Earth and Environmental Science Transactions of the Royal Society of Edinburgh, **102**, 1–16, 2011

Stoping and the mechanisms of emplacement of the granites in the Western Ring Complex of the Galway granite batholith, western Ireland

Bernard Elgey Leake

School of Earth and Ocean Sciences, Main Building, Cardiff University, Cardiff CF10 3YE, UK
Email: LeakeB@cardiff.ac.uk

ABSTRACT: The western end of the Galway granite batholith demonstrates the importance of stoping as a granite emplacement process, which is currently controversial, and also of space generation by uplift of the centre of a ring complex. The granite rings are shown (with a coloured 1:25 000 geological map) to be consanguineous, near coeval, and older than the 407–410 Ma late molybdenite mineralisation. A newly-recognised Mace–Ards granite, around and injected by the Aplitic Murvey-type granite of the ring core (both lacking hornblende and titanite), has biotite–muscovite–cordierite orbs and sulphide–granite orbs, showing separation of immiscible hydrous and sulphide fluids from the late magma which, with vugs, indicates a low pressure, near-roof site. The outer ring of the Errisbeg Townland granite (ETG, the main batholith granite with K-feldspar phenocrysts), was emplaced by progressive outward stoping of the country rock metagabbro, as shown by mapping, and by chemical fractionation of feldspars, biotites and bulk rocks, to the marginal, dry, fine-grained aphyric, in part garnetiferous, highly fractionated, siliceous Murvey granite. Stoping ceased when, after previously invading dense metagabbro, the outer ring complex reached the low-density Roundstone granite, which is shown for the first time to be older than the Galway batholith. This arresting of the batholith intrusion shows that stoping was such a significant process that emplacement ceased when stoping became impossible. The inside edge of the ETG grades into the slightly later, intrusive, aphyric Carna granite, which shows inward fractionation to the wet magma of the Mace–Ards granite. The ring complex core was injected by highly fractionated, dry, Aplitic Murvey-type granite, intensely hydrothermally altered by late magmatic water. The radially outward dipping, inclined igneous layering in the ETG shows that the original ETG centre was pushed upwards by the intruded Carna granite and eroded away. The Galway granite and its nearby magmatism matches the low Ba and Sr, high Th and Rb, Scottish Cairngorm Suite and similarly has few appinitic rocks associated with it. Magmatism extended over >45 Myr from ∼425 Ma to 380 Ma. It originated by slab breakoff and consequent rise of the asthenosphere, causing deep crustal melting.

KEY WORDS: Cairngorm Suite, granite emplacement, magma pulses, magmatic cordierite, orbicular granite

The western end of the Galway granite, western Ireland, is dominated by a ring complex which contrasts with the arrangement of the granites in the main part of the batholith (Figs 1, 2). The purpose of this account is to present the first detailed map of the complex, to describe the constituent granites, their dispositions and order of intrusion, and to unravel the mechanisms responsible for their emplacement. These turned out to be outward stoping and central uplift. Also, the hitherto unknown relative age of the Roundstone and Galway granites is determined for the first time.

Although much of the Galway granite has been mapped in detail, there are still major gaps, that were last examined in the 1860s by the Geological Survey of Ireland, as was the ground east and southeast of Kilkieran (Fig. 1) (Kinahan *et al.* 1871, 1878). The western part of the batholith has been described in detail only in the Roundstone–Murvey region (Leake 1974) and at Mace in an unpublished PhD Thesis (Derham 1993). Mace has been completely re-mapped for this account. The geology of the remainder of the ground west of the Carna area mapped by Wright (1964) has been depicted only on the reconnaissance maps of Leake (1974), Max *et al.* (1978) and Long *et al.* (1995). The underwater data of Max *et al.* (1978) was consulted. The southern edge of the Roundstone granite and its adjoining country rocks were mapped by Harvey (1967) in an unpublished PhD Thesis, but the southern and central parts of the Roundstone granite, described here, were last examined in the 1860s by the Geological Survey of Ireland as referenced above. The granite names are those used in their first descriptions, and are widely accepted, and follow the convention of recording the places of their initial description. The unmapped areas, and the wide age range of the intrusions, rule out identifying one batholith-wide sequence of intrusions at present.

The granite ages for the Galway batholith are summarised in Feely *et al.* (2003, 2006, 2010), and range over 30 Myr from earlier than 407–410 Ma (Re–Os on late molybdenite) to at least 383 Ma, with the main bulk of the granite ranging from 402 Ma or earlier to 394 Ma (U–Pb on zircon), from which it is clear that the presently described granites must pre-date 407–410 Ma. The country rocks are 470 Ma metagabbro injected by 467 Ma quartz diorite gneiss (Friedrich *et al.* 1999) as described by Harvey (1967), Bremner & Leake (1980) and Leake (1989).

 doi:10.1017/S175569101100911X

Fieldwork was carried out between 1957 and 1965 and completed between 2001 and 2007, with the laboratory work done over many years. Much more detailed information is available on the 1:10 560 field maps, copies of which are held by the Geological Survey of Ireland and, together with rock specimens, field notebooks and thin sections, by the Hunterian Museum, University of Glasgow.

1. The granite types and their mutual relations

The granite types identified in order of intrusion in the area are the Roundstone, the Errisbeg Townland and the Carna with the Cuilleen, all of which contain hornblende and titanite (Figs 2, 3 (folded map)). They were followed by the newly named Mace–Ards, and then the three varieties of the Murvey granite, the Main Murvey, the Garnetiferous and the Aplitic types, with the final granite, the Mill Lough microgranite, all of which generally lack hornblende and titanite. All the granites are largely made of plagioclase, quartz and K-feldspar and have the chemical compositions summarised in Table 1. Using the Streckeisen (1976) rock classification, they range from granodiorites through granite to alkali-feldspar granite. The occurrence of these rocks is shown in Figures 2 and 3. Brief petrographic and modal descriptions are given in the Appendix and the crucial characteristics of each type in order of intrusion are as follows (dykes are dealt with later).

1. *Roundstone granite*: biotite, hornblende, titanite and K-feldspar phenocrysts <2·5 cm long;
2. *Errisbeg Townland granite* (ETG) the same, but the phenocrysts are up to 4 cm long;
3. *Carna granite* has the same mineralogy but is aphyric, i.e. non-phenocrystic;
4. *Cuilleen granite* has the same mineralogy and K-feldspar phenocrysts as the ETG, but they are more abundant than in the ETG;
5. *Mace–Ards granite* lacks hornblende and titanite, has oligoclase, a little (5%) biotite and is generally aphyric, but an area with K-feldspar phenocrysts <2 cm long is shown in Figure 3.
6. *Murvey granites* are aphyric, lack hornblende, have albite, only a trace of biotite, muscovite and titanite and are fine-grained, the grain-size being ~3 mm for the *Main Murvey granite*, but <1 mm for the titanite-free *Aplitic Murvey granite* and the *Garnetiferous Murvey*, which has igneous almandine–spessartine garnet. All are dry granites low in hydrous minerals.
7. *Mill Lough microgranite* lacks hornblende, has a little biotite and is a felsic microgranite.

Although the Roundstone granite has an observed faulted contact with the ETG (Fig. 3), all the remaining granites, except the Mill Lough microgranite, which is later than the main ring-forming granites, and the Mace Pier aplitic granite, have transitional contacts which testify to the near-coeval magmatism of the Western Ring Complex. The contacts of the Carna and Cuilleen granites, and the ETG and Murvey granites at Murvey, where the ETG loses its K-feldspar phenocrysts over ~25 m, are the sharpest transitions, occasionally being over less than 5 m. There is no suggestion of one granite magma injecting the other, as there is with the Mill Lough microgranite and the Mace Pier body, which includes xenoliths of the surrounding Mace–Ards granite. The northern edge of the Carna granite grades into the ETG, with gradual increase of K-feldspar phenocrysts, over varying distances up to 300 m (Fig. 3).

2. The emplacement of the granites

2.1. Roundstone granite

The part of the Roundstone granite shown in Figure 3 was emplaced by intrusion with a 300 m-wide halo of thin aplitic (quartz, K-feldspar, albite and igneous garnets), and some pegmatitic, veins in the country rock parallel to the mapped steep edge of the granite. These veins, being the only preserved ones, were the last ones frozen in the process of stoping off blocks of the metagabbro, as will be described in more detail for the ETG. They occur W and SW of Roundstone and south of Bertraghboy Bay and are mostly too thin (1–3 m) to show on Figure 3.

Occasionally, xenoliths of the country rock are found in the granite, especially near the southern margin but occasionally further in, as on the SW point of Inishnee at [736.378], where a 5 m-long xenolith of metagabbro occurs with a flat-lying foliation. All this suggests that the magma intruded southwards and pushed upwards, causing pieces of the country rock to fall into the magma and sink through it, being helped by the much higher density (>3·0) of the solid metagabbro over that of the granite magma. The northern edge of the granite is not considered here.

The southwestern part of Inishnee is crossed by a series of ~120°N faults which increase in frequency to the SW and predate the intrusion of the porphyry and felsite dykes, because the dykes either cross the faults without displacement or follow pre-existing fault lines. The 120°N faults are believed to be related to fracturing connected with the emplacement of the slightly later ETG, the fractures being parallel to the ETG margin, as explained more fully below. However, there is evidence that the Roundstone granite was not completely solid when this fracturing occurred because exactly parallel to, and within this fracture zone, is a belt containing a swarm of aplites (with a few 120°N quartz veins), especially from 300–1000 m at 30°N from the SW point (at [735.378]) of Inishnee. Further north than this (1 km), the number of aplites falls abruptly and their direction changes to 10–60°N. This implies that when the fracturing occurred, the part of the Roundstone granite with 120°N aplites was largely crystallised, but with a little residual highly fractionated magma, which flowed into the opening fractures and drained the surrounding granite. Less than 300 m from this SW point there are far fewer aplites, and fewer thick (>10 cm) ones, which suggests that at the time of ETG emplacement, the edge of the Roundstone granite (Fig. 3) was more solidified than the interior and yielded less residual magma and fewer aplites, while the interior zone (>1 km from the SW point) was either not affected by the fracturing or was insufficiently crystallised to fracture and yield aplites. Thus, overall, the Roundstone granite emplacement preceded that of the ETG, but possibly not by very long if the Roundstone granite was not completely crystallised when the ETG intruded.

