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# Sr and Nd isotope evidence for successive crustal contamination of Slieve Gullion ring-dyke magmas, Co. Armagh, Ireland

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**Abstract** – The Palaeogene Slieve Gullion Igneous Centre in southern Armagh, Northern Ireland, consists of a layered central intrusive complex surrounded by a prominent and slightly older ring-dyke that intrudes both Lower Palaeozoic sedimentary rocks and the Caledonian Newry Granodiorite pluton (452 Ma). The ring-dyke comprises two major rock types: porphyritic felsite and porphyritic granophyre. We analysed both ring-dyke lithologies, both types of country rock, and a local Palaeogene basalt dyke sample for Sr and Nd isotopes. Trace element and whole rock data for this suite suggest that there are two distinct groups of both felsite and granophyre: one Si-rich and one Si-poor, most likely representing two magmas from a zoned chamber and their mushy chamber wall equivalents (McDonnell *et al*. 2004). Isotope data show the low-Si rocks to be higher in radiogenic Sr than the high-Si rocks, which is inconsistent with a simple AFC-scenario of increasing sediment assimilation with higher degrees of differentiation. However, using MORB-type basalt as a starting composition, the low-Si ring-dyke rocks can be modelled through AFC with Lower Palaeozoic sedimentary rock as the contaminant. The decreasing $^{87}Sr/^{86}Sr$ trend from low-Si to high-Si dyke rocks, in turn, represents a second stage of contamination. Selective assimilation of the most fusible portions of Newry Granodiorite, which is lower in radiogenic Sr than the local sedimentary rocks, appears to be the most plausible solution. The Sr and Nd data are consistent with (a) at least a two-stage contamination history during upper crustal residence and storage, whereby fractionating magmas of basaltic and intermediate composition are contaminated by local sedimentary rocks, giving rise to rhyolite magmas that experience additional shallow contamination by Newry Granodiorite, and (b) a zoned rhyolite magma chamber where high-Si magma is stored in the upper part of the chamber where crystallization and crustal contamination are most extensive.

Keywords: ring-dyke, Northern Ireland, crustal contamination, isotopes.

## 1. Introduction

Ring-dykes are approximately circular sheet intrusions in plan view that form when magma rises along a steep, outward-dipping ring fracture. Many have been described from the Palaeogene centres in both Scotland and Ireland (e.g. Bailey *et al*. 1924; Richey & Thomas, 1932; Richey, 1932, 1961). These intrusions commonly encompass central collapsed blocks and many also display compositional diversity (e.g. Sparks, 1988).

The Palaeogene Slieve Gullion Igneous Centre, together with the Antrim lavas and igneous centres at Carlingford and the Mourne Mountains, form the NE Ireland portion of the British Palaeogene Igneous Province (BPIP) (e.g. Upton, 1988; Gamble, Wysoczanski & Meighan, 1999). Activity at these centres is believed to have been the result of plume-related crustal attenuation during the Palaeogene, which ultimately resulted in the opening of the Northeast Atlantic (White & McKenzie, 1989; Saunders *et al*. 1997). The Slieve Gullion Igneous Centre is situated west of the Mourne Mountains in south County Armagh, with its southeastern section within north County Louth (Fig. 1). It consists of a sheeted central intrusion (Slieve Gullion hill, *c*. 577 m; Irish Ordnance Survey) surrounded by a prominent, slightly older, silicic ring-dyke some 12 km in diameter (Richey & Thomas, 1932; Reynolds, 1951; Emeleus, 1962; Elwell, Brück & O'Connor, 1974; Gamble, 1979; Gamble, Meighan & McCormick, 1992). The Slieve Gullion centre intruded into both the southwestern portion of the Caledonian Newry Granodiorite pluton (Meighan & Neeson, 1979) and the Lower Palaeozoic sedimentary rocks of the Longford Down Terrane.

The ring-dyke consists of two principal lithologies: porphyritic felsite and porphyritic granophyre (Fig. 2a–c). There is a Si-enriched felsite concentrated at the outer margins of the ring-dyke in an approximately 1 m wide zone, which is seen to grade into a less Si-enriched felsite toward the interior of the intrusion (Emeleus, 1962; McDonnell *et al*. 2004). Granophyre samples also show a Si-enriched facies, which is in turn concentrated in the central part of the intrusion. The several-metres-thick Si-enriched granophyre grades

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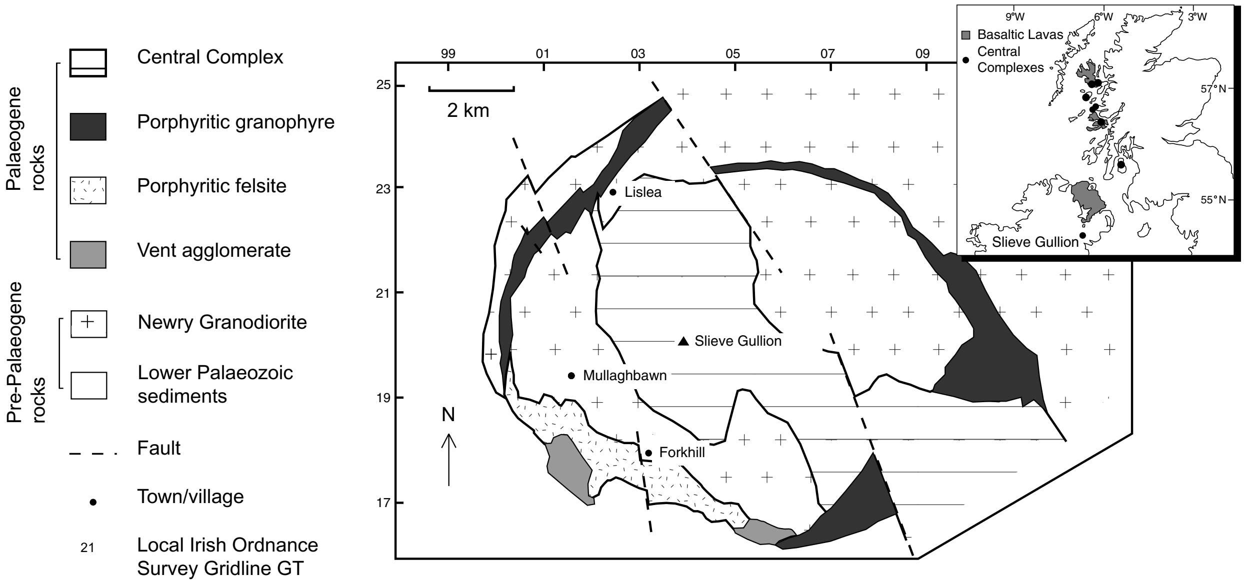


