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Intrusive history of the Slieve Gullion ring dyke, Ireland: implications for the internal structure of silicic sub-caldera magma chambers

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ABSTRACT

The Palaeogene Slieve Gullion Igneous Complex comprises a layered central intrusion surrounded by a slightly older ring dyke. The ring dyke contains two major intrusive rock types. About 70% of the ring dyke is occupied by porphyritic granophyre and 30% by porphyritic felsite. Locally complex relationships between the two lithologies are observed. Major and trace element compositions suggest that there are two distinct chemical groups within each lithology: a Si-rich felsite, concentrated in a ~1 m wide zone at the outer margins of the dyke which grades into a less Si-rich felsite towards the interior. Similarly, a Si-rich granophyre, concentrated in the centre of the intrusion grades outwards into a Si-poor granophyre facies.

These rock relationships and geochemical variations suggest that a complex magma chamber hosted a stratified granitic magma body and various wall/floor magma facies. Low density, high-Si felsite magma from the top of the chamber was tapped first, followed by less Si-rich felsite magma as evacuation proceeded. The granophyres probably originate from the chamber walls/floor, representing more mushy equivalents of the felsite magma. Little granophyre magma was tapped during the early stages of the evacuation sequence. As evacuation continued, probably aided by trap-door caldera collapse, the 'granophyre magmas' intruded the already emplaced and slightly cooled felsite, forming the complexly zoned structure of the Slieve Gullion ring intrusion.

Keywords: Slieve Gullion, ring dykes, magma chamber dynamics, caldera collapse.

Introduction

Ring dykes are cylindrical sheet intrusions that form when magma rises along a steep, usually outward-dipping, ring fracture. They commonly delimit central collapsed blocks and display a sub-circular outcrop pattern. These intrusions were first described in the Tertiary igneous centres of the British Isles by Bailey *et al.* (1924) and later by Richey (1932, 1961), who recognized them in both Britain and Ireland. Many ring dykes and sheet intrusions display compositional zoning (Hildreth, 1979; Smith, 1979; Mahood, 1981), with the majority of these becoming more silicic corewards ('normally zoned intrusion'; cf. Fridrich and Mahood, 1984) but reverse zonations have also been documented, e.g. in the Sande cauldron, Norway and the Little Chief granite, California (cf. Stephens and Halliday, 1980; Fridrich and Mahood, 1984).

The Slieve Gullion Tertiary Complex is located west of the Mourne Mountains in south County Armagh, Northern Ireland, the southern portion crossing into County Louth (Ireland). Along with the Carlingford Centre, the Mourne Mountains and the Antrim basalts, Slieve Gullion forms the NE-Ireland part of the British-Irish Tertiary Igneous Province (Upton, 1988; Gamble *et al.*, 1999), believed to be related to plume activity and

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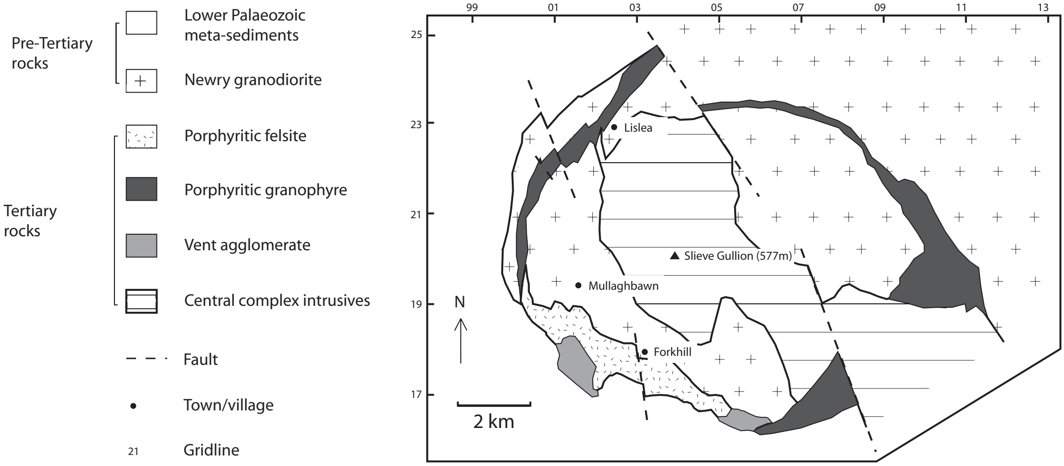


FIG. 1. Geological sketch map of the Slieve Gullion ring complex.

the opening of the North Atlantic (White and McKenzie, 1989; Saunders *et al.*, 1997). The Slieve Gullion complex consists of a roughly circular arrangement of hills, the ring dyke, ~12 km in diameter, encompassing a central intrusion that forms Slieve Gullion (~577 m) (Richey and Thomas, 1932; Emeleus, 1962; Elwell *et al*., 1974; Gamble, 1979). The ring dyke varies in width across the complex. At Forkhill it measures ~1 km in width, decreasing to 0.25 km west of Mullaghbawn village. In the north around Lislea, an average width between 0.75 and 1 km is recorded. The ring dyke has been intruded into both the Lower Palaeozoic metasediments of the Longford-Down belt and the south-west portion of the Caledonian Newry granodiorite pluton (Meighan and Neeson, 1979) (Fig. 1). The ring dyke consists of two principal felsic rock types, porphyritic felsite and porphyritic granophyre (Fig. 2), which are surrounded by a series of brecciated country rocks. The latter are historically termed the Vent

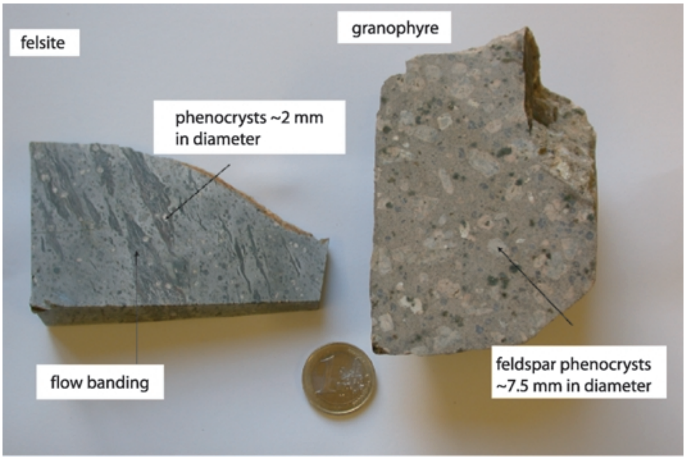


FIG. 2. Hand specimens of porphyritic felsite (left) and porphyritic granophyre (right). The felsite consists of a dark grey matrix containing phenocrysts of quartz and Or-rich K-feldspar, ~2 mm in diameter. Flow-banding defined by fiamme is a common feature. The granophyre is light grey in colour and contains larger Or-rich K-feldspar phenocrysts (~7.5 mm) along with phenocrysts of quartz similar in size to those in the felsite. (1-Euro coin, 23 mm wide, for scale).

