink granite porphyries to felsites. They cut all the granite types, aplites, and country rocks. They were not subdivided in the field because of the variation along individual dykes and the presence of dark margins.

In the east the porphyry dykes are very linear with a marked north–south strike and sharply chilled margins. Towards the centre of the area in the coarse porphyritic granite the dykes increase in their outcrop, become more irregular in shape and have less chilled margins. West of the Barna fault they become more regular, their course often being fault-controlled.

Fine-grained grey or buff felsites occur rarely and show excellent flow banding. They represent the last stages in the dyke sequence and cut the earlier porphyries.

One thin dolerite dyke of possibly Tertiary age strikes north–south and cuts the coarse porphyritic foliated granite. Similar dykes have been reported by Wright (1961) and Lawrence (1968).

Petrography

The biotite-poor aphyric granite has a hypidiomorphic equigranular texture and is very similar to the Murvey Granite at Carna and Lettermullen. Mean modal analyses are given in table I, and using Streckeisen's (1967) classification it is a 'normal granite'.

Alkali feldspar is orthoclase microperthite, poikilitically enclosing some plagioclase, chloritized biotite, and accessory magnetite, zircon, sphene, and apatite. Quartz has sharp extinction and plagioclases are normally zoned with centres of An_{16} to An_{10}

and rims of An_8 to An_6, sericitization being concentrated at the cores of the grains. The aplitic variety of the biotite-poor aphyric granite contains some interstitial muscovite.

TABLE I. *Granite modal analyses compared with those of previous workers*

	A	B	C	D	E	F	G	H	I
No of analyses.	9	7	5	23	5	8	4	7	6
Quartz	37·4	34·4	34	29·1	28·5	28	28·0	24·1	25
K-feldspar	32·6	33·8	36	30·3	30·8	31	24·5	23·9	27
Plagioclase	26·5	29·8	28	33·9	33·5	34	35·4	41·6	38
Biotite+chlorite	2·85	1·8	0–2	5·64	6·2	5	8·35	6·5	6
Hornblende	—	—	—	0·17	0·6	0·5	1·85	2·0	2
Ore	0·54	0·2	tr.	0·55	0·5	0·5	0·83	1·1	1
Apatite	0·05	tr.	tr.	0·10	0·1	tr.	0·13	0·5	tr.
Sphene	0·02	tr.	tr.	0·18	0·1	tr.	0·35	0·3	tr.
Zircon	0·01	tr.	tr.	0·05	tr.	tr.	0·06	tr.	tr.
Allanite	0·03	tr.	tr.	0·01	tr.	tr.	0·03	tr.	tr.

A. Biotite-poor aphyric granite. B. Murvey Granite (Wright, 1964). C. Murvey Granite (Lawrence, 1968). D. Coarse porphyritic granite. E. Errisbeg Townland Granite (Wright, 1964). F. Errisbeg Townland Granite (Lawrence, 1968). G. Coarse porphyritic foliated granite. H. Carna Granite (Wright, 1964). I. Carna Granite (Lawrence, 1968).

Samples for modal analysis were selected from those rocks that have been chemically analysed. Modal analyses were determined using an automatic point counter with a horizontal step of 0·3 mm and a vertical step of 0·1 mm on three thin sections for each analysis.

The coarse porphyritic granite and coarse porphyritic foliated granite are hypidiomorphic inequigranular granites and can both be classified as 'normal granites' (Streckeisen, 1967). The coarse porphyritic granite is modally similar to the means of the Errisbeg Townland Granite of Wright (1964) and Lawrence (1968), table I. The coarse porphyritic foliated granite has a mean modal composition near the Carna Granite of the two latter authors but the Carna Granite (an aphyric type) has no textural equivalent in the Galway area.

Quartz decreases slightly westwards and is interstitial to plagioclase and biotite. In the east the extinction of the quartz in the porphyritic granite is fairly sharp becoming increasingly undulose westwards. Quartz in the coarse porphyritic foliated granite has patch extinction and is frequently recrystallized to a fine-grained aggregate, which forms a belt-like mosaic sweeping round the feldspar crystals. Elongated or sheared quartz aggregates have sutured or highly implicated grain margins, giving a 'metamorphic' texture. Some annealing recrystallization has taken place to give relatively large, unstrained quartz crystals in a fine grained aggregate.