Figure 1. Principal geological map of the Slieve Gullion Ring Complex after McDonnell *et al*. (2004) with inset of regional map. Grid system from the Ordnance Survey of Ireland.

outwards into low Si compositions, and is inferred to represent the youngest of the intrusive rocks (McDonnell *et al*. 2004). The ring-dyke rocks are surrounded by a series of brecciated country rocks known historically as the vent agglomerates of Forkhill (principally brecciated granodiorite) and Camlough Breccia (brecciated Palaeozoic sedimentary rocks) (Richey & Thomas, 1932; Emeleus, 1962; McDonnell *et al*. 2004). These rocks are believed to be the result of highly gas-charged eruptions that occurred prior to caldera collapse and ring-dyke emplacement. Also present in the centre are more limited outcrops of Palaeogene basalt together with abundant Palaeogene dolerite and gabbro dyke intrusions (Richey & Thomas, 1932; Emeleus, 1962).

Earlier workers recognized the complex rock relationships in the Slieve Gullion ring-dyke (e.g. C. H. Emeleus, unpub. Ph.D. thesis, Univ. Oxford, 1956; Emeleus, 1962) and believed them to be the result of a two-stage intrusion history. Recent work by McDonnell *et al*. (2004) has further investigated the relationship between the felsite and granophyre of the ring-dyke on the basis of whole rock major and trace element analysis and density and viscosity modelling. These data indicate that the high-Si ring-dyke rocks form a distinct group as do the low-Si ring-dyke rocks, with both groups being contemporaneous. These groups probably originated from the same parent magma rather than representing separate and discrete magmatic events (McDonnell *et al*. 2004). The magma chamber where both magmas are believed to have evolved was pictured by these authors as a concentrically zoned and internally stratified chamber and may be used to explain the distribution of felsite and granophyre across the ring-dyke intrusion.

A major concern in the British Palaeogene Igneous Province has long been the origin of such highly silicic rocks (cf. Gamble, 1979; Meighan, Gibson & Hood, 1984; Thompson *et al.* 1986; Sparks, 1988; Bell & Williamson, 2002; Troll, Donaldson & Emeleus, 2004). Although the intrusive history of the Slieve Gullion ring-dyke has been investigated in previous studies (e.g. Emeleus, 1962; McDonnell *et al*. 2004), no modern attempt to unravel the petrogenetic history of these rocks on the basis of isotopic data has been presented so far. The various crustal terranes that underlie the BPIP are likely to have imprinted their own distinctive elemental and isotopic characteristics on the ascending magmas (e.g. Gamble, Meighan & McCormick, 1992; Geldmacher *et al*. 2002). As Slieve Gullion is one of the few Palaeogene centres south of the Highland Boundary Fault, its contamination history is an ideal testing ground for the influence of variable crust on the isotope chemistry of evolved British Palaeogene Igneous Province magmas. Here we employ Sr and Nd isotope ratios to unravel the petrogenesis of the Slieve Gullion ring-dyke magmas, shedding light on storage and differentiation mechanisms prevalent in the Slieve Gullion system.

## 2. Field occurrence and petrography

### 2.a. Country rocks

#### *2.a.1. Lower Palaeozoic sedimentary rocks*

The sedimentary rocks are part of the Central Belt of the Lower Palaeozoic Longford Down Terrane and crop out to the west of the Slieve Gullion centre (Fig. 1). They vary in lithology from coarse sandstones to shales across the area, and the rocks in the southwest are

