Journal of the Geological Society, London, Vol. **169**, 2011, pp. 157–171. doi: 10.1144/0016-76492011-044.

Lateral versus vertical emplacement in shallow-level intrusions? The Slieve Gullion Ring-complex revisited

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Abstract: Recent studies on shallow-level arcuate intrusions have identified numerous examples of horizontal mineral fabrics. These are commonly interpreted as reflecting considerable lateral flow during magma emplacement, thus querying established 'semi-vertical' ring-dyke models. We question the recent lateral emplacement model proposed for the Palaeocene Slieve Gullion Ring-complex, NE Ireland, where the absence of steep fabrics in parts of the ring-complex has been used to support a shallow, semi-horizontal sheet intrusion mechanism. We argue that such simple flow models cannot be applied to explosive ring-fissure eruptions and that fabric data alone do not warrant rejection of the ring-dyke model. Moreover, the apparent 'absence of steep intrusive contacts' along the intrusion's perimeter is readdressed and we present numerous examples of outcrops (27) with steep-sided geometries. The Camlough Breccias are reinterpreted as the product of gas-driven tuffisites injected along the active ring-fault (rather than of purely tectonic origin). Crucially, the porphyritic microgranite and porphyritic rhyolite ring-dyke rocks exhibit geochemical and petrographic signatures of contamination by the geographically restricted Palaeozoic Newry granodiorite and are best explained through crustal interaction vertically beneath the ring-complex. Subsequently, these silicic magmas rose into ignimbrite feeders along a caldera ring-fault system that was emplaced into near-surface vent-filling breccias.

The Palaeocene Slieve Gullion Ring-complex lies in south Co. Armagh, on the border with Co. Louth, in NE Ireland (Fig. 1a). It is about 14 km across and consists of an arcuate intrusion of porphyritic microgranite and irregular bodies of porphyritic rhyolite, together with distinctive breccias, and is emplaced into granodiorite (the 'Newry granodiorite') at the southwestern end of the late Palaeozoic (Caledonian) Newry Igneous Complex (Fig. 1) (Richey & Thomas 1932). The complex forms a prominent ring of low hills (200–300 m) (Fig. 2) surrounding, though predating, the Slieve Gullion Central Sheeted Complex (Fig. 1a) (Reynolds 1951; Bailey & McCallien 1956; Gamble 1979). The Slieve Gullion Ring-complex has long been considered to represent a classic example of a ring-dyke (e.g. Richey & Thomas 1932) but recently the ring-dyke emplacement model has been reinterpreted by Stevenson *et al*. (2008) based on data primarily obtained from anisotropy of magnetic susceptibility (AMS) measurements. In this contribution we confirm the evidence for the ring-dyke geometry of the Slieve Gullion Ring-complex and in doing so draw inferences on the origin of horizontal mineral fabrics in ring-dyke intrusions. We argue that they do not represent significant lateral flow of magma during fissure eruptions but instead must represent post-magma emplacement processes.

Geology of the Slieve Gullion Ring-complex

The dyke-like form of the Slieve Gullion Ring-complex was first recognized during the initial geological survey of Ireland (Egan 1877; Nolan 1877) and was investigated in detail by Richey & Thomas (1932) who distinguished several components (Fig. 1a): (1) the agglomerate-filled Forkhill Vents, regarded as explosion breccias resulting from the degassing of rising silicic magma; (2) Porphyritic Felsite (now termed 'porphyritic rhyolite'), occurring as plugs and irregular sheet-like bodies intruded into and closely associated with agglomeratic breccias in the Forkhill Vents (now termed 'Forkill Breccias', after Stevenson *et al*. (2008), but with Forkhill being changed to Forkill as on modern Ordnance Survey maps); (3) Porphyritic Granophyre (now termed 'porphyritic microgranite') forming a dyke-like body through about 270° of arc, representing a particularly good example of a ring-dyke; (4) the Breccias of Cam Lough (now termed the 'Camlough Breccias'), a zone of intensely veined, deformed and shattered rocks principally developed along the outer margins of the ring-complex. The Camlough-type brecciation significantly shatters and veins the porphyritic microgranite of the Slieve Gullion Ring-complex, together with the country-rock Caledonian Newry granodiorite, Silurian metasedimentary rocks and Palaeocene dolerite and gabbro plugs. The porphyritic rhyolite and the Forkill Breccias are much less affected. The relationships of the components of the ring-complex are shown schematically in Figure 1b.

The ring-dyke emplacement model for both the porphyritic rhyolite and the porphyritic microgranite has been questioned by Stevenson *et al*. (2008) who put forward a radical reinterpretation based on data obtained from AMS measurements, new field observations and reinterpretation of aspects of earlier studies. Stevenson *et al*. (2008) also updated the petrological terminology to conform to current nomenclature for igneous rocks (e.g. LeMaitre 2002).

Stevenson *et al*. (2008) proposed that (1) the porphyritic rhyolite is 'the down-faulted vestige of a moderately welded ignimbrite sheet', and (2) the porphyritic microgranite (also termed the 'peripheral granite') is the lower part of an originally gently outward-dipping intrusive sheet, the steeply outward-dipping margins resulting from faulting along 'the main ring fault', evidence for which is preserved in the Camlough Breccias, which were considered to be predominantly of tectonic origin. The sequence of events

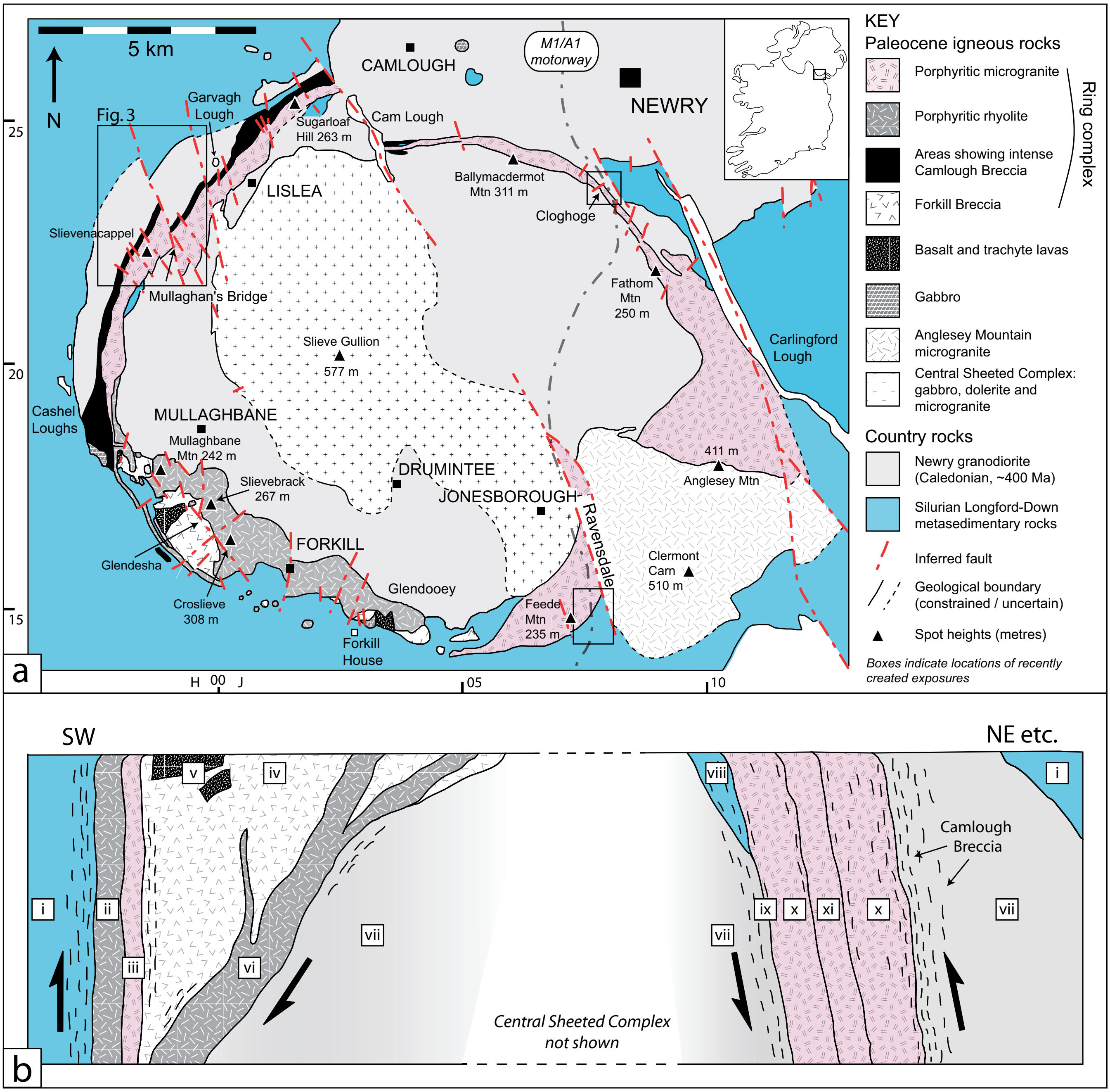

Fig. 1. (**a**) Geological sketch map of the Slieve Gullion ring-complex, showing localities and spot heights. Black boxes indicate localities where new exposures have been created by road works (modified after Richey & Thomas 1932, plate LV). Inset: Regional map of Ireland. (**b**) Schematic cross-section of the Slieve Gullion ring-dyke. The SW of the intrusion: (i) Folded and cleaved Silurian metasedimentary rocks, with intensely developed veining and shattering (the Camlough Breccias) at and near the ring-fault zone. (ii) Porphyritic rhyolite ring dyke segment (also termed the Outer or Carrive ring-dyke). (iii) Later dyke-like intrusion of porphyritic microgranite parallel to (ii). (iv) Forkill Breccias, containing clasts of metasedimentary rock (i), granodiorite (vii), gabbro, rare Camlough Breccias, also rafts and clasts of brecciated lavas (v). Intruded by the Inner porphyritic rhyolite (vi). (v) Rafts and clasts of fragmented, altered olivine basalt and trachyte, presumed to have been derived from lavas in the Palaeogene Antrim Lava Group. (vi) Porphyritic rhyolite (the Inner Rhyolite) in steeply to shallowly inclined sheets, plugs and veins. Unaffected by Camlough Breccias. (vii) Caledonian Newry granodiorite, commonly heavily altered within the ring-dyke. The NW, north, NE and south parts of the intrusion: (viii) Silurian metasedimentary rocks downfaulted within the ring-dyke and commonly affected by the Camlough Breccias. (ix) Intense development of Camlough Breccias in pre-porphyritic microgranite rocks at and along the inner contact of the ring-dyke. (x) Porphyritic microgranite ring-dyke (a central zone contains rounded acid inclusions (Fig. 3)). The ring-dyke is commonly involved in Camlough Breccias along its outer contact but to a much lesser extent elsewhere. It is in steep, chilled contact with granodiorite (vii) along its inner contact. Locally porphyritic rhyolite-like domains are present within the porphyritic microgranite. (xi) Inner, later intrusion of porphyritic microgranite in the central part of the ring-dyke (e.g. at Feede Mountain; Table 2, xiv). This intrusion is not affected by the Camlough Breccias. (The Slieve Gullion Central Sheeted Intrusion and other post-ring-dyke intrusions are not shown on the schematic cross-section).