K-feldspar decreases slightly westwards, occurring as megacrysts and anhedral grains in the groundmass. Euhedral plagioclase and biotite inclusions are often aligned parallel to the crystal faces of the host and up to twelve zones, indicated by extinction differences, can be present in one phenocryst. In the coarse porphyritic granite the K-feldspar is orthoclase microperthite but as the coarse porphyritic foliated granite is approached the structure becomes dominantly microcline. In the coarse porphyritic foliated granite the K-feldspar crystals act as rigid blocks in a 'plastic' groundmass of quartz and mica and are cracked, broken, and microfaulted. Crystals may become rounded when their appearance is similar to that of the 'eyes' in augen gneiss.

Plagioclase increases westwards from about 32 % near the contact with the biotite-poor aphyric granite to about 37 % west of the Barna fault. It occurs as euhedral or subhedral, normal and oscillatory zoned crystals, often in aggregates. In the east the cores, usually heavily sericitized, are about An_{25} with rims of An_{12}, while in the west An_{33} cores have rims of An_{20}. In the coarse porphyritic foliated granite the plagioclase is mechanically deformed in a similar manner to the K-feldspar.

Biotite increases from 5 % in the east to about 10 % in the coarse porphyritic foliated granite. It is pleochroic (α pale straw, β and γ dark brown) and often altered to chlorite. In the coarse porphyritic foliated granite biotite crystals with their (001) cleavage near the foliation plane show translation gliding and become streaked out, whilst those lying at a high angle to the foliation plane are microfolded or bent.

Green hornblendes altered to chlorite and carbonate accompany biotite in the coarse porphyritic granite about $2\frac{1}{2}$ miles west of the country-rock contact. Hornblendes in the coarse porphyritic foliated granite are usually fresh and euhedral and sometimes bent or fractured. Hornblende also occurs as irregular clots of small crystals associated with iron ore and surrounded by biotite and sphene. These clots have been reported by previous authors working on the Galway Granite and may represent disseminated fragments of xenoliths.

Accessory minerals tend to form clusters. Iron ore is found as small euhedral crystals, often in aggregates, included in all the essential minerals but especially in biotite and hornblende. Sphene, apatite, and zircon are all euhedral, the last mineral showing oscillatory zoning. Allanite can mantle all the other accessories but is often euhedral with oscillatory zoning, showing a pale yellow-brown core and an orange-brown rim.

Xenoliths occur in the coarse porphyritic granites, the least-granitized ones being medium grained and having a relict fabric of euhedral biotite, plagioclase, and hornblende with interstitial quartz and an over-all quartz-diorite or granodiorite composition. The original plagioclase has cores of An_{40-28} and is overgrown by porphyroblastic plagioclase of the same composition as that of the adjacent host granite. Quartz invades the xenoliths increasingly as granitization proceeds, forming porphyroblasts, sometimes with a mafic rim. K-feldspar forms porphyroblasts in the more granitized xenoliths. In the coarse porphyritic foliated granite the xenolith minerals show the same deformation stages as those in the surrounding granite.

Geochemistry

Granites and aplites. Collection on a systematic grid basis was not possible because of the variable exposure but samples were collected so as to give a reasonable over-all coverage (fig. 3). Only fresh, unweathered rocks, with no obvious inhomogeneity such as layering, abundant xenolith fragments, veining, or strong fracturing were

TABLE II. *Mean chemical analyses (with standard deviations) of granites, xenoliths, and aplites*