Agglomerates of Forkhill and the Camlough Breccias. Earlier Tertiary intrusions of dolerite and gabbro and some Tertiary basalt have also been mapped in the area (Richey and Thomas, 1932; Emeleus, 1962).

The complex relationships between the various ring-dyke rocks were previously recognized by Emeleus, (1956, 1962) and thought to result from a two-stage intrusive history. We employed field observations, petrography, major and trace-element analysis, and viscosity and density calculations to further clarify the relationship between the felsite and granophyre rocks and to reconstruct in detail the emplacement history of the ring-dyke intrusions. In particular, we address the question of whether the ring-dyke rocks represent unrelated magmatic episodes that happen to intrude the same structural weakness, or whether the rocks represent different magma types of the same magmatic episode, i.e. are genetically linked. Our results shed light on the behaviour of felsic magmas in caldera-fault conduits and have implications for the structure of the sub-Slieve Gullion magma chamber and potentially similar intrusions elsewhere.

Field occurrence and petrography

Country rocks

Lower Palaeozoic metasediments

These sediments form part of the Central Belt of the Longford-Down inlier, to the west of the Slieve Gullion Centre (Fig. 1). Towards the south-west of the centre the metasediments underlie rolling agricultural land and are generally fine-grained. Chlorite, muscovite and quartz can be seen in thin section. Internal laminations within beds can result in some colour variation from lighter grey to green/grey. The rocks are well bedded with bed thickness ranging from ~10 to ~40 cm. Laminations and coarsening upwards sequences may be seen in both hand specimen and thin section. Moving northwards near Aughanduff (IH 9806 1771), the metasediment facies is dark-grey in colour, with grains of quartz ~1 mm in diameter clearly visible amongst finer-grained chlorite and muscovite. Close to the ring dyke, the metasediments have undergone further thermal metamorphism, with hornfelsed textures and disturbed bedding visible.

Newry granodiorite

The Caledonian Newry granodiorite (425 Ma; Meighan *et al*., 2003) crops out predominantly on the central plain moat between the ring dyke and Slieve Gullion hill (Fig. 1), where generally, it is extremely rotten. Overall it is a coarse-grained, grey granodiorite. Equigranular (2–3 mm) grains of quartz, feldspar and varying amounts of biotite and hornblende are visible in hand sample with smaller amounts of secondary muscovite identifiable in thin section. The modal proportions of mafic minerals vary considerably from ~10 to ~60% and this variation can be seen both on an outcrop and a regional scale.

Tertiary rocks

Early Tertiary basalts

Early Tertiary basalts are exposed at several locations across the centre, e.g. south of Mullaghbawn Mountain (IH 9878 1713) and Glendooey. In hand specimen, they appear dark grey with an overall red tinge. Although they are very fine-grained, some isolated lath-shaped plagioclase feldspar crystals, Fe-Ti oxides and chlorite are apparent. In thin section, ophitic augite may be seen. These basalts are quite vesicular and many vesicles contain secondary mineralization (carbonate ± zeolites).

Vent Agglomerate

Vent Agglomerate outcrops are predominantly exposed adjacent to the ring dyke at Mullaghbawn Mountain, Slievebrack, Croslieve and Cashel Mountain (IH 9772 1977). This breccia is composed chiefly of Newry granodiorite clasts ranging from sub-millimetre to metre size, with pieces of gabbro, basalt and Palaeozoic sediments also present (Richey and Thomas, 1932; Emeleus, 1956). This brecciation is the result of highly gas-charged eruptions prior to caldera collapse and thus predates the emplacement of the ring dyke (Emeleus, 1956, 1962). Outcrops generally have a reddish, oxidized tinge to them and are strongly weathered. The clasts are contained within a dark grey/green matrix which appears to consist almost entirely of very finely comminuted minerals derived from the Newry granodiorite. In thin section, quartz and feldspar make up >50% of matrix components, with hornblende, biotite and opaque minerals also present. While this breccia is generally clast supported, some individual outcrops have a higher matrix to clast ratio. Few internal structures or sedimentary structures are recognized in the Vent Agglomerate.

A variant of the Vent Agglomerate that contains more non-Newry granodiorite material also crops out in the complex, in close proximity to the ring dyke's southwestern edge (e.g. IH 9759 1919; IH 9763 1897). This breccia is mostly composed of clasts of Lower Palaeozoic metasediments which are clearly visible on the surface of the rock and measure ~5 cm × ~3 cm on average, with the largest clasts up to ~10 cm × ~5 cm. Fragments of dolerite and microgabbro also occur. There are no sedimentary structures within the rock and overall it is massive. The breccia is generally clast supported with no matrix visible.

Porphyritic felsite

The porphyritic felsite of the main ring dyke is a hypocrystalline rock with a very fine-grained, dark-grey matrix that appears a much lighter grey when weathered. Contained within this matrix are 25–30% phenocrysts, including both quartz (~10–15%) and ~10% feldspar (K-feldspar is the dominant variety, present mostly as sanidine), each measuring up to 2 mm in diameter, along with small rounded lithic clasts of the same dimensions, recognized as basaltic in composition from thin-section analysis (cf. Emeleus, 1962). The rock also contains small amounts (<1%) of pyroxene and fayalite olivine, along with ⩽5% opaques and volcanic glass (Emeleus, 1962).