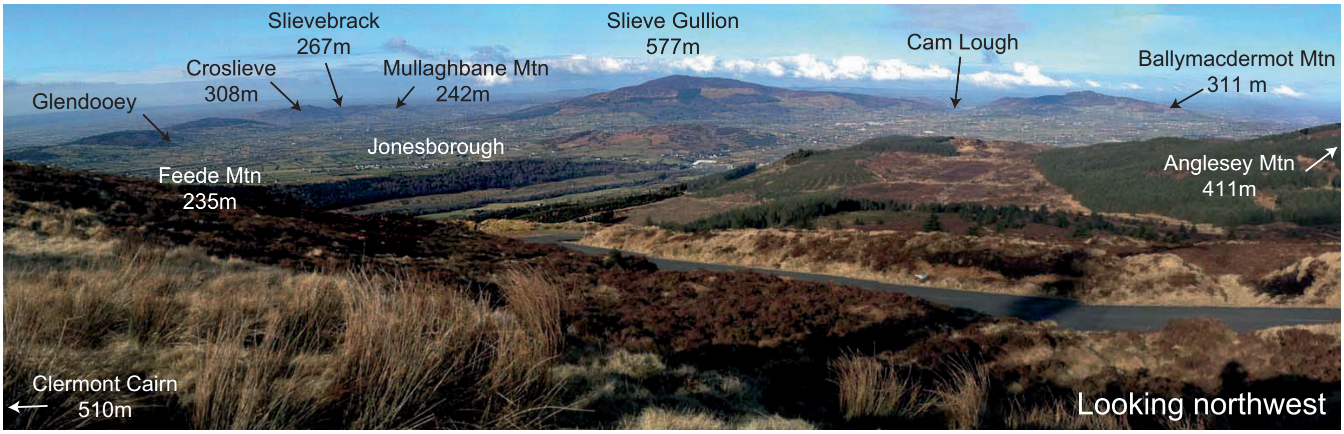

Fig. 2. Panoramic view from Clermont Cairn (SE corner of the ring), showing the topography of the area. The porphyritic rhyolite and porphyritic microgranite form the low ring of hills surrounding Slieve Gullion, the highest point of the complex, formed by the Central Sheeted Complex (SGSC).

(Stevenson *et al*. 2008, fig. 17) was initiated by incipient ring-faulting and subsidence accompanied by pyroclastic eruptions. The Camlough Breccias formed in response to continued ring-faulting and subsidence, accompanied by further ignimbrite eruptions (of porphyritic rhyolite magma), with the Forkill Breccias possibly representing debris from landslides off unstable caldera walls. During an ensuing phase of resurgence, the porphyritic microgranite was emplaced as a regional sheet at or close to the base of the ignimbrite, possibly associated with 'some piston-like uplift inside the ring-fault' and probably 'bound by the ring-fault (the Camlough Breccias) on the western and north-western side'. Finally, a major phase of resurgence occurred when the Slieve Gullion Central Sheeted Complex was emplaced, resulting in 'doming of the initially flat porphyritic granite sheet and further ring-fault movement'. Subsequent intrusion of the cross-cutting Anglesey Mountain microgranite (Fig. 1a) may have locally disrupted fabrics in the SE of the porphyritic microgranite.

Although we welcome the new data and agree that aspects of the original ring-dyke model require reappraisal in the light of recent investigations (e.g. O'Driscoll *et al*. 2006; Stevenson *et al*. 2007), we have significant reservations about this reinterpretation. Although the authors are undoubtedly correct in asserting that there is a paucity of field evidence of fabrics in the porphyritic microgranite, this is not true of contacts. As in many igneous complexes, contacts at Slieve Gullion can be elusive but examples occur, they have been recorded, and they reveal much about the intrusions (Richey & Thomas 1932; Emeleus 1956, 1962; McDonnell *et al*. 2004; Troll *et al*. 2008; and unpublished field mapping by J. E. Richey, J. Gamble & C. H. Emeleus). This information is summarized in Tables 1 and 2.

Lateral versus vertical magma flow in the Slieve Gullion Ring-complex?

Our aim is to place emphasis on field observations and discuss the AMS results in general terms only. The underlying hypothesis that Stevenson *et al*. (2008) tested using the AMS data is based on the emplacement model of Richey (1928, 1932), which was rephrased by O'Driscoll *et al*. (2006). There, a central subsiding block of bell-jar shape opens up a ring-fracture into which magma is injected. In this scenario a shear fabric will be imposed onto the injected magma parallel to the steep walls of the ring intrusion. Stevenson *et al*. (2008) argued that the absence of such a steep shear fabric and the presence of a partly flat-lying fabric revealed by AMS measurements are indicative of a horizontally emplaced sheet intrusion rather than a ring-dyke. However, recent experimental evidence suggests that ring-dyke emplacement will result in semi-chaotic particle movement during ring fissure flow (Kennedy *et al*. 2008). Furthermore, ring-dykes may in fact form in a number of phases and over considerable periods of time as, for example, the active ring-dyking currently observed at Rabaul caldera (Saunders 2005), a phenomenon that has also recently been suggested for ancient ring-complexes (e.g. Kennedy & Stix 2007) and for which there is evidence at Slieve Gullion (Richey & Thomas 1932, fig. 10; McDonnell *et al*. 2004; Troll *et al*. 2008). This raises considerable doubt regarding the validity of the hypothesis formulated by Stevenson *et al*. (2008). The absence of a steep shear fabric does not therefore negate the existence of a ring-dyke system *per se*. In addition, AMS is a notoriously difficult tool to interpret (see Stevenson *et al*. 2008, p. 169). Generally, the method is thought to record the final movement of a liquid before it solidified. This may include actual magma flow, but may also record cumulus processes such as compaction or crystal mush migration and/or crystal growth processes (see O'Driscoll *et al*. 2006, 2007, 2008; Stevenson *et al*. 2007). As final magma emplacement in the crust normally displays a combination of such processes, the resulting AMS data will also be affected and it remains to be unequivocally shown that the data presented for the Slieve Gullion Ring-complex are truly indicative of pure magma transport during the main stage of emplacement. On the contrary, we argue that field evidence unequivocally demonstrates that the Slieve Gullion Ring-complex represents a ring-fissure eruption and that therefore the presence of horizontal mineral fabrics helps reveal the nature of post-magma emplacement processes operating in these ring-dyke systems. Besides the general concern regarding the interpretation of the AMS data, the Stevenson *et al*. (2008) model requires an element of central up-doming of the original flat-lying sheet intrusion by the later Slieve Gullion Central Sheeted Complex. If this is the case, the originally flat-lying fabric should dip away steeply from the later central intrusion. Such an 'up-tilt' should be detectable with palaeomagnetic methods, which are sensitive to post-emplacement rotation or tilt of $\leq 10°$ from an original magnetic field (e.g. Szérémeta *et al*. 1999; Petronis *et al*. 2009; Delcamp *et al*. 2010).

As AMS data alone may not provide a unique solution at Slieve Gullion, we remain to be convinced about a reinterpretation based largely on the use of such data, and look forward to seeing new and old models tested for tilting and rotation caused by the central intrusion using palaeomagnetic approaches. In the mean time, we shall focus on traditional field data and rock geometric relationships.

Table 1. *Description and localities of contacts between porphyritic rhyolite and Forkill Breccias (unless otherwise stated)*

	Locality	Details	Source
i	Glendooey, just E of the road fork at [J 035 150]	The contact dips 71° WNW, towards the porphyritic rhyolite, which veins adjoining basalt	JG
ii	Glendooey, *c.* 400 m SSE of the road fork at [J 035 150]	Porphyritic rhyolite is in steep junction with basalt, with vertical flow structures (fiamme) in the rhyolite, which contains many silicic and basic xenoliths	JG
iii	*c.* 400 m NE of Forkill House [J 028 146]	The porphyritic rhyolite has a steep outward-dipping (80°) contact against the Forkill Breccias, which it veins, and contains many xenoliths	JG
iv	A short distance NNE of Forkill House [J 028 146]	A sheet or dyke of porphyritic rhyolite intrudes feldspar-phyric basalt (ex-flow). The sheet extends SE from the main body of the rhyolite, it is *c.* 15 m wide, is exposed for about 200 m, and dips steeply to the SW	JG
v	Slievenabolea [J 053 144]	Numerous veins of black porphyritic rhyolite cut the Forkill Breccias, enveloping single clasts	JER, CHE
vi	Carewamean [J 046 147]	Numerous veins of black porphyritic rhyolite cut the Forkill Breccias, enveloping single clasts	CHE
vii	Abandoned quarry at about [H 982 185] on the ridge 1.6 km WSW of Mullaghbawn	Semi-vitreous, deep brown porphyritic rhyolite is in steep contact with Newry granodiorite. The fiamme in the marginal rhyolite are deformed into flat-lying cigar-like structures with long axes parallel to contact, which dips 50° WSW	CHE
viii	450 m ENE of road junction at [H 994 156], near Carrive Grove	Porphyritic rhyolite is in steep, sharp contact with Forkill Breccias, with a dyke-like projection into the breccia	CHE
ix	*c.* 1.3 km N10°E of road junction at [H 994 156]	Porphyritic rhyolite is in steep contact with Forkill Breccias and a broad rhyolite dyke projects into the breccia	CHE
x	250 m SSE of Belmont [H 999 180]	The junction between Newry granodiorite and porphyritic rhyolite on the NE end of Slievebrack is noted as 'steeply crossing a spur'. Fluxion structures (fiamme) in the adjoining porphyritic rhyolite are inclined 65° WSW	JER
xi	800 m S13°E of Croslieve summit [J 002 164]	Marginal porphyritic rhyolite contains Newry granodiorite and Silurian metasedimentary xenoliths (the latter up to 1 m diameter). The contact was not exposed (but could be located to <2 m); a thick (*c.* 80 m near-vertical) dyke-like mass of rhyolite extends SSE into the Silurian rocks. A sample (G307) of the rhyolite close to the metasedimentary rockss appeared sheared, with white feldspar phenocrysts drawn out into steeply dipping rod-like structures	CHE
xii	The active quarry at Forkill [J 0059 1603]	A thick (*c.* 35 m) inclined (60–80°) sheet of porphyritic rhyolite is exposed. This displays an up to 10.5–1 m wide marginal breccia, which in turn contains clasts of folded porphyritic rhyolite and coarse-grained granitic inclusions (see Fig. 5)	McDonnell *et al.* 2004

It should be noted that these observations in part predate the Irish Grid and grid references cited are therefore approximate only. Sources: JG, J. Gamble's 6 inch and 24 inch field maps and notes thereon; JER, J. E. Richey's 6 inch field maps and Richey & Thomas (1932); CHE, C. H. Emeleus' 6 inch field maps and notes.