2.2. The emplacement of the western part of the Galway batholith

2.2.1. Outward emplacement of the margin. Most of the Galway batholith has an ESE to ENE northern margin (Fig. 1) that is parallel to, and largely controlled by, the concordant strike of the country rock metagabbro with its injections of quartz diorite gneiss. The reasons for this were in part supposed by Leake (2006) to be connected with a releasing bend in a major sinistral strike-slip fault which progressively opened up extensional spaces towards the granite margin for granite magma to fill. The emplacement of the ETG and its deeper Central Block equivalent, the Megacrystic granite, took place

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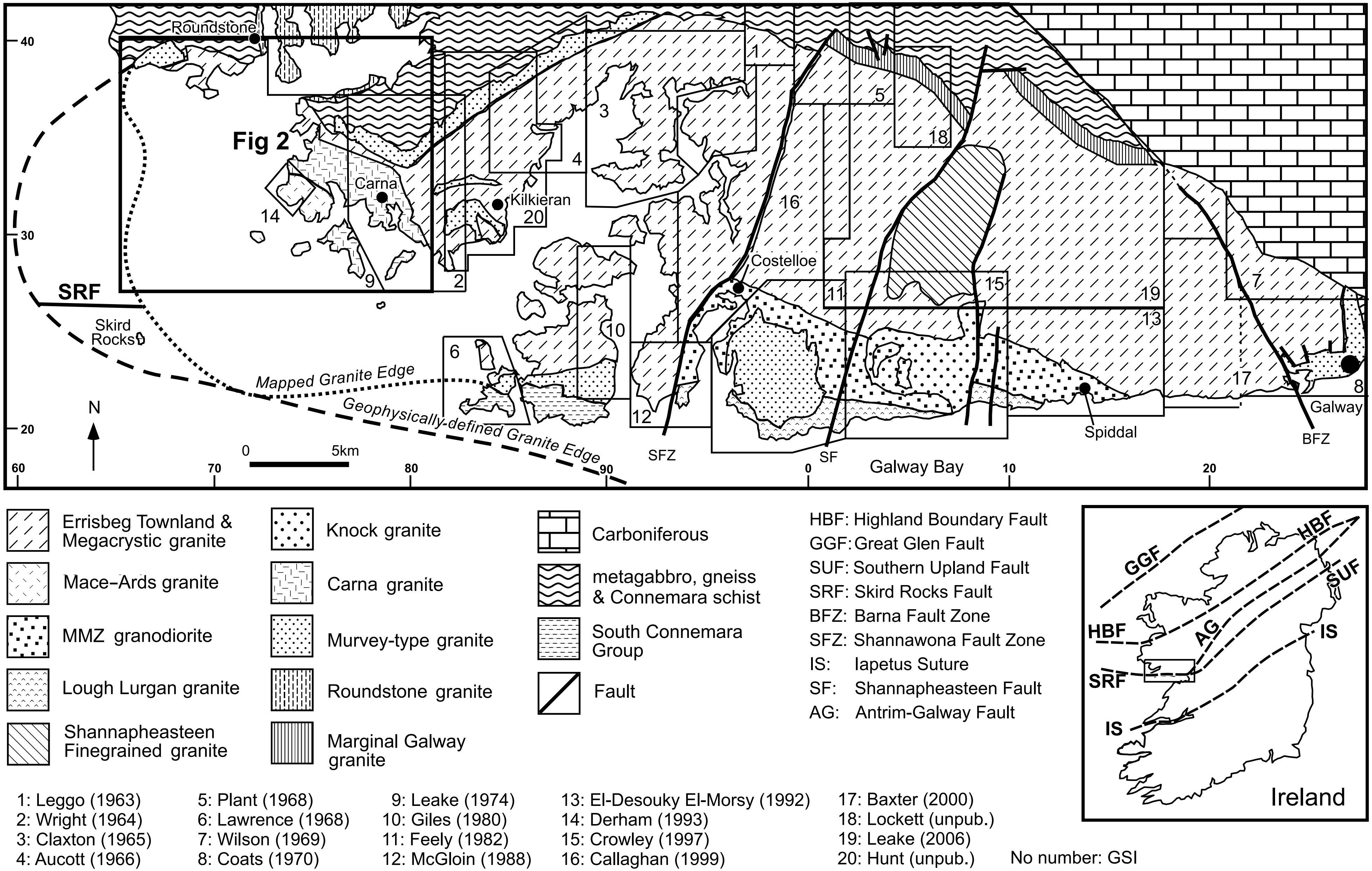

Figure 1 Outline of the setting of the Galway granite and of the major components of the batholith, showing the area mapped in detail in the west by the present author, as shown in Figures 2 and 3. A summary of the previously mapped areas and the related references are also shown, with the references not otherwise in the text being given in full in Leake (2006). GSI=Geological Survey of Ireland; MMZ=Mingling–Mixing Zone. The Central Block lies between the Shannawona and Barna Fault Zones and was originally much deeper, so that the upper parts of the batholith lie to the east and west of this Block.

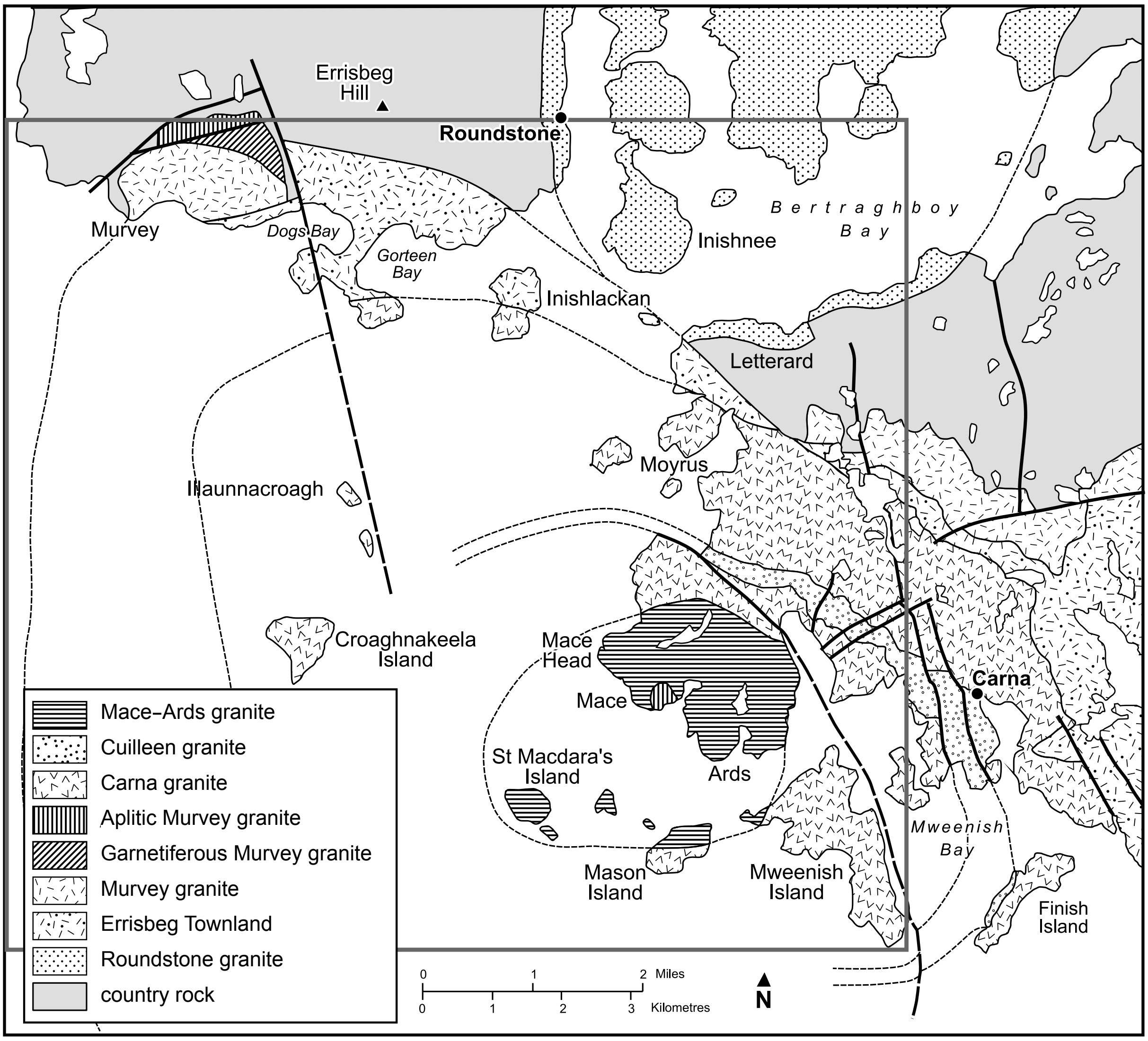

Figure 2 Geological sketch map of the western part of the Galway granite and the southern part of the circular-shaped Roundstone granite, depicting the ring structure of the western end of the Galway batholith. This is shown in more detail in Figure 3, which is the outlined area in Figure 2.

by injections of successively more fractionated pulses of magma towards the edge of the batholith (Leake 2006). The last, most fractionated, derivative, the Murvey granite, occurs along much of the northern margin and also along what little is seen of the southern margin (Fig. 1). However, the position of the ring complex at the west end of the batholith, its circular character and the lack of tectonic extensional fracturing, suggests that the ring complex owes its emplacement mainly to magmatic, not tectonic influences. It is possible that the main batholith was also emplaced by repeated similar processes, because the Megacrystic granite is ~10 Myr younger than the ring complex (Feely *et al.* 2010).

Figures 3 and 4 reveal the manner of emplacement of the ETG, by stoping ESE to SE elongate slabs of the metagabbro along vertical fractures which run parallel to the strike of the granite margin and, in the present ground, cut across the strike of the poorly foliated to massive metagabbro country rock. The first stage in the process, well seen up to 500 m from the outer margin of the ETG, is an ESE to SE fracturing into which thin (5–100 cm) fine-grained aplitic veins were intruded, occasionally with spessartine-almandine garnets, or rarely garnet and tourmaline. Initially these are only a few metres in length, but one or two widen out and lengthen as the granite margin is approached. Most of the veins stay small, <30 m long even quite close to the granite margin, as shown best in Figure 4, and remain mostly parallel to the main ETG–country rock contact. A few major veins, e.g. from [703.395] to [722.387], near Cregduff Lough, SW of Roundstone, expand and wedge off long slabs (up to 1 km) which may become fragmented themselves, e.g. in Letterard around [748.365]. The granite in the major veins gradually becomes more porphyritic closer to the main outcrop of the ETG, and the prised-off high density metagabbro blocks fell into the magma and sank, with virtually no reaction at the present level of erosion. This is because the 470 Ma metagabbro does not begin to melt until well over 900°C (Leake 1989), whereas the granite magma is likely to have been below 700°C. The magma injections, judging from those mapped in Figure 4, were probably 5–30 m thick, and presumably seamlessly amalgamated, giving an apparently uniform granite. This was heated from the inside by the hotter, slightly more mafic, later intrusion of the Carna granite, dealt with below. This slow cooling, and the ETG composition, promoted the growth of K-feldspar phenocrysts in the ETG. The whole of the above is indicative of magmatic, not tectonic, processes wedging apart and stoping the country rock.

