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Zonation of the Newry Igneous Complex, Northern Ireland, based on geochemical and geophysical data

P.E. Anderson [a,*], M.R. Cooper [b], C.T. Stevenson [a], A.R. Hastie [a], M. Hoggett [a], J. Inman [a], I.G. Meighan [b,c,d], C. Hurley [e], R.J. Reavy [e], R.M. Ellam [c]

[a] School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK
[b] Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF, UK
[c] Scottish Universities Environmental Research Centre, Rankine Avenue, Scottish Enterprise Technology Park, East Kilbride, G75 0QF, UK
[d] School of Natural Sciences, Department of Geology, Trinity College, Dublin 2, Ireland
[e] School of Biological, Earth and Environmental Sciences, University College Cork, Cork, Ireland

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ABSTRACT

The Late Caledonian Newry Igneous Complex (NIC), Northern Ireland, comprises three largely granodioritic plutons, together with an intermediate–ultramafic body at its northeastern end. New whole-rock geochemical data, petrological classifications, and published data, including recent Tellus aeromagnetic and radiometric results, have been used to establish 15 distinct zones across the four bodies of the NIC. These become broadly younger to the southwest of the complex and toward the centres of individual plutons. In places, zones are defined by both current compositional data (geochemistry and petrology) and Tellus results. This is particularly clear at the eastern edge of the NIC, where a thorium-elevated airborne radiometric signature occurs alongside distinct concentrations of various elements from geochemistry. However, in the northeastern-most pluton of the NIC, a prominent ring-shaped aeromagnetic anomaly occurs independent of any observed surface compositional variation, and thus the zones in this area are defined by aeromagnetic data only. The origins of this and other aeromagnetic anomalies are as yet undetermined, although in places, these closely correspond to facies at the surface. The derived zonation for the NIC supports incremental emplacement of the complex as separate, distinct magma pulses. Each pulse is thought to have originated from the same fractionally crystallising source that periodically underwent mixing with more basic magma.

1. Introduction

The zonation of an igneous body represents the systematic change in composition, structure, or geophysical properties throughout the body (Cooper et al., in press; Richey, 1928; Schetselaar et al., 2000). Zonation can be gradational (Bowen, 1919; Exley, 1996) or expressed through more abrupt lithological changes (Hecht and Vigneresse, 1999; Kryza et al., 2014; Pitcher, 1997; Richey, 1928). In the latter case, the pluton can often be subdivided into distinct zones, which may reflect incremental emplacement via separate magma pulses. (Coleman et al., 2004; Farina et al., 2012; Hecht and Vigneresse, 1999; Lipman, 2007; Miller, 2008; Pitcher, 1997; Richey, 1928; Stevenson et al., 2007). Geochronological studies show that such plutons can be constructed over periods of several million years (Annen, 2011; Barboni et al., 2013, 2015; Matzel et al., 2006; Miller et al., 2011; Schoene et al., 2012).

Many studies demonstrate the success of using geophysical techniques to investigate zonation in igneous intrusions (Benn et al., 1999; Mishra, 2011; Petford et al., 2000; Schetselaar et al., 2000; Vigneresse, 1990). Of these, aeromagnetic and airborne radiometric surveying allows large areas to be covered and provide relatively shallow-penetrating signatures, which can often be correlated with surface geology. For example, Schetselaar et al. (2000) use aeromagnetic results to identify a previously undetected unit boundary within the Western Slave Granitoid in northeast Alberta.

Airbourne radiometric data usually record proportions of common isotopes of potassium, uranium, and thorium (^{40}K, ^{238}U, and ^{232}Th), which can be assumed to represent total proportions of the respective elements in the bedrock (e.g., Cook et al., 1996; Dempster et al., 2013; Grasty, 1975; Keaney et al., 2013; Martelet et al., 2006; Schetselaar et al., 2000). Unlike aeromagnetic results, these data relate to composition of only the uppermost several centimetres of the ground. Hence, the radiometric signature of an area will often yield concentrations of

* Corresponding author.
E-mail address: mark.cooper@detini.gov.uk (M.R. Cooper).

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the three elements within the local topsoil, although these concentrations usually correspond to the composition of the underlying bedrock (e.g., Cook et al., 1996; Martelet et al., 2006).

Here we provide new whole-rock geochemical and petrological data on the Newry Igneous Complex (NIC). This is examined alongside existing petrological, geochemical, aeromagnetic, radiometric, and geochronological data (Cooper et al., in press; Meighan and Neeson, 1979; Neeson, 1984; Reynolds, 1934, 1936, 1943) to provide a new detailed zonation for the NIC. This new zonation pattern will require a re-examination of the emplacement of the NIC. We outline possible emplacement implications and suggest relevant hypotheses.

2. Geological background

The Newry Igneous Complex (NIC) is a Devonian, exclusively I-type intrusion located in Northern Ireland (Fig. 1) (Cooper and Johnson, 2004a, 2004b; Cooper et al., in press; Meighan and Neeson, 1979). The NIC forms part of the Southern Uplands–Down–Longford Terrane associated with final closure of the Iapetus Ocean in the Late Silurian–Early Devonian (Anderson, 2004; Bluck, 1985; Brown et al., 2008; Leggett, 1987; Miles et al., 2013; Needham and Knipe, 1986). Broadly speaking, the NIC comprises three separate, largely granodioritic plutons (Meighan and Neeson, 1979; Neeson, 1984; Reynolds, 1934), which are referred to as the Rathfriland (northeast), Newry (central), and Cloghoge (southwest) plutons (Fig. 1) (Cooper et al., in press). The Rathfriland pluton hosts a Devonian intermediate–ultramafic body at its northeast margin (Cooper and Johnson, 2004a; Meighan and Neeson, 1979; Neeson, 1984; Reynolds, 1934, 1936), referred to as the Seeconnell Complex (Fig. 1) (Inman et al., 2012). Additionally, the Cloghoge pluton has been extensively intruded by a large Palaeogene subvolcanic complex, known as the Slieve Gullion Complex (Cooper and Johnson, 2004b; Neeson, 1984; Richey, 1928; Stevenson et al., 2007) (Fig. 1).