	Biotite-poor aphyric granite	Coarse porphyritic granite	Coarse porphyritic foliated granite	Xenoliths	Aplites	Aplitic biotite-poor aphyric granite
No. of samples	9	61	50	23	16	7
SiO_2 %	74.50 ± 0.76	70.38 ± 1.88	66.85 ± 1.69	59.98 ± 3.92	75.35 ± 1.03	75.38 ± 0.06
Al_2O_3	13.43 0.33	14.28 0.45	14.90 0.46	14.93 1.31	13.48 0.50	13.20 0.37
TiO_2	0.20 0.03	0.33 0.07	0.48 0.06	0.92 0.15	0.08 0.04	0.11 0.04
Fe_2O_3	0.61 0.13	1.09 0.25	1.58 0.20	2.35 0.30	0.31 0.22	0.33 0.19
FeO*	0.63 0.15	1.18 0.35	1.80 0.28	3.63 0.85	0.30 0.13	0.39 0.18
MgO	0.48 0.09	1.24 0.31	1.84 0.24	3.35 0.97	0.19 0.27	0.24 0.11
CaO	0.92 0.24	1.93 0.42	2.93 0.37	4.76 0.82	0.74 0.20	0.71 0.38
Na_2O	3.86 0.22	4.21 0.31	4.15 0.44	4.00 0.54	4.39 0.70	4.66 0.26
K_2O	4.59 0.20	4.25 0.36	3.94 0.48	2.79 0.63	4.83 0.72	4.51 0.28
MnO	0.053 0.01	0.080 0.01	0.097 0.01	0.160 0.03	0.048 0.01	0.054 0.01
P_2O_5	0.06 0.02	0.16 0.06	0.29 0.05	0.71 0.31	0.30 0.05	0.02 0.02
H_2O†	0.50 0.06	0.86 0.18	1.16 0.19	1.78 0.43	0.44 0.20	0.41 0.15
TOTAL	99.83	99.99	100.02	99.36	100.46	100.01
S ppm	329 ± 111	139 ± 65	160 ± 54	314 ± 106	130 ± 128	89 ± 31
Cl	159 36	143 42	137 34	140 30	116 22	146 37
Ni	5 2	11 4	22 4	62 36	3 2	4 1
Cu	16 3	18 10	36 6	49 12	17 17	13 7
Zn	40 3	63 8	79 6	114 22	31 8	35 5
Ga	15 3	18 5	20 6	22 6	15 4	14 4
Rb	256 16	204 35	153 28	148 43	264 82	343 68
Sr	123 25	307 100	464 81	485 162	75 39	71 52
Yt	9 2	12 2	14 2	16 4	8 4	12 2
Zr	136 14	175 17	227 18	313 50	68 21	112 7
Nb	11 1	13 3	13 3	17 6	12 6	17 3
Ba	336 38	610 215	973 220	786 324	167 95	122 87
La	18 3	25 6	33 6	36 11	8 4	12 6
Ce	39 2	52 9	69 7	84 22	26 5	34 5
Nd	9 5	15 6	23 7	31 9	7 4	5 3
Sm	6 3	8 4	8 4	7 3	8 4	8 2
Pb	62 6	58 8	51 5	53 43	77 20	70 23
Th	55 6	47 8	34 8	27 11	54 16	58 5
U	11 2	11 4	8 3	8 3	16 8	14 4
FeO/Zn	135	185	227	325	94	107
K/Rb	161	180	217	159	162	114
Rb/Sr	1.89	0.75	0.35	0.34	6.42	9.33
Ba/Sr	2.93	1.99	2.08	1.61	2.46	1.82
Ba/Rb	1.67	3.31	6.45	5.50	0.72	0.40
(La+Ce+Nd+Sm)/Yt	8.0	8.3	9.5	9.9	6.1	4.9

Analyses by X-ray fluorescence using the method of Leake *et al.* (1969).
* FeO determined by dissolving the rock in a H_2SO_4/HF mixture and titrating against standard $K_2Cr_2O_7$.
† H_2O determined by a modified Penfield method.

collected. Individual analyses of the 166 rocks are available from the authors but for the purposes of this general study the overall chemical trends can be deduced from the means and standard deviations of the analysed elements for each main granite type and the aplites (table II).

The major element variations as summarized in fig. 2 illustrate clearly that the granites form one continuous sequence and show the trends usually associated with magmatic differentiation, the increase in Niggli si being accompanied by increases in Niggli k, alk, and al, while c, fm, p, ti, and mg all decrease. The over-all fractionation trend is from the coarse porphyritic foliated granite through the coarse porphyritic