Lithologies of the Slieve Gullion Ring-complex

The mineralogy and detailed petrography of the ring-dyke rocks were described by H. H. Thomas (Richey & Thomas 1932), with additional information subsequently provided by Emeleus (1956, 1962), Emeleus & Smith (1959), Bell & Emeleus (1988), McDonnell *et al.* (2004) and Stevenson *et al.* (2008). The porphyritic rhyolite contains phenocrysts (20–30 vol.%) of sanidine, bipyramidal quartz, andesine-oligoclase plagioclase, ferrohedenbergite and fayalite. Feldspar phenocrysts are generally 2 mm or less and the other minerals <1 mm. The phenocrysts may be euhedral, embayed or appear broken. Marginal porphyritic rhyolite is charged with minute magnetite crystals and has a fine-grained and 'flow-banded' (= deformed, devitrified fiamme) matrix, coarsening away from the contact to a mosaic of quartz, feldspar, opaque oxides and green amphibole. Small (<1 cm) angular to subangular xenoliths of basalt, granodiorite and hornfelsed Silurian siltstone are generally present, with larger country rock xenoliths more common near the margins. The porphyritic microgranite contains phenocrysts (up to *c.* 50 vol.% in margins) of sanidine-orthoclase, andesine-oligoclase, quartz, hedenbergite, amphibole (which may rim clinopyroxene) and rare fayalite. Quartz and feldspar are granophyrically intergrown in the groundmass of the marginal, fine-grained 'microgranite' and may occur as spherulitic structures. In the more central parts, the rock has an interlocking granitic-textured groundmass. The feldspar phenocrysts range in size (≤1 cm) but are distinctly larger than those present in the porphyritic rhyolite (however, see McDonnell *et al.* 2004). Large (up to 1 m diameter) rounded or lobate-shaped inclusions of non-porphyritic or sparsely porphyritic microgranite are abundant in some central parts of the porphyritic microgranite (Fig. 3) (Emeleus 1970). Small (<5 cm diameter), often diffuse mafic inclusions rich in amphibole and opaque oxides, a few of which have doleritic or basaltic cores, are also common and are widely distributed (Richey & Thomas 1932; Troll *et al.* 2008).

Generally, the porphyritic microgranite is in sharp, chilled contact with porphyritic rhyolite (Emeleus 1962, plate 5, fig. 5; Stevenson *et al.* 2008, fig. 11). However, detailed investigation of the contact relationships of the porphyritic rhyolite and porphyritic microgranite on the ridge west of Mullaghbane (Fig. 1a) has shown that the two lithologies have lobate liquid–liquid contacts and were intruded essentially contemporaneously in closely spaced pulses (Fig. 4). Similarly, lobate inclusions of porphyritic microgranite also occur in the porphyritic rhyolite sheet exposed in Forkill quarry close to the village of Forkill (Table 1, xii) (McDonnell *et al.* 2004, fig. 3b).

The porphyritic rhyolite and the Forkill Breccias

Exposed contacts between the porphyritic rhyolite and Forkill Breccias or country rocks have been recorded at several localities (Richey & Thomas 1932; Emeleus 1956, 1962; McDonnell *et al.* 2004) and additional information has been obtained from these authors' field sheets and those kindly made available to us by

Table 2. *Description and localities of the porphyritic microgranite inner and outer contacts*

Contacts	Locality	Details	Source
Inner contact			
i	400 m W15°S of Ballynasack Bridge [H 983 202]. East of the minor road	A specimen of fine-grained porphyritic microgranite (G425) was taken <1 m from brecciated Newry granodiorite of the Camlough Breccias. The porphyritic microgranite appears to be unbrecciated	JER, CHE
ii	1.6 km SW of Lislea church [J 007 241] and 600 m E25°N of Mullaghan's Bridge [H990 224]	Fine-grained porphyritic microgranite (G278, G389) is chilled against Newry granodiorite. Specimens G387–394 were taken across the contact. Neither porphyritic microgranite nor granodiorite shows significant brecciation or veining	CHE
iii	Path *c*. 800 m NNE of Cashel Bridge [H 978 210]	An unbrecciated specimen of typical, fine-grained marginal porphyritic microgranite (G64) was taken here but the contact with adjoining Silurian metasedimentary rocks (*c*. 1 m distant) was not exposed	CHE
iv	400 m to the SE or SSE of Slievenacappel [H 982 221], beside semi-derelict (1953) farm at [H 986 220]	Unbrecciated porphyritic microgranite (G80, etc.) is in contact with veined and brecciated Newry granodiorite. The contact dips at *c*. 70° SE, towards Slieve Gullion. Camlough Breccia (of granodiorite; G81, 82) was taken from pieces adhering to the surface of porphyritic microgranite	CHE
v	Hillside *c*. 400 m NNE of Mullaghan's Bridge [H 990 224]	Specimens of unbrecciated marginal porphyritic microgranite were obtained close to the contact with veined and brecciated Newry granodiorite (G85, G86 respectively about 8 and 30 cm from the granodiorite). Nearby, closely spaced veining permeates the breccias, which have weathered to low parallel ridges resembling slates set on edge	CHE
vi	*c*.200 m S of Fathom Mountain [J 092 221]	Marginal porphyritic microgranite [G380] and unbrecciated Newry granodiorite [G381] were collected *c*. 1 m apart. The contact appeared to be near-vertical	CHE
vii	*c*. 400 m NW of the summit of Fathom Mountain [J 092 221]	The exposed contact (G382) between fine-grained porphyritic microgranite (G383) and Newry granodiorite (G384) affected by Camlough Breccias dips steeply to the east	CHE
viii	*c*.800 m N30°W of Fathom Mountain [J 092 221]	The contact between porphyritic microgranite is well seen and dips at 60–65° slightly north of east. The Newry granodiorite is foliated for *c*. 2.5 cm from the contact and is granulitized at a distance of *c*. 25 cm. The porphyritic microgranite is very fine-grained at the contact and contains small quartz and feldspar phenocrysts, but over a distance of *c*. 30 cm it becomes coarser with normal-sized phenocrysts	JER
ix	Cloghoge Mountain between [J 0796 2363] and [J 0823 2302] and south of the roundabout at the Dublin Road railway bridge	Porphyritic microgranite is seen in contact with a Palaeocene basalt dyke near the southern end of this road cutting. The basalt dyke is faulted internally very close to the contact but part of its original chilled margin against the porphyritic microgranite is preserved. The porphyritic microgranite is slightly veined and fragmented, but the deformation is significantly less intense compared with Cam Lough quarry (locality x; see below). The basalt dyke appears to be exploiting a primary steep contact between the porphyritic microgranite and the Newry granodiorite. At the northern end of the road cut at [J 0796 2363], porphyritic microgranite is in contact with strongly chloritized granodiorite. The contact trends 145°/85° NE and appears to have undergone little subsequent movement. The porphyritic microgranite is slightly veined and foliated, with a fabric oriented 125°/52° NE. (This part of the section is not readily accessible and much was covered subsequent to these observations) The inner contact of the porphyritic microgranite and Newry granodiorite is exposed in the accessible new roadcut on the northbound slip road on the west side of the motorway at [J 081 236]. There has been much movement at the contacts and the exposures are remarkable for the degree of hydrothermal alteration shown by the porphyritic microgranite and granodiorite; basic dykes are also present	DJC, VRT, FM
x	Cam Lough quarry [J 037 246]	Brown weathered porphyritic microgranite is in contact with Silurian metasedimentary rocks intruded by Newry granodiorite. The junction dips steeply north at 65° and is marked by a zone of Camlough Breccias, which extends into the porphyritic microgranite and the underlying metasediments. Freshly quarried blocks of the microgranite exhibit excellent examples of these breccias (Figs 6a, b and 9). In this area, the outer contact of the Caledonian pluton is over 1 km north of the quarry, which implies significant downthrow within the ring-fault (see Cooper & Johnston 2004*b*, fig. 5.1), even allowing for the possible sheeted character of this contact (e.g. Reynolds 1944)	DJC, VRT, FM; also Cooper & Johnston 2004*a*, photograph 9)
Outer contact			
xi	Gully eroded along small fault c. 300 m ESE of Garvagh Lough [H 9887 2445]	Richey described porphyritic microgranite chilled against Camlough Breccias (Richey & Thomas 1932, p. 836). On re-examination (in 1954) it appeared that both Newry granodiorite (G101) and porphyritic microgranite (G100, G247) were brecciated and veined hereabouts. The microgranite is the finer-grained marginal variety and is less brecciated than the nearby granodiorite. The brecciated granodiorite is cut by thin rhyolite sheets, possibly offshoots from the porphyritic microgranite (JER), which are also cut by sparse, thin dark veins. There was some displacement of the sheets along these veins, the overall effect being of a downthrow towards the south (i.e. the inside of the ring-structure). Flow-lines in one sheet appeared to indicate movement from the direction of the porphyritic microgranite into the brecciated granodiorite. Offsets in the sheets were partly steps in the intrusion and partly fault movement on the veins (see Fig. 8)	CHE

(Continued)

