A NEW EXPOSURE OF A CALDERA FAULT SEGMENT AT THE SLIEVE GULLION IGNEOUS CENTRE: IMPLICATIONS FOR THE EMPLACEMENT OF THE EARLY RING-COMPLEX

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Abstract

A contact zone between porphyritic microgranite of the early ring-complex of the Paleocene Slieve Gullion igneous centre and Lower Palaeozoic metasedimentary rocks of the Longford–Down inlier was exposed along a 300m section excavated during construction of the new M1 motorway. The outcrop displays a thin sliver of Longford–Down metasediment in contact with porphyritic microgranite in a steep, and locally intensely crushed, contact zone that dips away from the ring-complex. This outcrop pattern is reminiscent of a 'caldera-superfault'. Given the recent discussion on sheet versus ring-dyke emplacement of the early ring-complex at Slieve Gullion, this new evidence argues in favour of the traditional ring-dyke model with magma ascending along an active ring fracture associated with caldera subsidence.

Introduction

We report on a new outcrop section along the M1 motorway at Ravensdale, Co. Louth, about 8km north of Dundalk (Location IJ 07981 14632; see Fig. 1). This section was exposed in May 2007 and was accessible prior to opening of the motorway (2 August 2007) for a limited period. It is unclear at the time of writing if the outcrop will remain exposed, but there is a possibility it may be covered by steel mesh to increase slope stability at a later date (D. Murphy, *pers. comm.*, see www.siac.ie, last verified 24 November 2008). The section was inspected on 24, 27 June and 16 July 2007.

The outcrop extends for approximately 300m on a 6–7m high, steeply inclined (70°) rock-face orientated almost perfectly N–S. A schematic section is illustrated in Fig. 2. At the southern end of this section, a thick body of porphyritic, feldspar-rich, microgranite crops out. It closely resembles the 'Porphyritic Granophyre' of the early ring-dyke of Richey and Thomas (1932) and Emeleus (1962), but is much fresher in appearance. Additionally, zoned phenocrysts are seen in both Richey's 'Porphyritic Microgranite' (see plate 34B and accompanying text in Emeleus 1957) and the porphyritic microgranite exposed here. A contact zone between Longford–Down metasediment and microgranite is exposed further north along the section and is locally intensely crushed. This damage zone extends for more than 2m into both lithologies, indicating a major fault at this junction. This discovery is significant for the current discussion on the emplacement of the early Slieve Gullion ring-complex. In this discussion, the classic ring-dyke interpretation (Richey and Thomas 1932; Emeleus 1962; McDonnell *et al.* 2004) is challenged by a model based on a combination of anisotropy of magnetic susceptibility (AMS) measurements and field data (Stevenson *et al.* 2008). These authors suggest the early ring-complex represents a flat-lying, laterally extensive sheet, which was subsequently domed by the emplacement of the central layered intrusion resulting in a ring-like outcrop pattern. Our new evidence cannot easily be reconciled with this model.

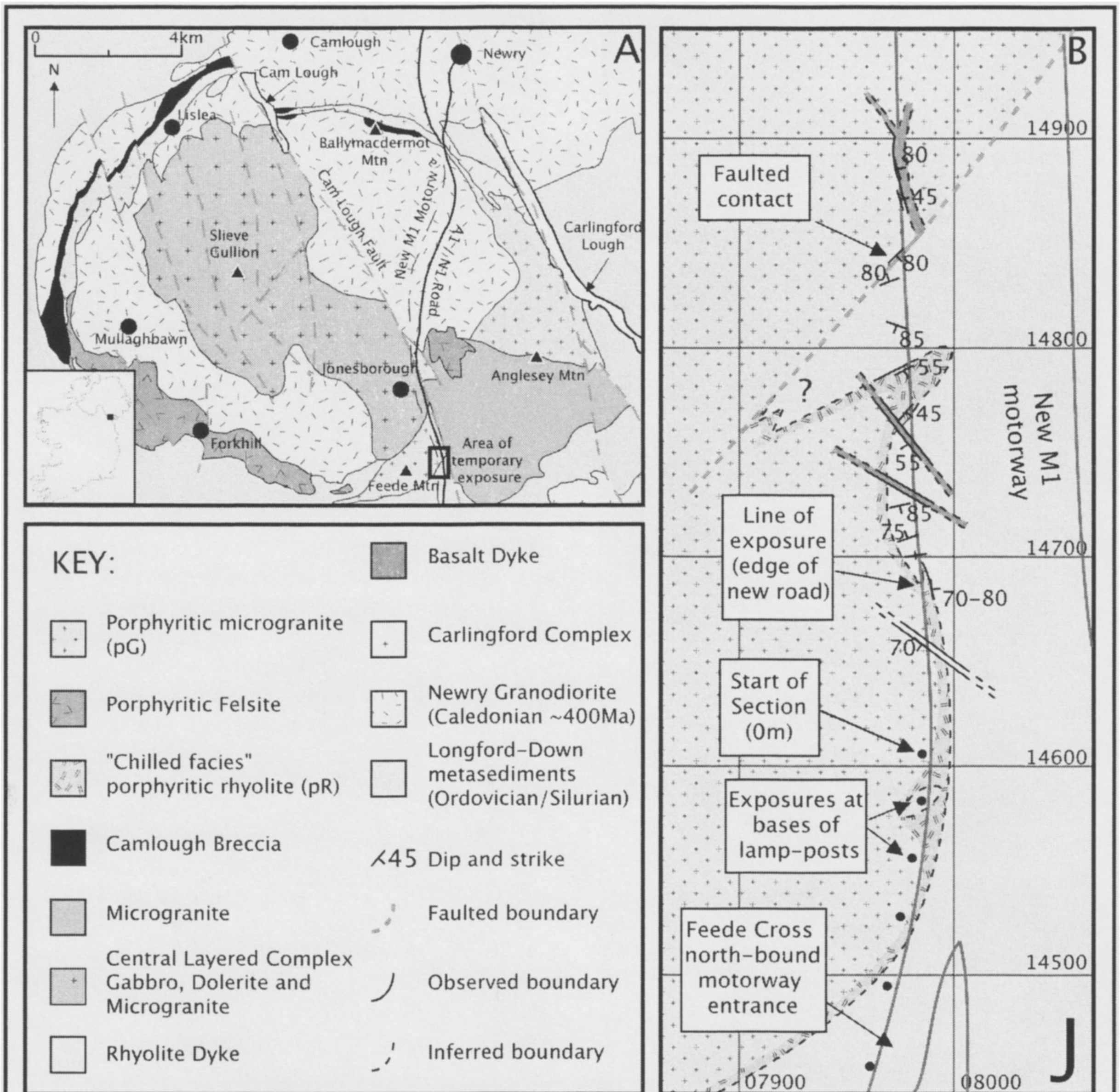


Fig. 1—Maps of the Slieve Gullion igneous centre. (A) Generalised geology of the Slieve Gullion centre after Cooper and Johnston (2004), showing region of new exposure at Feede Mountain (indicated by a black box); (B) Detailed map of the Feede Mountain exposure. Irish National Gridlines at 100m spacing are shown. *For colour versions of these maps and figures, see the PDF of this paper at www.ria.ie/publications*

Description of exposure

The engineering staff of Siac (see www.siac.ie) informed us that explosives were used at a minimum of 2m away from the currently exposed rock-face. More than twenty oriented and non-oriented samples were taken along the section and a representative set of 28 rock samples has been deposited in the collection of the Geological Museum at Trinity College Dublin (Catalogue numbers P19127 to P19154).