3. Previous work on the NIC

3.1. Composition

Previous petrological work shows that the NIC becomes generally more silicic to the southwest (Fig. 1) (Meighan and Neeson, 1979; Neeson, 1984; Reynolds, 1943). Individual plutons also display broad internal zoning. The Rathfriland pluton shows normal zoning, ranging in composition from an exterior composed of hornblende granodiorite to an interior composed of biotite granodiorite (Meighan and Neeson, 1979; Neeson, 1984) (Fig. 1). Normal zoning of the Cloghoge pluton is defined by a relatively abrupt change between an outer hornblende granodiorite and an inner (off-centre) felsic granodiorite (Neeson, 1984). In contrast, the Newry pluton shows reverse zoning, expressed by the occurrence of an outer biotite granodiorite and an inner hornblende granodiorite (Neeson, 1984) (Fig. 1).

3.2. Distinctive facies

3.2.1. Seeconnell Complex

The Seeconnell Complex represents a compositionally distinct body at the northeastern margin of the Rathfriland pluton (Meighan and

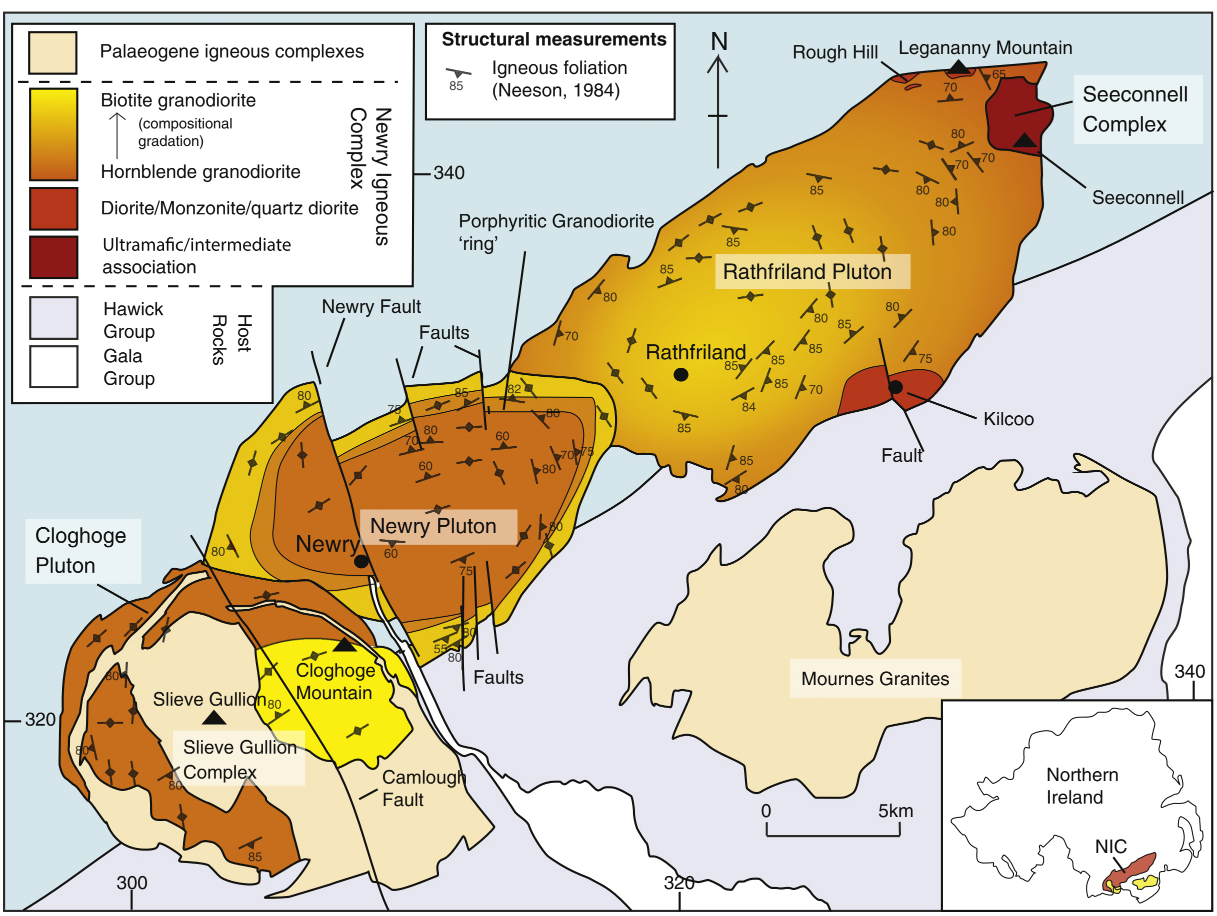
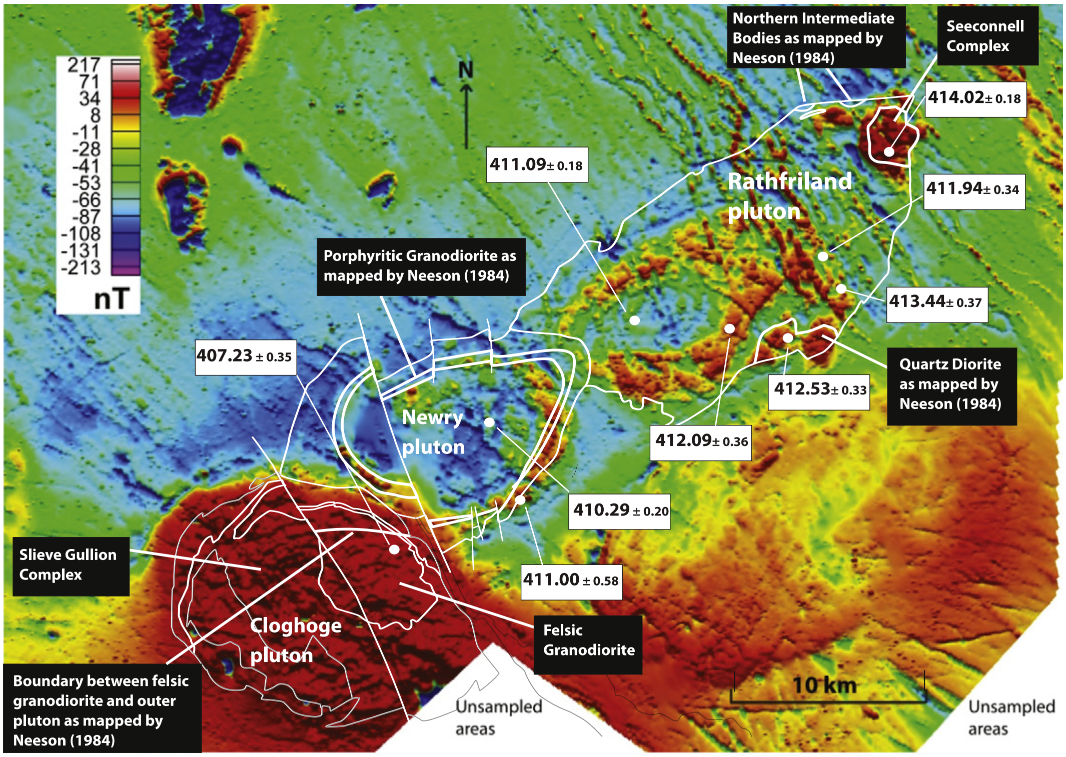