Table 2. *(Continued)*

Contacts	Locality	Details	Source
xii	600 m due east of the southern end of Cashel Lough Lower, at *c*. [H 975 202]	Richey's field sheets indicate an apophysis of porphyritic microgranite extending from the main ring of microgranite into the Newry granodiorite (Camlough Breccias), and he stated that microgranite is sound up to the Camlough Breccias. Despite sparse exposure, re-examination of the locality confirms that Richey's claim is tenable. Any actual contact is, however, obscured by vegetation and both Newry granodiorite and the porphyritic microgranite show brecciation and veining close to the contact	FM, DC
xiii	*c*. 65 m north of Sugarloaf Hill [J 013 254]	Porphyritic microgranite and Newry granodiorite are both brecciated and veined at and near the contact. JER noted that the contact is seen here	CHE
xiv	About 300 m SE of the summit of Courtney Mountain [J 005 253]	Camlough Breccias (ex-Newry granodiorite) are in steep contact with banded silicic rock (= marginal porphyritic granophyre) (JER). The contact is well exposed in a small, NW–SE-trending fault scarp about 50 m NW of a near-north–south-trending porphyritic dolerite dyke and is inclined outwards (i.e. NW) at 70°. Richey noted veins of a rhyolitic rock cutting the Camlough Breccias. The contact may also be exposed in a 'great cliff of felsite' (i.e marginal porphyritic microgranite) just west of the bend in the B134 road (at *c*. [J 010 251])	JER
xv	1.6 km east of Silverbridge [H964 180], a small quarry on the east of the minor road	Porphyritic microgranite in contact with crushed Newry granodiorite (Camlough Breccias). The crush lines are vertical and trend NW. The microgranite is part of the thin (10–20 m wide) dyke-like mass extending along the west side of the porphyritic rhyolite	JER
xvi	Feede Mountain [J 072 146]	A thick (*c*. 170 m) dyke-like body of sparsely porphyritic microgranite cuts normal porphyritic microgranite about 100–150 m north of the summit. The contacts are sharp but with only slight chilling, and they trend parallel to the margins of the main body of porphyritic microgranite (i.e. ENE to NE); 400 m SW of the summit the porphyritic granite has a chilled margin (for a 'few yards from screen', JER) of rhyolitic rock against a narrow, vertical screen of baked Silurian shales, which separates it from a c. 35 m wide dyke-like mass of sparsely feldspar-phyric and occasionally banded rhyolite or microgranite. The rhyolite is thought to have been contact-altered by the microgranite (JER). SSE of the summit the porphyritic microgranite is 'crushed' and ENE–WSW-trending zones of intense veining or crushing (= Camlough Breccias) occur elsewhere in the normal porphyritic microgranite, but not in the later, sparsely porphyritic microgranite	JER, CHE
xvii	Ravensdale road cutting [J 07981 14632]	Continuous exposures in a 300 m long, north–south section behind protective fencing on the west side of the M1 motorway, north of Feede Cross interchange, about 8 km north of Dundalk. From south to north, porphyritic microgranite has a chilled, porphyritic rhyolite facies at its steep intrusive contact with Silurian metasedimentary rocks; further on, a sheet of porphyritic rhyolite intrudes the metasedimentary rocks, and towards the end of the section porphyritic microgranite is in steep, faulted contact with them. The fault is sharp, but displays a damage zone of several metres on either side. Numerous thin, dark-coloured tuffisite veins (Camlough Breccias) are conspicuous in the microgranite and rhyolite and a steep composite (dolerite or rhyolite) dyke and basaltic dykes are present (Troll *et al*. 2008)	Troll *et al*. 2008.
Contacts between porphyritic microgranite and porphyritic rhyolite			
xviii	Ridge west of Mullaghbane, 500 m due west of farm (at [H 9860 1834])	A dyke of fine-grained porphyritic microgranite (G436) occurs between porphyritic rhyolite and Newry granodiorite, neither of which is brecciated. This is at the north end of a locality where the rhyolite is in contact with granodiorite (Table 1, locality vii)	CHE
xix	Ridge [H 978 186] west of Mullaghbane	Porphyritic microgranite and porphyritic rhyolite are in contact. The relationships are complex and suggest that the two lithologies were emplaced essentially contemporaneously. Neither is brecciated or veined	McDonnell *et al*. 2004
xx	NW and east of Carrive Grove [H 995 153]	Porphyritic rhyolite (Richey's Outer or Carrive Grove Felsite) is intermittently exposed for about 3 km in a narrow zone (<100 m) of rough ground (between about [H 002 153] and [J173 981]). Exposures are good towards the SE end, becoming less common to the NW. The porphyritic rhyolite is a dyke-like body margined by Silurian rocks (which appear to be involved in Camlough Breccias in places) on its SW side, and contributes to Forkill Breccias on the NE side. A short (<500 m) dyke of porphyritic microgranite is also present on the NE side of the porphyritic rhyolite, close to the road fork at [H988 165]	JER, CHE
xxi	Carrickinaffrin [J 005 152]	Porphyritic rhyolite forms a small plug probably cutting Forkill Breccias. Small patches of porphyritic microgranite were found chilled against rhyolite on the north side of the plug	J. V. Smith, sample 5/212b

It should be noted that these observations in part predate the Irish Grid and grid references cited are therefore approximate only. Sources: JER, J. E. Richey's 6 inch field maps and Richey & Thomas (1932); JG, J. Gamble's 6 inch and 24 inch field maps and notes thereon; CHE, C. H. Emeleus' 6 inch field maps and notes. Specimens with 'G' come from the collection of CHE. Additional note on Camlough Breccias: in thin section the breccias show every gradation from strongly cataclastically deformed rocks (e.g. OUMNH.8472 (G243), OUMNH.8474 (G245)) to tuffisites (e.g. OUMNH.8475 (G244)). Textures in the tuffisites may resemble some of the textures in the Forkill Breccias (e.g. OUMNH.8480 (G192)), but whereas the latter are little altered, epidote and sericitic mica are abundant in the tuffisites, indicating formation temperatures of at least 230–300 °C (e.g. Parry & Bruhn 1986; Ambrosio *et al*. 2010). In places veining is so intense that it obscures the protolith. Where the veining is closely spaced the breccias weather to low parallel ridges resembling slates set on edge, as seen about 400 m north of Mullaghan's Bridge [H 990 225; locality 2, v). OUMNH numbers refer to samples in the Oxford University Museum of Natural History.

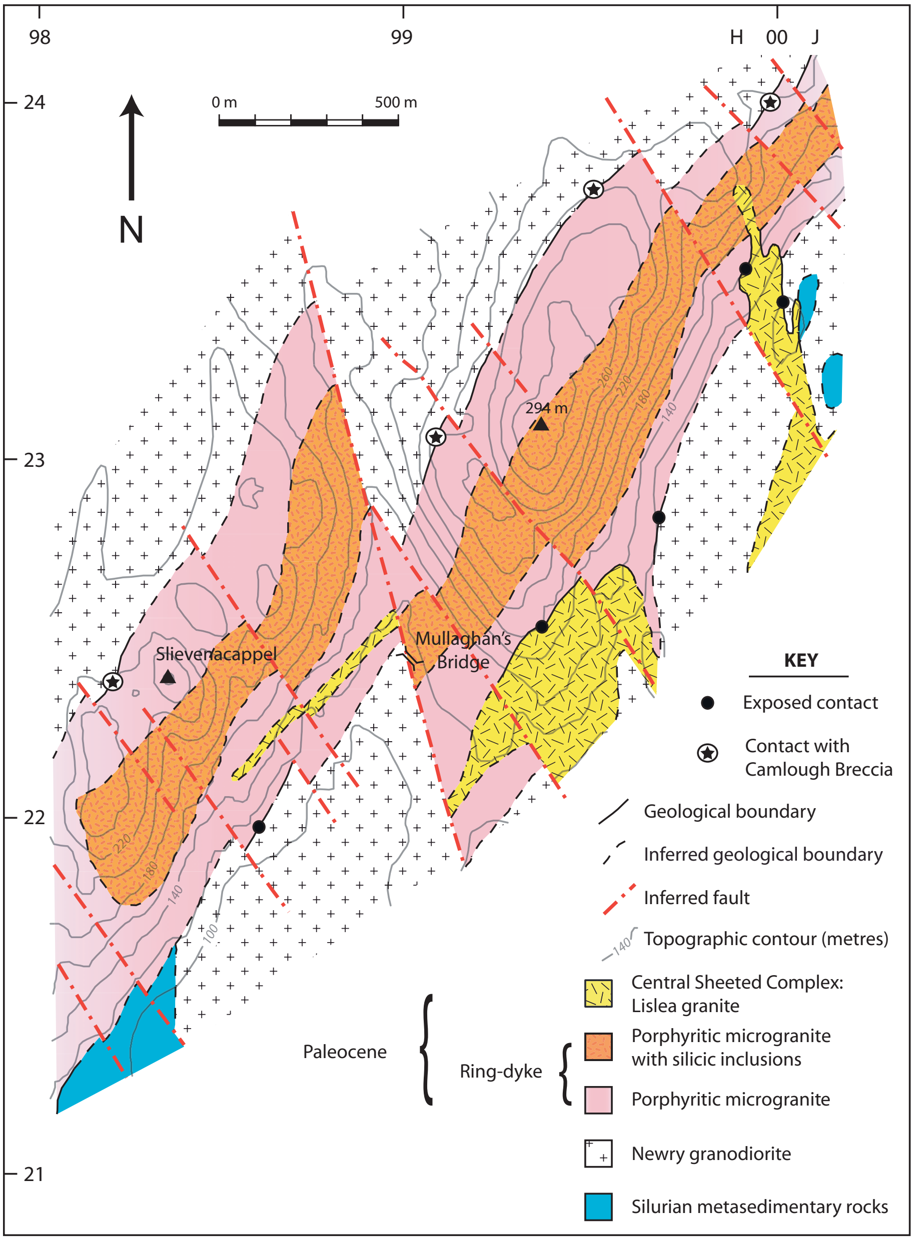

Fig. 3. Geological map of the ring dyke between Slievenacappel and Lislea (based on C.H.E.'s 1953–1955 6 inch maps). Noteworthy features are: (1) the central zone of inclusion-bearing porphyritic microgranite, which has steep boundaries (see McDonnell *et al.* 2004), cross-cutting the topographic contours; (2) the occurrence of Silurian rocks inside the ring-dyke; (3) key contacts where the ring-dyke porphyritic microgranite is chilled against earlier rocks.

J. Gamble. We have examined, or are aware of, at least 10 localities where porphyritic rhyolite is in sharp contact with earlier rocks and, in all instances, the measured dips on the contacts are at least 50°, and more commonly from 70° to vertical, with porphyritic rhyolite usually underlying Forkill Breccias (localities and details are summarized in Table 1). In addition to the larger bodies, porphyritic rhyolite may intrude as dykes or veins. Had there been only one or two exposed steeply dipping contacts these could perhaps have been dismissed as merely of local significance but as this is not so, we contend that moderately to steeply dipping contacts are the norm. Marginal porphyritic rhyolite is very fine-grained and may resemble devitrified glass, its streaky appearance resulting from the attenuation of fiamme and shards and, less commonly, of deformed phenocrysts (see Emeleus 1962; Bell & Emeleus 1988; McDonnell *et al.* 2004). Less steep contacts appear to occur along the inner (NNE) side of the porphyritic rhyolite on Mullaghbane Mountain and Slievebrack (Fig. 1), where structural contours on the inner contact and the internal structures of the rhyolite indicate a dip of about 10° SSW (see Emeleus 1962, fig. 3; Stevenson *et al.* 2008, fig. 10). However, other interpretations are possible, as any embayments or irregularities on the ring contacts would significantly affect the dips inferred from structural contours, as for example, on Slievebrack (Table 1, x). This raises the possibility that the base of the rhyolite is not entirely planar, but irregular and formed by coalescing pipes and dykes that are inclined outwards at moderate to steep angles (i.e. SW to WSW; see Walter & Troll 2001). The observed low and very variable dips and folds of fiamme might form during drawback and rheomorphic flow of ignimbrite material in these pipes. Furthermore, flat-lying 'flow structures' are found in steep-sided intrusions; for example, in the Loch Bà ring-dyke, Mull (D. Brown, personal communication).