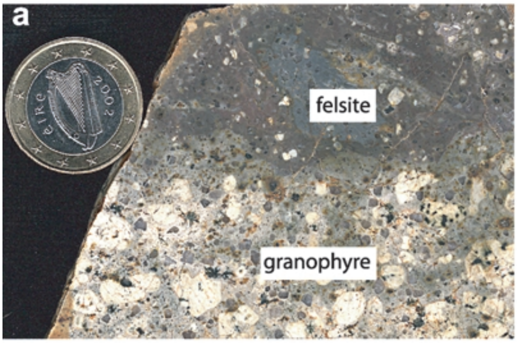
Present at some locations, e.g. at Mullaghbawn golf course (IH 9880 1812), are abundant xenoliths of Newry granodiorite. Trails of these xenoliths, along with alignment of flattened pieces of pumice (fiamme) (Bell and Emeleus, 1988) and phenocrysts help define flow within the felsite (Fig. 2).

Porphyritic granophyre

The porphyritic granophyre consists of a fine-grained, light grey/pink matrix and 35–45% phenocrysts of quartz (15%) and feldspar (20–25%), along with amphibole, clinopyroxene, opaque minerals, some minor fayalitic olivine and zircon (<5%). The average quartz phenocryst is 2 mm in diameter and can be round or irregular in outline. Feldspar phenocrysts are considerably larger at up to 7.5 mm in diameter and are sub-rounded (Fig. 2). They belong predominantly to the sanidine-orthoclase series (Emeleus and Smith, 1959); only minor plagioclase is present. Secondary chlorite and epidote are found locally.

Internal structure of the ring dyke

Of the two principal ring-dyke rock types, felsite crops out predominantly towards the south



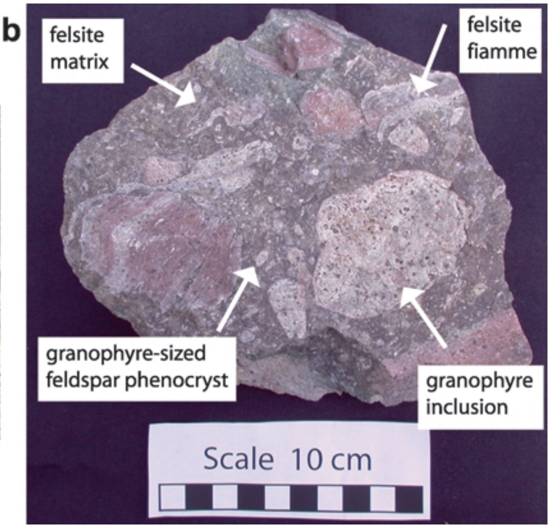


FIG. 3. (*a*) Contact between the felsite and granophyre of the ring dyke west of Mullaghbawn village. Note the undulating, lobate nature of the contact, and the thin chilled margin of the granophyre, which suggests that both 'magmas' were liquid simultaneously. 1-Euro coin (23 mm wide) for scale. (*b*) Lobate inclusion of granophyre within a body of felsite rock. Also contained within the felsite matrix are feldspar phenocrysts comparable in size to phenocrysts in the granophyre. Note the strongly flattened and folded felsite fiamme and the less strongly flattened granophyre inclusion, indicating a more rigid rheology for the latter.

of the intrusion and granophyre in the north (Fig. 1), with the two rocks exposed in contact at the ridge west of Mullaghbawn village (IH 9779 1836) and closely associated at Cashel Mountain. Previous field observations suggested that the felsite is the older of the two rocks with granophyre being a later and separate intrusion (e.g. Emeleus, 1962). However, closer examination suggests that the two rocks are effectively contemporaneous. At Mullaghbawn Ridge, where it initially appears that the granophyre simply underlies the felsite at this particular level, close examination of the contact shows an intermingling relationship between the two lithologies with lobate contacts and thin chilled margins surrounding blobs and veins of granophyre (Fig. 3*a*). This would suggest that both were liquid simultaneously but had a slight temperature difference. At Forkhill (IJ 0059 1603), where several felsite bodies intruded the Lower Palaeozoic metasediments, large amounts of rounded granophyre blobs, with characteristic feldspar phenocrysts measuring ~7.5 mm across, are contained within the felsite (Fig. 3*b*). As no granophyre crops out within this area (the nearest outcrop is some kilometers away) the simplest origin for these rounded inclusions is that they were carried up within the felsite magma from the magma chamber, where granophyre magma was residing simultaneously.

Major- and trace-element geochemistry

Analytical methods

Samples were prepared by cutting inclusion-free specimens into rough blocks measuring 8–10 cm^3, removing all weathered surfaces. The blocks were broken up in a jaw-crusher and the crushed samples hand-picked under a stereo-microscope, eliminating weathered fragments and foreign inclusions. Samples were then powdered by hand using a pestle and mortar.

Analysis by X-ray fluorescence (XRF) was carried out using a Philips PW 1050 apparatus at St Andrew's University, Scotland, with powder from six samples of porphyritic felsite and eight samples of porphyritic granophyre. Analysis of representative Newry granodiorite and Lower Palaeozoic metasediments was also undertaken. Samples were dried at 105ºC prior to analysis and all analyses performed with a Rh X-ray tube. Calibration was performed using international geological reference samples. (See www.st-andrews.ac.uk/gg/Research/Facilities/)

Results

The porphyritic felsite and porphyritic granophyre are found to be compositionally very similar in their major and trace-element compositions (Fig. 4*a* and Table 1). The data nevertheless confirm an earlier inference by Emeleus (1962) that there are two distinct groups of felsite and our