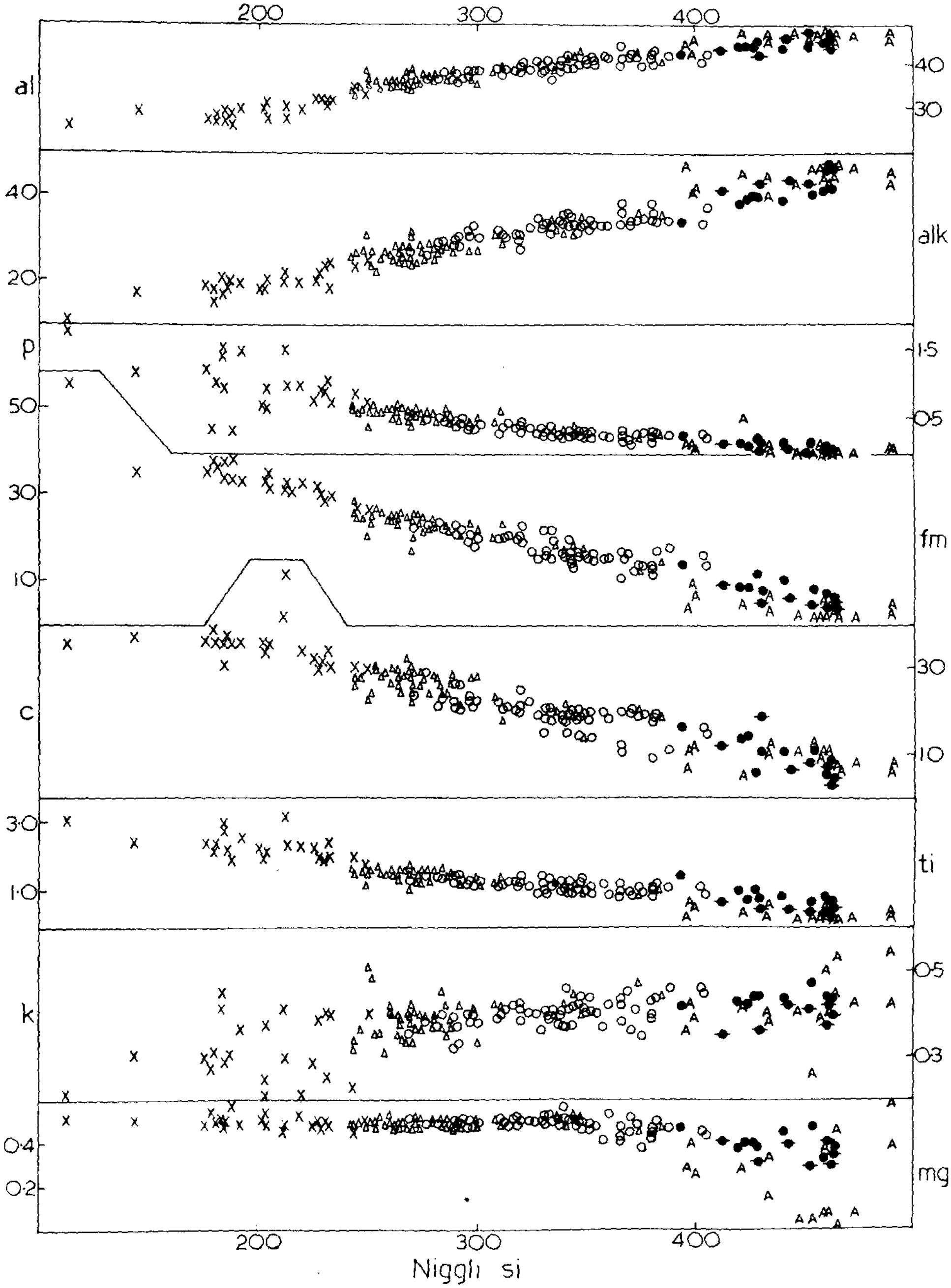

FIG. 2. Niggli number plots for granites, aplites, and xenoliths. ×, xenoliths; △ coarse porphyritic foliated granite; ○, coarse porphyritic granite; ● biotite-poor aphyric granite; ⬬ aplitic biotite-poor aphyric granite; A, aplites.

granite to the biotite-poor aphyric granite and aplites. This increasing trend of fractionation towards the margin of the pluton is also shown by trend surface analysis but the results are complicated by the effect of the Barna fault.

The overall increase of SiO_2 from west to east is shown in fig. 3 and this reflects the modal increase in quartz and K-feldspar at the expense of biotite, hornblende, and calcic plagioclase. The major feature brought out by this figure is the effect of the Barna fault. In the south there is a sharp rise eastwards of about 3 % SiO_2 across this fault whilst in the north-west the effect of the fault is not at all obvious. This indicates that it is a fault of hinge nature with a larger vertical displacement southwards.

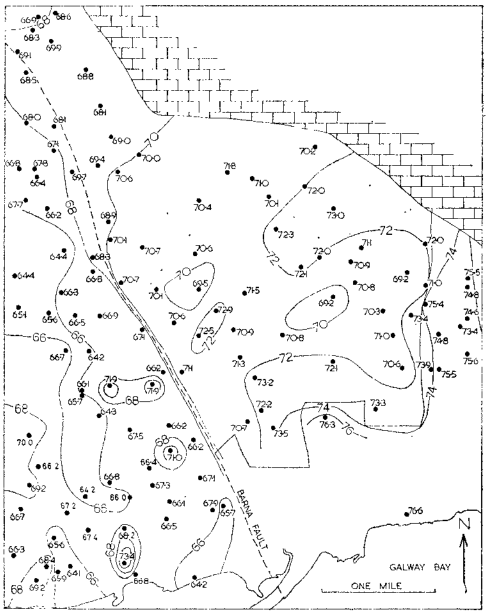

FIG. 3. Hand contoured SiO_2 % variation in the granites near Galway. Contour interval 2% SiO_2.