Fig. 1. Geology and internal structure of the NIC based on former work (GSNI, 1997; Neeson, 1984; Reynolds, 1934). Surrounding host rocks and other nearby intrusions are also shown.

Neeson, 1979; Reynolds, 1934) (Fig. 1). It is known to be cross-cut by the main part of the Rathfriland pluton (Neeson, 1984), and U–Pb geochronology shows that it is the oldest part of the NIC (Cooper et al., in press) (Fig. 2). The Seeconnell Complex contains a large and variable set of internal facies, consisting of two monzonites, diorite, meladiorite, and biotite pyroxenite (Meighan and Neeson,



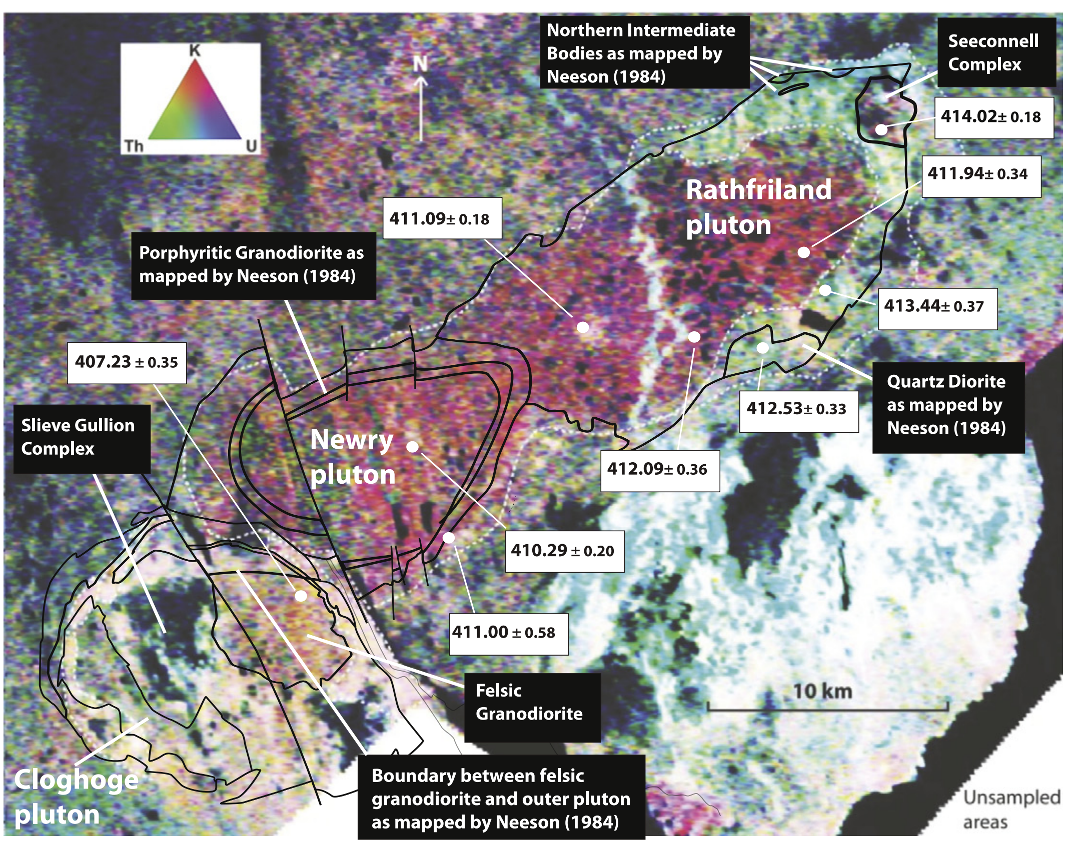


Fig. 2. Recent Tellus geophysical data and U–Pb dates for the NIC. The outline of the NIC is marked as a solid white line, as are faults showing significant displacement and labelled internal divisions of the NIC: (a) aeromagnetic data with superimposed U–Pb dates; (b) radiometric data with superimposed U–Pb dates (modified from Cooper et al. (in press)).

1979; Neeson, 1984; Reynolds, 1934, 1936). The distribution of these facies within the Seeconnell Complex is intricate and has not been mapped as part of the current study.

3.2.2. Intermediate bodies

A small area in the north of the main Rathfriland pluton exhibits similar monzonitic and dioritic compositions to the Seeconnell Complex (Neeson, 1984; Reynolds, 1934) (Fig. 1). This has been divided into three intermediate bodies in the vicinity of Rough Hill and Legananny Mountain (Neeson, 1984) (Fig. 1). The compositional similarity of these bodies to the Seeconnell Complex is thought to reflect similar ages of intrusion (Neeson, 1984). Thus, together with the Seeconnell Complex, the bodies most likely predate other parts of the NIC.