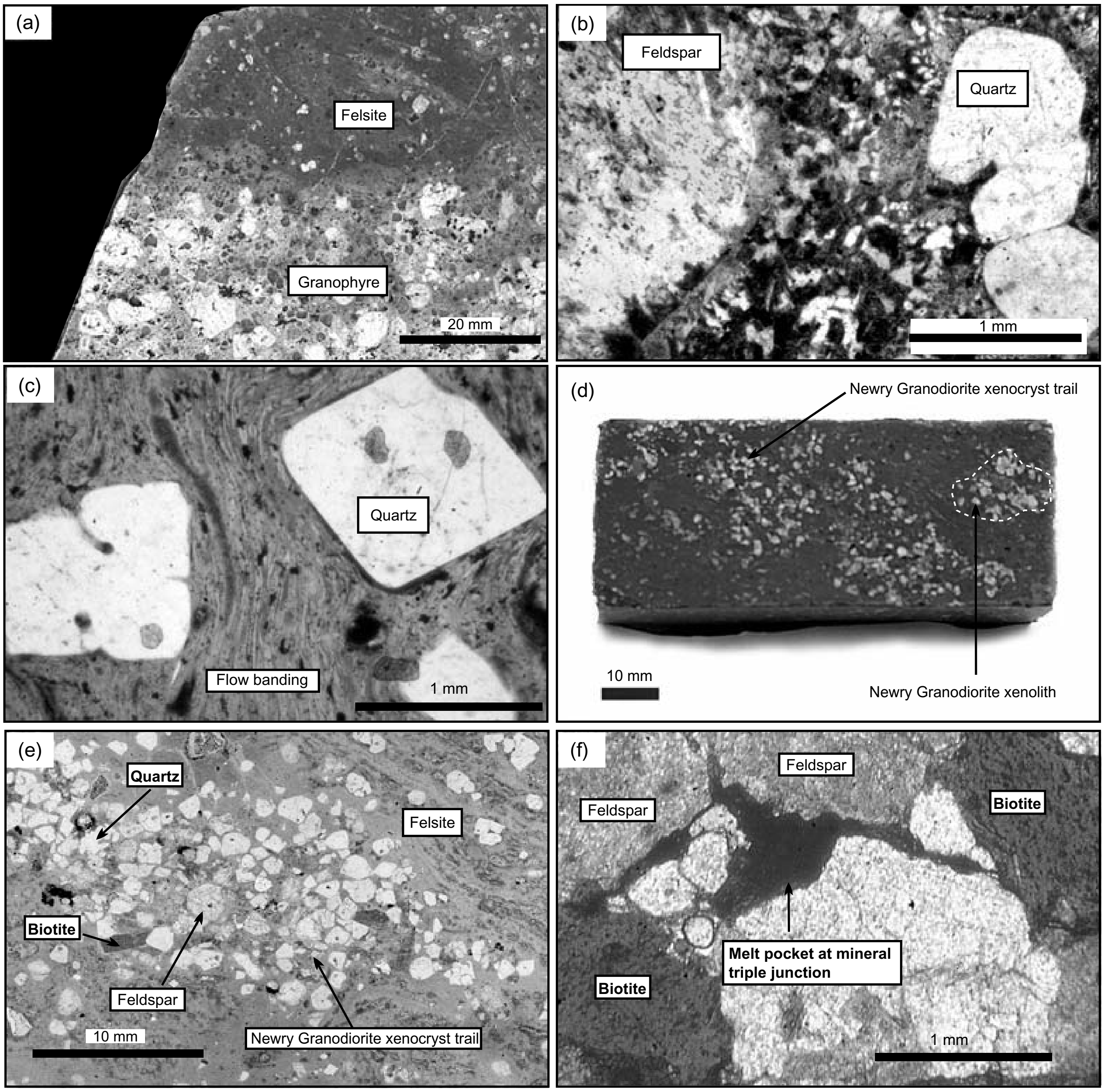


Figure 2. (a) Felsite and granophyre in contact in hand sample (from McDonnell *et al*. 2004). (b) Thin-section photomicrograph of granophyre sample in PPL. (c) Thin-section photomicrograph of felsite sample in PPL. (d) Newry Granodiorite xenolith and xenocryst trails in a hand sample of felsite from Mullaghbawn Golf Course [IH 9880 1812]. (e) Newry Granodiorite xenolith and xenolith trail in a thin-section of felsite in PPL. (f) Thin-section photomicrograph of partial melting textures in a Newry Granodiorite xenolith in PPL.

considerably finer-grained than in more northerly outcrops. Chlorite, muscovite and quartz (up to 1 mm) are the dominant minerals present.

The sedimentary rocks are well-bedded and bed thickness ranges from 10 cm to 40 cm; internal laminations within beds can result in colour variation from light grey to green-grey.

#### 2.a.2. *Newry granodiorite*

The Newry Granodiorite pluton is Ordovician in age (*c*. 452 Ma: Meighan *et al*. 2003) and belongs to the Caledonian granite suite of Scotland and Ireland. Outcrops are predominantly located on the central, moat-like plain between Slieve Gullion and the ring-dyke. It is a coarse-grained granodiorite and the mineralogy consists of equigranular grains of quartz, feldspar and varying amounts of biotite and hornblende visible in hand specimen (hornblende measuring 2–3 mm in diameter). Smaller amounts of secondary muscovite are identified in thin-section.

### 2.b. Slieve Gullion centre

#### 2.b.1. *Porphyritic felsite*

Felsite crops out predominantly toward the south of the complex where it occupies the ring-dyke almost exclusively, as at Forkhill [IJ 0059 1603] (Fig. 1). At some marginal locations within the felsite, such as the Mullaghbawn golf course [IH 9880 1812], outcrops contain abundant xenoliths of Newry Granodiorite (Fig. 2d, e). In thin-section, many of the xenoliths display pockets of glass between minerals (former melt), suggesting partial melting of some portions of the Newry country rock (Fig. 2f). Trails of xenoliths, xenocrysts and flattened pumice (fiamme; Bell & Emeleus, 1988) help to define flow within the felsite (see McDonnell *et al.* 2004).

The felsite is a hypocrystalline rock consisting of a very fine-grained, dark grey matrix containing 20–30 % phenocrysts (Fig. 2a, c). Phenocrysts include both quartz (10–15 %) and feldspar (10 %; mostly sanidine), both measuring about 2 mm in diameter on average. The felsite also contains lesser amounts (< 1 %) of pyroxene and fayalitic olivine along with < 5 % opaques. Glass shards, fiamme and small rounded, basaltic clasts (2 mm in diameter) occur.

### 2.b.2. *Porphyritic granophyre*

Granophyre outcrops occupy the bulk of the ring-dyke, especially toward the north of the centre, but west of Mullaghbawn, granophyre may be found together with felsite in one outcrop (Emeleus, 1962; McDonnell *et al.* 2004) (Fig. 2a). Outcrops of granophyre are absent further south (Fig. 1).

The porphyritic granophyre consists of 35–45 % phenocrysts contained within a fine-grained grey-pink matrix. The dominant phenocrysts are quartz (15 %) and feldspar (18–20 %); the latter is often complexly zoned, but amphibole, clinopyroxene, opaque minerals, minor fayalitic olivine and zircon are also present. The average quartz phenocryst measures 2 mm in diameter with feldspar crystals considerably larger at up to 7.5 mm in diameter. These feldspars belong predominantly to the sanidine–orthoclase series with only minor plagioclase present (Emeleus, 1962).