Chemical analyses show that the granite veins in the metagabbro are not isochemical with the ETG but tend towards, or even approach, the composition of the Murvey granite, i.e. being richer in SiO_2 and K_2O and poorer in TiO_2, FeO, MgO,

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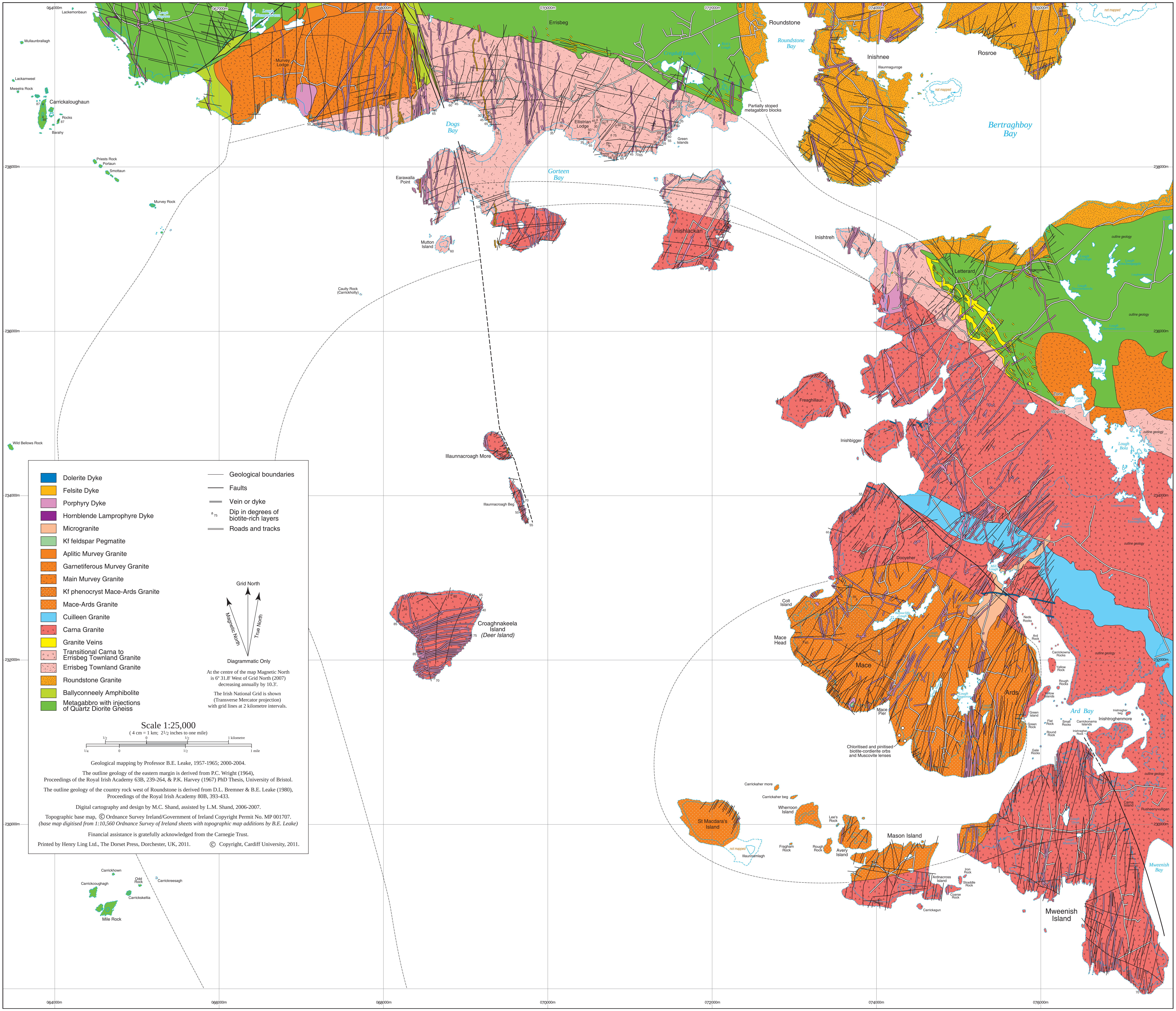

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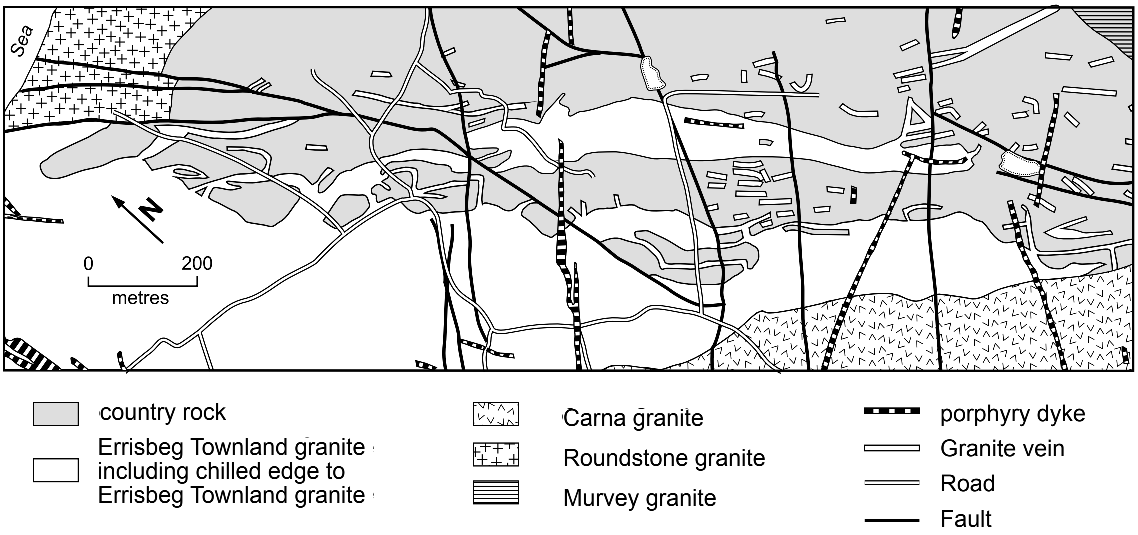

Figure 4 Injection, prising off and arrested stoping of metagabbroic country rock by the Errisbeg Townland granite, Letterard, near [748.362]. The parallelism of the granite veins in the country rock to the main trend of the granite edge shows that they are important precursor veins and not trivial.

P_2O_5, and H_2O than typical ETG (Tables 1 & 2; Fig. 5). Thus the long vein near Cregduff Lough, mentioned above, has a complete transition from a composition similar to ETG near its root in that granite, to a composition like that of the Main Murvey granite near the vein end. Here it is a fine-grained aplite with rare garnet, topaz, fluorite and tourmaline that approaches the Garnetiferous Murvey granite composition (Table 2: 1, 2). Most likely, the stoping finished at least in part because the silica-rich, dry Murvey granites became too viscous to intrude, as such fractionated dry compositions have viscosities of several orders of magnitude higher than ETG (Bottinga & Weill 1972; Zhang *et al.* 2003). Such viscous magmas would not have been involved until the end-stages, so that earlier stoping would have been easier.

The marginal Murvey-type granite continues westward round the concave arc of the batholith margin north of Carna and then stops abruptly in Moyrus just west of [760.357], as in the SE part of Figures 2 and 3. There is then over 8 km of the granite margin, extending from Moyrus and Letterard to [685.399] on the southern slopes of Errisbeg Hill, north of Dogs Bay, in which there is no Murvey granite, after which the Murvey granite, in its type locality, re-appears. Here there is a clear outward sequence from the ETG to the Main Murvey, to the Garnetiferous Murvey to the Aplitic Murvey, which was later greisened (Table 2: 3) and mineralised with late molybdenite dated by the Re–Os method at $410{\cdot}6 \pm 1$ Ma (Selby *et al.* 2004). This dates the end of the outward magmatic sequence.

The reason for the absence of the Murvey granite along the indicated edge of the ETG is related to two factors. Of first importance is the fact that the central third of this edge is against the Roundstone granite which, being of similar low density ($\sim 2{\cdot}7$) to the ETG, was much more difficult to stope than the much denser ($>3{\cdot}0$) mafic to ultramafic metagabbro. This area is the only one in which the Galway batholith comes against a distinct granite pluton, and it is significant that this is almost the only area without marginal Murvey granite. The virtually perfect circular outcrop of the Roundstone granite shows that almost none of it suffered stoping by the Galway batholith, so that stoping must have been impossible because of the properties of the Roundstone granite. The second factor is the isotropic nature of the Roundstone granite, without any foliation, and the discordant nature of the strike in the country rocks compared to the generally concordant strike along the northern edge of the batholith to the east of Figure 2. For most of the northern margin of the batholith, the fractures along which the granite was emplaced preferentially followed the moderately to steeply northward-dipping foliation of the country rock, as it was within the maximum of 30° of the preferred fracture direction. Jaeger & Cook (1979) have shown that such opening fractures will follow a pre-existing 'grain' so long as it is within 30° of the direction the fractures would have opened in an isotropic medium. The dip of the country rock from Moyrus to Letterard is gently to the north, so that the foliation is at a high angle to any would-be steep fracture. Similarly, west of Roundstone, Bremner & Leake (1980) have shown that the strike of the metagabbro is $\sim$N–S with steep dips. So in both these parts of the granite margin, the country rock foliation is about perpendicular to the direction of the steep ESE fractures along which the stoping shown in Figures 3 and 4 took place. The observed ETG–metagabbro contacts dip 50–60° northwards.

Some steep ESE fractures occur in the country rock on the southern side of Errisbeg Hill near the granite margin, and the nearly straight ESE edge of the ETG there attests to their previous controlling existence. Only a few veins of Murvey granite occur in the country rock, so opening these veins was difficult until the E–W country rock strike of Murvey was reached. Here, surface observations and drilling show the granite–country rock edge dips outward at 57°.

The evidence of the progressive outward chemical fractionation with declining Sr, TiO_2, CaO, P_2O_5, (tFeO+MnO+MgO) shown in Figure 5, and increased SiO_2, of the ETG towards the marginal Murvey granite, is the same as trends, documented in detail, from the Rosmuc area (Claxton 1971), the Central Block (Leake 2006), the eastern end near Galway (Coats & Wilson 1971) and for the southern margin (Lawrence 1968). They are an essential, but not necessarily synchronous, feature of the 80 km-long batholith and are not confined to the ring complex. This implies that stoping was a major emplacement process even if it is only pronounced in the upper parts of batholiths.