Another intermediate body occurs in the vicinity of Kilcoo in the southern part of the Rathfriland pluton (Meighan and Neeson, 1979; Neeson, 1984) (Fig. 1). However, this is defined as a quartz diorite and, as such, is significantly more felsic than the northern intermediate bodies and the Seeconnell Complex (Neeson, 1984). In fact, Neeson (1984) suggests that this quartz diorite relates more closely to the main part of the Rathfriland pluton than to any of the other more mafic bodies.

3.2.3. Porphyritic granodiorite

A distinct porphyritic granodiorite containing hornblende and biotite phenocrysts occurs within the Newry pluton (Neeson, 1984; Reynolds, 1943). This facies is thought to crop out as a narrow ring, separating the outer biotite granodiorite and inner hornblende granodiorite in this pluton (Neeson, 1984) (Fig. 1), although previous mapping has been based on limited exposure.

3.3. Geophysical data

The Tellus Project is an ongoing, comprehensive, and multi-award winning geological mapping project of Northern Ireland, managed by the British Geological Survey (BGS), the Geological Survey of Northern Ireland (GSNI), and the Geological Survey of Ireland (GSI) (Leslie et al., 2013). Part of the initial phase of this project, taking place in 2005/2006, was the Tellus Regional Airborne Geophysical Survey of Northern Ireland, arranged in partnership between the BGS and the Geological Survey of Finland. Aeromagnetic and radiometric data for the NIC from this survey were interpreted by Anderson (2015) and Cooper et al. (in press). Cooper et al. (in press) use these results to divide the NIC into a number of geophysical zones, although prior to the current study, these have not been correlated with specific lithologic units.

3.3.1. Aeromagnetic data

Aeromagnetic data reveals a number of distinct positive aeromagnetic anomalies within the NIC, including two ring-shaped anomalies within the Rathfriland and Newry plutons, respectively (Fig. 2A). The aeromagnetic ring within the Newry pluton corresponds, in part, to outcrop of the porphyritic granodiorite, whereas the aeromagnetic ring within the Rathfriland pluton lacks a corresponding surface facies (Fig. 2A). The other positive aeromagnetic anomalies approximately correspond to mapped locations of the Seeconnell Complex, intermediate bodies, and both the Caledonian and Palaeogene parts of the Cloghoge pluton (Fig. 2A). The anomaly corresponding to the Seeconnell Complex is slightly larger in extent than this body. Cooper et al. (in press) state that the positive aeromagnetic anomaly in the area of the Cloghoge pluton corresponds to the Palaeogene Slieve Gullion Complex (see Fig. 1). Despite the correlation of several of positive aeromagnetic anomalies with petrological characteristics, the original cause of these anomalies has been poorly understood.

Less prominent areas of negative aeromagnetic signature are also present throughout much of the Rathfriland and Newry plutons, as well as over a large area occupied by Palaeozoic sediments to the northeast of the NIC (Fig. 2A).

3.3.2. Radiometric data

Ternary radiometric data indicate an area of thorium enrichment at the eastern rim of the Rathfriland pluton (Fig. 2B). This signature spans the entire eastern rim of the pluton, apart from the Seeconnell Complex, which displays a more mixed radiometric signature (Fig. 2B). The remaining (western) Rathfriland pluton and entire Newry pluton display a potassium-elevated radiometric signature (Fig. 2B). This signature does not appear to show fluctuations relating to any of the three distinct previously defined facies of the Newry pluton (Fig. 1). The Cloghoge pluton displays a distinct mixed thorium- and potassium-elevated signature (Fig. 2B).

3.4. Geochronology

Cooper et al. (in press) report nine U–Pb zircon ages for the NIC, which range from ca. 414 to 407 Ma (with errors of 0.18–0.58 Myr at 2σ) (Fig. 2). The dates confirm that the NIC was intruded sequentially from northeast to southwest, with the Seeconnell Complex representing the oldest part. These dates also show that the Rathfriland and Newry plutons become younger towards their respective centres (Fig. 2). Overall geochronology suggests that there were large hiatusus in emplacement not only between plutons, but also within plutons.

3.5. Large scale mapping

The pluton margins illustrated in Fig. 1 (as well as Figs. 2–5) correspond to the most recent mapping of this area by the Geological Survey of Northern Ireland (GSNI, 1997). However, this mapping reveals a different location of the Newry–Cloghoge pluton boundary to Neeson's (1984) study of the NIC (Fig. 1). Therefore, the location of this boundary is investigated and confirmed in the current study (see Discussion).

4. Methods

For this study, 133 samples were collected from across the NIC (see Appendix 1 for sampling locations), which were analysed geochemically and petrologically. Data obtained are used alongside existing compositional and geophysical data (Cooper et al., in press; GSNI, 1997; Neeson, 1984) on the NIC to constrain a new detailed zonation for the complex.

4.1. Geochemistry

Samples were reduced to approximately fist-sized blocks by removing weathered surfaces and sub-samples for petrological characterisation (see below). All samples were then delivered to the British Geological Survey (BGS) in Keyworth, United Kingdom, to undergo whole-rock geochemical analysis. Samples were crushed and milled before analysis through lithium borate fused bead XRFS (0.9 g split) and sodium peroxide fusion ICP-MS (0.2 g split). Loss on ignition was determined gravimetrically (1 g split). Full details of geochemical analysis are provided in Appendix 2.

4.2. Petrological classifications

Whereas all samples are geochemically analysed, fifty-two samples are additionally used to provide petrological classifications. These were selected from particular areas of the NIC in order to better constrain surface composition where existing data were lacking or variable. Petrological classifications were made simply by visual estimation of approximate modal proportions of minerals within each sample and determining a relevant descriptive rock name (e.g., hornblende biotite granodiorite).