At the start of the section (IJ 07981 14632), labelled 0m in Figure 2, pinkish-grey porphyritic microgranite (pG) contains potassium feldspar and plagioclase phenocrysts 3–15mm in size. The feldspars show strong zonation, often with pink potassium feldspar cores and white plagioclase rims or *vice versa*. Similarly zoned feldspars are commonly found elsewhere in the porphyritic microgranite ring-dyke (see Plate 34B in Emeleus (1957) and Troll *et al.* (2005)). Phenocrysts are less obvious on fresh surfaces, but are very prominent on weathered and/or fracture surfaces. Dark green and grey mylonitic tuffisite bands are present, and small mafic enclaves of up to 5cm across, often with embayed, lobate contacts, occur. Tuffisite is defined herein as a

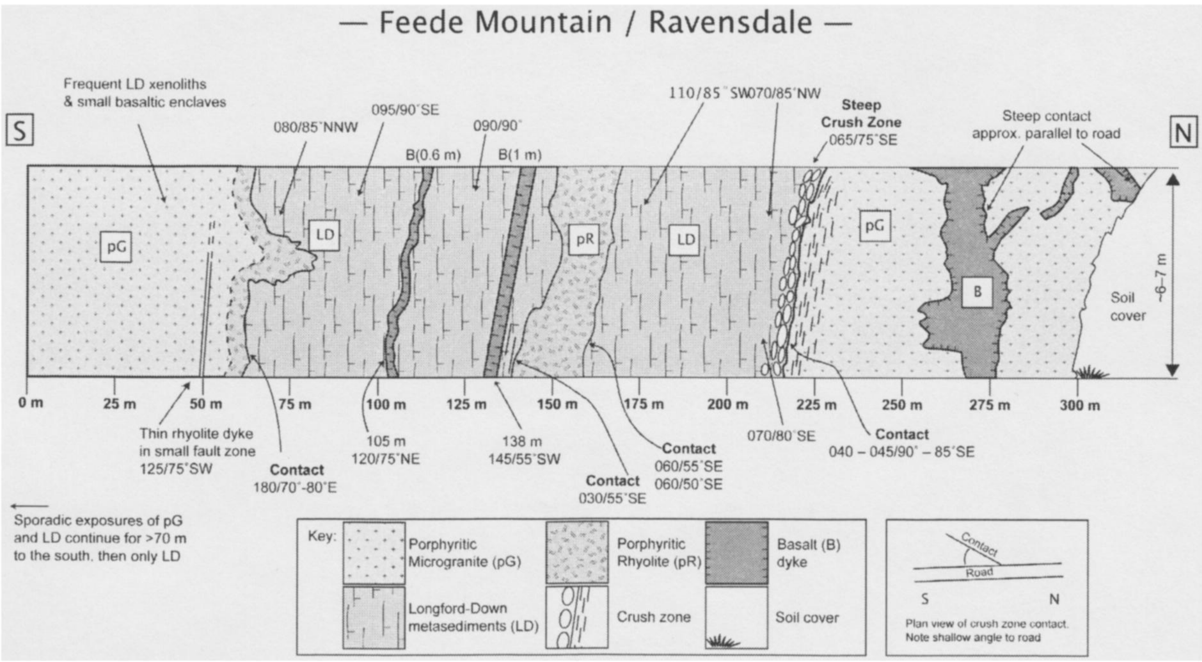


Fig. 2—Schematic log of the newly exposed road section at Feede Mountain.

rock resulting from fracturing of viscous magma with material being transported and deposited by a migrating fluid phase, such as magmatic volatiles (see Figs 3 and 4 specifically Figs 3a,b; 4a).

Before the start of the logged section, south of '0m' (Fig. 1), small exposures were revealed at the bases of six lamp-posts, which were subsequently covered by topsoil. Lamp-posts numbers 1 (at '0m'), 3 and 4 all exhibited porphyritic microgranite, while lamp-posts numbers 2, 5 and 6 exposed Longford–Down metasedimentary rock. The distance between each lamppost is approximately 35m.

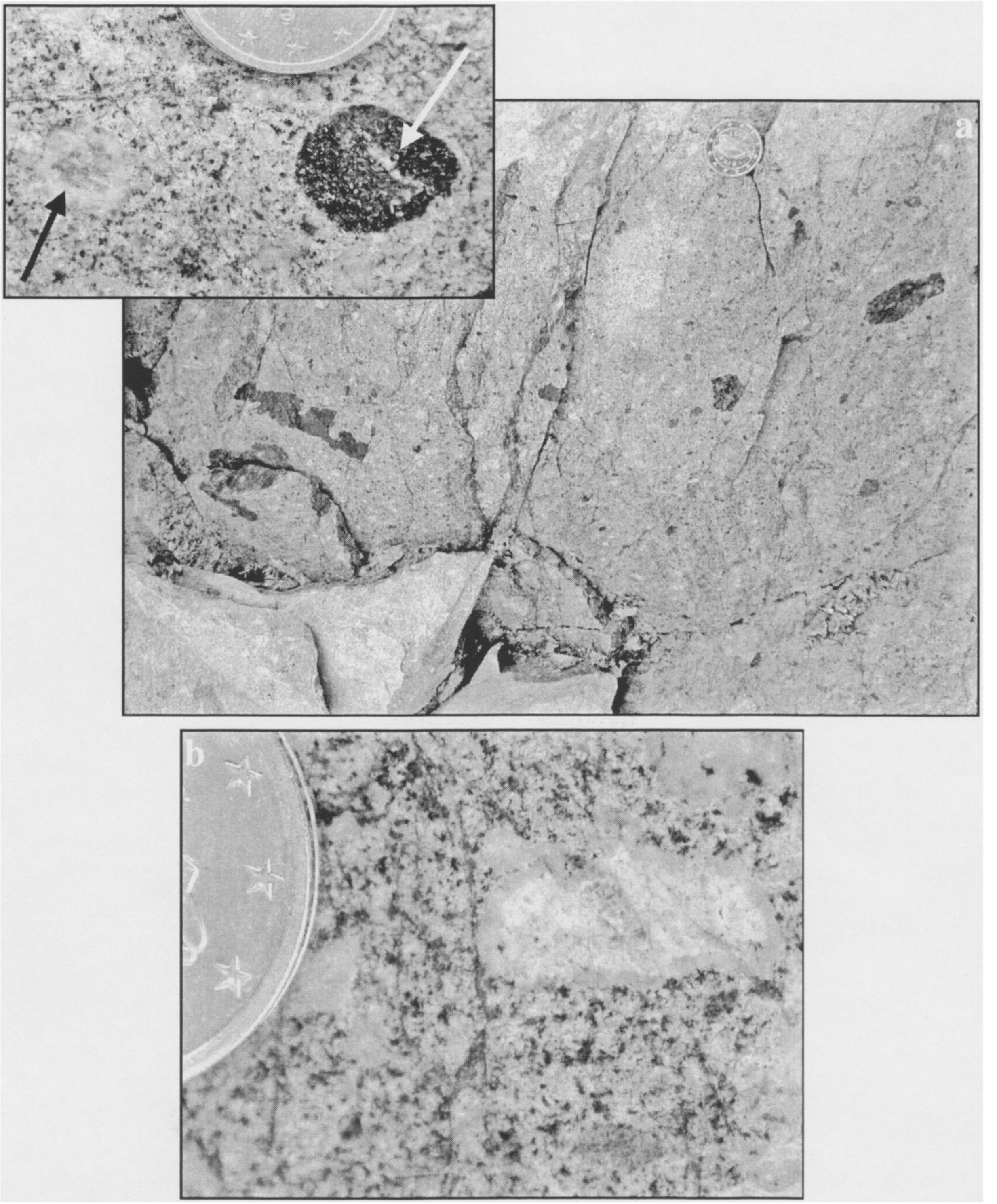
At 21m, the pG is slightly darker in appearance and contains a higher proportion of plagioclase phenocrysts together with small mafic enclaves. Xenoliths of metasedimentary rock are also present, ranging in size from 1–10cm.

At 35m, the outcrop of pG with elongate mafic enclaves and occasional tuffisite bands continues. Small xenoliths (1–3cm) of Newry Granodiorite are common, with some of the xenoliths displaying pink potassium-feldspar or white plagioclase rims (e.g. Fig. 3h).