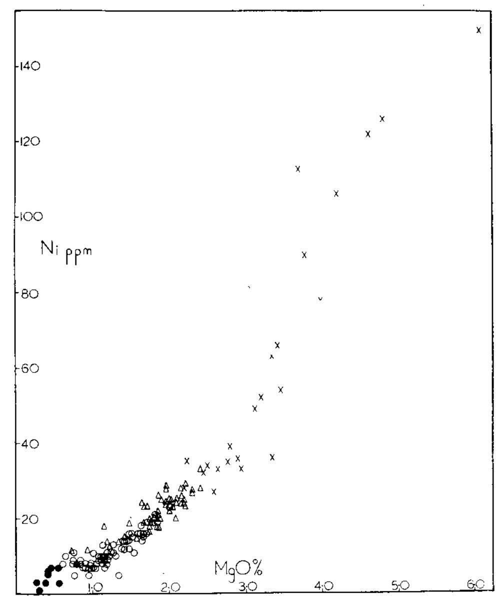

FIG. 4. MgO–Ni plot for granites and xenoliths. Key as in fig. 2.

In table II MnO is seen to be at about the same level in the aplites as in the biotite-poor aphyric granite whilst all other femic oxides are considerably lower in the aplites. The highest MnO is present in the latest aplites, the most Mn-rich aplites containing spessartine garnets. The presence of garnets in the Galway Granite and its aplites has been reported by previous authors and their chemistry has been investigated by Leake (1968).

Nickel decreases with fractionation along with but at a faster rate than MgO (fig. 4) and chiefly occupies octahedral sites in hornblende and biotite, being preferentially enriched in the early crystal sites. Copper decreases with fractionation and is probably in biotite and magnetite as noted by Azzaria (1962) and Mursky (1968). Occasional high values of Cu and Zn are found in samples containing late sulphide veins. Zinc is predominantly present in biotite as noted by Tauson and Kravchenko

(1956). Taylor (1965) suggested that the ratio of Fe^{2+} to Zn decreases during the fractionation of silicate melts; the average values for the granite sequence (table II) accord with this prediction.

Rubidium shows the usual coherence with K (fig. 5A), increasing through the normal granite sequence with fractionation. The K/Rb ratios for the granites increase towards the granite margin, most of the values lying within the range (150–300) considered normal by Taylor (1965). The enrichment of Rb in the more fractionated phases is well illustrated in fig. 5A by the aplites, some of which lie well on the Rb-rich side of the K/Rb = 150 line.

Strontium decreases with fractionation and shows a strong negative correlation with Rb (fig. 5B). The Rb/Sr ratio (table II) is an index of fractionation in granites, for the bulk of Rb is present in K-feldspar while Sr enters early-formed Ca and K sites, the Rb/Sr ratio therefore essentially representing the fractionation of the felsic minerals.

Barium has a well-established relationship with K, which is the only major element of comparable size. Unlike Rb, Ba enters K-feldspar in preference to biotite and this, together with the dominance of K-feldspar over biotite in the granites means that most of the Ba in the rock occurs in the K-feldspar, the decrease of Ba eastwards being largely due to its fractionation relative to K in the K-feldspars.

Barium and Sr have a good correlation (fig. 5D) the Ba/Sr ratio being approximately equal to two for all the granites. The Ba/Rb ratio (fig. 5C) falls through the granite sequence, the Ba/Rb ratio essentially indicating the fractionation of the K-feldspar.

Lead shows a slight increase with fractionation (table II), having a positive correlation with Rb and K_2O and is probably present in K-feldspar. Thorium increases similarly but does so independently from Pb, there being no significant correlation between them. Generally associated with Th is U, which has a much more erratic distribution than Th, as noted by Ragland *et al.* (1967).

Five rare-earth elements have been determined, La, Ce, Nd, Sm, and Yt. The coarse porphyritic foliated granite has a rare-earth pattern that is dominated by the light rare-earth elements and as fractionation proceeds the light rare-earth elements become depleted relative to Yt (table II). This trend is continued into the aplites and the garnet-bearing aplites are notably Yt-enriched (JRW 125d containing 46 ppm Yt); Yt probably substitutes for Mn in the spessartine molecule in the scheme $Al^{3+}Yt^{3+} \rightleftharpoons Mn^{2+}Si^{4+}$. The Susamyr batholith (Haskin *et al.*, 1966) shows a similar, though more pronounced, rare earth element variation, the (La+Ce+Nd+Sm)/Yt ratio decreasing from 9·4 in the granodiorite–granite phase through 3·3 in the leucogranite phase to 0·4 in the aplites.