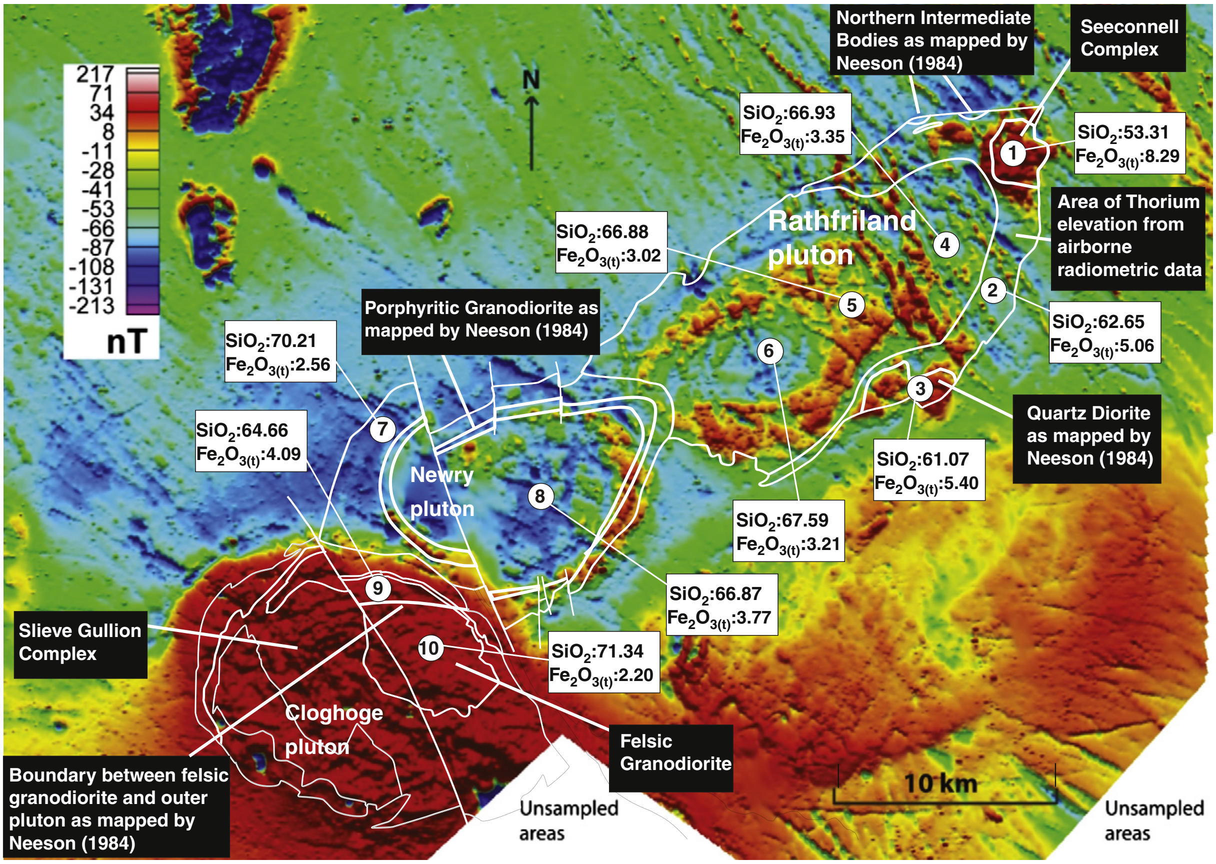


Fig 3. Areas of the NIC for which representative concentrations (shown in Table 1) are determined, superimposed on recent Tellus aeromagnetic data published by Cooper et al. (in press). Representative concentrations of SiO_2 and $Fe_2O_{2(t)}$ (wt %) are provided as annotations. Areas of the NIC are labelled 1–10, which correspond to the following: 1: Seeconnell Complex; 2: Thorium-elevated Rathfriland pluton rim, excluding quartz diorite; 3: Quartz diorite; 4: Area inside of thorium-elevated Rathfriland pluton rim and outside of Rathfriland pluton positive aeromagnetic ring; 5: Rathfriland pluton positive aeromagnetic ring; 6: Centre of Rathfriland pluton; 7: Outer Newry pluton; 8: Inner Newry pluton; 9: Outer Cloghoge pluton; 10: Off-centre Cloghoge pluton core.

5. Results

5.1. The Rathfriland pluton

The geochemistry of the ultramafic–intermediate Seeconnell Complex is variable (see Appendix 3), due to the range of lithologies previously mapped (Meighan and Neeson, 1979; Neeson, 1984; Reynolds, 1934). However, the mean concentrations of various elements confirm that this is the most basic part of the NIC (Area 1 in Table 1 and Fig. 3). Within the Seeconnell Complex, mean concentrations of the radiometric elements potassium (K_20) and uranium (U) are relatively high (3.98 wt% and 3.5 ppm, respectively) and thorium (Th) is moderate (12.4 ppm) in relation to other parts of the NIC (Fig. 4). This is consistent with the interpretation of the Seeconnell Complex as a zone of 'mixed' radiometric signature from airborne data reported by Cooper et al. (in press).

Mean major element concentrations become generally more silicic towards the centre of the Rathfriland pluton (Figs. 3, 5). Excluding the Seeconnell Complex, the most significant shift in geochemical concentration within the Rathfriland pluton occurs between the area of airborne Th elevation in the eastern part of the pluton (Areas 2–3 in Table 1 and Fig. 3) and the inner and southwestern parts of the pluton (Areas 4–6 in Table 1 and Fig. 3). Current results confirm that the area of airborne Th elevation also corresponds to geochemical Th elevation (mean concentration of 19.2 ppm—Fig. 4). Geochemistry additionally reveals low SiO_2 and high $Fe_2O_{3(t)}$ in this area relative to the inner and southwestern parts of the pluton (Fig. 5). These results support the compositional distinction of the eastern Rathfriland pluton rim indicated by the airborne radiometric data of Cooper et al. (in press) and suggest that the area is more basic than the inner and southwest parts of the pluton.