In view of the differing views of the importance of stoping in granite intrusion, whether it is merely a late trivial marginal process or a major emplacement mechanism (Glazner & Bartley 2006, 2008; Clarke & Erdmann 2008; Paterson *et al.* 2008; Yoshinobu & Barnes 2008), the evidence of Figure 4 and also figure 4 in Leake (2006), which shows progressive stoping

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Table 1 Chemical analyses of the Roundstone and Western ring complex granites. Chemical analyses are by XRF and wet methods as described either in Leake *et al.* (1969) or Harvey *et al.* (1972). tFe_2O_3 in [brackets] is not included in the total, as Fe_2O_3 and FeO are each determined.

wt. %	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	70·96	76·80	74·19	75·16	69·71	68·63	69·97	69·59	70·75	70·32	69·96	69·38	69·67	66·92
Al_2O_3	14·31	12·51	13·90	13·57	14·35	14·75	14·65	14·89	14·75	14·80	14·68	14·58	14·63	15·09
TiO_2	0·29	0·04	0·09	0·14	0·35	0·41	0·37	0·37	0·28	0·31	0·35	0·34	0·35	0·43
tFe_2O_3	–	–	1·29	–	–	–	–	[2·66]	2·40	[2·50]	[2·52]	2·93	[2·73]	–
Fe_2O_3	0·66	0·22	–	0·44	1·05	0·81	0·72	0·49	–	0·49	0·3	–	0·30	1·21
FeO	1·48	0·22	–	0·63	1·71	2·08	1·84	1·95	–	1·95	2·00	–	2·00	1·65
MnO	0·07	0·08	0·03	0·04	0·08	0·08	0·07	0·06	0·06	0·06	0·06	0·07	0·06	0·07
MgO	1·03	0·28	0·40	0·38	1·14	1·33	0·99	0·92	0·80	0·84	0·99	0·95	0·97	1·92
CaO	2·01	0·36	0·82	0·71	2·39	2·79	2·13	2·53	2·06	2·23	2·46	2·67	2·57	2·76
Na_2O	3·82	4·16	3·45	3·89	4·14	3·86	3·61	3·84	3·40	3·56	3·57	3·37	3·47	3·74
K_2O	4·28	4·76	4·93	4·71	4·11	3·94	4·08	3·47	4·20	3·93	3·89	3·96	3·92	3·98
P_2O_5	0·12	0·01	–	0·05	0·17	0·19	0·14	0·14	–	0·14	0·14	–	0·14	0·22
H_2O	0·70	0·40	–	0·41	0·63	0·89	0·85	1·22	–	1·22	1·00	–	1·00	0·91
Total	99·73	99·84	99·10	100·13	99·83	99·76	99·42	99·47	98·70	99·85	99·40	98·25	99·08	98·90
ppm														
Ba	798	–	–	–	1183	1023	911	920	–	–	989	–	–	923
Ce	49	–	–	–	48	51	47	–	–	–	53	–	–	61
Cr	84	–	–	–	116	91	75	–	–	–	–	–	–	52
Cu	47	–	–	–	33	45	52	–	–	–	99	–	–	–
Ga	18	–	–	–	18	18	18	–	–	–	16	–	–	–
Ni	16	–	–	–	21	18	10	–	–	–	6	–	–	10
Pb	56	–	–	–	56	41	48	–	–	–	58	–	–	38
Rb	231	–	277	–	188	168	224	180	–	–	182	178	180	159
Sr	257	–	152	–	319	321	–	298	–	–	274	333	303	751
Th	30	–	–	–	30	23	–	–	–	–	–	–	–	31
Y	30	–	9	–	27	22	–	21	–	–	21	12	16	6
Zn	55	–	–	–	57	65	–	–	–	–	–	–	–	–
Zr	85	–	58	–	84	99	–	72	–	–	82	103	93	138

Column 1: Average of nine Errisbeg Townland granites.
Column 2: Average of four Garnetiferous Murvey granites, Murvey.
Column 3: Average of three Aplitic granites near Mace Pier, Mace (Derham 1993).
Column 4: Average of two main Murvey granites from Murvey.
Column 5: Average of two transitional Errisbeg Townland to Carna granites.
Column 6: Average of 31 Carna granites.
Column 7: Average of two Cuilleen granites.
Column 8: Average of two Mace–Ards granites.
Column 9: Average of 17 Mace–Ards granites (Derham 1993).
Column 10: Average of 8 and 9 above, i.e., 27 Mace–Ards granites.
Column 11: Average of three K-feldspar phenocrystic Mace–Ards granites.
Column 12: Average of three K-feldspar phenocrystic Mace–Ards granites (Derham 1993).
Column 13: Average of columns 11 and 12, i.e., six K-feldspar phenocrystic Mace–Ards granites.
Column 14: Average of six Roundstone granites (Harvey 1967).

at the margin of the Central Block of the Galway granite, is that it was important in the Galway batholith. The geophysical evidence, based mainly on gravity (Murphy 1974; Murphy & Jacob 2001) shows that the batholith extends in all directions underground beyond the surface outcrop (Fig. 1). This agrees with the outward dip of the granite–metagabbro contact, so that the stoped blocks could have fallen into the magma by both inward tipping and downward descent into underlying magma, being prised off by upward magma injections along near vertical fractures. Although stoping does not overall create space, the process exploits space made available by other means, such as sinking of the magma chamber floor or uplift of the roof.

2.2.2. Inward emplacement of the ring complex. The transitional contact of the Carna and the ETG shows a gradual increase in the size and abundance of K-feldspar phenocrysts northwards over ~300 m SW of Gorteen Bay near [695.376]. This transition zone continues across the junction of the two types right across the map to its eastern edge, but the width narrows eastwards to less than 60 m and the transition zone has not been separately shown in Figure 3 SE of Inishtreh. Figure 3 shows that the Carna granite cuts across the ETG, so the most likely interpretation of the transitional junction is that the Carna granite intruded the ETG magma and both magmas coexisted and crystallised side by side, with mutual mixing which blurred the contact. The Carna granite magma pulses were interrupted by a phase of Cuilleen granite intrusion before resuming to gradually give way to the Mace–Ards intrusion. The Cuilleen granite is similar to the Carna granite and only slightly less mafic, more felsic and potassic (Table 1: 6, 7). Its abundant prominent K-feldspar phenocrysts probably reflect increased magmatic water (Leake 2006).

Figure 5 shows the chemical variations with position across the ring complex from the Murvey granites at the edge of the batholith to the Aplitic Murvey-type granite centre of the Mace–Ards granite, using the outer edge of the near-uniform-width Cuilleen granite as a zero position. Distances measured outwards from the Cuilleen granite are positive and those

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Table 2 Chemical analyses of granite veins, aplites, aplitic granites and mafic enclaves. Chemical analyses are by XRF and wet methods as described either in Leake *et al.* (1969) or Harvey *et al.* (1972). tFe_2O_3 is not included in the total, as Fe_2O_3 and FeO are each determined.

wt. %	1	2	3	4	5	6	7	8	9	10
SiO_2	72·58	74·73	75·32	69·51	71·89	75·39	71·30	76·78	62·65	59·98
Al_2O_3	13·51	14·01	14·17	15·33	14·21	13·97	15·73	12·15	15·32	14·93
TiO_2	0·24	0·03	0·13	0·30	0·26	0·12	0·05	0·05	0·73	0·92
tFe_2O_3	–	–	–	–	–	–	–	–	–	–
Fe_2O_3	0·72	0·01	1·28	0·56	0·02	0·08	0·00	0·38	1·95	2·35
FeO	1·08	0·57	0·29	1·61	1·76	0·78	0·62	0·24	2·53	3·63
MnO	0·08	0·45	0·15	0·06	0·04	0·03	0·01	0·01	0·10	0·16
MgO	0·77	0·03	0·81	0·91	0·49	0·23	0·10	0·27	3·07	3·35
CaO	1·56	0·12	1·84	2·23	1·93	1·49	1·39	0·67	3·38	4·76
Na_2O	4·16	4·56	0·06	3·85	4·14	4·17	4·97	4·37	3·90	4·00
K_2O	4·27	4·95	3·93	4·15	3·70	3·50	5·28	4·83	4·89	2·79
P_2O_5	0·08	0·01	0·04	0·15	0·08	0·03	0·02	0·01	0·46	0·71
H_2O	0·67	0·21	1·72	1·07	0·96	0·24	0·50	0·26	1·45	1·78
Total	99·72	99·68	100·45	99·73	99·48	100·03	99·97	100·02	100·43	99·36
ppm										
Ba	–	–	–	1047	992	141	338	–	1160	786
Ce	–	–	–	40	40	45	23	–	75	84
Cr	–	–	–	66	81	12	61	–	107	–
Cu	–	–	–	65	31	21	21	–	69	49
Ga	–	–	–	18	15	18	19	–	17	22
Ni	–	–	–	7	4	5	1	–	56	62
Pb	–	–	–	36	38	51	70	–	99	53
Rb	–	–	–	175	163	174	220	–	271	148
Sr	–	–	–	305	267	193	161	–	300	485
Th	–	–	–	16	19	25	20	–	25	27
Y	–	–	–	20	21	26	23	–	23	16
Zn	–	–	–	62	49	32	31	–	87	114
Zr	–	–	–	67	67	56	21	–	132	313

Column 1: Granite dyke in country rock, 85 m WSW of Cregduff Lough, SW of Roundstone (BL3220).
Column 2: Garnetiferous aplite dyke. End of same dyke as 1. Location in Leake (1968), (BL3490).
Column 3: Greisened Murvey granite from borehole at northern edge of Murvey granite. Includes 0·71 wt. % CO_2 (BL428A).
Column 4: Average of two analyses of late stage Mill Lough Microgranite crossing Carna granite (BL3648 & BL3649).
Column 5: Typical aplitic Mace–Ards granite (BL3687).
Column 6: Typical aplite in Errisbeg Townland granite (BL3342).
Column 7: Typical aplite in Carna granite (BL3676).
Column 8: Typical aplite in Roundstone granite (BL3222).
Column 9: Typical mafic enclave (or cognate xenolith?) in Errisbeg Townland granite (BL3219).
Column 10: Average of 23 cognate xenoliths or mafic enclaves in the Errisbeg Townland granite near Galway from Coats & Wilson (1971).

measured inwards are negative. Because three granites (ETG, Carna and Murvey) all form, in different places, the outer margin of the granite, plots of distances from the country rock or from the ring complex centre do not clearly distinguish the different compositions of these granites. The magma pulses became more fractionated both outwards across the ETG and inwards across the Carna granite to the Mace–Ards granite and to the central Aplitic Murvey-type granite found near Mace Pier at [740.315]. This reflects loss of hornblende and titanite, decline of apatite, and the increasingly sodic nature of the plagioclase in passing from the Carna granite to the Mace–Ards and Aplitic Murvey-type granites. Figure 6 shows that the Fe+Mn enrichment of biotites analysed by electron microprobe (Leake 1974) relative to Mg (i.e. the mg ratio) gives a corroborative pattern of inward and outward fractionation. Similarly, granite Rb increases and Sr declines, giving markedly higher Rb/Sr towards both the central and exterior Murvey granites.

It is significant that the K-feldspar phenocryst-bearing Mace–Ards granite has virtually the same chemical, modal and feldspar compositions as the aphyric Mace–Ards granite (as shown in Table 1: 10, 13), with 3·92 wt. % and 3·93 wt. % K_2O respectively and modal K-feldspar of 26·4 vol. % and 26·0 vol. %. This suggests that the phenocrystic phase is due to increased water content in the magma, facilitating growth of larger K-feldspars, as documented by Leake (2006). This increase in water is in agreement with other evidence, given below. Small patches (not veins) of aplitic Mace–Ards granite also occur, but these have lower H_2O and are a little more fractionated (Table 2: 5). As in the Carna granite, there are occasional near-vertical layers thought to reflect slight variations in the magma pulses and post-emplacement movement.