Xenoliths. The major element chemistry of the xenoliths shows them to be more basic than the host granite (table II). The xenoliths themselves form a chemical series related to their degree of attack by the host granite, illustrated by fig. 3 in which they form an approximately linear extension of the main granite sequence projected towards lower Niggli si values.

The xenoliths are enriched in Ni relative to MgO (fig. 4). The xenoliths are thought to represent an early, basic phase of the granite in which Ni entered the octahedral

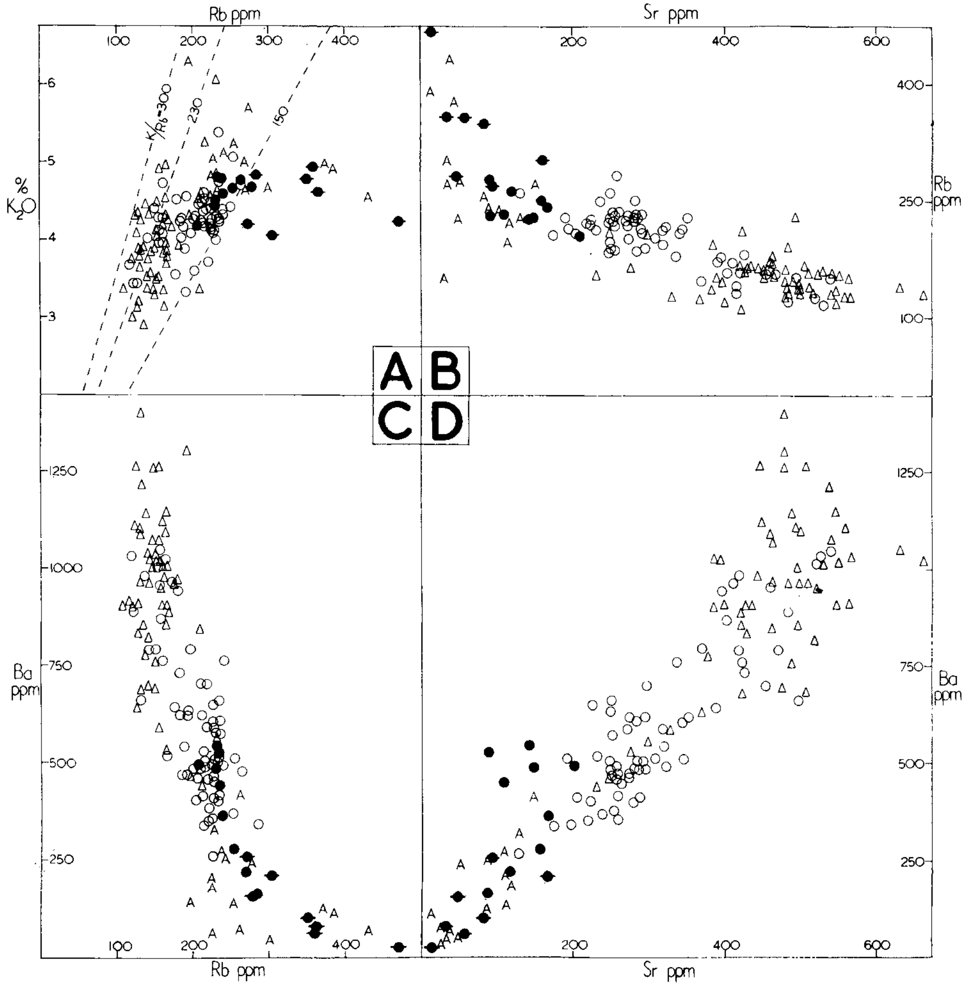

FIG. 5. A, K_2O–Rb; B, Rb–Sr; C, Ba–Rb; and D, Ba–Sr plots for granites and aplites. Key as in fig. 2.

sites of the early crystallizing fractions, the xenoliths being of roughly uniform composition before being broken and distributed by and reacting with the later granite magma. Higher values of Cu and Zn in the xenoliths are evidence of their presence in the mafic minerals and the higher FeO/Zn ratio (table II) compared with the granites illustrates enrichment of Fe^{2+} relative to Zn in the early crystallizing fractions, as suggested by Taylor (1965).

The control of mineralogy on trace element distribution is illustrated by Rb, which has a mean value of 148 ppm in the xenoliths, close to the coarse porphyritic foliated granite (153 ppm), the latter having a much higher K-feldspar content, compensated for in the xenoliths by biotite. The distribution of the rare earth elements in the xenoliths (table II) is very similar to that in the coarse porphyritic-foliated granite.