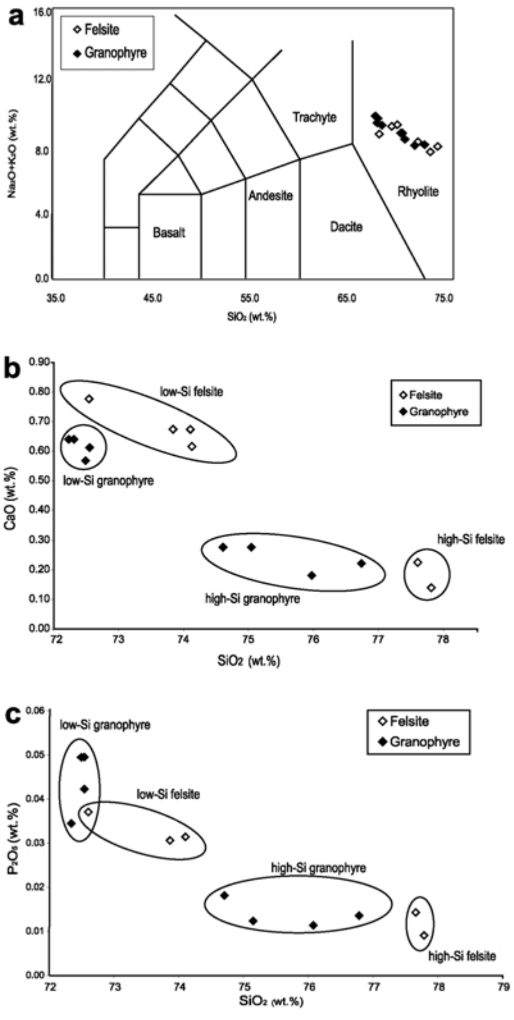


FIG. 4. (*a*) TAS plot of the felsite and granophyre samples. All data plot in the rhyolite field and are chemically very similar. (*b*) CaO *vs*. SiO_2 indicates four separate groups of data. These groups represent high-Si and low-Si felsite and high-Si and low-Si granophyre. Both granophyre sub-groups have similar or lower CaO concentrations to their associated felsite fields. (*c*) P_2O_5 *vs*. SiO_2 again picks out four separate fields of data.

TABLE 1. Major (wt.%) and trace element (ppm) concentrations of ring-dyke and country rocks.

Sample no	SG-F1	SG-F2	SG-F3	SG-F4	SG-F5	SG-F6	SG-G1	SG-G2	SG-G3	SG-G4	SG-G5	SG-G6	SG-G7	SG-G8	SG-NG-3	SG-LDS-2
Rock type	felsite	felsite	felsite	felsite	felsite	felsite	granoph.	granoph.	granoph.	granoph.	granoph.	granoph.	granoph.	granoph.	granite	sediment
Si-level	low	low	low	low	high	high	high	low	high	low	low	high	high	low		
SiO_2	73.85	72.5	74.1	74.13	77.83	77.65	76.78	72.13	75.09	72.52	72.54	75.95	74.65	72.55	63.4	56.85
TiO_2	0.22	0.24	0.22	0.21	0.14	0.14	0.17	0.25	0.18	0.26	0.25	0.18	0.18	0.28	0.77	0.83
Al_2O_3	12.73	12.64	12.62	12.78	10.94	10.88	11.5	13.19	12.15	13	13.09	12.01	12.69	12.93	15.56	13.2
Fe_2O_3	3.37	4.5	3.24	3.21	3.15	3.31	2.92	3.52	2.83	3.7	3.66	3.07	3.23	3.84	5.15	6.49
MnO	0.07	0.07	0.06	0.06	0.04	0.04	0.04	0.07	0.04	0.06	0.06	0.03	0.05	0.07	0.09	0.14
MgO	0.04	0.1	0.11	0.08	0.03	0.04	0.03	0.08	0.12	0.09	0.08	0.06	0.03	0.09	2.45	6.23
CaO	0.66	0.77	0.67	0.61	0.13	0.22	0.22	0.63	0.27	0.61	0.57	0.17	0.27	0.63	3.43	5.44
Na_2O	3.46	2.95	3.4	3.37	3.02	3.02	3.27	3.38	3.11	3.37	3.36	3.54	3.46	3.32	4.13	1.08
K_2O	5.22	5.35	5.32	5.35	4.6	4.57	4.46	5.4	4.85	5.38	5.47	4.25	4.97	5.38	3.17	5.52
P_2O_5	0.03	0.04	0.03	0.03	0.01	0.01	0.01	0.03	0.01	0.05	0.04	0.01	0.02	0.05	0.32	0.2
V	7	12	10	5	12	15	8	7	12	9	7	4	6	8	80	97
Cr	4	5	5	2	7	7	3	2	4	2	1	3	3	1	54	116
Ni	3	5	4	4	6	4	3	3	3	3	5	2	4	4	18	45
Cu	8	14	6	6	8	9	6	7	6	7	5	11	8	6		
Zn	85	96	70	63	72	106	81	84	62	78	86	69	89	89	59	80
Ga	22	22	22	22	23	22	21	22	23	22	21	24	23	22	20	15
Rb	166	167	170	174	179	192	183	165	206	163	166	181	214	164	105	176
Sr	32	32	30	30	13	14	23	39	25	38	38	28	29	38	648	165
Y	59	56	46	41	59	77	63	66	64	64	64	55	50	66	14	38
Zr	428	444	423	393	339	326	355	472	387	486	454	385	358	490	207	90
Nb	26	29	28	27	34	34	31	29	31	30	28	30	28	30	12	13
Ba	413	432	362	367	41	37	160	489	229	488	499	234	264	463	786	502
La	79	77	65	57	67	87	68	80	104	78	77	52	67	82	19	14
Ce	160	160	132	127	128	139	144	149	137	146	146	124	144	147	99	28
Nd	62	60	49	42	42	60	46	63	57	61	59	32	46	64		
Hf	22	10	12	9	12	13	14	13	13	13	15	11	11	16		
Pb	28	29	29	29	31	32	25	24	20	24	24	25	25	25	20	13
Th	21	21	21	20	24	25	23	20	24	20	20	22	21	20	9	11
U	2	6	3	2	5	6	6	4	4	4	4	3	5	4		

data suggest, moreover, two groups of granophyre. These groups represent high- and low-Si felsites and granophyres and form distinct clusters in all plots (Figs 4, 5, 6). The high-Si facies of both felsite and granophyre (similarly with the low-Si facies) appear to be chemically more closely related to each other than are the two felsites and the two granophyres.

Discussion

Relationship between felsites and granophyres

The field and petrological observations and the overlapping compositional ranges of felsites and granophyres imply that the two originated from the same parent magma, rather than from unrelated magmatic episodes. This proposed common origin of the felsites and granophyres is consistent with preliminary Sr and Nd isotopic data that suggest a continuous ‘assimilation and fractional crystallization’ (AFC) trend for the felsite and granophyre samples with Palaeozoic sediments and Newry granodiorite as end-member contaminants (Troll *et al.*, 2004). However, despite the overall compositional similarity of the ring-dyke rocks, a major feature of the major and trace-element results is the existence of two separate data fields within the granophyre and felsite groups, consistent with field observations. High-Si granophyre has larger phenocrysts of feldspar (~7.5 mm in diameter) than those in the felsites (~2 mm in diameter) and where granophyre forms the only rock type occupying the ring fault, the high-Si variety is generally found in the centre of the intrusion. Approaching the edge of the intrusion and the contact with the country rock, low-Si granophyre becomes dominant with large phenocrysts almost absent. This ‘normal zoning’ is most strongly developed in the north of the area towards Lislea where it coincides with a central zone containing numerous rounded microgranite inclusions (cf. Emeleus, 1962). Owing to the variable width of the ring dyke itself, high-Si granophyre facies can range from ~50–300 m wide and the low-Si facies from ~1–50 m wide at a given location.