East of Mace, in the Ards parts of the intrusion around [743.311], the Mace–Ards granite contains irregularly distributed 5–7 cm-spheroids ('orbs') of largely chloritised biotite with pinitised cordierite, intergrown with minor muscovite and sometimes minor quartz and feldspar. Around these aggregates are rims, up to 4 cm thick, of biotite-poor granite, making prominent white circles (spheroids) around dark cores. Illustrations and fuller descriptions are given in Feely *et al.* (2006), but no explanation of this phenomenon has yet been published. Nearby at [743.310] there are 10–15 cm-vugs containing muscovite but largely empty. These vugs and orbs are consistent with crystallisation near, or at, water saturated

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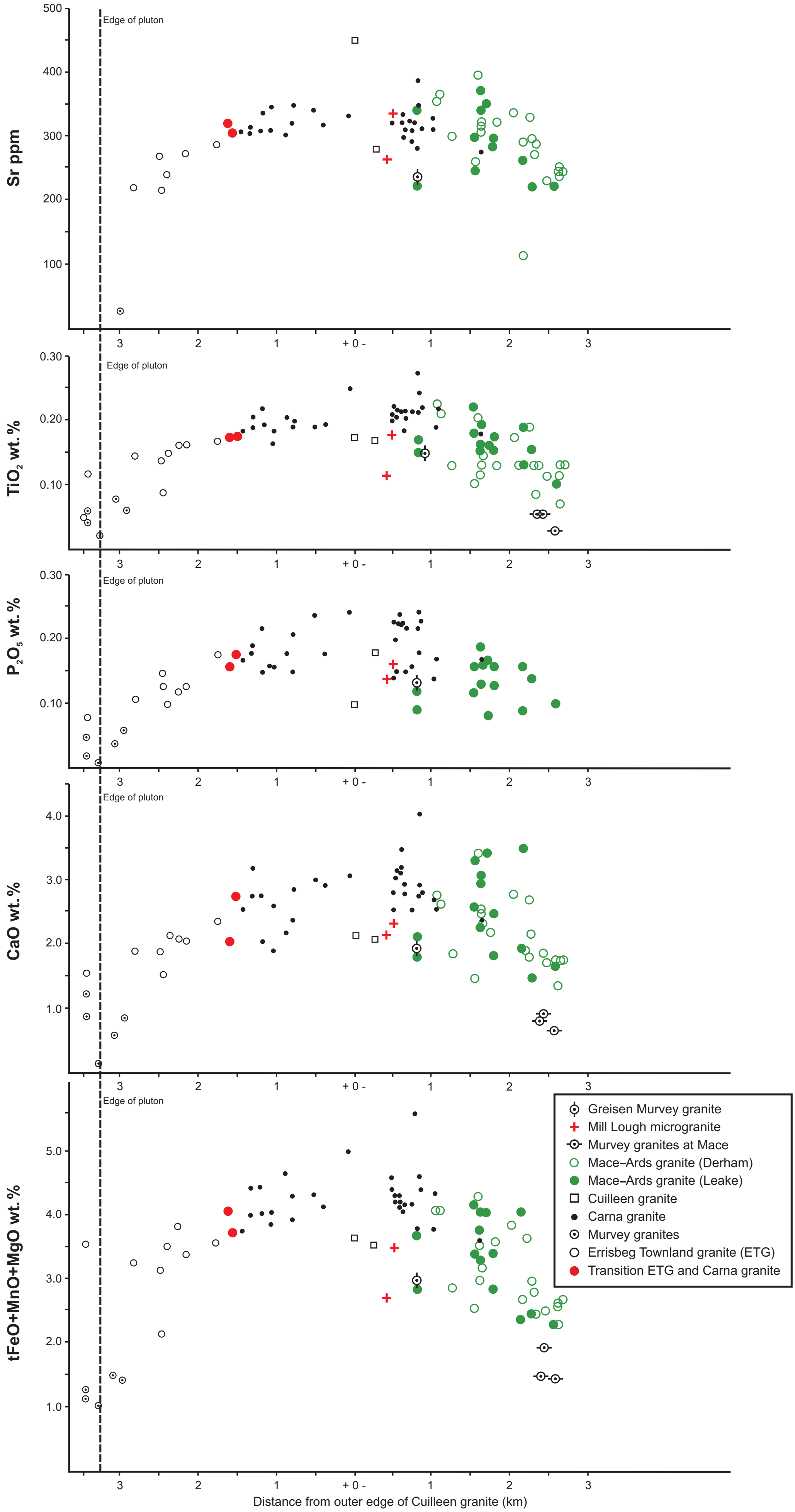

Edge of pluton
Sr ppm
TiO2 wt. %
P2O5 wt. %
CaO wt. %
tFeO+MnO+MgO wt. %
Distance from outer edge of Cuilleen granite (km)
Greisen Murvey granite
Mill Lough microgranite
Murvey granites at Mace
Mace–Ards granite (Derham)
Mace–Ards granite (Leake)
Cuilleen granite
Carna granite
Murvey granites
Errisbeg Townland granite (ETG)
Transition ETG and Carna granite

conditions. There are no pelitic or aluminous country rocks enveloping the western part of the batholith. With one exception, only metagabbro and quartz diorite gneiss (Leake & Tanner 1994) xenoliths have been found in the granites, so aluminous contamination of the magma is ruled out. The only exception is a few low-Al quartzose gneiss and feldspathic quartzite xenoliths at [750.323], just outside the Mace–Ards granite. The cordierite in the orbs is of primary magmatic origin, arising from a water-rich, fractionated, slightly peraluminous magma. Abbott & Clarke (1979) and Erdmann *et al.* (2009) have shown that below 800 °C, if a silicate liquid is in equilibrium with two feldspars, such as K-feldspar and oligoclase or andesine, and biotite, with or without muscovite, it can, under conditions near to, or at, water saturation, reach the cotectic crystallisation of biotite and cordierite as seen here. It can also involve the peritectic reaction of biotite and muscovite to give cordierite plus liquid. Commonly, late stage muscovite growth, pinitisation of cordierite and chloritisation of biotite, all observed in the present orbs, follow as the water-rich residual fluid reacts with the earlier-formed minerals. This, the vugs and the spherical orb shapes, all suggest immiscible fluid-rich droplets in the granite magma, supporting fractionation to an unusually water-rich end magma. Such a deduction is entirely consistent with other accounts of orbicules in granite batholiths, such as those of Sinclair & Richardson (1992), who stress the need for high fluid content at shallow level, i.e. low (<2 kb) pressure near the granite roof. Leake & Ahmed-Said (1994), using hornblende barometry on the ETG near Roundstone, showed crystallisation of the ETG at 1·5 kb to <2·6 kb, while Leake & Cobbing (1993) have shown that the granite east of the present area and west of Kilkieran (Fig. 1) is actually adjacent to the roof of the batholith.

Further evidence of high water content in the Ards–Mace granite magma occurs on the south coast of Mace at [737.314], where one of the few K-feldspar pegmatites mapped anywhere in the area of Figure 3 occurs. This is a curious, largely brecciated, apatite-bearing K-feldspar (up to 10 cm crystals) pegmatite associated with the Mace–Ards granite and, on its west side, with a syn-magmatic dark porphyry-like dyke ('microgranodiorite'), that injected the granite but also occurs as xenoliths in the granite, which must therefore have been only partially crystallised when the dyke was intruded. The brecciation of all three rocks followed. The K-feldspar pegmatite not only suggests a fluid-rich environment of growth but, according to Derham & Feely (1988) and Feely *et al.* (2006), who have described the occurrence in detail, the feldspars and the granite clasts were brecciated and silicified by hydrous P-, K- and SiO_2-rich fluids that were carried up by fluid overpressure to their present position before the later quartz veins were emplaced. The residue of these water-rich fluids formed the breccia matrix. Most significant is the occurrence in the microgranodiorite of 2 cm-diameter orbicules with magnetite-pyrite cores rimmed by microgranodiorite, and orbicules of microgranodiorite rimmed with magnetite and pyrite. These suggest the separation of sulphide droplets from a granite magma and granite droplets in a sulphide magma, both later coated by movement of the droplets into either immiscible granite, or sulphide magmas. At the centre of the breccia are quartz pods containing magnetite clots which oxygen isotopes show crystallised between 568 °C and 655 °C (Gallagher *et al.* 1992), i.e. late magmatically.

Finally, three additional facts support fractionation to a water-rich culmination, before the intrusion of the relatively dry Aplitic Murvey of Mace Pier and the Mill Lough bodies. These formed presumably after separation of the magma into a magmatic phase and an immiscible fluid-rich phase. First, the probe analyses of ten biotites (Leake 1974) from what is now termed the Mace–Ards body, show in Figure 6 no F enrichment compared with 12 from the Carna granite, with both sets averaging 0·59 wt. % F, indicating a substantial (OH) content. In contrast, biotites from the ET and Murvey granites which, for the latter average 1·35 wt. % F, suggest that at Murvey, the final magma was less hydrous. Secondly, the molybdenite Mo was removed and concentrated from the residual melts by exsolving fluids because the fluid–melt partition coefficient ($D_{Mo,\ fluid/melt}$ = 17–20) strongly favours the fluid (Audétat 2010). Thirdly, the extensive fluid inclusion studies of Feely and others, summarised in Feely *et al.* (2006), have shown that the earliest inclusions in the granite quartz, in what is here termed the Mace–Ards granite, were of high temperature (~450 °C), low to moderate salinity and water-rich, and such fluids deposited the late magmatic molybdenite-mineralised quartz veins and had a subsequent complex history at lower temperatures.

Accordingly, it is proposed that the Western Ring Complex fractionated inwards at low pressure to a water-rich culmination, with actual separation of immiscible water-rich fluids in the penultimate magmas. Fluid was then released, and the main pre-dyke magmatic phase ended with the intrusion of the cross-cutting, relatively dry, Mace Pier Aplitic Murvey-type granite and the Mill Lough microgranite, both of which are fine-grained and aphyric, inconsistent with crystallisation from a wet magma. The Mill Lough body cuts across the Mace–Ards, Carna and Cuilleen granites and is evidently later than all these granites but precedes the porphyry dykes and quartz veins which cross it (Fig. 3). Chemically and modally however, the Mill Lough body (Table 2: 4) is much closer to the Mace–Ards granite (Table 1: 10) than to the Mace Pier granite. Its fine-grain size suggests that it is probably a late-stage intrusion of the same magma, but drier, and more quickly cooled with its dyke-like geometry. The aplitic texture of the Mace Pier body may be the result of very rapid magmatic crystallisation when the fluid phase separated, perhaps under a sudden pressure drop, only to later vigorously attack and mineralise the Aplitic granite, which is why both at Mace and Murvey it is the most hydrothermally altered and mineralised of the ring complex granites, as described in detail by Gallagher *et al.* (1992). Re–Os dating of two samples of the Mace molybdenite in the Aplitic Murvey granite yielded 407·3 ± 1·5 Ma (Selby *et al.* (2004) for both, dating the end of the core magmatism and consistent with the 412 ± 15 Ma U–Pb zircon date of the Carna granite (Pidgeon 1969). Oxygen isotopes show that the main molybdenite mineralisation in

Figure 5 Plots of the chemical compositions of the granites for ppm Sr, wt. % TiO_2, P_2O_5, CaO, and the summation of total iron as FeO + MnO + MgO, from the granite veins in the country rock and the marginal granites (both on left) to the centre of the ring complex (right), showing both inward and outward fractionation. Because three granites (ETG, Carna and Murvey) all form, in different places, the outer margin of the granite, plots of distances from the country rock or from the ring complex centre do not clearly distinguish the different compositions of these granites. Accordingly, distances are measured from the outer edge of the Cuilleen granite; those towards the country rock being positive and those towards the Ring centre being negative. Samples from Croaghnakeela Island assume the Cuilleen granite outcrop is circular, checked by the *mg* values of the biotites on the trend in Figure 6.