### 2.b.3. *Palaeogene basaltic dyke*

To obtain a representative Palaeogene mafic Slieve Gullion composition, we sampled a basaltic dyke that cross-cuts the ring-dyke in Forkhill quarry [IJ 0059 1603]. We used this sample instead of pre-ring-dyke basalts or some of the small basalt clasts in the ring-dyke as these flows and clasts are generally highly altered and/or extremely hard to extract.

## 3. Analytical methods

Samples were prepared by removing all weathered surfaces and cutting rough, apparently inclusion-free, blocks between 8–10 cm$^3$. The blocks were crushed using a jaw crusher and the resulting chips were hand-picked under a stereo-microscope to eliminate weathered fragments and country rock xenoliths. Samples were then powdered by hand using an agate mortar and pestle.

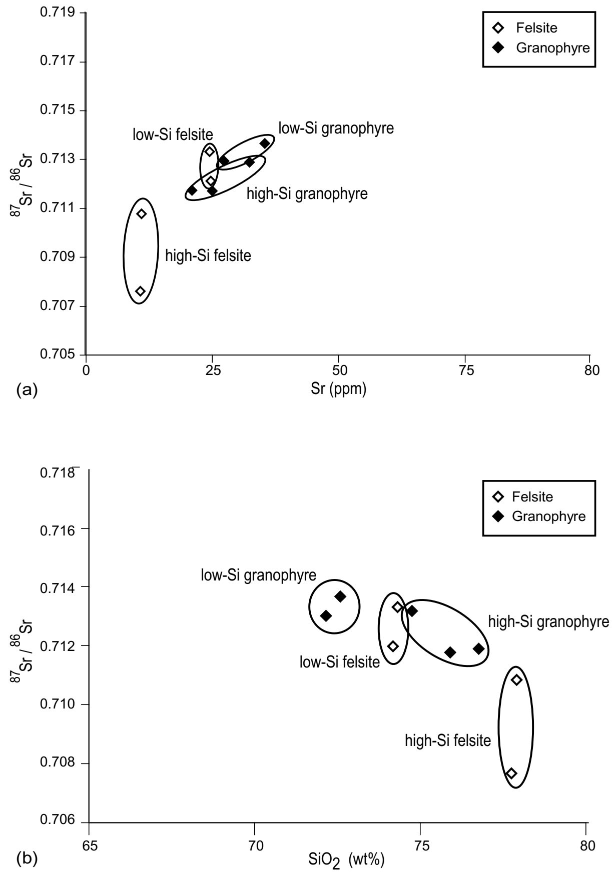


Figure 3. (a) $^{87}Sr/^{86}Sr$ v. Sr (ppm) plot for Slieve Gullion ring-dyke magmas. Errors are smaller than symbol size. (b) $^{87}Sr/^{86}Sr$ v. $SiO_2$ plot for Slieve Gullion ring-dyke magmas. Petrographic groups of McDonnell *et al.* (2004) are indicated by ellipses. Note the marked trend of increasing $^{87}Sr/^{86}Sr$ with decreasing $SiO_2$.

Sr and Nd isotope analyses were carried out at the Isotope Geosciences Unit of the Scottish Universities Research and Reactor Center (SUERC), East Kilbride, Scotland. Standard analyses and analytical procedures are outlined in Barbero *et al.* (1995). Total procedure blanks for Sr and Nd were < 300 pg. NIST SRM987 gave $^{87}Sr/^{86}Sr = 0.710254 \pm 22$ (2 SD, n = 34) and the internal laboratory Nd standard (JM) gave $^{143}Nd/^{144}Nd = 0.511511 \pm 8$ (2 SD, n = 12) during this study.

## 4. Results

Representative samples from the ring-dyke, the country rocks and a local Palaeogene basalt dyke were selected for Sr and Nd isotope analysis from the sample suite of McDonnell *et al.* (2004). Sr and Nd isotopic data for the selected samples are given in Table 1 and illustrated in Figure 4a. All isotope ratios for the ring-dyke rocks

Table 1. Sr and Nd isotopic data

| Sample no. | Rock type | $^{87}Sr/^{86}Sr_m$ | Rb (ppm) | Sr (ppm) | $^{87}Sr/^{86}Sr$ (57 Ma) | $^{143}Nd/^{144}Nd_m$ | Sm (ppm) | Nd (ppm) | $^{143}Nd/^{144}Nd$ (57 Ma) |
|---|---|---|---|---|---|---|---|---|---|
| SG-G1 | Grano. | 0.733007 ± 18 | 186 | 21 | 0.711787 | 0.512468 ± 8 | 12 | 62 | 0.512424 ± 8 |
| SG-G2 | Grano. | 0.731903 ± 16 | 217 | 27 | 0.712917 | 0.512496 ± 7 | 10 | 59 | 0.512455 ± 7 |
| SG-G6 | Grano. | 0.729047 ± 16 | 183 | 25 | 0.711693 | 0.512468 ± 6 | 10 | 49 | 0.512424 ± 6 |
| SG-G7 | Grano. | 0.724919 ± 16 | 165 | 33 | 0.713006 | 0.512426 ± 7 | 14 | 78 | 0.512384 ± 7 |
| SG-G8 | Grano. | 0.724644 ± 16 | 165 | 36 | 0.713593 | 0.512429 ± 8 | 14 | 77 | 0.512387 ± 8 |
| SG-F3 | Felsite | 0.728937 ± 19 | 173 | 24 | 0.711906 | 0.512433 ± 7 | 10 | 57 | 0.512391 ± 7 |
| SG-F4 | Felsite | 0.729342 ± 18 | 169 | 25 | 0.713275 | 0.512458 ± 6 | 9 | 49 | 0.512417 ± 6 |
| SG-F5 | Felsite | 0.747525 ± 16 | 181 | 12 | 0.710796 | 0.512465 ± 6 | 12 | 59 | 0.512419 ± 6 |
| SG-F6 | Felsite | 0.747823 ± 18 | 195 | 12 | 0.707673 | 0.512471 ± 7 | 16 | 79 | 0.512425 ± 7 |
| SG-NG-3 | NG | 0.708177 ± 23 | 10 | 563 | 0.708136 | 0.512363 ± 8 | 5 | 30 | 0.512328 ± 8 |
| SG-PS-2 | LDS | 0.724985 ± 20 | 124 | 149 | 0.722829 | 0.512195 ± 7 | 5 | 20 | 0.512134 ± 7 |
| SG-PB3 | PBD | 0.705967 ± 18 | 1 | 179 | 0.705948 | 0.512799 ± 22 | 4 | 12 | 0.512799 ± 22 |