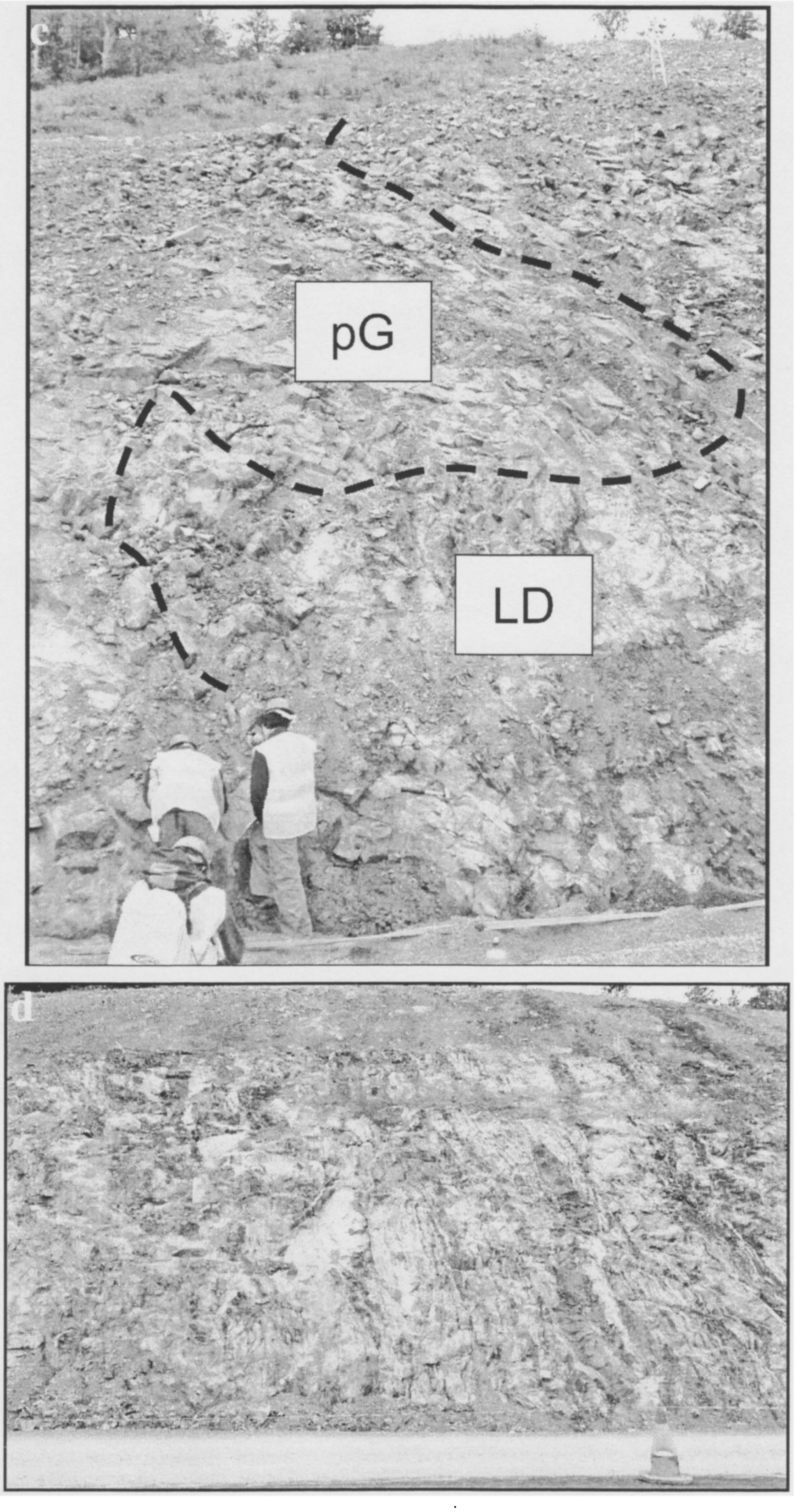
At 50m (IJ 07976 14686) a thin rhyolite dyke with orientation 125/075° SW cuts the porphyritic microgranite (Fig. 2). The porphyritic microgranite once again has potassium-feldspar cores with plagioclase rims, but the reverse of this zoning pattern also occurs. The phenocrysts are up to 15mm across. Zoning is visible with the naked eye and the modal content of phenocrysts is between 30–40%. No obvious crystal alignment was detected. Tuffisite veins are present again, as are small basaltic enclaves up to several cm in length (Fig. 4b). Crystal transfer, whereby phenocrysts from microgranite have migrated into the mafic enclaves, is frequently observed.

At 63m (IJ 07986 14688), the first major contact of granophyre with Longford–Down metasedimentary rock occurs (Fig. 2). To the south of the contact, a pG with abundant pink potassium feldspar and white plagioclase phenocrysts (up to 15mm in size) is encountered. Both zoning types are present in the feldspars and no clear alignment is obvious. Near the contact the groundmass of the microgranite becomes much more fine-grained, forming a chilled marginal facies of porphyritic rhyolite (pR). Abundant subangular fragments of metasedimentary rock are observed in the porphyritic microgranite. Locally, intense tuffisite veining occurs within the microgranite, and especially in the marginal rhyolite. The northern side of the contact shows Longford–Down metasediment with bedding orientation 080/90° to 85° NNW. The overall contact dips steeply (70–80°) to the east and strikes approximately parallel to the road (north–south), thus implying that the microgranite is actually lying behind a thin veneer of Longford–Down metasediment. A finger (protrusion) of microgranite (*c*. 2m wide) breaks through this veneer of Longford–Down metasediment about 3m above the road (Figs 2; 3c).

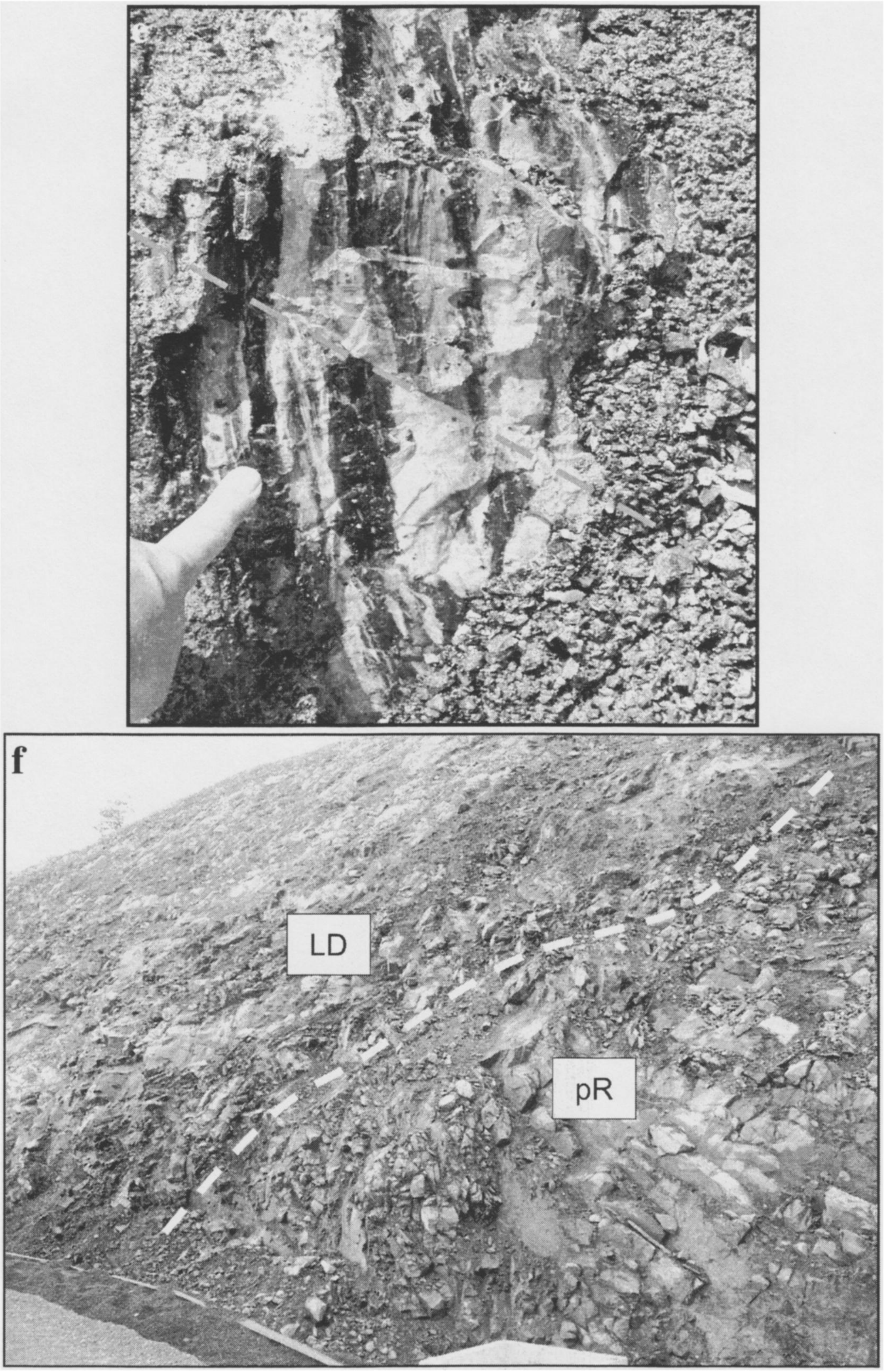
At 72m (IJ 07968 14699), the strike of the Longford–Down metasediments is 070/75° NW. The bedding