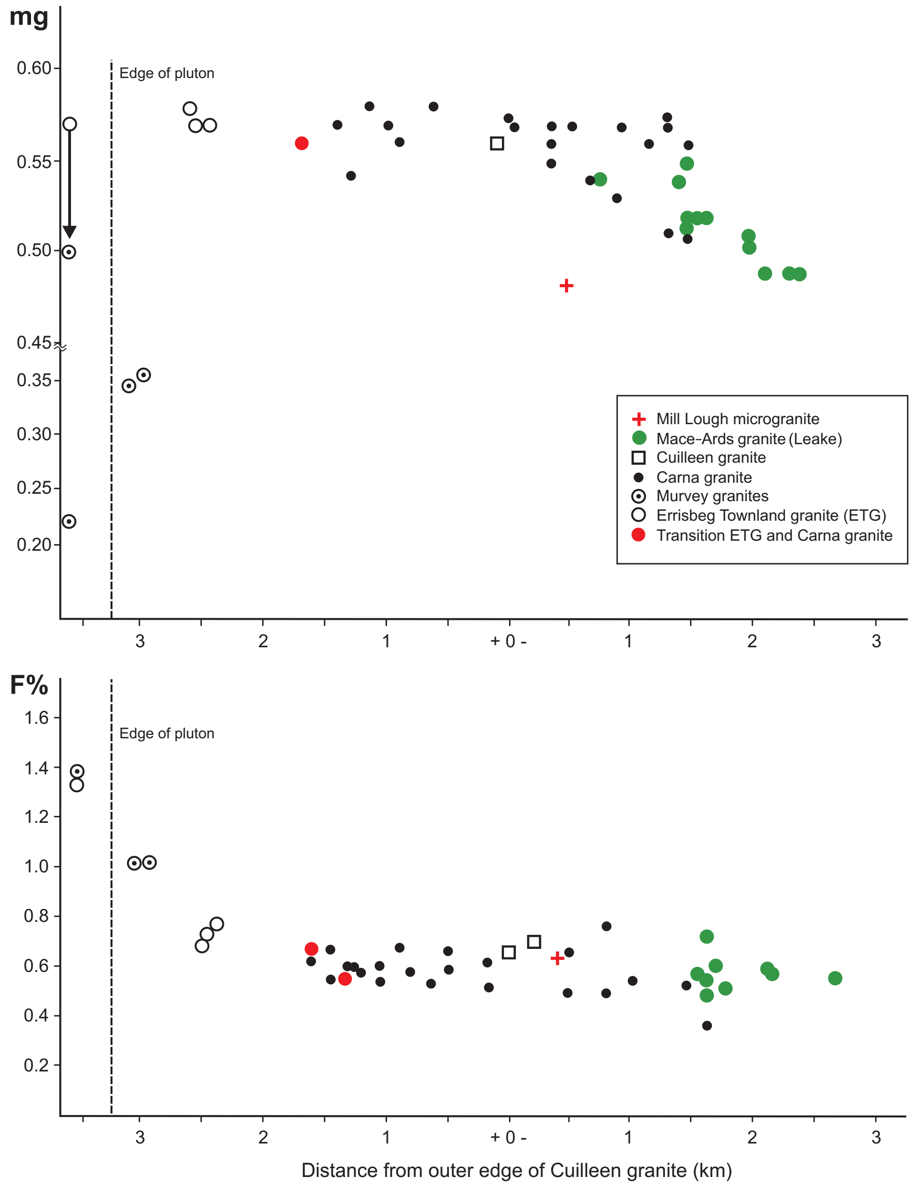

Figure 6 Plots of F % and molecular (Fe_2O_3+FeO+MnO)/MgO (=*mg*) in biotites across the Western ring complex (probe analyses in Leake 1974). Symbols and scale as in Figure 5. Arrow and line shows fractionation in biotites in the long (nearly 1 km) granite vein in the country rock SW of Roundstone which varies from ETG to Murvey granite and contains near the end, fluorite, topaz and tourmaline, consistent with late fractionation to a F- and B-rich residue.

NE-striking quartz veins took place between 360°C and 453°C at only 1·2–2 kb (Gallagher *et al.* 1992), i.e. again quite near to the surface, which is significant, as shown below. The relative compositions and fractionations of all the granites in the Complex are summarised in Figures 5 and 7.

2.2.3. Creation of the space for the ring complex. Important is the disposition in the ETG, and less commonly in the Carna granite, of numerous layers with 10 cm- to 2 m-thick biotite-rich portions and K-feldspar-rich, biotite-poor portions, presumably representing the felsic part complementary to the gravity-settled mafic biotite-rich part. Dozens of these layers, which can be seen clearly only on coastal 100% exposure, as they weather preferentially, are marked on Figure 3 and illustrated in Feely *et al.* (2006). They generally strike between E and ESE (but often N–S on Croaghnakeela Island) and dip outwards towards the country rock at amounts typically from 50° to 80° in the Carna granite, but at lower amounts from 20° upwards in the ETG. Most of these layers are thought to originate from shearing and consequent remobilisation within the nearly consolidated granite magma as it emplaced its way upwards, the biotite compositions (Leake 1974) being identical to those in the adjoining unsheared granite.

Distinct from these biotite layers are steeply dipping layers in the Carna granite, sometimes crossing each other, presumably recording near-vertical movement as the granite 'inched' upwards. Also distinct are schlieren bands of smeared-out sheared microdioritic mafic enclaves (cognate xenoliths?), recognised by their gradation into undeformed enclaves and the short lateral extent (1–2 m) of the bands. All the granites except the Mill Lough and Aplitic Murvey types contain scattered rounded microgranular mafic enclaves, ~20 cm in diameter, of fine-grained plagioclase, hornblende, biotite and quartz with minor magnetite, long apatite needles, K-feldspar and titanite. Chemical analysis of a typical mafic enclave from the ETG is shown in Table 2. Analysis 9 is similar to 23 cognate xenoliths or enclaves studied by Coats & Wilson (1971), the average of which is analysis 10. All these enclaves have dioritic compositions (Streckeisen 1976). They probably originated from early, relatively mafic, crystallisation in the

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roof zone. This was dragged down and dispersed by a combination of its higher density and convection currents in the magma (Bea 2010).

Some of the biotite-rich concentrates noted above show graded bedding, with the more felsic part invariably lying above the mafic part. The layering was presumably originally not as steeply dipping as now. Each layer is made of quartz and two feldspars with up to 40% of biotite, with several percent each of magnetite and hornblende and with titanite partially replaced by ilmenite. Biotites are up to 5 mm long. The layers were tipped up by the greater rise of the centre of the ring complex compared with the periphery, giving radially outward dips shown in detail in Figure 3. Thus, on the northern side of the ring complex, dips are towards the N or NNE, on the western side, as in Croaghnakeela Island, to the west, and at Doolick rock ([680.269]) just over 1 km south of the southern limit of Figure 3, the banding strikes NW–SE and dips SW at 20°.

On the north sides of Dogs and Gorteen Bays (Fig. 3) biotite layering is especially well seen, with relatively low dips (20–45° to the N), and is associated with right-way-up cross-bedding in graded layers. Both cross and graded bedding are primary magmatic in origin and not due to remobilisation by shearing, as there is no shearing evident in the perfectly exposed wave-washed surfaces. Also, instead of being confined to narrow zones less than 1 m wide, the layered granite is up to 3 or 4 m thick and forms a stacked series of layers dipping gently northwards, indicating that they too were tipped up by rising granite to the south. Similarly, Lawrence (1968) reported upward-younging gravity-settled layers dipping to the south on the south side of the batholith on Gorumna Island (Area 6 in Fig. 1) where the Carna granite is north of the ETG, which itself lies north of the Marginal Murvey-type granite, supporting the tipping up of the layers by a rising centre of the batholith.

Accordingly, there is good evidence that the space for the ring complex was made by upward movement of the whole Complex, in part magmatically and in part along vertical movement zones, pushing the covering of ETG, the marginal Murvey granite, the country rocks and any possible volcanic cover upwards, to be eroded away. The ETG marginal envelope was tilted radially outwards and is still preserved. Such a process would be easiest near to the roof of the batholith above the ring complex, and is consistent with the known shallow depth of formation of the Complex and the proximity of the roof of the batholith immediately east of the present area (Leake & Cobbing 1993).

The above deductions accord with the irregular occurrence in the Carna granite, especially northeast of the Cuilleen granite outcrop, of a faint, near-vertical foliation striking 120–140°N, which closely corresponds to the strike of the magnetic vertical foliation of 135°N detected by King (1966). This was ascribed by him to be the result of a combination of magmatic flow followed by lateral compression due to a later phase of granite central intrusions, a remarkably prescient deduction considering the ring complex had not then been recognised. The magma pulses would have flowed upwards along a strike of ~135°N, which is close to the strike of the Cuilleen granite outcrop (Fig. 3). In that there is no strong foliation, the lateral compression was minor, not major.

The upward movement of the ring complex, as it was either pushed up from below or rose under the influence of its low specific gravity compared with that of the country rock envelope, continued in the latest magma stages and even long after the magma had entirely solidified. This conclusion is based first on the aplite veins, which are believed to have formed under the influence of early fracturing of the nearly solid granite. The earliest aplites are the E–ESE-striking ones, seen best in the ETG. They are the thickest (up to 1·5 m) and longest (continuously traceable for up to 300 m, e.g. at [695.391]) which shows they drained the residual magma in the host granite when it was most abundant. Also, they are generally cut by the later, thinner, much shorter, near N–S set, which must have formed after the E–W extensional phase started. Although the early E–W aplites are often near-vertical, there is a strong tendency, especially south of Errisbeg, to dip to the south at amounts down to 65–70° (details on field maps), suggesting that the upward inching of the granite was not vertical near to the batholith margin but slightly outwards as it spread upwards and laterally. By the time the extensional phase opened up the N–S fractures, the volume of residual granite magma was so little that only short, thin veins could be formed. These views are supported by the steeply southward dipping E–ESE master jointing along the northern margin, which passed into near-vertical to steeply southward dipping faults, the largest of which are marked on Figure 3. The earliest movements on these joints and faults pre-date the N–S porphyry and felsite dykes, which usually cross them, or terminate against them. All these features reflect late upward movements. The master E–ESE joints and faults and the N–S joints disappear south of Letterard and seem to be replaced by a multitude of minor ESE- and NNE- to NE-striking joints, numerous NE faults and one major SE-striking fault, that runs up the east side of Mweenish Island, across Ard Bay to Moyrus beach, south of Inishbigger, all preceded by NE-striking aplites.