Current geochemistry also reveals significant variation within the eastern Rathfriland pluton rim (Areas 2–3 in Table 1 and Fig. 3). This is shown in Fig. 5 through a number of samples containing particularly low SiO_2 and high $Fe_2O_{3(t)}$ that are labelled 'anomalously basic samples'. The samples cluster close to the Seeconnell Complex and intermediate bodies (including the quartz diorite). The 'anomalously basic samples' in the northern part of the Rathfriland pluton can be separated from those in the south of the pluton due to their higher $Fe_2O_{3(t)}$ concentrations (Appendix 1A and 3A).

Petrological classification shows that the quartz diorites in the eastern Rathfriland pluton (Area 3 in Fig. 3) correspond closely to the positive aeromagnetic signature in this area (Fig. 6). The location of these quartz diorites is also consistent with mapping of the pluton by Neeson (1984) (Figs. 1 and 6).

Within the inner part of the Rathfriland pluton (Areas 4–6 in Table 1 and Fig. 3), there is comparatively little geochemical change, in terms of both mean concentrations (Table 1 and Fig. 3) and mapped concentrations (Fig. 5). Hence the prominent shift in aeromagnetic signature corresponding to the positively aeromagnetic ring does not appear to reflect a change in composition.

5.2. The Newry pluton

The Newry pluton is less compositionally complex than the Rathfriland pluton, with much of the variation being determined by

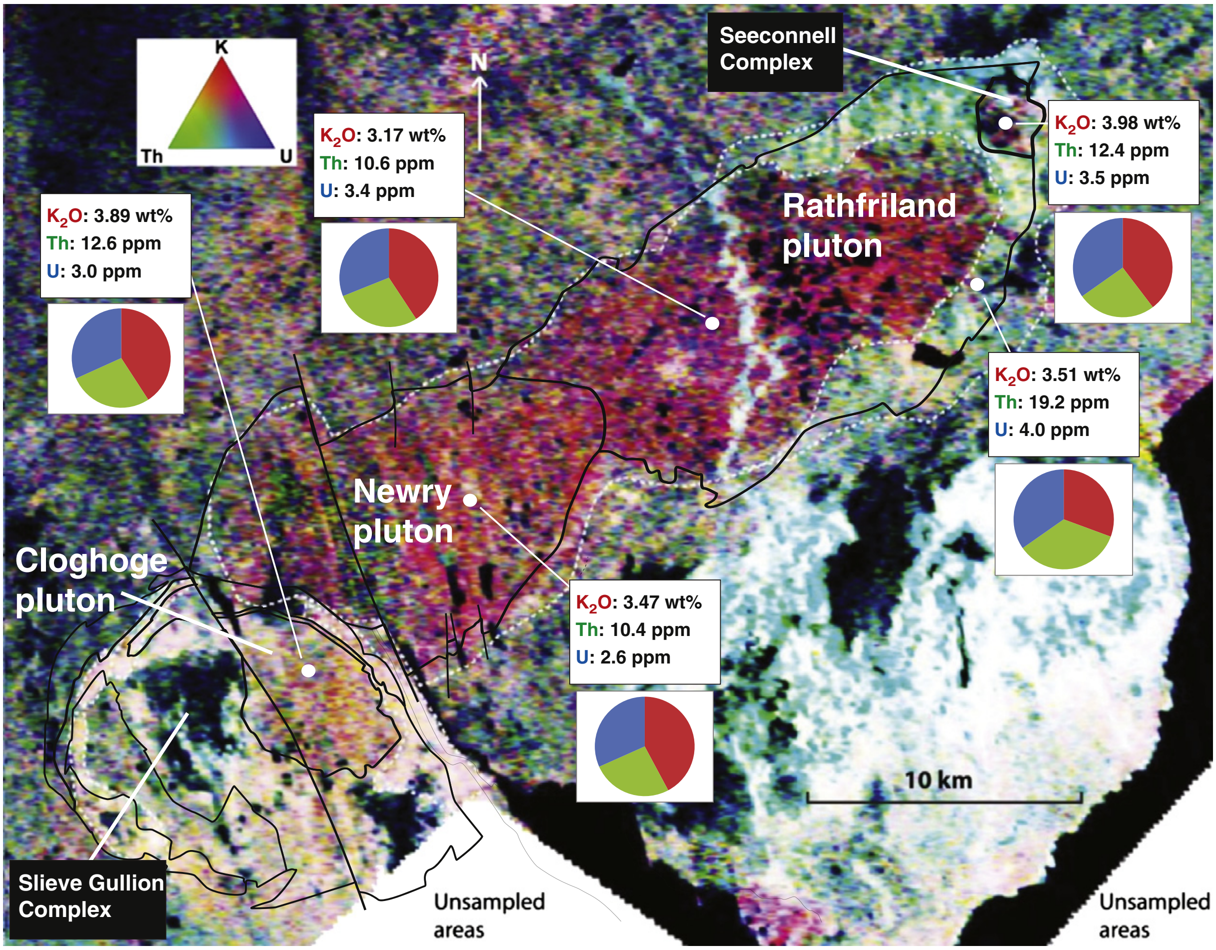


Fig. 4. Comparison between recent Tellus radiometric data published by Cooper et al. (2016) and mean concentrations of radiometric elements (K_2O, Th, U) from current data. Mean concentrations are calculated for the Seeconnell Complex, the thorium-elevated Rathfriland pluton rim, the inner Rathfriland pluton, the Newry pluton, and the Cloghoge pluton. Pie charts show normalised concentrations of K_2O, Th, U from current data (red = K_2O, green = Th, blue = U).

the presence of a distinctive porphyritic granodiorite facies (Fig. 1). Geochemical and petrological results broadly confirm the reverse zoning of the Newry pluton (Areas 7 and 8 in Table 1 and Fig. 3; Figs. 5 and 6). This is shown by an inward decrease in SiO_2 (from 70.33 to 66.87 wt% in Fig. 3; also see Fig. 5A) concentrations and an inward increase in $Fe_2O_{3(t)}$ (from 2.44 to 3.77 wt% in Fig. 3; also see Fig. 5B), together with a higher proportion of biotite and felsic granodiorites in the outer part of the pluton (Fig. 6). Several porphyritic granodiorite samples are also observed close to where these are mapped by Neeson (1984) (Fig. 6). Altogether these results broadly support the former division of the Newry pluton into an outer biotite granodiorite, a porphyritic granodiorite ring, and inner hornblende granodiorite (Neeson, 1984), although significant compositional variation is also apparent throughout (Figs. 5 and 6).