A similar feature is observed in felsite exposures around Forkhill where obvious colour variations within the rock are indicative of a chemical variation. No obvious variation in the quartz concentration is visible in outcrop but geochemical analysis suggests marginal felsite to be higher in Si than the felsite towards the centre of the intrusion (Emeleus, 1956) (Figs 4, 5, 6).

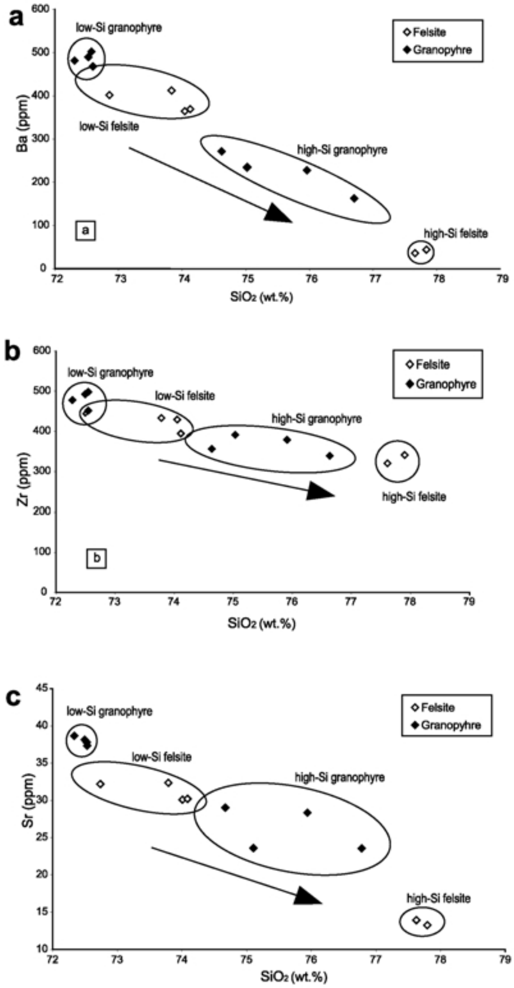


FIG. 5. (*a*) Ba *vs*. SiO_2. Four separate fields of data are again evident. Note also that within these groups granophyre samples consistently have higher Ba concentrations than their corresponding felsite groups. (*b*) Zr *vs*. SiO_2. Because Zr concentration decreases with increasing SiO_2 (arrows = zircon fractional crystallization), Zr may be used as a differentiation indicator in this rock suite. (*c*) Sr *vs*. SiO_2. Four separate groups of data emerge representing high-Si and low-Si felsite and granophyre. Sr decreases steadily with increasing melt evolution (i.e. increasing SiO_2) consistent with feldspar fractionation (arrow).

The high-Si facies is concentrated at the outer margins of the ring dyke in a ~1 m wide zone, grading inwards into a petrographically similar but less Si-rich felsite (Emeleus, 1956, 1962), some ~50–1000 m wide. Thus, the felsite part of the body may be termed a ‘reverse-zoned

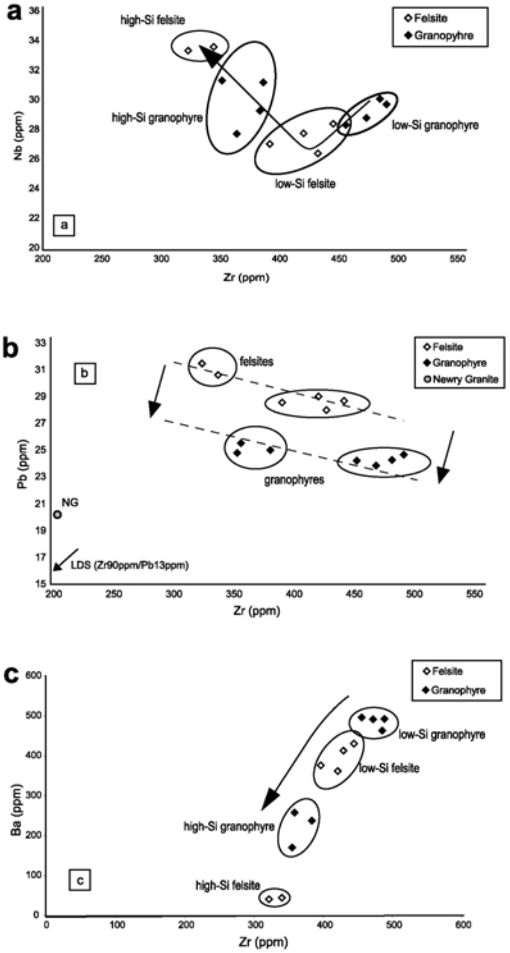


FIG. 6. (*a*) Nb *vs*. Zr. (*b*) Pb *vs*. Zr. Four data fields are clearly developed in 6*a* and 6*b*. In 6*b* both granophyre fields have lower Pb values than the corresponding felsite groups. This feature may be the result of selective contamination. LDS: Longford Down sediments. (*c*) Ba *vs*. Zr. Among the four data fields both granophyres have higher Ba values than their associated felsite fields, consistent with the granophyre magma representing a crystal concentrate within the magma chamber (see text for details).

intrusion', following the terminology of Stephens and Halliday (1980).