3. Later magmatism; the dyke phases

This account is but an introduction to a long and involved dyke history, not yet unravelled. Typical chemical analyses of the dykes are shown in Table 3. The dyke sequence was: appinites (hornblende–plagioclase) or lamprophyres (Leake 1986) only found outside the batholith; plagioclase ± quartz porphyries, sometimes with black, near-glassy, edges; felsites; and dark porphyry dykes. The last are not always distinguishable from the earlier plagioclase porphyries which, with the felsites, are much the most common. Mohr (2003) has shown that the porphyry dykes are dacites, using the nomenclature of Le Maitre *et al.* (1989), but porphyry is still generally used because of its phenocrysts. Much later dolerites, e.g. the E–W dyke south of Mill Lough at [755.328], are not thought to be related to the batholith magmatism, being of both Carboniferous (Mitchell & Mohr 1987) and Tertiary (Mohr 1982) in age. A major period of late extensional movements that opened generally N–S fractures right across the batholith and the country rocks, resulted in most of the batholith dykes being predominantly N–S in direction.

The appinites consist of sericitised plagioclase, hornblende, chloritised biotite, with accessory epidote, apatite and possible magnetite. The plagioclase ± quartz porphyries have either a fine-grained sericitic and saussuritic groundmass, or a plagioclase, quartz, biotite ± K-feldspar groundmass, sometimes with graphic texture involving quartz and K-feldspar, with phenocrysts of partly sericitised zoned plagioclase, erratically present rounded quartz and a few chloritised biotites, minor epidote and magnetite or ilmenite. The felsites consist of fine grained quartz, sodic plagioclase and K-feldspar with phenocrysts of those minerals plus scraps of altered biotite, muscovite and a little magnetite. The dark porphyries have variable amounts of sericitised plagioclase, K-feldspar, quartz-rich groundmass, chlorite after biotite, minor hornblende and are often not petrographically distinct from the earlier porphyries. Some, like analyses 10 and 11 in Table 3, have been strongly altered hydrothermally, losing Ca.

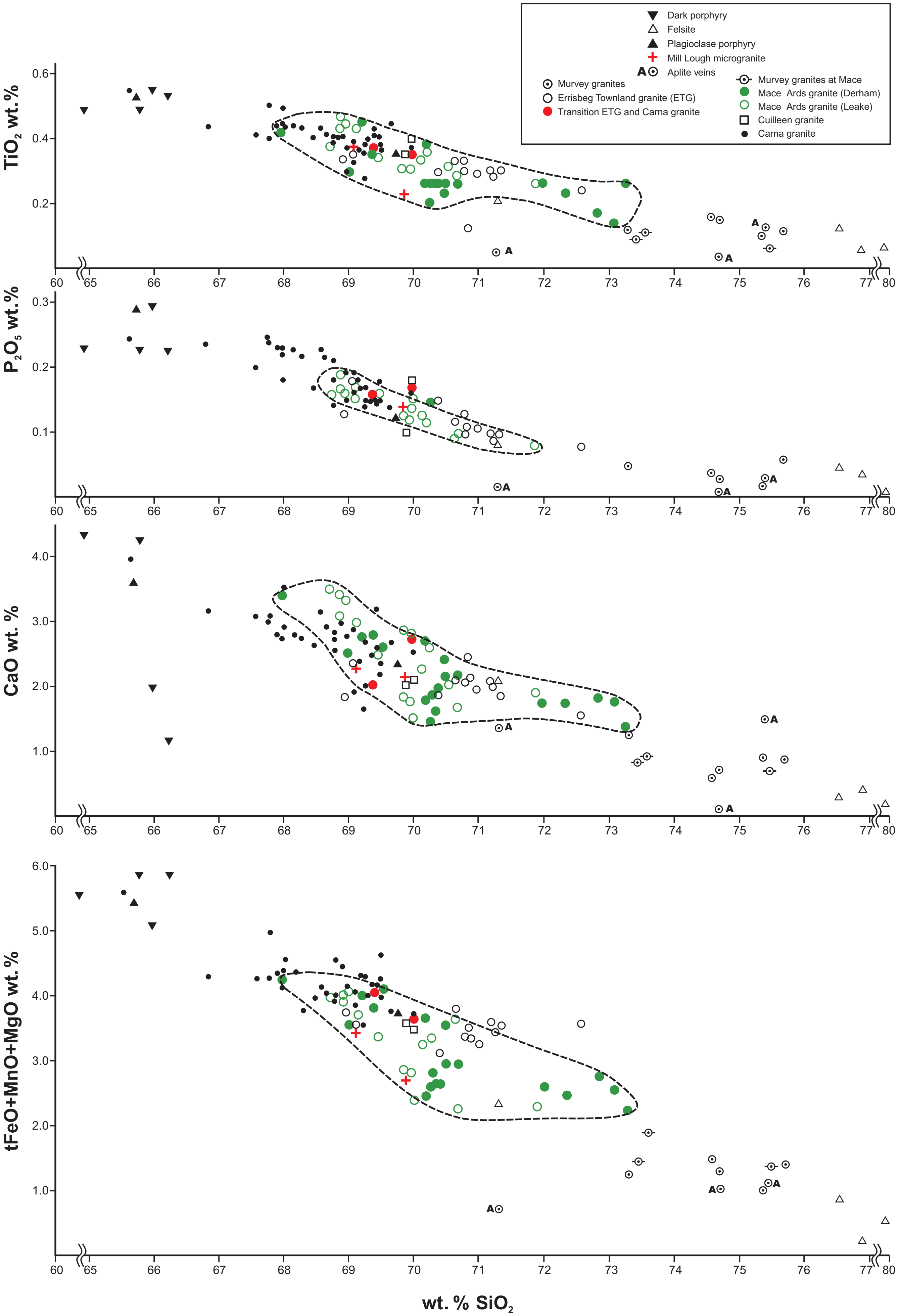

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Table 3 Chemical analyses of dykes related to the Galway batholith magmatism. Chemical analyses by M. A. Thornton (1964).

wt. %	1	2	3	4	5	6	7	8	9	10	11
SiO_2	47·39	69·75	65·70	71·32	76·91	76·54	79·62	64·24	65·79	66·25	65·98
Al_2O_3	14·43	15·25	15·46	15·48	13·17	12·17	11·01	15·40	15·58	16·29	16·90
TiO_2	0·93	0·35	0·53	0·20	0·06	0·13	0·07	0·49	0·50	0·53	0·55
Fe_2O_3	6·35	1·41	2·07	0·93	0·08	0·61	0·28	2·03	2·02	1·84	1·43
FeO	3·82	1·30	2·08	0·55	0·10	0·17	0·14	2·08	2·09	2·48	2·45
MnO	0·24	0·04	0·08	0·01	0·01	0·01	0·00	0·09	0·08	0·08	0·08
MgO	4·56	1·10	1·44	0·95	0·08	0·16	0·20	1·69	1·88	1·69	1·24
CaO	11·84	2·35	3·62	2·08	0·37	0·27	0·15	4·34	4·26	1·15	1·93
Na_2O	0·90	3·83	3·68	4·45	3·97	2·81	3·31	4·16	4·02	4·01	3·95
K_2O	5·94	3·21	3·92	2·98	4·29	5·48	4·22	3·23	2·98	3·70	3·23
P_2O_5	1·20	0·12	0·30	0·08	0·04	0·05	0·01	0·23	0·23	0·23	0·31
H_2O	1·57	1·30	1·32	0·55	0·35	0·67	0·53	1·42	1·76	1·40	0·92
Total	99·17	100·01	100·20	99·58	99·43	99·07	99·44	99·40	100·19	99·65	99·11

Column 1: Biotite-hornblende altered-feldspar apatite appinite, Kill, Errislannan (BL2666).
Column 2: Plagioclase porphyry dyke, south of Lough Phreaghaun (BL2796).
Column 3: Plagioclase porphyry dyke, north of Dogs Bay (BL 2704).
Column 4: Felsite with quartz, plagioclase and K-feldspar phenocrysts, Illaunurra (BL2512A).
Column 5: Felsite, very fine grained, Earawalla Point, SW Dogs Bay (BL2727).
Column 6: Centre of felsite dyke, South Murvey in ETG, NW Dogs Bay (BL444A).
Column 7: Edge of same felsite (BL444B).
Column 8: Centre of dark porphyry cutting felsite. In ETG, SE Murvey, NW Dogs Bay (BL2704A).
Column 9: Edge of same dark porphyry (BL2704C).
Column 10: Dark porphyry with traces of hornblende. Cuts BL2727 felsite (5 above); (BL2728).
Column 11: Chilled edge of same dark porphyry (BL2728A). Includes 0·14% CO_2.

The appinites do not cross the batholith but are cut by porphyry dykes (e.g. at [637.466]). Such dykes are the Connemara representatives of the appinite suite in the Dalradian rocks of Scotland and Donegal and related to the late Caledonian granites. The first post granite dykes were ~E–W plagioclase porphyries crossing Croaghnakeela Island ([685.325]). Although these dykes have dark chilled edges, their centres are coarse, almost granite-like, indicating very slow cooling, presumably because the enclosing Carna granite was hot and not entirely crystallised. In agreement, some of the dykes (e.g. at [691.322]) were broken up into xenoliths in the granite they had intruded by late movement of the granite, perhaps due to partial remobilisation by the heat from the intruded dykes. These E–W dykes would then have slowly cooled with the main body of the granite. Most of the aplites on Croaghnakeela Island and even a K-feldspar (10 × 23 × 15 cm)-quartz pegmatite at [690.328] also strike E–W, reflecting early E–W fracturing, perhaps related to cracking of the ring complex carapace by deeper rising granite still being emplaced below the present level of erosion.

Cutting the E–W dykes on Croaghnakeela Island and moving them 10 m dextrally, is a N–S plagioclase porphyry dyke, which suggests that the major batholith-wide E–W extensional phase had started by the time of its intrusion. Many N–S porphyry dykes (Table 3: 2, 3) occur in the area and throughout the batholith, and 5 km east of the present area, Mohr (2003) has shown they overlapped with Murvey granite there whose molybdenite was subsequently dated at 402·2 ± 1·1 Ma (Feely *et al.* 2010). Some of these dykes were extremely rich in volatiles, giving fluid-generated breccias, consistent with proximity to the batholith roof (Hunt & Mohr 2007). In the present area, the early nature of the N–S porphyries is revealed only where they are crossed by later felsites as in Murvey at [682. 396], or where felsite was intruded along the centre of an earlier porphyry as at [692.396], or when xenoliths of the earlier dyke occur in the felsite, as with black porphyry xenoliths at [679.384]. Because of the limited distribution of felsites, it is not known whether most of the mapped porphyry dykes pre-date or post-date the felsite dykes. It is possible that there was only one N–S porphyry dyke phase, briefly interrupted locally by felsite intrusions.