Cooper et al. (in press) show that the mapping of the porphyritic granodiorite by Neeson (1984) correlates with a prominent positive aeromagnetic ring. However, in the eastern part of this pluton, the shape of the aeromagnetic ring is inconsistent with Neeson's mapping of the porphyritic granodiorite (Fig. 6). Since exposure is poor in this area, aeromagnetic data are considered to outweigh former mapping in determining the general trend of the facies.

This study further elucidates the relationship between the porphyritic granodiorite and the positive aeromagnetic ring in the Newry pluton. Petrological results show that the inner part of the

Fig. 5. Concentrations of (a) SiO_2 and (b) $Fe_2O_{3(t)}$ from current geochemical results, superimposed on recent Tellus aeromagnetic data published by Cooper et al. (in press). Concentrations of each element are represented by points that are shaded on a greyscale ranging from white (0 on the scale) to black (100 on the scale). Key compositional changes occur within moderately silicic granodiorites (rather than between samples at the extremes of the concentration range), thus the shading range applied to sample points is set in order to emphasise variation in these. This is achieved by displaying any concentration value that is at or below the 5th percentile in the total concentration range for each element as a white point (i.e., a greyscale value of 0). Any concentration value that is at or above the 95th percentile in the total concentration range for each element is in turn displayed as a black point (i.e., a greyscale value of 100). Thus the effect of any anomalously low or high concentrations in obscuring variation within the more common rocks of the complex is removed. Further adjustment is also made in order to emphasise concentrations within the 25th–75th percentile range. Firstly, concentrations that are between the 5th and 25th percentile in the total range are set a greyscale value of 0–25 according to the following equation: *Greyscale Value* = ((*Sample concentration* − *5th Percentile concentration*)/(*25th Percentile concentration* − *5th Percentile concentration*)) × *25*. Concentrations that are between the 75th and 95th percentile in the total range are set a greyscale value of 75–100 according to the following equation: *Greyscale Value* = *100* − (((*95th Percentile concentration* − *Sample concentration*)/(*95th Percentile concentration* − *75th Percentile concentration*)) × *25*). Thirdly, concentrations that are between the 25th and 75th percentile in the total range are set a greyscale value of 25–75 according to the following equation: *Greyscale Value* = *25* + (((*Sample concentration* − *25th Percentile concentration*)/(*75th Percentile concentration* − *25th Percentile concentration*)) × *50*). Therefore, changes in composition within the 'middle range' granodioritic samples within the complex are observed more easily than they would be if shading of points was entirely proportional to concentration.