It is suggested from field, petrographic, and chemical evidence that most of the xenoliths belong to an earlier, basic phase of the granite; similar xenoliths have been described from other parts of the Galway Granite (e.g. Lawrence, 1968). Many examples of cognate xenoliths are given in the literature (e.g. Emeleus, 1963; Brammall and Harwood, 1932; Townend, 1966) and the xenoliths in the Galway Granite near Galway are typical—ovoid, granodioritic in mineralogy, presence of granoblastic textures, and occurrence in a porphyritic adamellitic host—so that their origin has a wide context. Their widespread uniformity and occurrence away from the country rock margin is in accord with an origin involving the redistribution of an early basic phase.

Petrogenesis

The Galway Granite batholith is continuously zoned with a granodioritic centre and a more acidic margin. There is usually a distinct alkali-rich marginal facies to the batholith. The gradual compositional change away from the margin points to an original magmatic phase, the end-products being the results of differentiation and crystallization caused by changing pressure and temperature conditions. Post-magmatic changes have been superimposed to give a final product with a complex history.

Most of the granites consist of more than 80 % of the normative minerals Q, Ab, and Or. A biotite–hornblende mesonorm has been used (Parslow, 1969) as this calculates out minerals such as biotite that are actually present. The weight percentages have been plotted on a projection of the phase surfaces on to the water-free face of the Q–Or–Ab–H_2O experimental system (Tuttle and Bowen, 1958) in fig. 6. The normative compositions show a trend of increasing fractionation and suggest that the isobaric minimum in the natural system had some control over their crystallization. Experimentally determined isobaric minima are water-saturated, a condition that is probably rarely attained in natural granite magmas and thus the granite normative compositions can be expected to deviate from the experimentally determined minima.

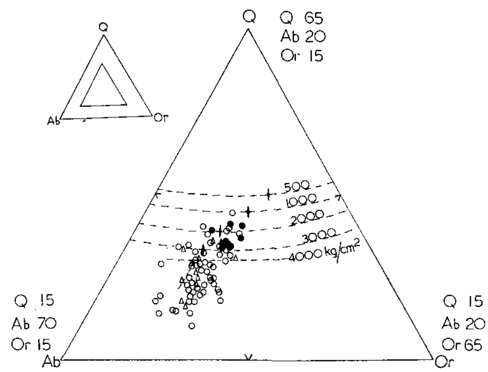

FIG. 6. Q–Or–Ab biotite–hornblende mesonorm plot for granites with (Q+Or+Ab) more than 80 % of normative minerals. Key as in fig. 2.

Zoned granite intrusions are fairly common but the usual pattern is for a mafic margin with a felsic core, the opposite trend to the Galway Granite, and these 'normally zoned' granites are envisaged to have crystallized from the margin inwards (Hahn-Weinheimer and Ackerman, 1967); using the same criteria would lead one to the conclusion that the Galway Granite crystallized from the centre outwards.

The Enchanted Rock Batholith of Texas (Ragland *et al.*, 1968) is a zoned intrusion, becoming increasingly basic towards the centre. Ragland *et al.* have proposed a petrogenetic model involving the multiple injection of a granitic magma differentiating at depth.

The Lakeview Mountains pluton, a part of the southern California batholith, shows similar zoning and Morton (1969) and Morton *et al.* (1969) suggest that crystallization commenced with the marginal silicic magma and proceeded to the more basic centre, where the greatest concentration of pegmatite bodies occurs.

The Galway Granite, from field evidence, is considered to have been emplaced by the removal of the pre-existing rocks, mechanically displaced, probably upwards. Sr isotope studies have shown that inappreciable contamination of the magma by crustal material has occurred (Leggo *et al.*, 1966) indicating that country rock xenoliths have not been extensively dissolved.

The continuous zoning of the Galway Granite and the lack of contact effects indicate that the magma crystallized under steady-state conditions. A thermal gradient must have existed, the temperature decreasing outward from the centre of the magma chamber into the host rocks. Any sharp temperature gradient at the contact of the granite with the country-rock contact would have resulted in early marginal crystallization. To maintain uniform partial pressure throughout the magma, water would have diffused and distributed itself to the regions of lowest temperature and pressure, this migration upwards and outwards effectively lowering the liquidus temperature at the granite margin. Compositional gradients in the magma are thought to have developed during the early crystallization period, by alkalis and other volatiles accompanying the migrating water and the early, high-temperature, minerals displacing upwards and outwards the residual magma. As the crystallization proceeded, the differentiation accelerated as the alkalis and silica moved towards the margin of the batholith. There is little suggestion of crystal settling, though cumulophyric hornblende, biotite, or plagioclase groups may represent early association of the nuclei of these crystals.