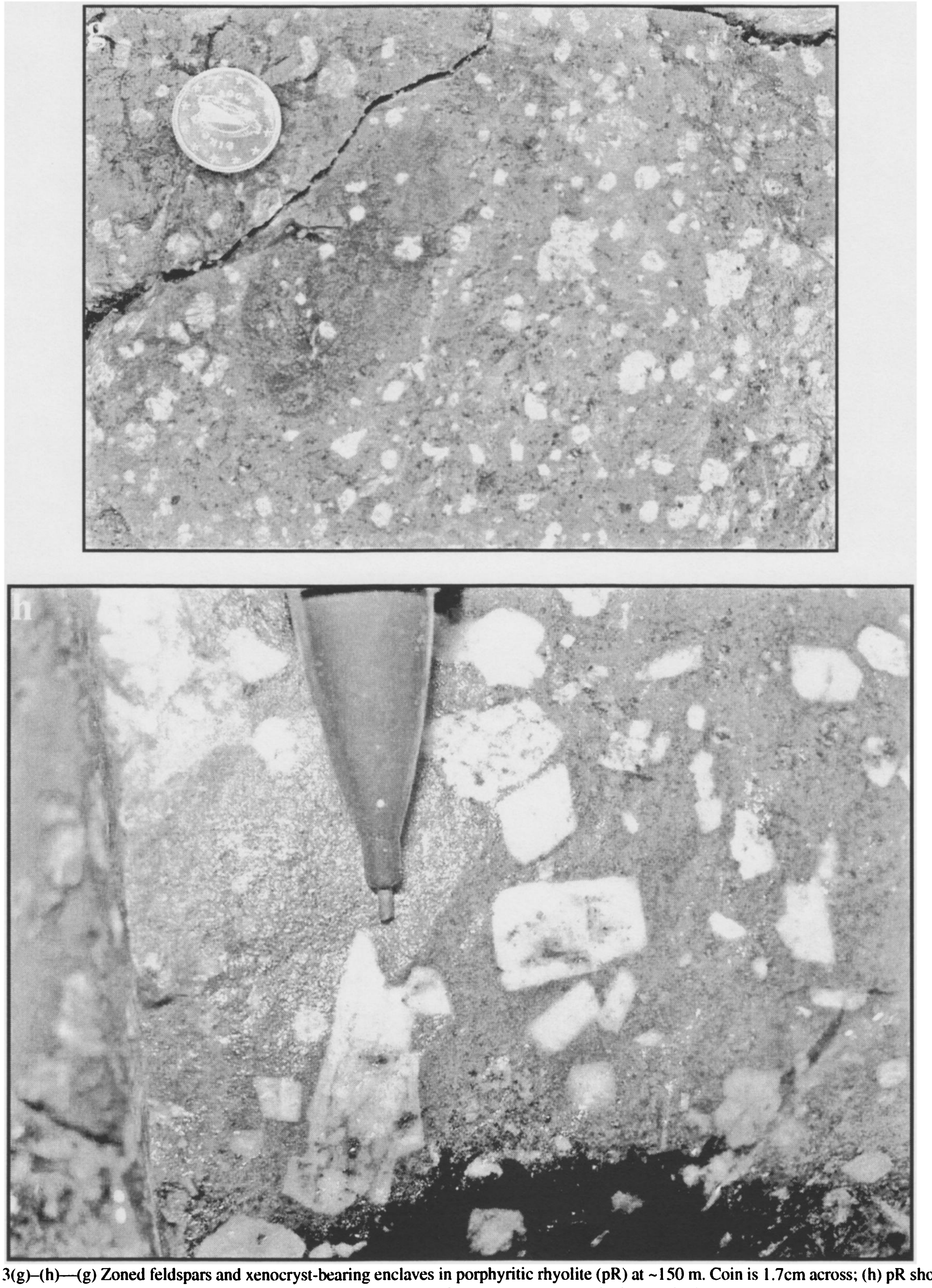
Figs 3(a)–(b)—(a) Mafic enclaves in porphyritic microgranite (pG). Coin is 2.5cm across *Inset:* Mafic enclave containing a xenolith of the microgranite (white arrow) and zoned feldspar within microgranite (indicated by a black arrow). Coin is 1.7cm across; (b) K-feldspar phenocryst with plagioclase rim in pG. Coin is 1.7cm across.



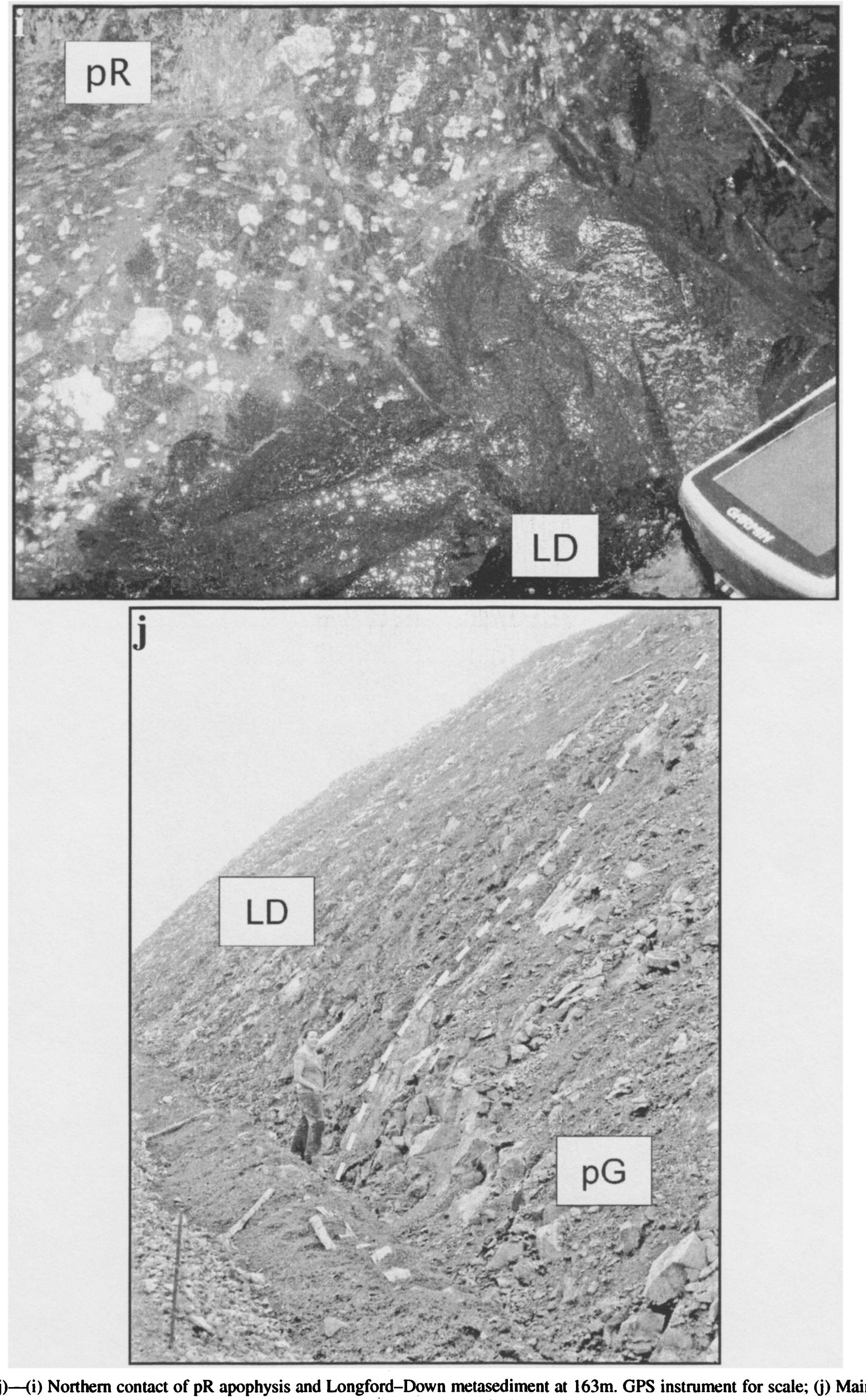
Figs 3(c)–(d)—(c) pG finger (protrusion) in Longford–Down metasediments at 63m; (d) Hornfelsed Longford–Down metasediments striking at approximately 90° to the road (at 63–140m).