To summarize, the combined field evidence shows that the porphyritic rhyolite occurs as a number of generally steep-sided bodies of varying size with intrusive relationships with the Forkill Breccias and earlier rocks. Whereas single bodies may be dyke-like, the porphyritic rhyolite as a whole is clearly not a continuous ring-dyke, like, for example, Loch Bà, Mull (see Sparks *et al.* 1999), with the possible exception of the Outer or Carrive Felsite

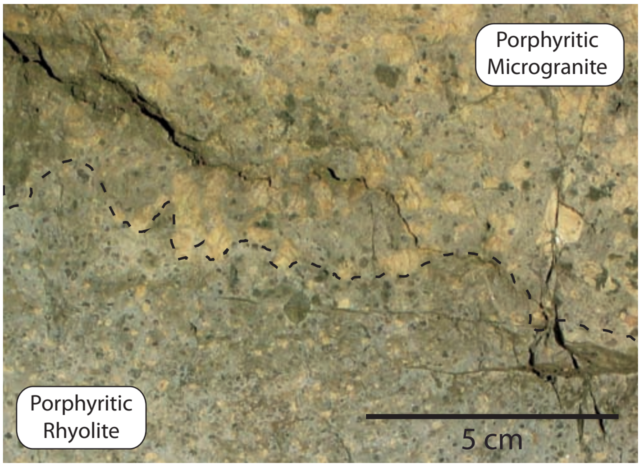

Fig. 4. Liquid–liquid contact between porphyritic rhyolite and porphyritic microgranite on the ridge west of Mullaghbane [H 978 186] (Table 2, xix). The lobate contact and the lack of a chilled margin should be noted.

(Table 2, xx) (Richey & Thomas 1932). Rather, it comprises a swarm of plugs and steep sheets forming a vent complex on and close to the continuation of the ring-fault (see Troll *et al*. 2000, 2004; Holohan *et al*. 2009). The reinterpretation of the porphyritic rhyolite as a surficial ignimbrite flow (Stevenson *et al*. 2008) is considered below.

The Forkill Breccias and the emplacement level of the porphyritic rhyolite

The coarse fragmental Forkill Breccias are characterized by chaotic assemblages of subangular to subrounded blocks of country rock (gabbro, granodiorite, basalt, trachyte, Silurian metasediments) and rare fragments of Camlough Breccias, in a matrix dominated by pulverized granodiorite or, less commonly, metasedimentary rocks (Fig. 5). Closely associated are rafts of basalt, olivine basalt, feldspar-phyric basalt and trachyte, most probably derived from Palaeocene lavas. Porphyritic rhyolite clasts are generally lacking and crystal fragments resembling broken rhyolite phenocrysts are very uncommon in the breccia matrix. Although clasts of one rock-type may dominate an exposure, other rocks are usually present (e.g. sparse, well-rounded blocks of coarse gabbro in granodiorite-dominated breccia in Glendesha), indicating that the breccias did not result exclusively from *in situ* shattering.

The suggestion that the Forkill Breccias were formed by landslides or similar mechanisms (Stevenson *et al*. 2008, fig. 17), rather than through explosive activity as envisaged by Richey & Thomas (1932) and Emeleus (1962), is attractive and especially so in the light of recent studies elsewhere in the British Palaeogene Igneous Province (Troll *et al*. 2000; Brown & Bell 2007; Brown *et al*. 2009; Holohan *et al*. 2009). In any case, the breccias have been poorly cemented and were readily penetrated by porphyritic rhyolite (Table 1, v and vi).

The porphyritic rhyolite between Croslieve and Mullaghbane Mountain has been interpreted as a shallow-dipping sheet, overlain by Forkill Breccias and underlain by Newry granodiorite and a small wedge of breccia (Emeleus 1962, fig. 3; Stevenson *et al*. 2008, fig. 12). If the porphyritic rhyolite is an ignimbrite surface flow, as suggested by Stevenson *et al*. (2008), then the overlying Forkill Breccias in Glendesha must post-date it and if, as suggested, these deposits originated as debris avalanches, they might have been expected to have incorporated material from the ignimbrite as

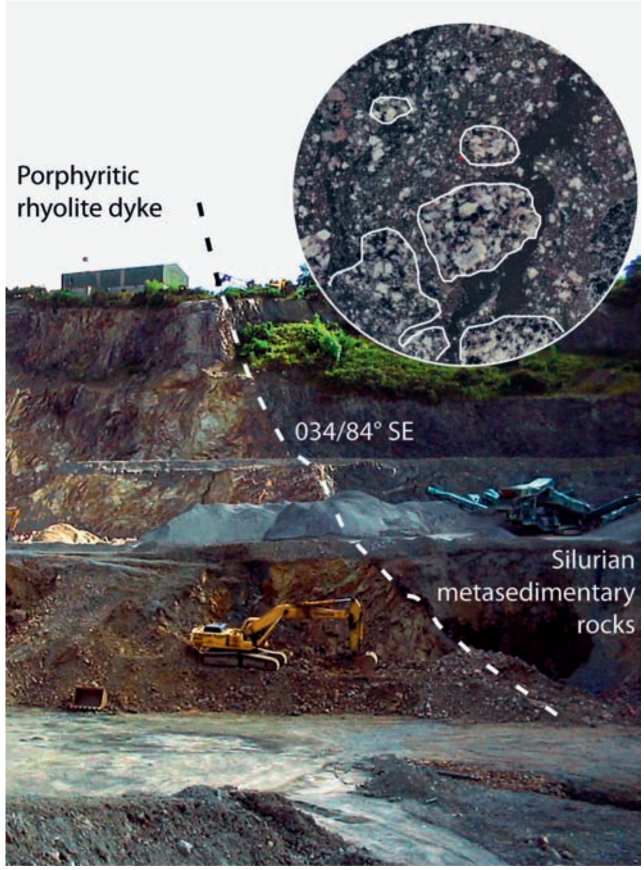

Fig. 5. The well-exposed intrusive contact of a massive porphyritic rhyolite dyke and Silurian metasedimentary rocks at the active Forkill quarry, looking NE (see McDonnell *et al*. 2004; Table 1, xii). Inset shows Forkill Breccias with clasts of granodiorite in a comminuted granodiorite matrix, exposed in the west of the quarry (diameter of circle is 10 cm).

they traversed its upper surface. Rhyolite fragments are, however, extremely uncommon in the Forkill Breccias, and where found, they are restricted to the margins of intrusions, as in the quarry west of Forkill (Table 1, xii). We consider that the evidence provided by the common exposed contacts, together with the many occurrences of dykes and veins of rhyolite, shows that the porphyritic rhyolite at the present level of erosion is predominantly intrusive. In particular, the dyke-like form of the Outer or Carrive Felsite (Richey & Thomas 1932) is generally accepted. Stevenson *et al*. (2008) noted the small degree of attenuation of the fiamme in the porphyritic felsite when compared with proven intrusive ignimbrites elsewhere (e.g. the Sabaloka complex, Sudan (Almond 1977); Rum (Donaldson *et al*. 2001)). This is perhaps an indication that at Slieve Gullion the porphyritic rhyolite was intruded into rocks very close to or even at the contemporary land surface, which is supported by the manner in which the rhyolite veins into the Forkill Breccias in the Slievenabolea–Carewamean area (Table 1, v and vi), suggesting that it was injected into a mass of loosely aggregated blocks (see Matthieu *et al*. 2008).

The porphyritic microgranite and the Camlough Breccias

The porphyritic microgranite and the Camlough Breccias form a large part of the 'Ring of Gullion', a prominent circle of small hills surrounding the Slieve Gullion Central Sheeted Complex (Figs 1a

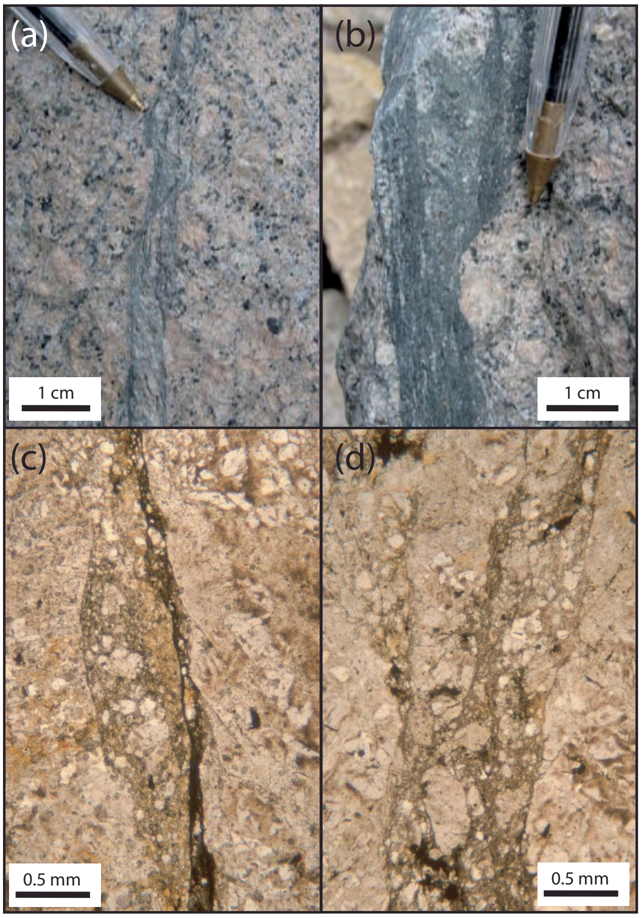

Fig. 6. Tuffisite bands from the Camlough Breccias. Field photographs (**a**) and (**b**) from Cam Lough quarry and photomicrographs (**c**) and (**d**) from Ravensdale (photomicrographs modified from Troll *et al*. 2008, fig. 4f).

Fig. 7. Faulted contact between porphyritic microgranite and Silurian metasedimentary rocks at Ravensdale (Table 2, xvii). The contact dips *c*. 80° SE and comprises a heavily crushed central zone (inset). The porphyritic microgranite shows strong extensive shearing and crushing up to 5 m away from the contact, with widespread mylonitic tuffisite and cataclasite veins.

and 2). The Camlough Breccias are characterized by numerous thin, dark anastomosing veins and zones a few millimetres to several centimetres in width and affect the Caledonian Newry granodiorite, Silurian metasedimentary rocks, and Palaeocene porphyritic microgranite and gabbro (Fig. 6). New minerals are commonly developed in the veins and fracture-fills and the microgranite and granodiorite are most commonly affected. Quartz and feldspar crystals are shattered, strained, deformed and displaced along these microfractures, hornblende is often altered to chlorite and pale green amphibole, epidote is commonly developed and feldspars may be sericitized, and there is abundant development of aggregates of minute opaque oxides. The structures form complex networks, locally with a strong parallelism, generally distinguishing the breccias from the more angular to rounded fragmental character of the Forkill Breccias (compare with Fig. 5). The pervasive veining may be so intense that it obscures the protolith and toughened the affected rocks (Table 2, v; see Stevenson *et al*. 2008), and the mineralogy of the veins indicates temperatures of at least 230–300 °C (e.g. Parry & Bruhn 1986; Ambrosio *et al*. 2010). The steeply dipping structures in the Camlough Breccias generally form zones that strike more or less parallel to the contact of the porphyritic microgranite and they were originally attributed to dynamic crushing during movement on the ring-fault (Richey & Thomas 1932; Stevenson *et al*. 2008). However, on Ballymacdermot Mountain (Fig. 1a) Richey & Thomas (1932, pp. 821 and 837) found that gaseous explosion had also contributed to the brecciation close to the inner edge of the porphyritic microgranite, which is not extensively veined hereabouts. Further indications of gas involvement were provided by Reynolds (1951, p. 134), who noted small vugs lined with quartz and epidote in the comminuted rocks. We consider the networks of veins in the vicinity of the ring-complex as a combination of cataclasites and 'tuffisites' (see Tuffen *et al*. 2003; Tuffen & Dingwell 2005) and thus genetically related to the intrusion itself. They reflect a complex, and episodic, interplay of explosive gas escape and dynamic crushing as the ring-fault moved and the silicic magmas migrated up the fracture, degassing (in part, explosively) as they ascended (e.g. Kokelaar 2007).