Grano. – Granophyre, NG – Newry granite, LDS – Longford Down sedimentary rock, PBD – Palaeogene basalt dyke.

were age-corrected to 57 Ma according to Rb–Sr whole rock isotopic data reported in O'Connor (1988).

The isotopic end-members of our sample set are the Palaeogene basalt dyke and the Lower Palaeozoic sedimentary rocks of the Longford Down Terrane. The Palaeogene basalt dyke has the lowest $^{87}Sr/^{86}Sr$ (0.705948 ± 18), and the highest $^{143}Nd/^{144}Nd$ ratio of 0.512799 ± 22. The most radiogenic $^{87}Sr/^{86}Sr$ value was obtained from the Lower Palaeozoic sedimentary rock (0.722829 ± 20) with a $^{143}Nd/^{144}Nd$ ratio of 0.512134 ± 7. Our value is consistent with previously reported values for similar lithologies in Scotland in O'Nions, Hamilton & Hooker (1983), Halliday (1984), and McCormick (A. G. McCormick, unpub. Ph.D. thesis, Univ. Queen's, Belfast, 1989), although it is at the radiogenic end of the spectrum. The Newry Granodiorite shows lower $^{87}Sr/^{86}Sr$ (0.708136) and a low $^{143}Nd/^{144}Nd$ ratio of 0.512328, consistent with data presented in McCormick (A. G. McCormick, unpub. Ph.D. thesis, Univ. Queen's, Belfast, 1989) and Dempsey, Halliday & Meighan (1990). The ring-dyke rocks cover a range of $^{87}Sr/^{86}Sr$ ratios from 0.707673 to 0.713593 with a very restricted variability in $^{143}Nd/^{144}Nd$, ranging from 0.512384 to 0.512455 (Fig. 4a). The low-Si rocks classified by McDonnell *et al.* (2004) are found to be higher in radiogenic $^{87}Sr/^{86}Sr$ than the high-Si rocks (Fig. 3).

## 5. Discussion

### 5.a. Sequential contamination of the ring-dyke magmas

Rocks of basaltic composition dominate the total magma budget in the British Palaeogene Igneous Province, providing an ample heat source for crustal melting and a reservoir for fractionation of silicic magmas (e.g. Gamble, Meighan & McCormick, 1992). The observed variations in Sr and Nd isotopes in the ring-dyke magmas point to substantial crustal modification of a fractionating, mantle-derived magma, similar to what has been suggested by Gamble, Meighan & McCormick (1992) for the Slieve Gullion Central Complex. This is also in keeping with the conclusions of McDonnell *et al.* (2004), who suggested that certain trends seen in the trace elements (e.g. Pb v. Zr) may be explained by open system fractionation, assimilating either Longford Down sedimentary rocks and/or Newry Granodiorite. In a plot of $^{87}Sr/^{86}Sr$ against $^{143}Nd/^{144}Nd$ (Fig. 4a), there is a marked trend toward Longford Down sedimentary rocks. However, this is the converse of that expected for conventional assimilation with progressive fractionation (AFC) (DePaolo, 1981). Instead of increasing $^{87}Sr/^{86}Sr$ ratios with increased $SiO_2$, the low-Si ring-dyke rocks are the most radiogenic. This negative correlation with $^{87}Sr/^{86}Sr$ is also evident when plotted against $SiO_2$ and Sr (ppm) (Fig. 3). The most reasonable explanation is a two-stage contamination process for the magmatic evolution of the ring-dyke magmas, with two contaminating end-members involved: the Longford Down sedimentary rock and the Newry Granodiorite. Based on work by O'Connor (1988) and Gamble, Meighan & McCormick (1992), a parental magma of depleted mantle-like isotopic composition can be envisaged for the Slieve Gullion centre and for much of the British Palaeogene Igneous Province as a whole (see also Ellam & Stuart, 2000). These magmas would have been highly susceptible to crustal contamination by more radiogenic crustal rocks due to their relatively low Rb/Sr ratios and unradiogenic Sr isotope ratios. Using such a MORB-type basalt as a parental end-member, Sr and Nd isotopic ratios similar to those observed in the low-Si dyke rocks can be produced by an AFC-type process (DePaolo, 1981), involving the assimilation of Lower Palaeozoic sedimentary rock ($r = 8.5$, ~10–15 % solidification). Such an AFC curve also intersects the isotopic ratios of the analysed Palaeogene basalt dyke that cuts the Slieve Gullion ring-dyke at Forkhill (~5 % solidification, Fig. 4b). In contrast, an AFC curve using the Slieve Gullion basaltic dyke rock as a starting composition (Fig. 4c) fails to produce an intersection with the low-Si ring-dyke rocks even for high assimilation rates. The best AFC-fit is thus given by a MORB-type starting composition, with a good match between modelled