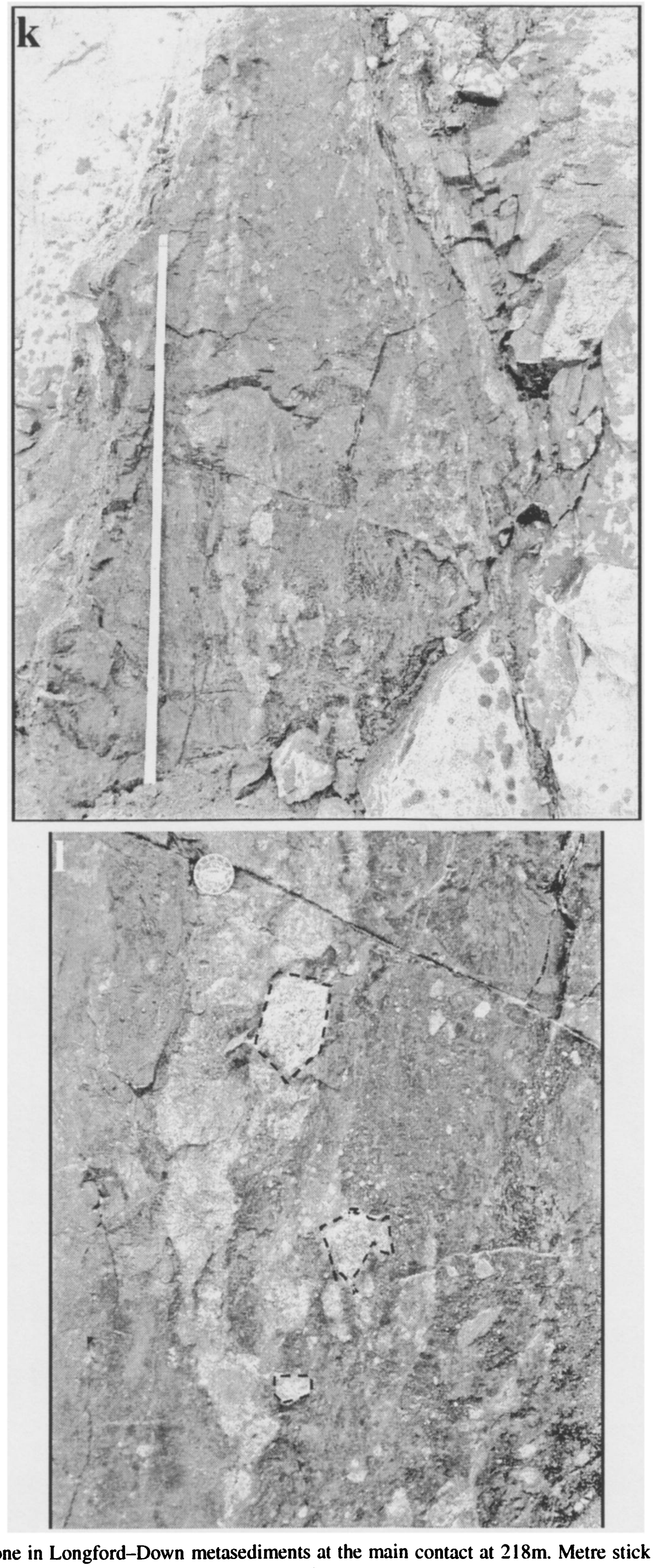
Figs 3(e)–(f)—(e) Micro-faulting in metasediments. Note the strong colouration in the bands, indicating high-temperature overprint (hornfelsing); (f) Southern contact between Longford–Down (LD) metasediments and porphyritic rhyolite (pR) apophysis at 145m.



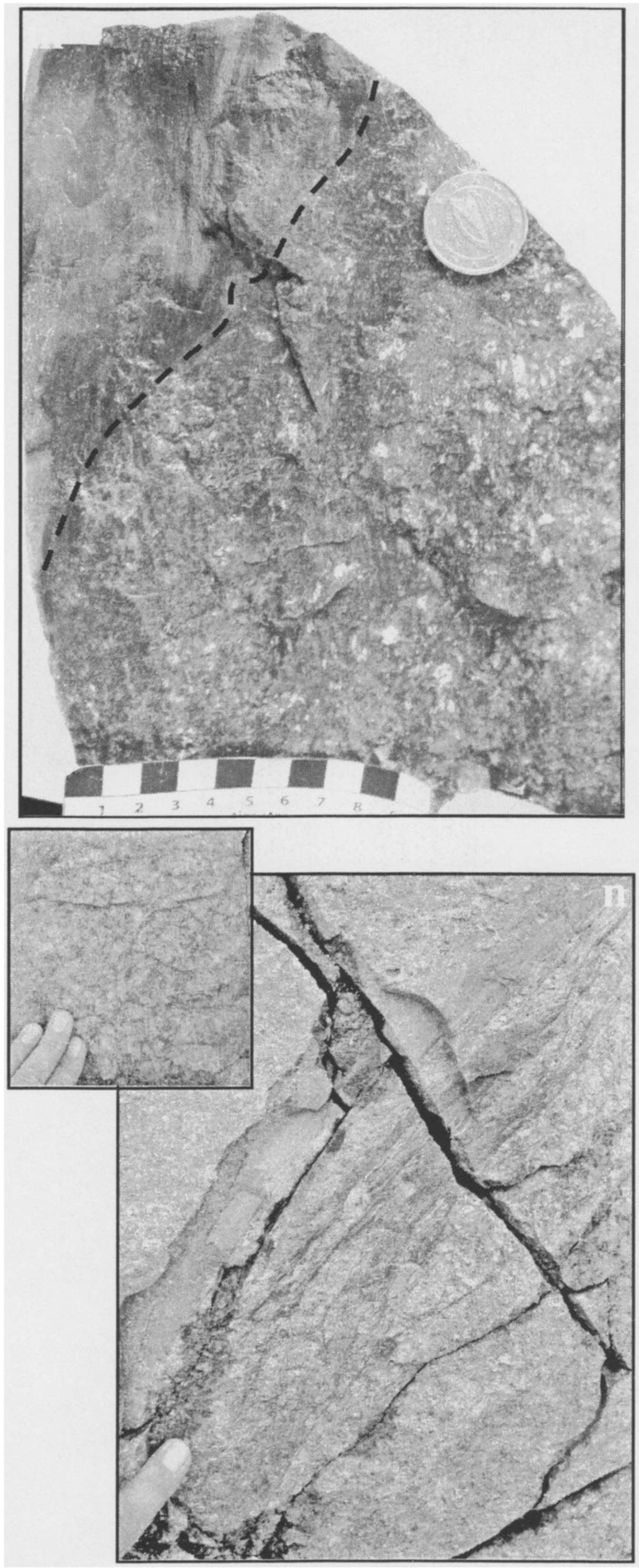
Figs 3(g)–(h)—(g) Zoned feldspars and xenocryst-bearing enclaves in porphyritic rhyolite (pR) at ~150 m. Coin is 1.7cm across; (h) pR showing zoned feldspars (e.g. below pencil tip) with Newry Granodiorite fragments as cores and with plagioclase overgrowth rims (e.g. also centre right).