The porphyritic microgranite is affected by the Camlough Breccias to a lesser extent than the adjoining Newry granodiorite. Veining and fragmentation are common in the fine-grained marginal facies of the porphyritic microgranite along the outer margins of the ring-dyke and may be examined in recent road cuttings at Cloghoge and near Feede Mountain (Fig. 1a), where a complex interplay between intrusion, veining and faulting is exposed (Table 2, ix and xvii) (Troll *et al*. 2008).

Richey & Thomas (1932, p. 819) described original unbroken outer contacts of the ring-dyke in the NW of the ring-complex, but on re-examination the fine-grained porphyritic microgranite is generally found to be brecciated although to a lesser extent than in the adjoining Newry granodiorite (Table 2, xi and xii). Least affected are thin felsitic sheets intruded into the brecciated Newry

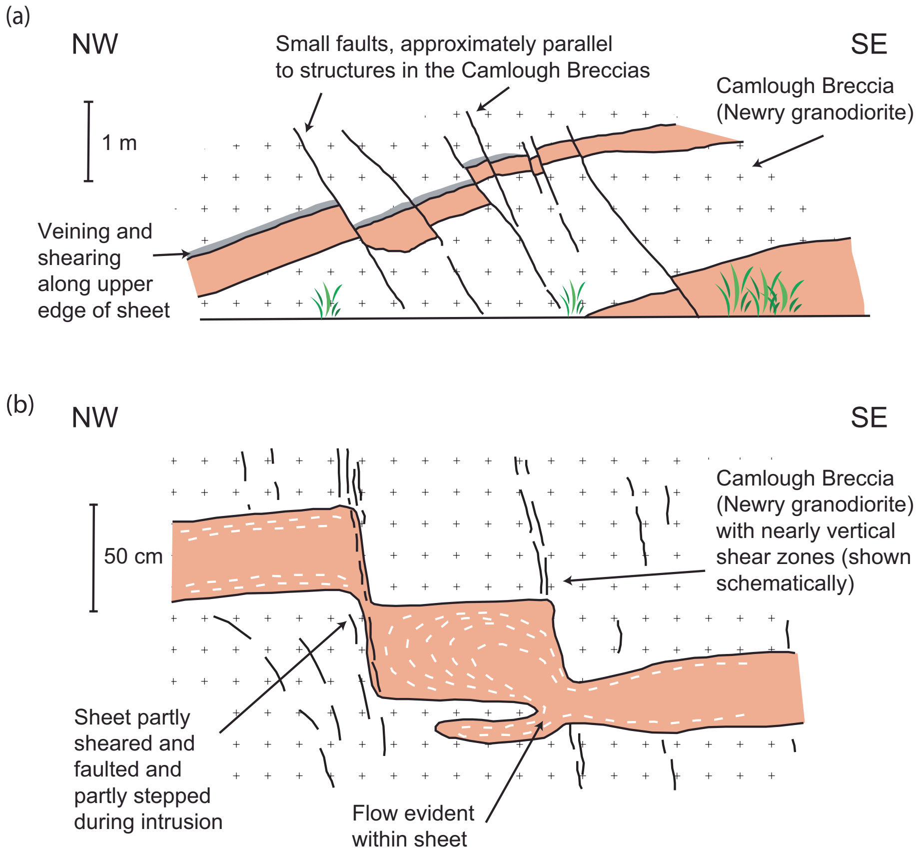

Fig. 8. (**a**) Sketch of locality *c.* 300 m ESE of Garvagh Lough [H 9887 2445] where thin flat-lying rhyolite sheets intrude Camlough Breccias (Table 2, xi). The sheets are cut by thin dark veins, which show some displacement (downthrown to the south). (**b**) Flow lines indicate movement from the main body of porphyritic microgranite towards the brecciated granodiorite. The offsets in the sheets appear partly to be steps in the intrusion and partly fault movement on the veins.

granodiorite close to the contact; these are stepped along a few steeply inclined fractures, across which they may also show minor fault displacement (Fig. 8). Flow structures in the sheets indicate that they were fed from a source towards the porphyritic microgranite. This locality encapsulates the sequence of events commonly found along the outer contact: initial intense veining and deformation affected the Newry granodiorite at and near to the ring-fault, followed by intrusion of the porphyritic microgranite, with a recurrence of veining, brecciation and induration, again concentrated on and near the fault contacts where the fine-grained, chilled porphyritic microgranite may be heavily overprinted by veining. Finally, continued intrusion of microgranite and rhyolite into the ring-fault was accompanied by further minor faulting and veining. These intrusions have probably fed explosive fissure eruptions and silicic dome complexes along the surface expression of the ring-fault (see Holohan *et al*. 2008).

Fine-grained, chilled porphyritic microgranite is exposed in sharp, generally steeply dipping contact with Camlough Breccias or unbrecciated Newry granodiorite and the porphyritic microgranite is generally finer-grained close to the inner margin of the ring-dyke whether or not the contact is exposed (e.g.Table 2, iii). Exposed contacts occur at several localities on the inner contact on the NW of the ring-dyke (Table 2, i, ii and iv), the NE (Table 2, vi, vii and viii) and in Cam Lough quarry (Table 2, x), which we view as a primary igneous contact affected by broad diffuse zones of high-temperature shattering, tuffisite veining and associated small-scale deformation (Figs 6 and 9).

Evidence of subsidence within the ring-fault is provided by rafts of basalt and trachyte lavas in the Forkill Breccias, which are compatible with foundering within a caldera. Elsewhere, in the north and NW of the ring-complex, central subsidence is also indicated by several occurrences of Silurian metasedimentary rocks along the inner contact of the ring-complex (Figs 1 and 3) and, notably at Cam Lough quarry, which exposes a contact between Silurian metasedimentary rocks and the southwestern part of the Caledonian Newry Igneous Complex (Cooper & Johnston 2004*a*) as well as the inner contact of the Slieve Gullion Ring-complex (Fig. 9; Table 2, x). In this area, the outer contact of the Palaeozoic Newry Igneous Complex is over 1 km north of the quarry, which implies significant downthrow within the ring-fault (see Cooper & Johnston 2004*b*, fig. 5.1), even when allowing for the possible sheeted character of this contact (e.g. Reynolds 1944).

Discussion

Field relationships

We agree with Stevenson *et al*. (2008, p. 174) that the outer contact of the Slieve Gullion Ring-complex is generally faulted, commonly with intense brecciation and induration. We argue, however, that these features are comparable with some of those displayed by ‘caldera superfaults’ undergoing contemporaneous magma injection (see Kokelaar 2007; Troll *et al*. 2008). Central subsidence on the ring-fault is supported by the preservation within the ring-complex of relics of the contact between the southwestern pluton of the Newry Igneous Complex and Silurian metasedimentary rocks and of fragments of Palaeogene lava flows (Figs 1 and 3). Evidence from intrusive contacts and the presence of a central xenolithic zone clearly indicates that for much of its circumference the porphyritic microgranite is a steep-sided, arcuate dyke-like intrusion. There are numerous examples of apparently faulted contacts, especially on the outer edge of the ring-dyke (Fig. 3), but even here the

Fig. 9. Steeply dipping contact at Cam Lough quarry (Table 2, x), showing porphyritic microgranite intruding the Silurian metasedimentary country rocks, looking NE. The contact dips at *c*. 65° north. Inset shows the brecciated and sheared fine-grained marginal porphyritic microgranite (top) directly at the contact with fragmental sedimentary rocks.

porphyritic microgranite is generally the fine-grained marginal facies. Furthermore, at the outer margins, fine-grained intrusive, slightly faulted and veined microgranite and rhyolite sheets associated with the porphyritic microgranite intrude intensely brecciated Newry granodiorite within the Camlough Breccias.

The Camlough Breccias are a key element in deciphering the development of the ring-complex. The breccias are best developed in Newry granodiorite and Silurian metasedimentary rocks close to or on the outer margin of the ring-complex, and some of the deformation demonstrably predates the earliest members of the ring-complex. Brecciation and veining, locally severe, is also typically, but not exclusively, present in porphyritic microgranite along and near its outer contact, where veins and stringers of brecciated rock are common. Significantly, the porphyritic microgranite involved in breccias near the faulted contacts is similar to fine-grained porphyritic microgranite close to proven intrusive contacts elsewhere, a feature more compatible with faulting of a steep-dipping dyke, rather than a flat-lying or gently domed sheet, which might be expected to juxtapose unchilled porphyritic microgranite and country rocks. West of Cam Lough, there is a steep, central zone characterized by numerous rounded silicic inclusions (Fig. 3). This zone, together with the ring-dyke away from the outer contact, is largely free from veins and deformation, indicating that the inclusion-bearing zone is in its original steep orientation. Dykes and veins of porphyritic microgranite and associated silicic rocks intruding country rocks, including early Camlough Breccias, may also exhibit minor veins and faults, although this is noticeably less than that found in the rocks they cut (Fig. 8). The Camlough Breccias thus provide a record of prolonged, if intermittent, activity on the ring-fault spanning the life of the Slieve Gullion Ring-complex. It is the nature of this activity that now requires consideration. On initial examination, the rocks may be identified as crushed and faulted granodiorite or porphyritic microgranite and, hitherto, the emphasis has been on the undoubted evidence of cataclasis (Richey & Thomas 1932; Emeleus 1956; Stevenson *et al*. 2008). Indications that explosive gas action also contributed to breccia formation were, however, noted (Richey & Thomas 1932; Reynolds 1951). Stevenson *et al*. (2008) made the perceptive observation that the Camlough Breccias coincided with much of the high ground of the Ring of Gullion and it is clear that the veining and brecciation has resulted in induration of the country rocks, especially the Newry granodiorite, in contrast to the marked erosion along numerous later NNW–SSE-trending faults (e.g. Richey & Thomas 1932, plate 55; Emeleus 1962, plate 6). The growth of new minerals in the breccias, including amphibole, epidote, chlorite and sericitic mica, is a testament to the sealing role of heated gases and fluids that traversed the vein systems (*c*. 300 °C). In thin section, veins in the breccias contain variable amounts of comminuted quartz and feldspar, which often show strain shadows, sometimes accompanied by composite fragments derived from the Newry granodiorite (Fig. 6). Offsets may occur across veins but in many instances this is not so and the veins typically resemble tuffisite injections in which there has been new mineral growth (notably amphibole and epidote) at moderately elevated temperatures. The small veins and veinlets filled with fine-grained comminuted material found in the Camlough Breccias in the vicinity of the ring-fault are therefore classified here as tuffisites; that is, fragmental rock broken as a result of small-scale shear and local gas migration (see Troll *et al*. 2000; Donaldson *et al*. 2001; Tuffen *et al*. 2003; Tuffen & Dingwell 2005). We note that Stevenson *et al*. (2007, 2008) used this type of rock as an indication of pure brittle (i.e. non-volcanic) deformation (e.g. at Cam Lough quarry). In our view, these breccias bear a resemblance to crackle breccias in mineralized areas, displaying signs of hot deformation with small-scale transport only, and are confined to the immediate vicinity of the ring intrusion in all occurrences. They share all the textural criteria of tuffisites and the Camlough Breccias are thus considered to be a volcanic–plutonic phenomenon. This casts considerable doubt on several aspects of the interpretation by Stevenson *et al*. (2007, 2008).