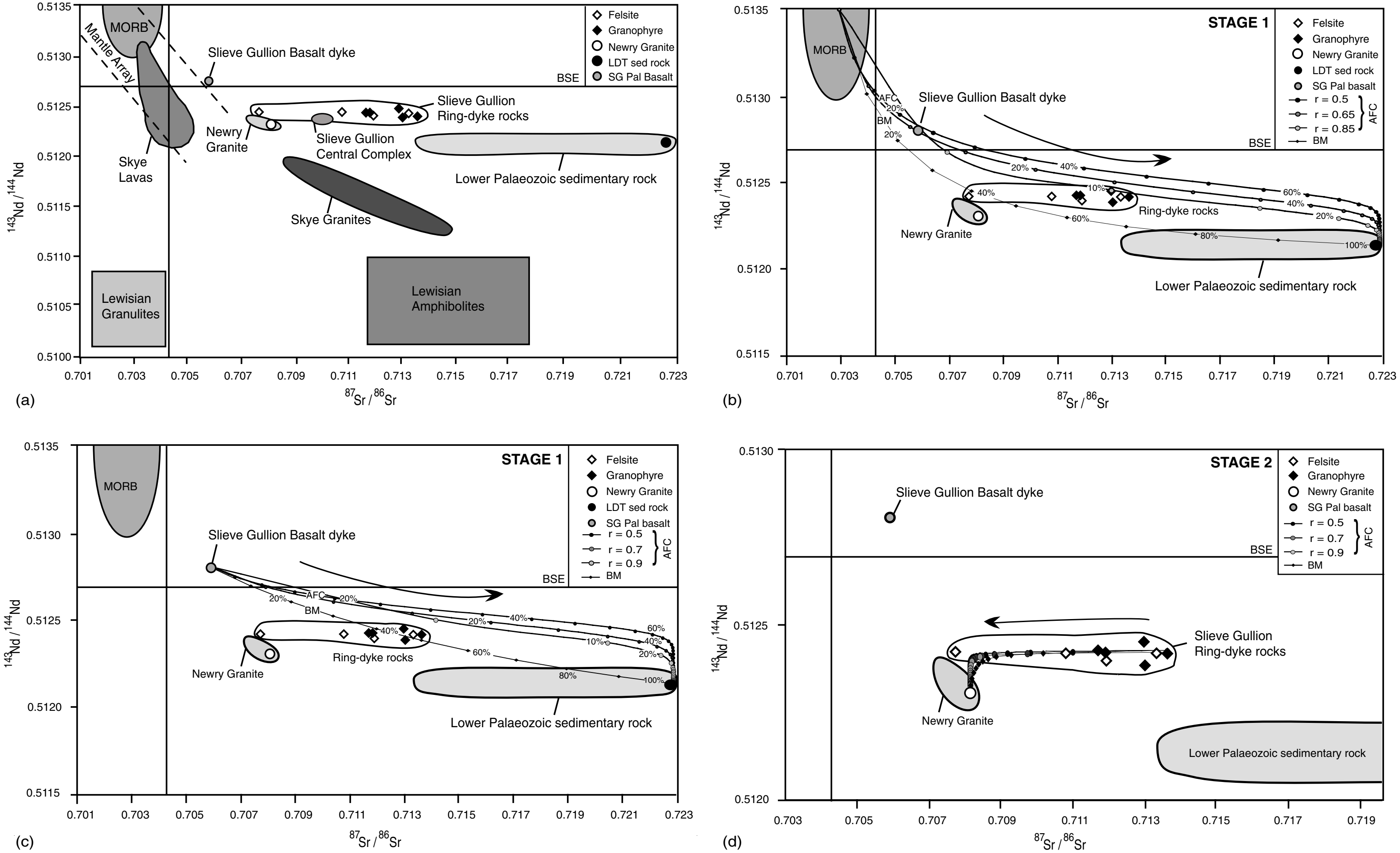


Figure 4. (a) $^{143}$Nd/$^{144}$Nd v. $^{87}$Sr/$^{86}$Sr summary diagram showing data from Slieve Gullion ring-dyke in relation to depleted mantle, the Slieve Gullion basalt dyke sample and local Longford Down sedimentary country rocks. Fields from Skye (for reference) and Lewisian amphibolites and granulites are from Dickin (1981). Slieve Gullion Central Complex from Gamble, Meighan & McCormick (1992), Lower Palaeozoic sedimentary rock field from Halliday (1984) and Newry Granodiorite from Dempsey, Halliday & Meighan (1990). Errors are smaller than symbol size. (b) $^{143}$Nd/$^{144}$Nd v. $^{87}$Sr/$^{86}$Sr diagram showing assimilation with progressive fractionation (AFC) and Binary Mixing curves using MORB-type starting composition and Longford Down sedimentary rock as contaminant. Arrow indicates evolutionary trend. Compositions similar to the low-Si dyke rocks are achieved by AFC (~ 10–15 % solidification) with relatively high assimilation rates (r = 0.85). Note basalt dyke sample lies on AFC curve (r = 0.85 at ~ 5 % solidification). (c) $^{143}$Nd/$^{144}$Nd v. $^{87}$Sr/$^{86}$Sr diagram with AFC and Binary Mixing curves using the Slieve Gullion basaltic dyke sample as a starting composition and Longford Down sedimentary rock as contaminant. Arrow indicates evolutionary trend. Note even high r-values fail to produce an intersection with low-Si ring-dyke rocks. (d) Subsequent contamination by Newry Granodiorite modelled by AFC and BM using low-Si granophyre as a starting composition. Arrow indicates evolutionary trend. This trend accounts for the negative correlation in $^{87}$Sr/$^{86}$Sr v. $SiO_2$ (toward less radiogenic Sr ratios).

and measured isotope ratios and trace elements. Binary mixing curves are also presented for both scenarios. In the first case (MORB to Longford Down Sedimentary rock) (Fig. 4b), only the high-Si ring-dyke rocks can be produced, failing to explain the low-Si compositions. In the second case (Slieve Gullion basaltic dyke to Longford Down Sedimentary rocks) (Fig. 4c), binary mixing can produce isotopic compositions similar to the low-Si ring-dyke rocks (50 % basalt, 40 % sedimentary rock). However, the modelled concentrations of Sr and Nd ppm (Sr = 164 ppm, Nd = 16) are not matched with the values observed in the samples (Sr = 35 ppm, Nd = 76). The best fit for this first stage of contamination is thus the AFC curve with a MORB starting composition (r = 0.85; solidification ∼10–15 %).