This observation is consistent with other major and trace element variations. For example, in a plot of Sr (ppm) *vs*. SiO_2 (wt.%) it may be seen that, while the four fields of data are well developed, both high-Si and low-Si granophyre have higher Sr values than their associated felsite groups (Fig. 5*c*). In rhyolite melts, Sr is highly compatible in K-feldspar (Kd_{Sr} ~3.8; Rollinson, 1993), the main feldspar in these rocks. Adopting the model of Marsh (1995), which proposes that minerals first crystallize on free surfaces such as walls and floor of the chamber and grow inwards as crystallization proceeds, K-feldspar would mainly crystallize in and along an inward-advancing solidification zone. As this solidification front advances, K-feldspar would become concentrated in the more strongly solidified parts of the advancing mush zone. In this semi-solidified mush, K-feldspar would probably experience further preferential growth due to percolating melts (i.e. adcumulus growth and corresponding convective fractionation). In places, e.g. the floor, additional concentration of K-feldspar may have been achieved by mechanical crystal aggregation such as sedimentary transport of crystals from the walls towards the chamber floor (cf. Wager and Brown, 1968). All of these processes would have led to high K-feldspar and thus high Sr concentrations in the mushy marginal zones, i.e. the granophyre magma. The same process could lead to granophyres displaying more elevated Ba concentrations than the felsite parent(s) (Fig. 5*a*) as Ba is also highly compatible in K-feldspar (Kd_{Ba} >4; Rollinson, 1993). In contrast, granophyre samples have similar or lower CaO (wt.%) values compared to the associated felsite samples (Fig. 4*b*). As K-feldspar is low in CaO and the granophyre has high concentrations of this mineral, the granophyre would be expected to have similar or even lower bulk CaO values than the felsite, if K-feldspar accumulation had occurred. In addition, a 'granophyre' cumulate/mush layer where K-feldspar grows or continues to grow, would allow CaO to become concentrated in the residual liquid, allowing for the slightly elevated CaO concentration in the felsite (cf. McBirney *et al*., 1985). Finally, the origin of granophyre from a cumulate or mush layer is consistent with it having larger and more abundant phenocrysts.

The chemical similarity and systematic compositional variation of the four rock types suggests that they are probably genetically related and have evolved from the same parental magma but experienced modification due to crystal fractionation, a feature frequently noted in other composite intrusions (e.g. Fridrich and Mahood, 1984). However, during this differentiation of felsite and granophyre, contamination may have played a major role also, as potentially implied by variation of certain trace elements. Granophyre samples have consistently lower Pb concentrations than felsite samples (Fig. 6*b*). The Kd_{Pb} between K-feldspar and rhyolitic melt is ~2.6, whereas plagioclase has a Kd_{Pb} of 0.972 (Rollinson, 1993). As the granophyre has a significantly higher concentration of K-feldspar, higher Pb values would be expected in a purely accumulative model. The fact that the reverse situation prevails is suggestive of preferential contamination of the granophyre magma by some crustal source. Both Newry granodiorite and the Lower Palaeozoic metasediments have much lower Pb values than the Tertiary intrusives (Figs 5*b*, 6*b*). Thus the source of the inferred contamination is probably a partial melt of Newry granodiorite (i.e. selective contamination). Considering that (1) it is through Newry granodiorite (or its brecciated version, the Vent Agglomerate) that both felsite and granophyre intruded, and (2) the fact that abundant xenoliths of once partially molten Newry granodiorite do occur, we suggest that Newry granodiorite had a strong influence on the magma compositions (see also Troll *et al*., 2004).

Structure of the magma chamber/magmatic system

With the field observations and geochemistry suggestive of all ring-dyke lithologies having been derived from the same parent magma, reconstruction of the magma chamber can be attempted. A single magma chamber is seen as the simplest explanation for this system. Examination of the petrography and geochemistry of the rock samples suggests that the granophyre is likely to represent a cumulate/mush layer within the system, enveloping a more liquid 'felsite magma' body (Fig. 8*c*).

This proposed layered structure is supported by viscosity and density calculations. Using suggested emplacement temperatures of 850ºC for felsite and 800ºC for granophyre (cf. Emeleus, 1962) and following the equations and correction procedures of Bottinga *et al.* (1982, 1983), Shaw (1972), and Marsh (1981), the emplacement viscosity and density of the erupted magmas were calculated. This took into account the major-element composition (XRF analyses), variable water concentrations, crystal sizes, mineral types and modal contents, and their average shapes. A shape factor of 0.7 was used for feldspar and an average crystal size of 7 mm and 1.3 mm in diameter for granophyre and felsite crystals respectively. The shape factor relates to the overall shape of the crystal with a factor of 1.0 being given to perfectly euhedral crystals, this figure tending towards zero as the crystal becomes more anhedral.

Results show that for a given water content (varying from 0 to 5% H_2O inclusive) both granophyres have consistently higher density and higher viscosity than their corresponding felsite samples (Fig. 7*a*,*b*). Also, for the same water contents, high-Si felsite is consistently less dense than low-Si felsite (Fig. 7*c*). This supports the notion that the high-Si felsite facies probably occupied a higher level in the layered magma chamber than the low-Si facies, with both enclosed in a 'skin' of mushy granophyre that had maximum thickness at the chamber floor (Fig. 8*c*). However, it also implies that mixing between felsite and granophyre was possible where variable water concentrations allowed for viscosity and density to approach each other (cf. Gamble, 1979).

On the outlined density and chemical grounds it is inferred that the magma chamber comprised zones consisting of high-Si magma and low-Si magma, each with a separate felsite and granophyre component. Simpler models (Fig. 8*a*,*b*) seem unable to account for the full spectrum of compositions and field relations observed. Instead of such simpler models, a concentrically zoned magma chamber similar to that of Marsh (1995) may be envisaged, but incorporating the process of convective fractional crystallization to achieve a zoned liquid interior. In such a chamber, crystallization and cooling would occur around all margins of the chamber and in this way cumulate/mush layers develop on the roof, walls and floor of the chamber (solidification fronts), as opposed to predominantly on the floor, as in more traditional magma-chamber models involving large-scale gravitational crystal settling as the dominant process (cf. Bowen, 1928; Wager and Brown, 1968) (Fig. 8*a*). In such a traditional floor-dominated cumulate model only one major granophyre facies would develop, thus posing problems to explain both field evidence and geochemistry (Fig. 8*a*). Moreover, the time needed to settle out crystals in such a way is probably too long considering the small size of the Slieve Gullion intrusion and the highly viscous character of the magmas involved (cf. Bartlett, 1969; Spera *et al*., 1982). Likewise, a simple onion-skin chamber (Fig. 8*b*) would only allow for one major type of granophyre magma to