The Camlough Breccias therefore record a complex history of events on the ring-fault, involving movement, cataclasis, tuffisite injection, gas migration and crystallization, similar to that accompanying pseudo-tachylite formation, although apparently not involving melting. Their development has been concentrated in the vicinity of and especially along the ring-fault and they are attributed to the combined effects of periodic movement on the fault and the escape, sometimes explosively, of gases from pulses of cooling and crystallizing rhyolitic magmas intruded into the ring-fault. Similar scenarios are envisaged elsewhere in the British Palaeogene Igneous Province; for example, in the Western and Eastern Red Hills Centres, Skye (Bell 1966; J. D. Bell, pers. comm.), where veins and brecciation are concentrated along commonly steep, inter-granite contacts and may be accompanied by wholesale explosive fragmentation (Wager *et al*. 1965). The close association between the Camlough Breccias, faulting and silicic magmatism also has parallels with the Palaeozoic Glencoe complex, where it is postulated that rapid subsidence on a caldera fault resulted in the explosive release of superheated water from fractures along the irregular fault surface, the injection of a fault intrusion and veining of the shattered surroundings (Kokelaar & Moore 2006; Kokelaar 2007).

Although the intense tuffisite veining, brittle deformation and displacement characteristics of the Camlough Breccias occur throughout the circumference of the ring-complex, their greatest development is in the western half (Fig. 1), indicating possible asymmetric central subsidence (Richey & Thomas 1932) or trapdoor subsidence (McDonnell *et al*. 2004). The intermittent movements recorded in the breccias may reflect progressive depletion of the magma chamber, with successive injections of porphyritic microgranite accompanied by progressively diminishing deformation and explosive gas release: the central zone of inclusion-bearing porphyritic microgranite is practically free from veining and on Feede Mountain brecciated and veined porphyritic microgranite has been intruded by undeformed porphyritic microgranite (Richey & Thomas 1932).

The porphyritic rhyolite, in turn, presents some initially puzzling features. There is only minor evidence that it was affected by the Camlough Breccias, yet it is either coeval with or slightly predates emplacement of the porphyritic microgranite (Emeleus 1962; McDonnell *et al*. 2004; Stevenson *et al*. 2008). A likely explanation is that any late movement on the SW quadrant of the ring-fault was concentrated along its extreme outer edge beyond the limit of any intrusion, consistent with trapdoor subsidence (McDonnell *et al*. 2004). We agree with Stevenson *et al*. (2008) that the porphyritic rhyolite is not a complete ring-dyke, only the Carrive (or Outer) Felsite is dyke-like. Nevertheless, at the present exposure level it is wholly intrusive, forming a vent-swarm of generally steeply inclined ignimbritic sheets, small plugs and other irregular bodies that cut the Forkill Breccias and are strung out along the SW quadrant of the ring-complex. These fill the gap where the porphyritic microgranite is either absent or poorly represented and we contend that both were fed from sources located along the ring-fault. The intrusive contacts with the Forkill Breccias exhibit features that suggest that the latter may have been poorly consolidated. The breccias have been regarded as vent agglomerates and attributed to explosive action following degassing of silicic magma (Richey & Thomas 1932; Emeleus 1962), raising the possibility that early extensive degassing and ignimbrite eruption depleted the magma and its volatile constituents along this part of the ring-dyke, leaving little magma available for subsequent intrusion, as evidenced by the thin, impersistent development of the porphyritic microgranite in the SW quadrant. The suggestion that the Forkill Breccias (or at least a portion of them) resulted from debris flows within a caldera (Stevenson *et al*. 2008) is attractive and merits further investigation (see Troll *et al*. 2000; Brown *et al*. 2009; Holohan *et al*. 2009).

A subaerial versus an intrusive origin for the porphyritic rhyolite has long been a matter of debate (e.g. Reynolds 1951, 1956; Emeleus 1962; Bell & Emeleus 1988). Stevenson *et al*. (2008) proposed the porphyritic rhyolite to be a rheomorphic surface ignimbrite deposit and part of the 'vent agglomerate' to represent a caldera infill breccia (very similar to a model proposed for Rum by Troll *et al*. (2000)). Despite our best efforts to identify criteria to distinguish between a subaerial versus an intrusive origin for these rocks, we could not positively identify the porphyritic rhyolite as a surface deposit (see McDonnell *et al*. 2004). Stevenson and co-workers largely based their interpretation on locally flat-lying welding fabrics. However, internal fabrics are insufficient criteria for identifying a subaerial deposit. Moreover, it is puzzling why a central feeder is envisaged for the porphyritic rhyolite, despite the strong evidence for dyke-like bodies in the outer fringe of the ring (e.g. at Forkill, Ravensdale and Carrive Grove; Tables 1 and 2). Although it seems that many ignimbrite feeder conduits have indeed steep foliations, this is not a prerequisite *per se*. Rather, folding may occur owing to backflow of material in a conduit, creating what looks like rheomorphic flow. This model would be consistent with strongly folded and oxidized fragments of porphyritic rhyolite that occur in the clast-rich marginal breccia of the porphyritic rhyolite dyke in Forkill quarry. Hence, a whole subsurface history is preserved in these clasts from (1) initially fluid and ductile to (2) partly inflated, with (3) increasingly more viscous behaviour to produce tight 'rheomorphic' folding and (4) eventual ripping of the rock from its original emplacement location and incorporation as a 'brittle' fragment into the dyke. Folding in rhyolite is thus not 'uniquely a surface feature' and may equally reflect viscous magma movement at depth (for example, from partly degassed portions of magma near the conduit walls (e.g. Tuffen *et al*. 2003; Kennedy *et al*. 2008)), hence increasing the variety of contact phenomena between the component parts of the intrusive suite (see below). Stevenson *et al*. (2008, p. 177) suggested that the shallow-lying magnetic fabrics have probably formed by flattening. This, they argued, is inconsistent with a 'passive' ring-dyke style of emplacement and more reflective of a flat(ish) sill top. We argue that the opening cavities in a ring-fracture, or a subsurface cauldron, will initially draw magma and gas into the fractures (e.g. Menand & Phillips 2007). There, magma will begin to vesiculate owing to decompression. When limited by cavity walls (for example, in the flat roof of a subsurface cauldron or in ring-faults near the surface (e.g. Walter & Troll 2001)), various degrees of flattening will unavoidably be imposed on the magma–gas mixture (see Wolff 1985; Sparks *et al*. 1999).

On the balance of evidence, the idea that the porphyritic rhyolite represents a surface deposit remains, in our view, unsubstantiated. We envisage an environment in the top few tens to hundreds of metres below the former land surface reflecting a caldera-fault hosted intrusive vent complex, broadly in line with previous suggestions (Richey & Thomas 1932; Emeleus 1962; McDonnell *et al*. 2004). In respect to the Forkill Breccias, a subsurface origin of fragmental rocks is equally conceivable and does not require subaerial deposition (see Kennedy *et al*. 2008); however, a surface origin for parts of these breccias cannot be excluded (see Troll *et al*. 2000; Holohan *et al*. 2009).

Petrology and geochemistry

Stevenson *et al*. (2008) made several observations on the relationships between the porphyritic rhyolite and the porphyritic microgranite west of Mullaghbane and concluded that the presence of some brittle relationships implies that the two magmas were not contemporaneous, but that the rhyolite was already solid when the later porphyritic microgranite intruded. This ignores the liquid–liquid relationships previously described (Fig. 4; see also Table 2, xix, and McDonnell *et al*. 2004, p. 169) as well as earlier observations on the significance of the apparently brittle relationships (Emeleus 1962). It is well known that progressive magma mixing with a considerable temperature contrast between the two mixing end-members will produce early chilling of enclaves that can then break in brittle fashion during later stages of vigorous mixing (e.g. Wiesmaier *et al*. 2011, and references therein). Subsequently, as the component magmas approach thermal equilibrium, fluid–fluid relationships may be preserved. Hence, brittle and fluid–fluid contacts are not mutually exclusive, but would be expected together in a rock suite that underwent progressive magma mixing over some period of time (see Gamble 1979; Eichelberger 1980; Arana *et al*. 1994; Coombs *et al*. 2003; Troll *et al*. 2004, 2005; Wiesmaier *et al*. 2011). The convincing lobate contacts shown in Figure 4 lead us to conclude that the two end-members display mixing that occurred partly in a liquid–liquid fashion and partly in a brittle–liquid fashion, depending on the state of solidification of the two magmas when intruded (McDonnell *et al*. 2004). Brittle deformation is but part of the story and to use it to support a significantly later age of the porphyritic microgranite is unjustified. A full assessment of textures recorded is rather more consistent with a complex history of magma mixing and mingling ranging from liquid–liquid to liquid–solid, reflecting progressive mixing and disintegration of two end-member magmas in a common conduit (see Freundt & Schminke 1992; Coombs *et al*. 2003; Kennedy & Stix 2003; Troll *et al*. 2004, 2005).