Rarely, porphyry dykes have banded layers in them which are folded, suggesting pushing of the magma northwards, as at [701.388]. While most of the porphyry dykes are less than 30 m in width, at Letterard at [742.363], two 30–40 m-wide N–S to NNW–SSE dykes join and expand to a width of 200–250 m, forming with the similar sized porphyry plug at Murvey ([670.388]), the two largest porphyry intrusions in the area. These Letterard dykes were intruded at the same time and close to the NE–SW-striking dykes which themselves follow the strong NE–SW fault set. The NE dykes retain the usual perpendicular relationship to the batholith margin, and with the N–S pair enables the general E–W extension to take place. The NE set reflects the influence of the anomalous NW strike of this part of the batholith edge.

The felsites also strike N–S, but are limited to three bands, one crossing Inishnee and two on the west and east sides of Dogs Bay. The felsites are often vertically banded parallel to the dyke length, with folding and brecciation of the bands as fracture movements continued after emplacement. The dykes tend to finger out northwards as though the magma had a southern, as well as a vertical, source, but felsites occur far outside the batholith in the country rock to the north (Leake &

Figure 7 Plots of the compositions of the granites and dyke rocks of the Western ring complex, wt. % SiO_2 against, wt. % TiO_2, P_2O_5, CaO and total Fe as FeO+MnO+MgO. The field of the newly defined Mace–Ards granite from ~68% to over 73% SiO_2 is outlined; the fractionated nature of the Murvey-type granites and the felsites is apparent and so is the less fractionated nature of much of the Carna granite and the porphyry dykes. Because Derham (1993) did not report P_2O_5, the range of the Mace–Ards granite field as regards P is incomplete.

https://doi.org/10.1017/S175569101100911X Published online by Cambridge University Press

Tanner 1994). The felsites (Table 3: 4–7; Fig. 7) are the most fractionated of the dyke magmas, being similar to the aplites, and the Garnetiferous and Aplitic Murvey granites.

Crossing the felsites is a later set of plagioclase porphyry dykes, seen cutting the felsites at Earawalla Point ([683.378]). There is evidence, from the differing chemistry of this group (Table 3: 8–11), that there may be more than one magmatic episode later than the felsites, but so few definite post-felsite porphyries are known that little can be concluded here. It is reasonable to assume that the N–S porphyry dyke episode was interrupted locally by the N–S felsite injections.

Mohr (2003), Leake (2006) and Figure 7 show that the compositions and variation trends of the dykes match those of the main phase batholith granites, being derived from similar, but later, magmas.

4. Concluding comments

The study reveals that the west end of the Galway batholith is a major, near-roof ring complex, emplaced by outward stoping and progressive inward intrusion combined with central uplift. It is later than the adjacent Roundstone granite and, being pre-407–410 Ma, is earlier than the main outcrop of the batholith, dated from 402 Ma to 394 Ma, but is not as old as the >422 Ma Omey granite (Feely *et al.* 2010). The ring complex cannot therefore be due to horizontal movement of magma from the main part of the batholith, as recently shown for the Trawenagh Bay granite in Donegal (Stevenson *et al.* 2008). The whole character of the ring complex may be explained by the convection of heterogeneous magma, as recently modelled by Bea (2010). The Galway granite magmatism and its limited associated appinites match the low Ba and Sr, high Th and Rb Scottish Cairngorm suite, and extend over at least 45 Myr from ~425 Ma to 380 Ma. Its origin is probably due to slab breakoff and the consequent rise of the asthenosphere causing deep crustal melting, as recently outlined by Neilson *et al.* (2010).

5. Acknowledgements

I thank Dr M. Feely of NUI Galway for continued help, including access to Dr J. M. Derham's (1993) Thesis. I acknowledge access to the data in Derham (1993), Harvey (1967) and Thornton (1964). I thank numerous boatmen for varyingly perilous landings and voyages to islands and rocks; Mr Mike Shand in the University of Glasgow for drawing Figure 3 and the Carnegie Trust for financial supporting it; Mr Alun Rogers in Cardiff University for expertly drawing the remaining figures and other help. Figure 1 is based on an original by Dr S. Baxter of NUI Galway. I thank M. Feely, C. T. E. Stevenson and I. Parsons, especially the last, for substantial improvements to the paper, and the School of Earth & Ocean Sciences, Cardiff University, for support and facilities, including thin sections by Mr L. Badham.

6. Appendix. Petrographic descriptions of the granites

Errisbeg Townland granite (Table 1: 1). Has 5–7 mm grain size, 30% each of quartz, plagioclase (normally zoned ~An_{35-15}) and phenocrystic (4 × 2 × 2 cm) K-feldspar (range of Or in perthitic intergrowth, Or_{85-97}), with 5% biotite (compositions in Leake 1974), a little green hornblende (composition in Leake & Ahmed-Said 1994) and magnetite, titanite, apatite and zircon, with secondary sericitisation of the plagioclase, and chloritisation of the hornblende and biotite. The last is also replaced by prehnite, andradite–grossular–hydrogrossular garnet (Leake 1998) and titanite. Secondary epidote, zoned allanite, pyrite and a little fluorite near the northern edge of the granite also occur.

Carna granite (Table 1: 6). Same mineralogy and secondary alteration as ETG (plus some ilmenite after titanite) but is aphyric, grain size 5–8 mm, with only 24% quartz and K-feldspar and plagioclase increased to 42%, while hornblende, titanite, apatite, magnetite and zircon amounts are slightly larger, and the plagioclase slightly more calcic, than in the ETG. The presence of hornblende and euhedral titanite, with a general lack of K-feldspar phenocrysts, is a distinctive combination of the Carna granite although a few bands with small, ~2 cm, K-feldspars occur.

Cuilleen granite (Table 1: 7). Modally similar to the Carna granite with normally zoned plagioclase ($An_{31}Ab_{68}Or_{1·7}$ cores to $An_{19}Ab_{81}Or_{1·7}$ rims) but the K-feldspar ($Or_{90}Ab_{9}An_{0·3}$ cores to $Or_{92}Ab_{7·5}An_{0·2}$ rims) occur almost entirely in pink phenocrysts which makes specimens distinctive in looking even richer in K-feldspar than the ETG, but the modes and chemistry show that the K-feldspar amounts are similar to those in the Carna granite and much less than in the ETG.

Murvey granite. Characteristically hornblende-free, usually aphyric. Finer grained (~3 mm) and more felsic than the remaining granites, and forms a number of different facies. The Main Murvey granite (Table 1: 4) has about equal quartz and K-feldspar ($Or_{93}Ab_{7}An_{0·2}$ cores to $Or_{97·6}Ab_{2·5}An_{0·1}$ rims), each ~34%, with 30% plagioclase, which is significantly more albitic than the remaining granites, typically having cores of $An_{13}Ab_{85}Or_{1·5}$ and rims of $An_{8}Ab_{91}Or_{1}$ with most of the grains being about An_8. There is only ~2% biotite, and traces of titanite, muscovite, magnetite and apatite. The Garnetiferous Murvey granite (Table 1: 2) is even finer grained, tending towards an aplogranite or with rounded quartz phenocrysts, with rare ~1 mm zoned spessartine–almandine garnets (Wright 1964; Leake 1968), sometimes with quartz centres, and traces of muscovite, but with little or no biotite, the mode being about 44% of quartz, 32% K-feldspar ($Or_{94}Ab_{6}An_{0}$), and 23% albite (~$An_{2}Ab_{96}Or_{2}$). The Aplitic Murvey granite of Murvey and Mace Pier (near [741.316]), have similar modes to the Garnetiferous Murvey granite, but lack garnets and are very fine grained (<1mm). Patches of green greisening (e.g. sample BL428A; Table 2: 3) and red hydrothermal alteration is common both at Murvey and Mace.

Mace–Ards granite (Table 1: 8–13). Has similarities to the main Murvey granite (>74 wt. % SiO_2) in lacking hornblende and titanite but is less siliceous (~70 wt. % SiO_2), coarser grained, more variable in texture and mineral proportions and the plagioclase is more calcic, being mostly normally zoned oligoclase, with andesine cores. Thus, probe analyses show cores of $An_{40-35}Ab_{59-63}Or_{1}$ and rims of $An_{17}Ab_{83}Or_{1}$. The Mace–Ards granite is composed of ~37·8 vol. % partly sericitised zoned plagioclase, partly enclosed by, and sometimes slightly corroded by, 26·0% zoned K-feldspar ($Or_{86}Ab_{13}An_{0·3}$ cores and $Or_{97}Ab_{3}An_{0·1}$ rims), 30·7% quartz, 4·7% biotite, variably altered to chlorite and a trace of hydrogrossular garnet. Traces of muscovite, apatite, allanite, epidote, zircon, magnetite and late pyrite with alteration rims of haematite occur. The modal figures are the average of 17 modal analyses given in Derham (1993) for samples from the Mace area of what is here named the Mace–Ards granite. The boundary line between the Carna and the Mace–Ards granites could not be reliably recognised in the field and has been drawn here (Fig. 3) using ~60 thin sections from carefully chosen locations to pinpoint the disappearance of hornblende and titanite. The latter persists a little further inward than the former.

Although much of the Mace–Ards K-feldspar is not phenocrystic, there are patches in which small (<2 cm in length) K-feldspar phenocrysts occur, and a mapped major area with phenocrysts or microphenocrysts. The phenocrystic Mace–Ards granite has virtually the same chemical, modal and feldspar compositions as the aphyric Mace–Ards granite, (as shown in Table 1: 10 and 13) with 3·92 wt. % and 3·93 wt. % K_2O respectively and modal K-feldspar of 26·4 vol. % and 26·0 vol. %. The phenocrysts are ascribed to slightly wetter magma pulses. Small patches (not veins) of aplitic Mace–Ards granite also occur, but have lower H_2O and are a little more fractionated (Table 2: 5).

Roundstone granite (Table 1: 14). Identical mineralogy to the ETG, but the K-feldspar phenocrysts are much smaller, reaching ~2·5 cm in length, and six modal analyses average 43·9% normally-zoned plagioclase (An_{35-24} but with thin rims to An_7), 24·9% quartz, 22·2% K-feldspar, often microcline, 7·4% biotite with chlorite, 0·9% hornblende, 0·4% euhedral titanite and traces of magnetite, apatite, zircon and secondary epidote, zoned allanite, garnet, prehnite and pyrite.

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MS received 10 July 2009. Accepted for publication 2 November 2010.