The decreasing $^{87}Sr/^{86}Sr$ trend from low-Si to high-Si ring-dyke rocks may in turn be explained by a subsequent selective assimilation of the most fusible portions of Newry Granodiorite, which possesses lower $^{87}Sr/^{86}Sr$ than the local sedimentary rock and similar $^{143}Nd/^{144}Nd$ ratios (Fig. 4d). This late contamination can be approximated as either binary mixing or as an AFC process since both are mathematically possible (Fig. 4d), though none produces a perfect fit for observed trace element concentrations. Since certain trace elements seem particularly affected by Newry Granodiorite contamination (McDonnell *et al*. 2004), it is conceivable that partial/selective contamination was the dominant mode of interaction (cf. Davidson & Tepley, 1997; Duffield & Ruiz, 1998; Knesel & Davidson, 2002). This is particularly likely as Newry Granodiorite is lower in $SiO_2$ than any of the ring-dyke rocks. Partial melting textures in thin-section suggest, however, a minimum melt fraction along quartz-feldspar grain boundaries, thus very probably providing a high-Si contaminant (Fig. 2d–f). The abundant occurrence of xenoliths and xenocrystal trails, particularly in the marginal felsite ring-dyke facies, suggests that besides interaction in the storage chamber (partial melting textures), incorporation of Newry Granodiorite also happened very late in the conduit. Although such samples were avoided for analysis, it is possible that some xenocrysts were contained in our felsite and granophyre samples (cf. Emeleus & Smith, 1959). For example, our most affected high-Si ring-dyke sample may well follow a binary mixing curve as a result of bulk incorporation of crystals and fragments from the country rock.

Assimilation of Longford Down sedimentary rocks is in accord with earlier findings on the Slieve Gullion Central Intrusion (Gamble, Meighan & McCormick, 1992). However, contamination by Newry Granodiorite was considered unlikely for these younger Slieve Gullion rocks (Gamble, Meighan & McCormick, 1992), although evidence is strong in the earlier ring-dyke rocks of this study. A number of reasonable explanations may be invoked for this: (a) the earlier ring-dyke magmas may have removed all easily fusible material from the Newry country rock, causing the subsequent Central Intrusion magma batches to experience little contamination or (b) the earlier magmas may have shielded the later ones from intensive interaction with the country rocks (cf. Thompson *et al*. 1986; Kerr *et al.* 1999). However, when considered in conjunction with our data, the data of Gamble, Meighan & McCormick (1992) plot well within the ring-dyke trend. It is thus also conceivable that these later Slieve Gullion rocks share a very similar history to the ring-dyke rocks, a feature that may be blurred by the 'obvious' Longford Down sedimentary rock contamination trend. However, the limited data set (n = 3) of Gamble, Meighan & McCormick (1992) does not facilitate a more detailed exploration.

### 5.b. Magma chamber structure

Trace element and major element data presented in McDonnell *et al*. (2004) suggest that the two distinct groups of both felsite and granophyre (a Si-rich group and a Si-poor group) most likely represent two compositional extremes that originated from a single parent and evolved through dominantly convective fractionation and contamination in a zoned magma chamber. The felsites represent the more liquid interior, and the granophyres the mushy chamber wall equivalents (Fig. 5) (McDonnell *et al*. 2004). This chamber structure, where a high-Si felsite magma was overlying a low-Si felsite, both encompassed by their more crystalline 'granophyre' equivalents, is supported by viscosity and density calculations (McDonnell *et al*. 2004) and may be the result of a process akin to convective fractionation (cf. Wörner & Schmincke, 1984; Sparks, 1988; Wolff, Wörner & Blake, 1990). In contrast, the mushy chamber wall granophyres formed from the arrest of crystals in inward migrating solidification zones and were modified by post-cumulus crystal growth and interstitial melt migration (McDonnell *et al*. 2004).

Although our isotope data alone are of limited use in reconstructing magma chamber processes, they offer a way of testing the model put forward by McDonnell *et al*. (2004). Whereas the solution we present is not unique, it does provide an explanation that is consistent with the model of McDonnell *et al*. (2004). Our data show the high-Si felsite to be most strongly affected by crustal contamination, in this instance by Newry Granodiorite, a feature that is common in composite silicic systems (e.g. Wörner, Staudigel & Zindler, 1985; Druitt & Bacon, 1989). In addition, both granophyres show a range of isotope ratios that is less radiogenic than the range of their felsite counterparts, which according to McDonnell *et al*. (2004) may be a function of the removal of interstitial liquid due to convective fractionation.

When contamination is initiated in such a scenario, the melt fraction of the magma would be most strongly