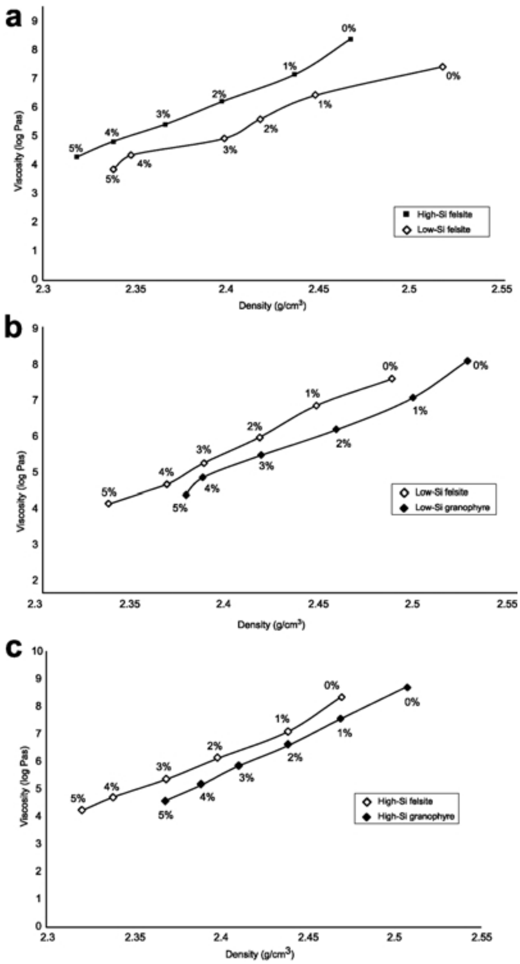


FIG. 7. (*a*) For given water contents, varying from 0 to 5%, high-Si granophyre magma has consistently greater density and viscosity values than high-Si felsite magma. (*b*) Similarly, low-Si granophyre magma has higher density and viscosity values than low-Si felsite magma for given water content. (*c*) High-Si felsite magma is consistently less dense and more viscous than low-Si felsite magma suggesting that the high-Si facies would have occupied higher levels within a common magma chamber.

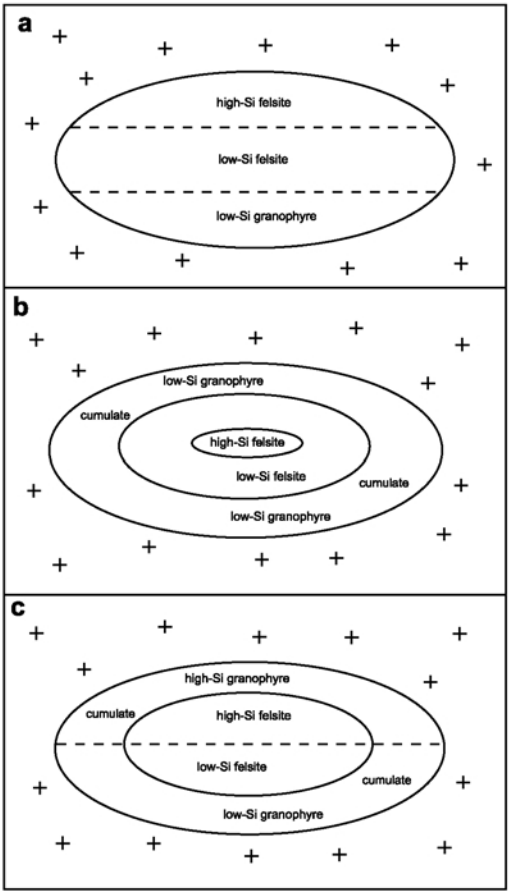


FIG. 8. (*a*) If a traditional model of gravitational crystal settling is envisaged, only one granophyre facies develops. As field evidence and geochemistry promote the existence of two separate granophyres, this model is unsuitable. (*b*) In a simple onion-skin model where the only process of crystal accumulation is that described by Marsh (1995), both high- and low-felsite magmas may develop, but only one granophyre facies. (*c*) Suggested magma chamber where a continuous cumulate/mush layer develops on all chamber walls. Both high- and low-silica regions are developed within the chamber due to convective fractionation, each with an associated felsite and granophyre component (see text for details).

form. However, convective fractionation and upward migration of evolved liquid may aid the formation of distinct felsite magmas in such a chamber, allowing zonation within the felsite body to develop too (cf. McBirney *et al.*, 1985; Sparks and Turner, 1984; Sparks, 1990; Martin, 1990) (Fig. 8*b*,*c*). The Si-rich felsite facies would become concentrated in the upper part of such a chamber. The granophyres that develop would therefore correspond to either the lower or upper felsite, i.e. a high-Si granophyre mush layer that corresponds to a high-Si felsite would develop and similarly, from a low-Si felsite magma facies, low-Si granophyre magma would result.