Figs 3(i)–(j)—(i) Northern contact of pR apophysis and Longford–Down metasediment at 163m. GPS instrument for scale; (j) Main contact (at 218m) between LD metasediments and pG, which is steeply inclined and at its base dips at ~80° to the SE



Figs 3(k)–(l)—(k) Crushed zone in Longford–Down metasediments at the main contact at 218m. Metre stick for scale; (l) Crushed zone in Longford–Down metasediments at 217m, *c*. 1m south of contact (in damage zone). Note the presence of angular and strung-out igneous clasts mixed with metsedimentary fragments. Coin is 2.5cm across.



Figs 3(m)–(n)—(m) Crushed porphyritic microgranite at 218m contact. Note the very small grain-size and the absence of unbroken zoned phenocrysts and enclaves, implying severe physical crushing and intermingling. Samples taken from 2m north of the contact show regular grain-size again. Coin is 2.5 cm across; (n) Wide and extensive mylonitic tuffisite veins in porphyritic microgranite near contact (~220m). *Inset:* locally pervasive tuffisite veins near contact (220m).

Figs 3(o)–(p)—(o) Contact of basaltic dyke with porphyritic microgranite at 276m. Notebook for scale; (p) Basaltic dyke at 270m, containing large angular porphyritic microgranite xenoliths, suggesting that dyke intrusion post-dates the solidification of the pG.

is locally highly irregular, but generally steep in dip. The metasedimentary rocks appear highly hornfelsed, showing intense green and black colouration, representing mineralogies rich in diopside and biotite, respectively (Figs 3d,e).

At 80m the overall orientation of bedding in metasediment is approximately 100/90°, and at 90m (IJ 07974 14726), the 'stripy' green and black metasediment is of similar orientation (095/90°). Irregular bands with microfractures, however, locally exhibit offsets of up to 10cm (Fig. 3e).

At 100m (IJ 07974 14740), the metasediment strikes 080/85–90° SE, consistent with the regional trend of the Longford–Down metasediments of about 060–070° (see Anderson 2004).

At 105m, a thin, near vertical but sinuous, basaltic dyke (0.6m wide) intrudes Longford–Down metasediment (Fig. 2). It trends approximately 120° with local dips of 75° NE. The dyke is feldspar-phyric with phenocryst-poor margins. The baked country-rock shows minor folding, but the general trend remains consistent.

At 136m (IJ 07977 14763), the metasediments strike approximately 090/90–80° SE. At 138m, another small basaltic dyke (about 1m wide) cuts through the metasediments and is inclined 145/55° SW.

High on the rock-face, at 145m (IJ 07969 14763), a contact is exposed between pR and a veneer of metasedimentary rock (see Fig. 2). The pR is again characterised by a significantly finer-grained groundmass than the pG. The contact is locally irregular, but has an overall orientation striking approximately 030–025° and dipping 55° SE (Fig. 3f).

At 155m (IJ 07968 14786), the pR still shows a finer-grained groundmass than the pG first encountered at 0m. Similar mafic enclaves occur, however, and the zoning is identical in the large phenocrysts of both the rhyolite and microgranite, suggesting that the two rock-types are closely related (Figs 3a,b,g,h; 4a,c). This hypothesis is supported by the similarity to the marginal fine-grained facies seen at 63m, suggesting that the pR lithology here at 155m represents a narrow microgranite apophysis that cooled quickly against the local country-rock.

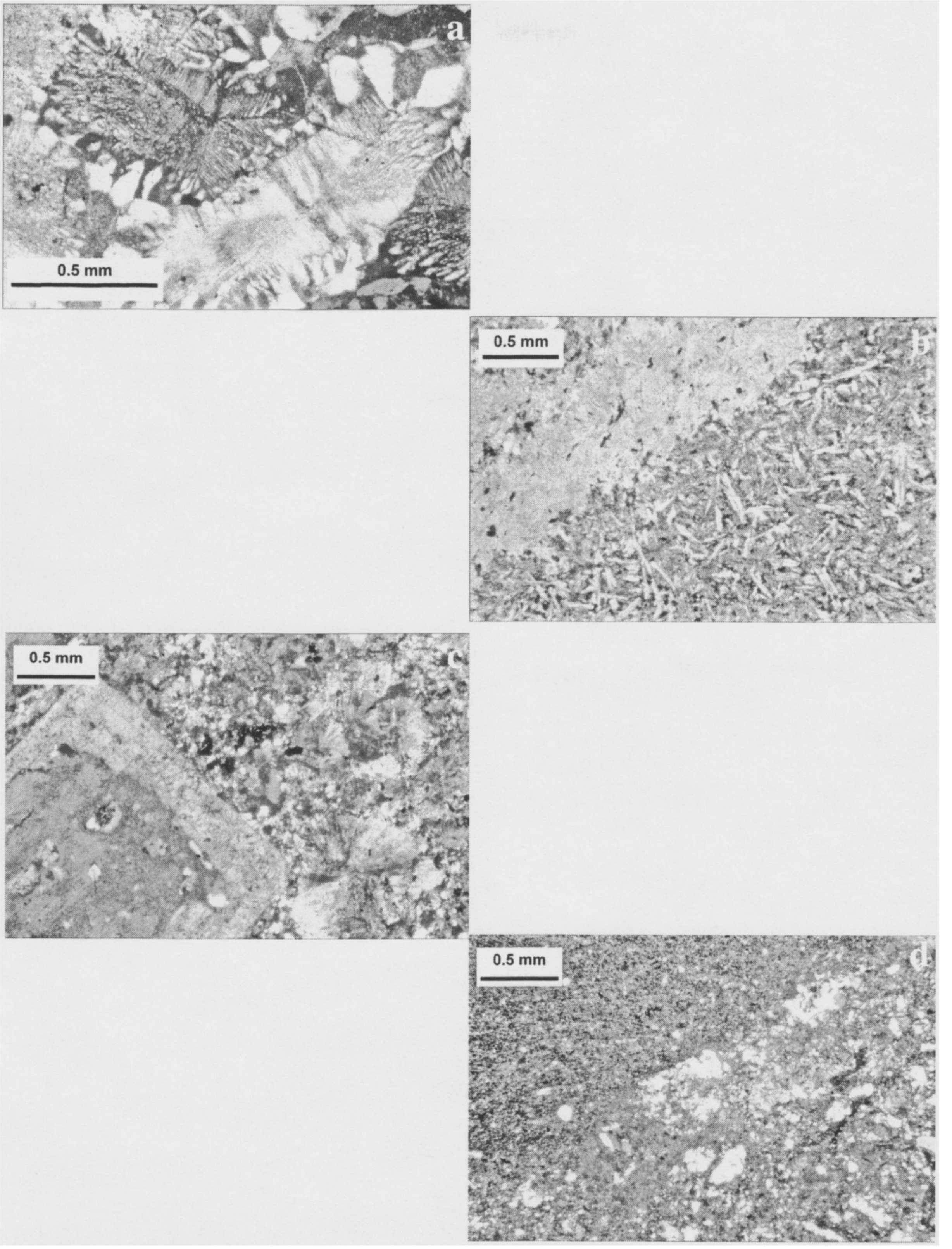
At 163m (IJ 07961 14809) another, locally irregular, contact of overall orientation 060/55° SE separates pR from the metasediments (Fig. 3i). This geometry supports the hypothesis that the finer-grained pR from 145–63m is indeed an offshoot, or apophysis, of the main body and is probably a chilled facies of the microgranite. The bedding in the Longford–Down metasediments on the northern side of this contact is 110/85° SW.

At 200m (IJ 07967 14836) metasediments show bedding orientations of 070/80° NW and at 215m (IJ 07965 14849), bedding in the metasediments is 070/90°.