Moreover, the discussion on 'vertical versus lateral' emplacement offered by Stevenson *et al*. (2008) overlooks some important geochemical features. They acknowledged that the two component magmas (porphyritic rhyolite and porphyritic microgranite) are 'compositionally almost identical' (Emeleus 1962; Stevenson *et al*. 2008, p. 181), an observation that has been used in previous papers to imply a genetic link between the two magmas (McDonnell *et al*. 2004; Troll *et al*. 2005). Troll *et al*. (2005) showed that compositional groups overlap and both record a history of early contamination by Silurian metasedimentary rocks, followed by contamination with Newry granodiorite in the upper crust (Fig. 3; Troll *et al*. 2005). The Stevenson *et al*. (2008) model suggests that the rhyolites erupted centrally and hence contamination by Newry granodiorite is conceivable. The SW pluton of the Caledonian Newry Igneous Complex coincides with the Slieve Gullion Centre (Fig. 1a) and a structural relationship between the two has been inferred. The Newry Igneous Complex extends beyond the Slieve Gullion Ring-complex only to the NE (the Caledonian trend), and there is no evidence for any other contemporaneous Palaeocene intrusive centre in that sector. Thus, the source for any laterally moving magma must have been located in the present-day Carlingford area and the adjacent offshore domains to the east and SE (Reay 2004; Stevenson *et al*. 2007, 2008). A magma that would start its lateral journey in this part of the crust, however, will not come into contact with Newry granodiorite until it actually reaches the Slieve Gullion Centre. A lateral sheet travelling this route would therefore have minimal contact time with this crustal rock-type and would be unlikely to result in a contamination signature that is equally intense to that of a magma that has risen through this rock type in a semi-vertical fashion (see Geldmacher *et al*. 2002; Meade *et al*. 2009). Moreover, there are Newry granodiorite xenoliths in the Ravensdale area of the ring-complex that are overgrown by plagioclase feldspar (Troll *et al*. 2008), pointing towards considerable interaction time between the microgranite magma and the granodiorite country rocks. This is most plausible if the microgranite magma rose in a semi-vertical fashion through the Newry granodiorite (or experienced lateral transport from the NE). As the compositions of the two end-member magmas constituting the Slieve Gullion Ring-complex are virtually identical, and as magma almost identical in appearance to the porphyritic microgranite was already available during emplacement of the porphyritic rhyolite, as evidenced by clasts in the Forkill dyke (McDonnell *et al*. 2004), the semi-vertical ascent hypothesis is far more compelling. A geographically (and geologically) distinct origin for two 'virtually identical' end-member magma types, on the other hand, appears unjustified. Significantly, Slieve Gullion is the site of major magnetic and positive Bouguer gravity anomalies (Cook & Murphy 1952; Reay 2004), indicating that the area is underlain by a large body of dense (mafic?) rock, similar to those anomalies identified beneath central igneous complexes elsewhere in the British Palaeogene Igneous Province (e.g. Rum and Skye; Emeleus & Bell 2005). This concealed mafic body was the heat engine that drove the Palaeocene magmatism, sourcing the magmas responsible for the gabbro and dolerite intrusions and generating the silicic rocks through fractionation of basaltic magmas, melting of Silurian metasedimentary rocks and partial melting of Newry granodiorite (see Gamble 1979; Troll *et al*. 2004, 2005).

Summary and concluding remarks

Field, petrographic and geochemical evidence from the porphyritic rhyolite and porphyritic microgranite members of the Slieve Gullion Ring-complex broadly supports the original contention by Richey & Thomas (1932) that this is a classic ring-dyke complex. During the Palaeocene, a large body of mafic magma was intruded into the southwestern granodiorite pluton of the Palaeozoic Newry Igneous Complex, generating silicic magma by fractionation of basaltic magma combined with the melting and partial melting of Newry granodiorite and Silurian metasedimentary rocks. The ring-complex was initiated when ring-faulting occurred above this silicic magma system, resulting in caldera subsidence accompanied by shattering of the faulted rocks through friction and gas action during the initial stages of formation of the Camlough Breccias, representing the combined products of cataclastic shattering and tuffisite injection. Explosive release of gases from rising silicic magmas may have generated the Forkill Breccias, as envisaged by Richey (1932) and Emeleus (1962). However, from their general characteristics and close association with foundered masses of basalt and trachyte lavas it is possible that these breccias are in part subaerial in origin. Silicic magma ascending the ring-fault underwent degassing and turbulent disintegration as it cooled and crystallized, causing the widespread distribution of small fragments of country-rocks throughout the porphyritic rhyolite, some fragmentation of phenocrysts, and vesiculation of the magma. Ignimbrite invaded the near-surface Forkill Breccias in a swarm of small dykes, plugs and steep-sided sheets, utilizing the southwestern part of the ring-fault. Emplacement may have been close to the contemporary surface, as evidenced by the pervasive veining of Forkill Breccias by porphyritic rhyolite, but final movement was at least locally in a highly viscous state (see Sparks *et al*. 1999), as recorded by distorted fiamme and shattered and strained phenocrysts found close to some intrusive contacts. The arcuate porphyritic microgranite is closely related to the porphyritic rhyolite (McDonnell *et al*. 2004; Troll *et al*. 2005) but appears to have had a magmatic history during which it became thoroughly mixed with basaltic magma, relics of which are scattered through the intrusion as small mafic enclaves (Emeleus 1962; Troll *et al*. 2008). Further mixing, with silicic material, took part in a restricted portion of the magma chamber, producing the rounded silicic inclusions occupying a central zone in the porphyritic microgranite. The occurrence and distribution of these inclusions lends further weight to the suggestion that there was compositional zoning in the magma chamber (McDonnell *et al*. 2004; Troll *et al*. 2005). Emplacement of the porphyritic microgranite overlapped with the porphyritic rhyolite and was accompanied by further movement on the ring-fault, which acted as a pathway for the silicic magma and the continued explosive release of exsolving gases, cataclasis and tuffisite injection. The preservation of steep, intrusive inner and outer contacts and the presence of Silurian metasedimentary rocks within the ring-complex, the petrographic evidence from porphyritic microgranite and Camlough Breccias in the outer contact zone, the disposition of the central xenolithic zone, and outcrop of the porphyritic microgranite east of Cam Lough all support that the interpretation by Richey & Thomas (1932) of the porphyritic granite as a classic ring-dyke is, in principle, correct. The ring-fault was the focus for movement and the explosive release of magmatic gases acted as a pathway followed by ascending silicic magmas in a complex series of overlapping intrusive and faulting events (Table 3). The non-magmatic textural features noted by Stevenson *et al*. (2008, fig. 14) were most probably imprinted during the latest movements, whereas the faint, discordant magmatic fabrics found by

Table 3. *Events in the evolution of the Slieve Gullion ring-dyke*

1	Generation of silicic magma following the emplacement at *c*. 60 Ma of a large body of mafic magma beneath the SW end of the Caledonian Newry Igneous Complex. The silicic magma comprises contributions from fractionation of the mafic magma and from melting of the country rocks (Silurian metasedimentary rocks and Caledonian granodiorite (Troll *et al*. 2005)
2	Ring-fracturing above the silicic magma, with movement on the fracture accompanied by penetrative, explosive release of gases giving the first phase of the Camlough Breccias, together with variable crystallization of the magma, which evolved to give slightly differing facies (McDonnell *et al*. 2004) and some of which mingled with still-liquid basaltic magma forming hybrid clots found in the porphyritic microgranite
3	Rapid rise of silicic magma in the SW quadrant of the ring-fault, accompanying or following central subsidence, with shattering of country rocks to give the Forkill Breccias (with rafts of pre-existing Palaeocene basaltic and trachytic lavas and gabbro plugs) and intrusion of the poorly consolidated, near-surface breccias by a plexus of ignimbritic sheets, dykes and plugs of porphyritic rhyolite, formed during violent, penetrative degassing of rapidly crystallized vent magma
4	Continued movement on the ring-fault and the sometimes explosive escape of gases was accompanied by intrusion of partially crystallized magma to give porphyritic microgranite along all but part of the SW quadrant. Emplacement of the microgranite overlapped or rapidly followed porphyritic rhyolite intrusion and tapped successively feldspar- and quartz-phyric magma containing numerous hybrid mafic clots and numerous non-porphyritic microgranite inclusions. The inclusions were probably in semi-solid, deformable state when emplaced; they occur in a central zone in the NW part of the porphyritic microgranite
5	The intrusion of small sheets and dykes of non-porphyritic or sparsely porphyritic microgranite post-dated nearly all the movement and gas release on the ring-fault and marked conclusion of the associated silicic magmatism
6	At a later stage, but probably also at about 60 Ma, the sparsely porphyritic microgranite ('Lislea granophyre') and other members of the Slieve Gullion Sheeted Complex were emplaced

those workers could well reflect turbulent conditions during emplacement of the porphyritic microgranite, as has been envisaged in the Ossippe Mountains Ring-complex (Kennedy & Stix 2007), and may have involved trapdoor subsidence (McDonnell *et al*. 2004). The steep solid-state fabrics recorded in the NE of the ring-dyke most probably resulted from late-stage compaction along steep-sided ring-dyke walls. The flat-lying signature of the AMS in the broad eastern part most probably originated from compaction during the latest stages of solidification and cooling in the transition from the steep to shallow parts of a partly bell-jar shaped intrusion. The magma would have released substantial amounts of gas at that stage and would have behaved as a viscous (rheomorphic) mass remaining in the vent(s) after the eruptive pressure had declined (see Sparks *et al*. 1999; Troll *et al*. 2000).

Instead of reinterpreting the Slieve Gullion Ring-complex in an entirely new fashion, we may rather need to broaden our concept of ring-dyke emplacement from Richey's original ideas to what has recently been learned from exposed ring-centres, active caldera volcanoes and experimental and numerical simulations (e.g. Saunders 2001, 2005; Walter & Troll 2001; Tuffen *et al*. 2003; Kennedy & Stix 2007; Kennedy *et al*. 2008; Holohan *et al*. 2008, 2009). Although we welcome the renewed interest in the Slieve Gullion Ring-complex, we remain to be convinced that a radical reinterpretation is required or justified. Although there may be several aspects that are viewed differently in the light of the modern volcanology, the broad concept of a caldera-related ring-fault and vent system remains our favoured emplacement model for the Slieve Gullion Ring-complex.

We are indebted to the Ulster Museum and the Geological Survey of Northern Ireland, respectively the custodians of J. E. Richey's and C.H.E.'s original 6 inch field sheets, for making these freely available, and to J. Gamble and the late J. Preston for providing access to unpublished large-scale maps. J. D. Bell kindly made available unpublished aspects of his work on Western Red Hills Granites, Skye, and we thank B. R. Bell for the information about the Eastern Red Hills. M. Price (Oxford University Natural History Museum) is thanked for making samples available. This work was supported by Science Foundation Ireland (SFI), Trinity College Dublin (TCD) and the Irish Research Council for Science and Technology (IRCSET). The helpful comments of B. R. Bell and an anonymous referee are gratefully acknowledged.

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Received 30 March 2011; revised typescript accepted 5 November
Scientific editing by Erdin Bozkurt.

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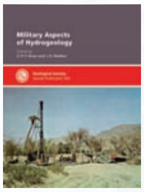

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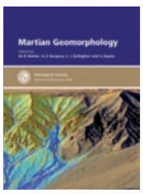

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