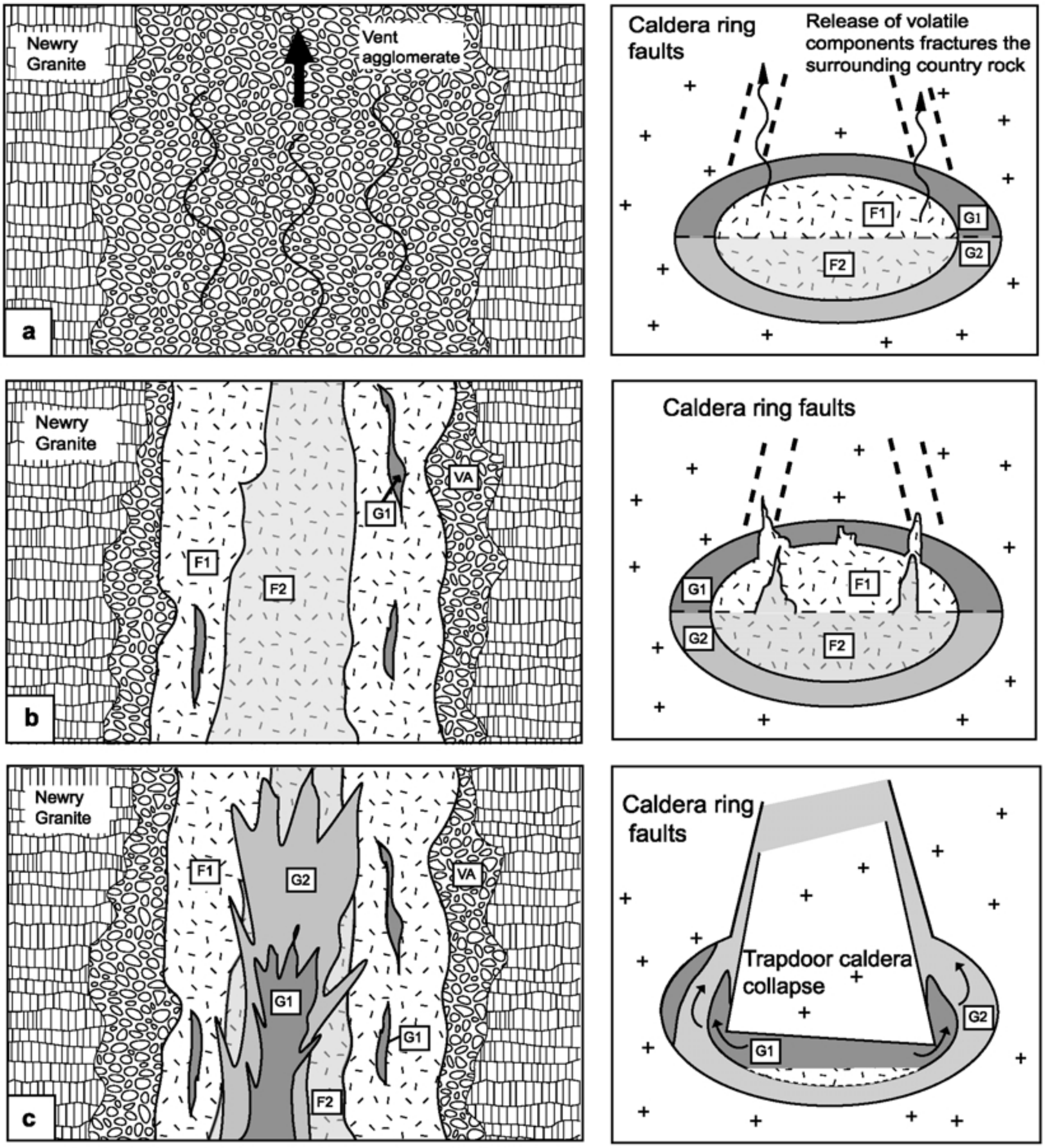


FIG. 9. Right hand side: Suggested cross-section through magma chamber and country rock. Left hand side: Suggested cross-section through eruption vent. (*a*) Gas eruptions prior to caldera collapse and ring-dyke emplacement cause extreme shattering and brecciation of the overlying country rock. This brecciation of the Newry granodiorite produced vent agglomerates, and weakened this part of the overburden, a feature subsequently exploited by ring-dyke intrusion and caldera collapse. (*b*) Both high- (F1) and low- (F2) Si felsite are tapped and intruded sequentially into the fissure. High-Si felsite precedes low-Si felsite, resulting in marginal facies having higher SiO_2 values. Contained within the felsite are blobs of granophyre magma (G1) resulting from the simultaneous tapping of a granophyre mush layer presumably from the chamber top. (*c*) Trap-door caldera collapse taps granophyre magma allowing it to intrude most of the ring fissure. Granophyre also displays two chemical facies. Lower Si granophyre (G2) is intruded first, with higher Si granophyre (G1) being tapped next. This emplacement sequence is best explained by collapse-related subsidence in the chamber resulting in high-Si granophyre dominating the centre of the composite part of the intrusion.

Magma-chamber evacuation

The observed felsite zoning in the ring dyke is best explained by rearrangement of a vertically graded magma column (similar to Fig. 8*c*), progressively tapping deeper levels of the underlying magma chamber, a phenomenon that is consistent with analogue experiments (Ramberg, 1981) and theoretical studies (Blake, 1981).

At Forkhill, both high- and low-Si felsite are exposed and both contain high-Si granophyre inclusions. The initial eruption tapped the upper region of high-Si felsite and entrained some blobs of high-Si granophyre magma from the semi-solidified chamber roof (Fig. 8*c*). Violent, gas-charged eruption of felsite was likely, as the presence of fiamme within this particular lithology suggests that the felsites represent feeder dykes to surface ignimbrite flows (cf. Troll *et al*., 2000). Continued eruption then tapped low-Si felsite, which was intruded into the centre of the already-emplaced high-Si felsite ring dyke. A similar sequence of events may be responsible for the large body of high-Si granophyre that underlies felsite at Mullaghbawn. As the eruption proceeded, deeper levels of the magma chamber were tapped at a late stage, thus allowing a large body of granophyre to be intruded into the already emplaced felsite.

When the entire ring dyke is considered, granophyre is the dominant rock type, making up approximately three quarters of the dyke. However, the high crystallinity of the granophyre would have made it difficult for the magma to move (cf. Marsh, 1998). A different evacuation mechanism is required from that described for particular sites above. A possibility may be trap-door subsidence of the caldera. After the eruption was initiated, the support for the chamber roof would have been reduced until collapse occurred. Assuming the central block subsided in a differential fashion, one side of the vent would have eventually tapped granophyre exclusively (Fig. 9). The opposite side would have tapped initially felsite magma, then low-Si granophyre and finally high-Si granophyre, squeezed into the vent by the collapsing roof (Fig. 9*c*).

Conclusion

Stage 1: Degassing and phreatic eruptions prior to caldera collapse and ring-dyke emplacement caused extreme shattering and brecciation of the overlying country rock. This brecciation of the Newry granodiorite and the metasediments produced the 'Vent Agglomerates' and weakened this part of the overburden, a condition subsequently exploited by ring-dyke intrusion and caldera collapse (Fig. 9*a*).

Stage 2: Both high- and low-Si felsite were tapped and intruded sequentially into the fissure. High-Si felsite preceded low-Si felsite, resulting in marginal facies having higher silica values. Contained within the felsite were blobs of granophyre magma resulting from disruption and tapping of a granophyre mush layer at the chamber top. The presence of granophyre magma blobs in felsite indicates that both magmas resided simultaneously within the same magma reservoir (Fig. 9*b*).

Stage 3: Trap-door caldera collapse tapped granophyre magma allowing it to intrude most of the ring fissure. The granophyre also displays two chemical facies: low-Si granophyre was intruded first, with high-Si granophyre next. This intrusion sequence resulted in high-Si granophyre dominating the centre of the ring dyke (Fig. 9*c*).

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