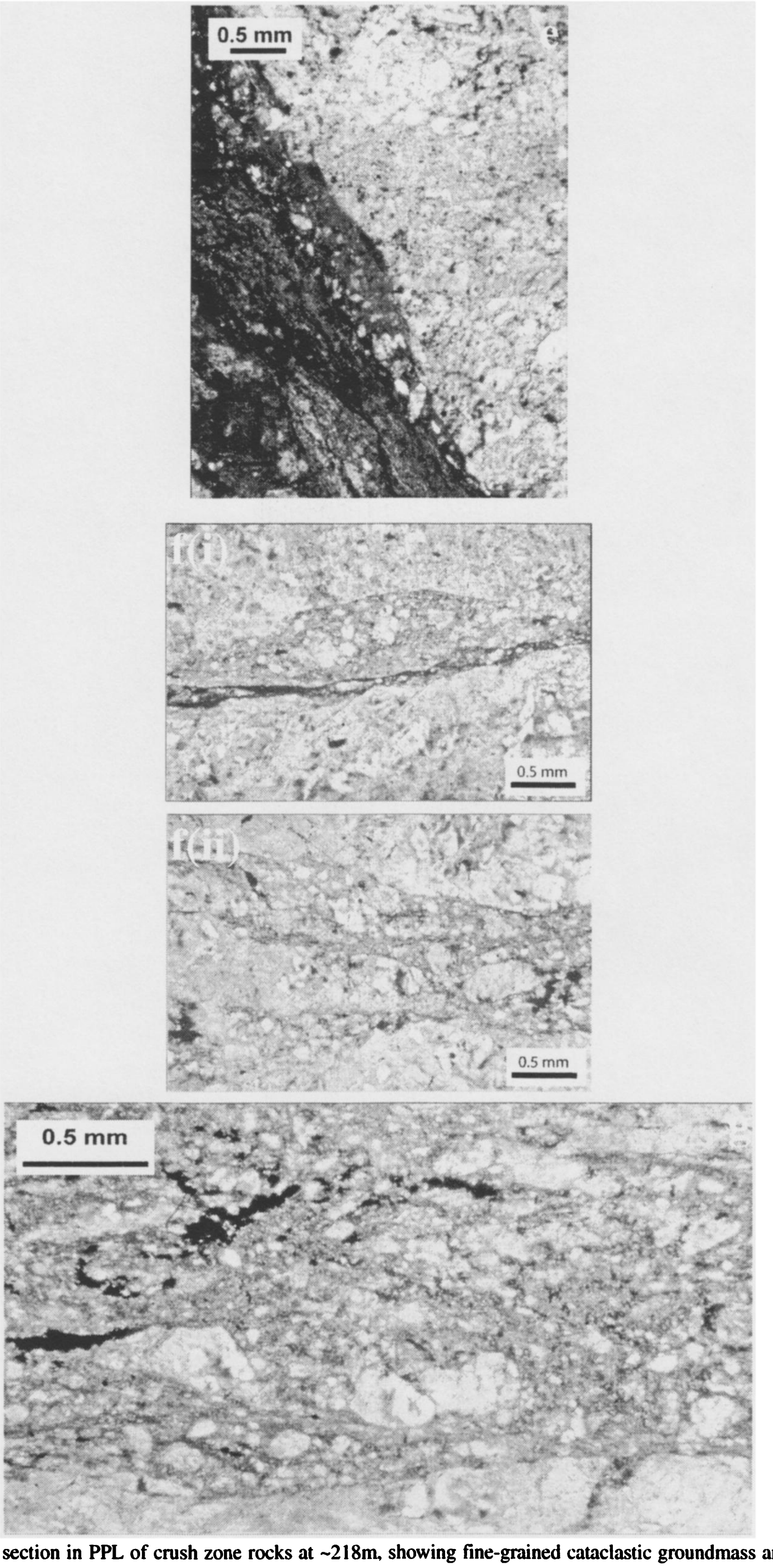
At 218m (IJ 07967 14850), a major contact is exposed between Longford–Down metasediments and pG, with an overall orientation of approximately 045/80–5° SE (Figs 2; 3j). Extensive brecciation in the metasediments close to this contact has led locally to a mixture of metasediment and igneous fragments (Figs 3k,l; 4d,e). The igneous clasts are frequently aligned in the crush zone in a plane that strikes approximately 055–065 and dips from 90–75° SE, thus broadly parallel to the contact in the core of the crush zone. On the northern side of the steep contact, pG is exposed but shows unusually small phenocrysts and no regular phenocryst zoning is visible (only relict fragments of zoned crystals), suggesting extensive shearing and crushing in the pG as well (Fig. 3m). Crystal size in the pG increases again (to a maximum phenocryst size of ~ 20mm) approximately 2m from the core of the crush zone, indicating a damage zone of about 5m in total width. Mafic enclaves are present several metres north of the contact, but they are conspicuously absent close to the contact, supporting intense physical mingling and shearing of highly viscous magma in the crush zone. Numerous mylonitic tuffisite and cataclastic veins are present in the damage zone (Figs 3n; 4f,g), reaching thicknesses of up to tens of centimetres, but also forming pervasive networks between thicker veins. Although irregular in nature, their overall trend is sub-vertical. These veins are similar to those considered characteristic for highly viscous flow regimes in steep to vertical conduits and silicic feeder dykes elsewhere (e.g. Tuffen *et al.* 2003, Tuffen and Dingwell 2005).

Between 258m and 278m, basalt is found in contact with pG. The steep contact dips towards the road and strikes approximately parallel to it (Fig. 3o). As a result, windows of microgranite appear through the basalt, which forms a veneer over the microgranite. At the base of the outcrop, both contacts of the basalt dyke can be observed, suggesting a feeder to the dyke up to 2m wide that flares out towards the top of the outcrop. A thin dykelet (0.3m) extends upward from the intrusion at its northern end. The main dyke also contains numerous angular xenoliths of microgranite from 20cm to 70cm across (Fig. 3p), which implies intrusion after the microgranite had solidified. The microgranite is again holocrystalline with abundant zoned feldspar phenocrysts up to 20mm across and a crystalline groundmass.

At 300m, the outcrop of pG is lost underneath a cover of soil that extends for the rest of the valley.



Figs 4(a)–(d)—(a) pG with granophyric texture at start of section (thin section in XPL); (b) Mafic enclave in porphyritic microgranite (thin section in PPL); (c) pR at offshoot (145m; thin section in XPL). Compare groundmass to that of the porphyritic microgranite (Fig. 4a.); (d) Crushing at contact in Longford–Down metasediments and porphyritic microgranite (at ~218m). (Thin section in XPL.) Compare grain size of the porphyritic microgranite (lower right) to that in Figs 4a,b.



Figs 4(e)–(g)—(e) Thin section in PPL of crush zone rocks at ~218m, showing fine-grained cataclastic groundmass and igneous fragments; (f(i,ii)) Mylonitic tuffisite veins at contact (220m) in porphyritic microgranite (thin section in PPL); (g) Pervasive tuffisite veining with cataclastic crushing in damage zone near main contact (~218m; thin section in PPL). Note smeared our mafic enclave.

Discussion

The Slieve Gullion igneous centre has been the subject of much research in the past 90 years, including work on the central Layered Complex (Reynolds 1951; Gamble 1979; Gamble *et al.* 1992) and the earlier ring-complex (Richey 1932; Richey and Thomas 1932; Emeleus 1962). A number of mechanisms for emplacement of the Slieve Gullion ring centre have been proposed, with Richey's ring-dyke model being widely accepted for most of the twentieth century (Richey 1932; Richey and Thomas 1932; Emeleus 1962). A recent reinvestigation by Stevenson *et al.* (2008), however, proposes a different mode of emplacement. These authors suggest that an early caldera-like volcanic vent complex was intruded by a sub-horizontal sheet of pG, prior to emplacement of the central layered intrusion. In this model, the layered intrusion is thought to have domed the pG sheet, causing preferential erosion of the central uplifted part of the sheet and resulting in a ring-like outcrop pattern. Although faulted outer contacts have been reported by Richey and Thomas (1932) and Emeleus (1962), Stevenson *et al.* (2008) point out that none are available for inspection at Slieve Gullion at present, depriving us of clear field relationships. Dyke-like bodies of porphyritic rhyolite and microgranite, however, are reported from the south-west of the ring-complex (e.g. north-east Glendesha and Forkhill Quarry, Emeleus 1962; McDonnell *et al.* 2004) and are likely to represent magma that ascended (in a partly fragmental fashion) through annular caldera-related conduit systems (see Walter and Troll 2001). Stevenson *et al.* (2008) regard these as accidental offshoots and do not consider them in detail in their paper. Moreover, steep-sided contacts of porphyritic granophyre that show intense crushing and evidence for multiple episodes of movement and injection were reported from Camlough Mountain to the north, Ballymacdermot Mountain to the north-east and Anglesey Mountain in the east–south-east of the complex (Richey and Thomas 1932). Referring to outcrops near Camlough Mountain and Ballymacdermot Mountain, Richey and Thomas (1932) state that it is 'self-evident that the granophyre (pG) hereabouts forms a dyke-like intrusion'.