Transfer of alkalis and silica upwards and outwards resulted in the formation of the biotite-poor aphyric granite at the granite margin and roof, the latter possibly represented by the outcrops of this granite at Corcullen.

During the period of crystallization of the deeper parts of the granite, some movement resulted in the still-mobile residual magma invading the host granite to give irregular bands of K-feldspar-rich granite. When the granite was solid and after the earliest aplites, dykes of a medium-grained granite were intruded to cut the K-feldspar-rich granite and its coarse porphyritic host. Shearing in the deeper parts of the batholith caused the recrystallization of the more basic coarse porphyritic granite, producing the foliation of the granite and its minor facies, and forming biotite layers. The aplite period continued after the imposition of the foliation and was followed by some faulting. A series of porphyry dykes were then emplaced followed by further faulting such as the large Barna fault.

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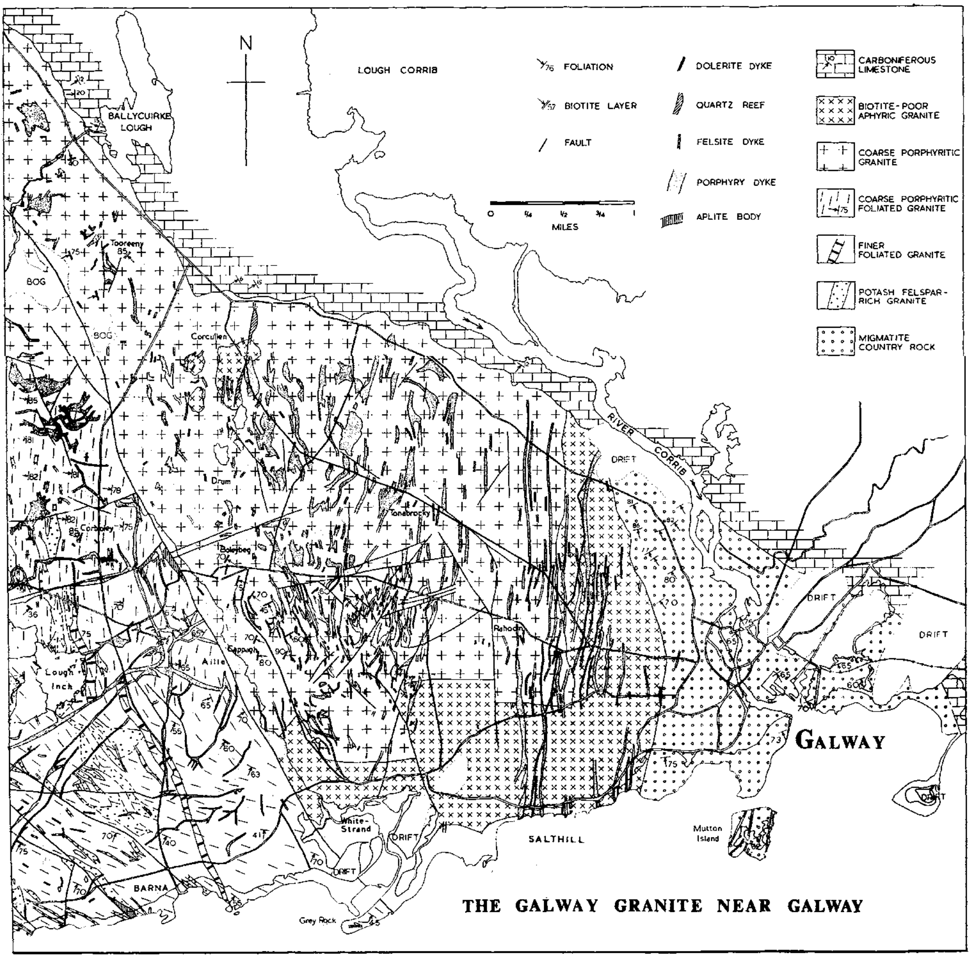

J. S. COATS AND J. R. WILSON ON THE GALWAY GRANITE

Geological map of the eastern end of the Galway Granite. An aphyric alkali granite at the margin of the pluton is followed by a coarse porphyritic granite that becomes increasingly basic westwards. To the west of a major fault the coarse porphyritic granite contains minor granite facies and a foliation is developed. The granites are cut by a series of porphyry dykes.