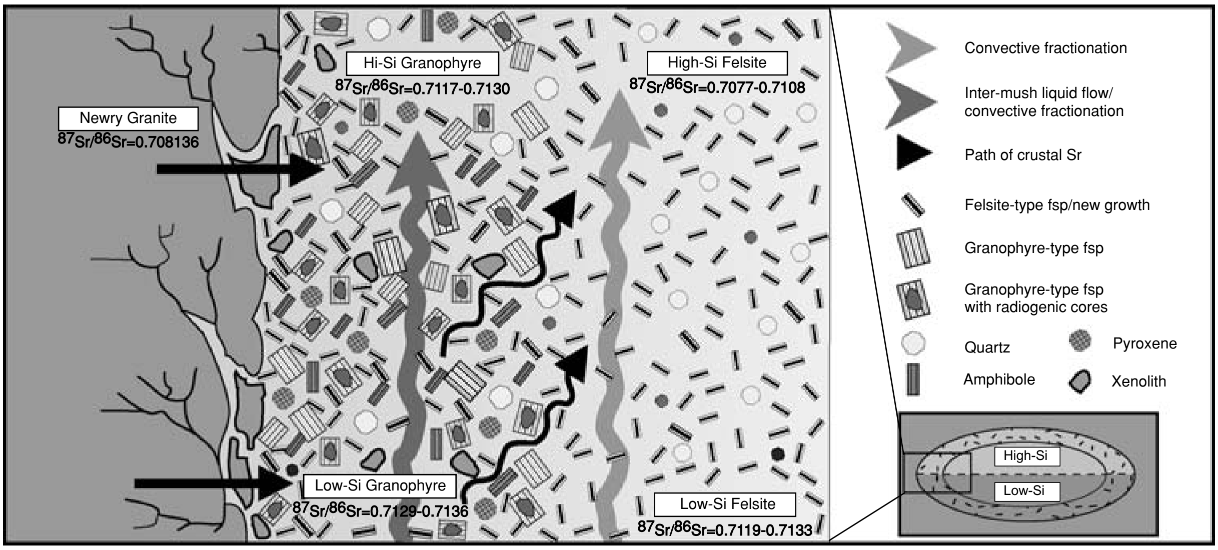


Figure 5. Schematic diagram of possible Slieve Gullion ring-dyke magma chamber in vertical contact with Newry Granodiorite chamber wall. Convective fractionation (grey vertical arrows) combined with crustal assimilation (black horizontal arrows) redistributes radiogenic crustal Sr from the chamber wall to chamber top (diagonal arrows), concentrating the liquid that is most strongly contaminated by Newry Granodiorite country rock in the roof zone of the chamber. The higher Sr isotope ratios in the granophyres are likely to be a function of the high abundance and large size of its complexly zoned feldspars, which probably reflect former stages of contamination, such as by very radiogenic Longford Down sedimentary rocks in many crystal cores. This suggests that the main volume of feldspar in the granophyre magmas grew before the onset of the second contamination stage (Newry Granodiorite) that provided much less radiogenic Sr to the system, potentially causing thin feldspar overgrowth rims with lower Sr isotope ratios to form.

affected in the beginning of such an assimilation process. Subsequently, crystals that grow from this melt will increasingly take up the contaminant in their outermost growth zones (Davidson & Tepley, 1997; Duffield & Ruiz, 1998). Crystals that mainly grew before contamination will show a change from core to rim, with rims reflecting the contamination most strongly. In the Slieve Gullion granophyre magmas, that lost interstitial melt during the last phase of crustal storage, similar and lower radiogenic whole rock values relative to their felsite counterparts imply that feldspars predominantly record a previous stage of contamination (with Longford Down sedimentary rocks). The whole rock value of the crystal-rich granophyre samples, being essentially a mixture of melt and crystals of various generations, is accordingly less reflective of the latest stage of contamination with Newry Granodiorite, although such a stage may be represented in small overgrowth rims of large, strongly zonal crystals (cf. Duffield & Ruiz, 1998). The bulk of the feldspar crystals in the granophyres, now represented as cores to large crystals (up to 7.5 mm), probably grew before or during contamination by Longford Down sedimentary rocks and prior to the main onset of Newry Granodiorite contamination (Fig. 5).

### 5.c. Crustal influence on British Palaeogene magmas

The influence of crustal contamination on isotope compostition is recorded in the geochemistry of magmas from virtually all British Palaeogene centres (e.g. Kerr *et al.* 1999; Ellam & Stuart, 2000; Bell & Williamson, 2002; Geldmacher *et al.* 2002). It has been shown by Geldmacher *et al.* (2002) that Palaeogene magmas that rose through different crustal terranes were exposed to different country rocks and thus record a different contamination history. These authors argue that magmas from the Rum Centre were mainly contaminated by Lewisian gneisses that form the upper crust north of the Moine Thrust Belt. Magmas at Ardnamurchan, however, were contaminated with Lewisian gneisses in the lower crust, with subsequent additional assimilation of Moine metasedimentary rock in the upper crust. Slieve Gullion lies south of the Northern Belt Median Fault (southern Uplands Fault equivalent in Ireland: Morris, 1987) and should therefore display a markedly different contamination history to those centres that intruded Archaean basement terranes in northern Scotland. The Slieve Gullion ring-dyke magmas record evidence for contamination with Southern Uplands-type local Palaeozoic mid- to upper-crustal sedimentary rocks plus shallow contamination with Ordovician granitic crust, emphasizing the severe effect of crustal heterogeneity on ascending plume magmas (cf. Ellam & Stuart, 2000). An additional earlier contamination of Slieve Gullion magmas (e.g. for the basaltic dyke sample) in the deep crust cannot be ruled out since the evidence for such an event would be strongly obscured by the two upper crustal contamination events. The nature of the deep crust beneath the Longford Down Terrane is, moreover, only poorly constrained. Xenoliths in Carboniferous lamprophyres in Co. Down (Anderson & Oliver, 1996) suggest that an ancient island arc-type basement underlies the Longford Down sedimentary rocks, and that this may in turn be underlain by Avalonian or exotic terranes (cf. Trewin & Rollin, 2002). Evidence for lower crustal magma-crust contamination may be preserved in the very inner cores of some of the strongly zoned feldspar phenocrysts of the ring-dyke rocks and awaits *in situ* analytical approaches.

## 6. Conclusions

The Sr and Nd isotope ratios of the Slieve Gullion ring-dyke magmas are consistent with at least two stages of contamination during upper crustal residence and storage. We propose a model whereby fractionating magmas of basaltic and intermediate composition are contaminated by local sedimentary rocks, giving rise to rhyolite magmas that experience additional shallow contamination by the most fusible portions of the Newry Granodiorite. We envisage the last stages of fractionation and contamination to occur in a zoned rhyolite magma chamber with high-Si magma being stored in the upper part of the chamber, recording the most extensive crustal contamination in this system.

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