The field evidence from this new outcrop records another marginal contact of the ring-complex's porphyritic microgranite, forming a steep crush zone (at 218m in Fig. 2) that curves along the outer margin of the ring intrusion (see Fig. 1). The curved nature of the contact was also mapped by Richey (1932) and Emeleus (1957). Richey's field maps (6" Louth 4NE) trace this SW–NE trending outer contact for *c.* 1km across the southern slopes of Feede Mountain, with the last exposure of porphyritic granophyre appearing ~100m west of the current exposure. The contact was then extrapolated across the main road at IJ 081 163. This is somewhat north of the current exposures, suggesting the contact may have been offset by one of the many NNW–SSE faults mapped in the area, probably the continuation of the Cam Lough Fault (Fig. 1). At this point the ring-dyke is also much wider than at any other point in its annular outcrop. This may in part be due to multiple intrusions (see Richey 1932), however, an oblique normal fault that has a downthrow to the east and some right-lateral movement would expose part of the flat-lying top of the intrusion, thus providing a wider exposure, as well as explaining the offsets seen along the Cam Lough Fault to the north-west of the centre. Richey also records a fine-grained chilled facies to the porphyritic microgranite near its contact with metasediments in this area, similar to that seen in our logged section.

The extensive crushing at the contact (at 218m in Fig. 2) is thus akin to descriptions from other localities at Slieve Gullion, though much more severe, (see Richey and Thomas 1932; Emeleus 1957, 1962), and also to other typical caldera-bounding ring-faults in classic caldera complexes such as Glencoe (Moore and Kokelaar 1997, 1998; Kokelaar and Moore 2006; Kokelaar 2007). Moreover, internal textures in the porphyritic microgranite are extremely similar to those reported from silicic feeder dykes from Iceland, showing abundant tuffisite and cataclastic veins that fill microfractures (see Tuffen *et al.* 2003; Tuffen and Dingwell 2005), thus building up an integrated picture of upward-directed caldera-related magma transport within Slieve Gullion's early ring-complex. As this new evidence is consistent with earlier descriptions of faulted outer contacts elsewhere by e.g. Richey (1932), and also, as dyke-like masses of 'ring-complex' rocks occur at several other locations (Emeleus 1962; McDonnell *et al.* 2004; Troll *et al.* 2005), we suggest that these features are probably typical of the ring's outer contact. These observations coupled with the new evidence presented here, strongly support the more traditional view of a ring-dyke and are not consistent with an extensive lateral sheet as proposed by Stevenson and co-workers. Although the emplacement mechanism is perhaps not exactly as originally envisaged by Richey and Thomas (see Richey and Thomas 1932; Walter and Troll 2001; McDonnell *et al.* 2004), our new field data show a striking resemblance with the key features of their ring-dyke model. New outcrop information, combined with modern views on caldera faulting and fissure flow, therefore creates a picture that supports the more traditional model of ring-dyke emplacement and accompanying caldera collapse, rather than the recent reinterpretation involving substantial lateral magma emplacement.

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References

Anderson, T.B. 2004 Southern Uplands–Down–Longford Terrane. In W.I. Mitchell (ed.), *The geology of Northern Ireland. our natural foundation*, 41–60. Belfast. Geological Survey of Northern Ireland.

Cooper, M.R. and Johnston, T.P. 2004 Palaeogene intrusive igneous rocks. In W.I. Mitchell (ed.), *The geology of Northern Ireland, our natural foundation*, 179–98. Belfast. Geological Survey of Northern Ireland.

Emeleus, C.H. 1957 Studies of the granophyres and related rocks of the Slieve Gullion Tertiary igneous complex, Ireland. Unpublished D. Phil thesis, University of Oxford.

Emeleus, C.H. 1962 The porphyritic felsite of the Tertiary ring-complex of Slieve Gullion, County Armagh. *Proceedings of the Royal Irish Academy* **62B**, 55–76.

Gamble, J.A. 1979 Some relationships between coexisting granitic and basaltic magmas and the genesis of hybrid rocks in the Tertiary central complex of Slieve Gullion, northeast Ireland. *Journal of Volcanology and Geothermal Research* **5**, 297–316.

Gamble, J.A., Meighan, I.G. and McCormick, A.G. 1992 The petrogenesis of Tertiary microgranites and granophyres from the Slieve Gullion central complex, NE Ireland. *Journal of the Geological Society of London* **149**, 93–106.

Kokelaar, P. 2007 Friction melting, catastrophic dilation and breccia formation along caldera superfaults. *Journal of the Geological Society of London* **164**, 751–4.

Kokelaar, B.P. and Moore, I.D. 2006 *Classic area of British geology: Glencoe caldera volcano, Scotland.* Keyworth, Notts. British Geological Survey.

McDonnell, S., Troll, V.R., Emeleus, C.H., Meighan, I.G., Brock, D. and Gould, R.J. 2004 Intrusive history of the Slieve Gullion ring dyke, Ireland: implications for the internal structure of silicic sub-caldera magma chambers. *Mineralogical Magazine* **68**, 725–38.

Moore, I. and Kokelaar, P. 1997 Tectonic influences in piecemeal caldera collapse at Glencoe Volcano, Scotland. *Journal of the Geological Society* **154**, 765–8.

Moore, I. and Kokelaar, P. 1998 Tectonically controlled piecemeal caldera collapse: a case study of Glencoe Volcano, Scotland. *Geological Society of America Bulletin* **110**, 1448–66.

Reynolds, D.L. 1951 The geology of Slieve Gullion, Foughill, and Carrickarnan: an actualistic interpretation of a Tertiary gabbro-granophyre complex. *Transactions of the Royal Society of Edinburgh* **62**, 85–143.

Richey, J.E. 1932 Tertiary ring-structures in Britain. *Transactions of the Geological Society of Glasgow* **19**, 42–140.

Richey, J.E. and Thomas, H.H. 1932 The Tertiary ring complex of Slieve Gullion, Ireland. *Quarterly Journal of the Geological Society of London* **88**, 653–88.

Stevenson, C.T.E., O'Driscoll, B., Holohan, E.P., Couchman, and Reavy, R.J. 2008 The structure, fabrics and AMS of the Slieve Gullion ring-complex, N. Ireland: testing the ring-dyke emplacement model. *Geological Society Special Publication* 302, 159–84.

Troll, V.R., Chadwick, J.P., Ellam, R.M., McDonnell, S., Emeleus, C.H. and Meighan, I.G. 2005 Sr and Nd isotope evidence for successive crustal contamination of Slieve Gullion ring-dyke magmas, Co. Armagh, Ireland. *Geological Magazine* **142**, 659–68.

Tuffen, H., Dingwell, D.B. and Pinkerton, H. 2003 Repeated fracture and healing of silicic magma generate flow banding and earthquakes? *Geology* **31**, 1089–92.

Tuffen, H. and Dingwell, D. 2005 Fault textures in volcanic conduits: evidence for seismic trigger mechanisms during silicic eruptions. *Bulletin of Volcanology* **67**, 370–87.

Walter, T.R. and Troll, V.R. 2001 Formation of caldera periphery faults, an experimental study. *Bulletin of Volcanology* **63**, 191–203.

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