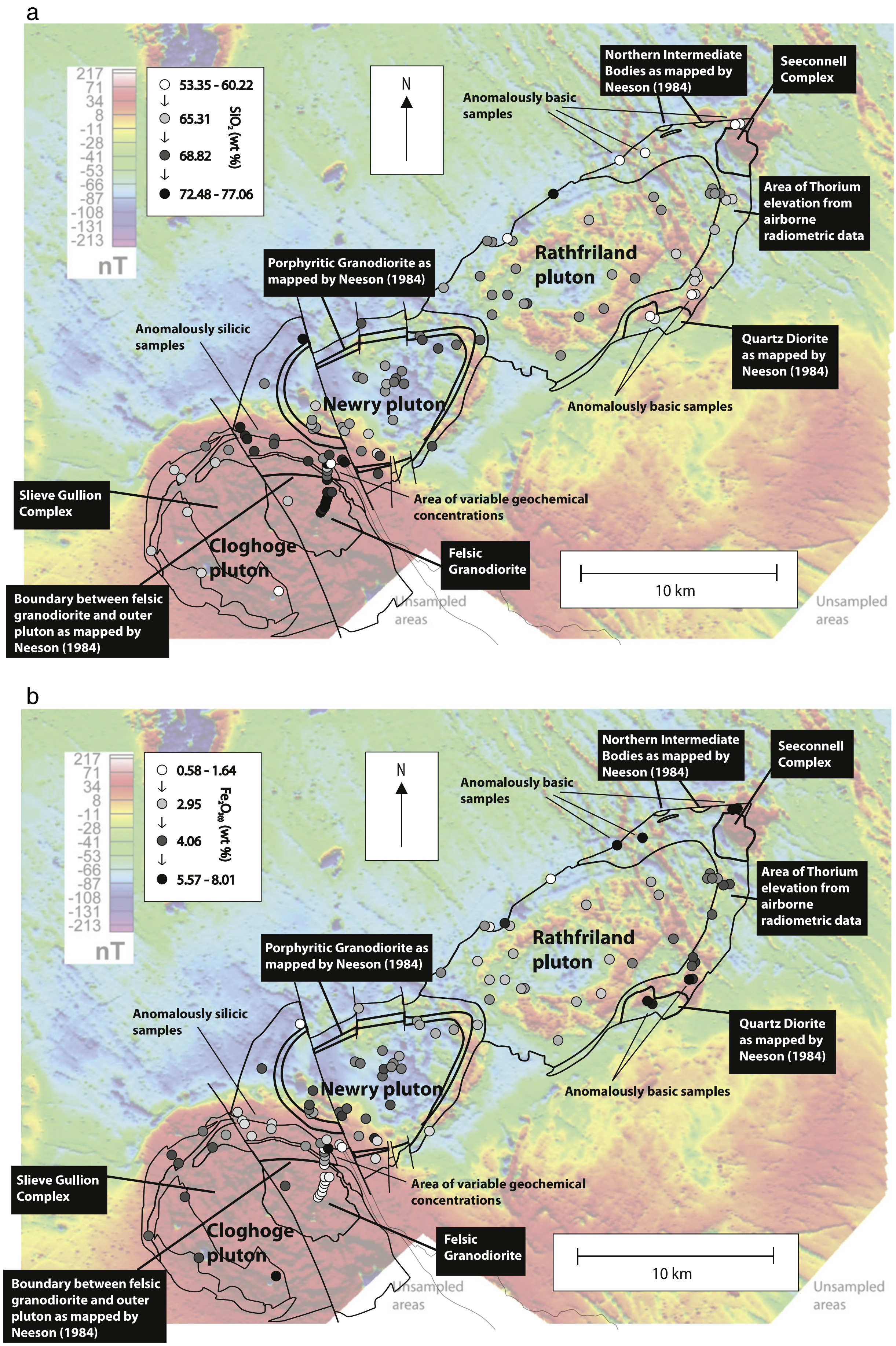

a
217
71
34
8
-11
-28
-41
-53
-66
-87
-108
-131
-213
nT
53.35 - 60.22
65.31
68.82
72.48 - 77.06
SiO_2 (wt %)
N
Northern Intermediate Bodies as mapped by Neeson (1984)
Seeconnell Complex
Anomalously basic samples
Area of Thorium elevation from airborne radiometric data
Rathfriland pluton
Porphyritic Granodiorite as mapped by Neeson (1984)
Anomalously silicic samples
Quartz Diorite as mapped by Neeson (1984)
Newry pluton
Anomalously basic samples
Slieve Gullion Complex
Area of variable geochemical concentrations
Cloghoge pluton
Felsic Granodiorite
10 km
Boundary between felsic granodiorite and outer pluton as mapped by Neeson (1984)
Unsampled areas
Unsampled areas
b
217
71
34
8
-11
-28
-41
-53
-66
-87
-108
-131
-213
nT
0.58 - 1.64
2.95
4.06
5.57 - 8.01
Fe_2O_{3t} (wt %)
N
Northern Intermediate Bodies as mapped by Neeson (1984)
Seeconnell Complex
Anomalously basic samples
Area of Thorium elevation from airborne radiometric data
Rathfriland pluton
Porphyritic Granodiorite as mapped by Neeson (1984)
Anomalously silicic samples
Quartz Diorite as mapped by Neeson (1984)
Newry pluton
Anomalously basic samples
Slieve Gullion Complex
Area of variable geochemical concentrations
Cloghoge pluton
Felsic Granodiorite
10 km
Boundary between felsic granodiorite and outer pluton as mapped by Neeson (1984)
Unsampled areas
Unsampled areas

Table 1
Representative geochemical concentrations for Areas 1–10 of the NIC (labelled in Fig. 3). Refer to Appendix 1A/1B for sampling locations and Appendix 3A/3B for geochemical concentrations of individual samples within each area. Mean concentrations are calculated using data from all samples, apart from those close to the ambiguous porphyritic granodiorite boundary (Samples N20A–N24 in Appendix 3A/3B).

Area	No. of samples	SiO_2	TiO_2	Al_2O_3	Fe_2O_3t	Mn_3O_4	MgO	CaO	Na_2O	K_2O	P_2O_5	Rb	Sr	Zr	Th	U
		wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
1	26	53.31	1.38	14.62	8.29	0.14	6.76	6.77	3.05	3.98	0.80	123.0	1198	179	12.4	3.5
2	13	62.65	0.85	15.47	5.06	0.09	3.63	4.07	3.75	3.55	0.29	138.7	579	275	19.6	4.1
3	2	61.07	0.86	15.64	5.40	0.11	4.42	4.49	3.80	3.25	0.28	113.3	655	181	15.8	3.1
4	13	66.93	0.51	15.57	3.35	0.06	2.37	2.84	4.07	3.31	0.17	115.4	506	158	12.8	2.7
5	8	66.88	0.45	15.94	3.02	0.06	1.75	2.99	4.22	3.06	0.16	110.5	485	126	7.8	2.0
6	4	67.59	0.49	15.71	3.21	0.06	1.71	2.50	4.22	2.94	0.15	107.0	399	120	9.1	2.5
7*	15	70.21	0.38	15.22	2.56	0.05	1.30	2.50	4.22	2.94	0.15	123.2	313	127	10.7	2.7
8*	14	66.87	0.63	15.73	3.77	0.08	1.92	2.70	4.09	3.28	0.19	105.4	426	129	10.3	2.6
9	14	64.66	0.76	15.43	4.09	0.08	2.23	3.40	4.05	3.66	0.38	120.2	582	192	12.4	3.4
10	12	71.34	0.30	14.60	2.20	0.05	0.96	1.29	3.87	4.33	0.12	159.0	216	138	13.3	2.7

* This study shows that an area mapped as the inner Newry pluton by Neeson (1984) likely represents the outer Newry pluton (i.e., peripheral to the porphyritic granodiorite). Due to this ambiguity, samples from this area are not included in calculation of mean geochemical concentrations.

aeromagnetic ring generally corresponds to porphyritic granodiorite, whereas the outer part of this ring generally corresponds to non-porphyritic facies (Fig. 6). Hence the aeromagnetic signature of the porphyritic granodiorite is outward-shifted, rather than precisely matching the outcrop distribution of the facies. This may be due to subsurface penetration of aeromagnetic data (Schetselaar et al., 2000), which would result in an outward-shifted signature if the porphyritic granodiorite is outward-dipping (Fig. 7). This interpretation is consistent with the outward-dipping fabrics within the pluton as shown in Fig. 1. Exception occurs in the western part of the Newry pluton where the positive aeromagnetic anomaly correlates more closely with surface exposure and with former mapping of the porphyritic granodiorite. Fabrics in this part of the pluton are also steep to vertically dipping (Fig. 1). Hence, in this area, it is likely that the porphyritic

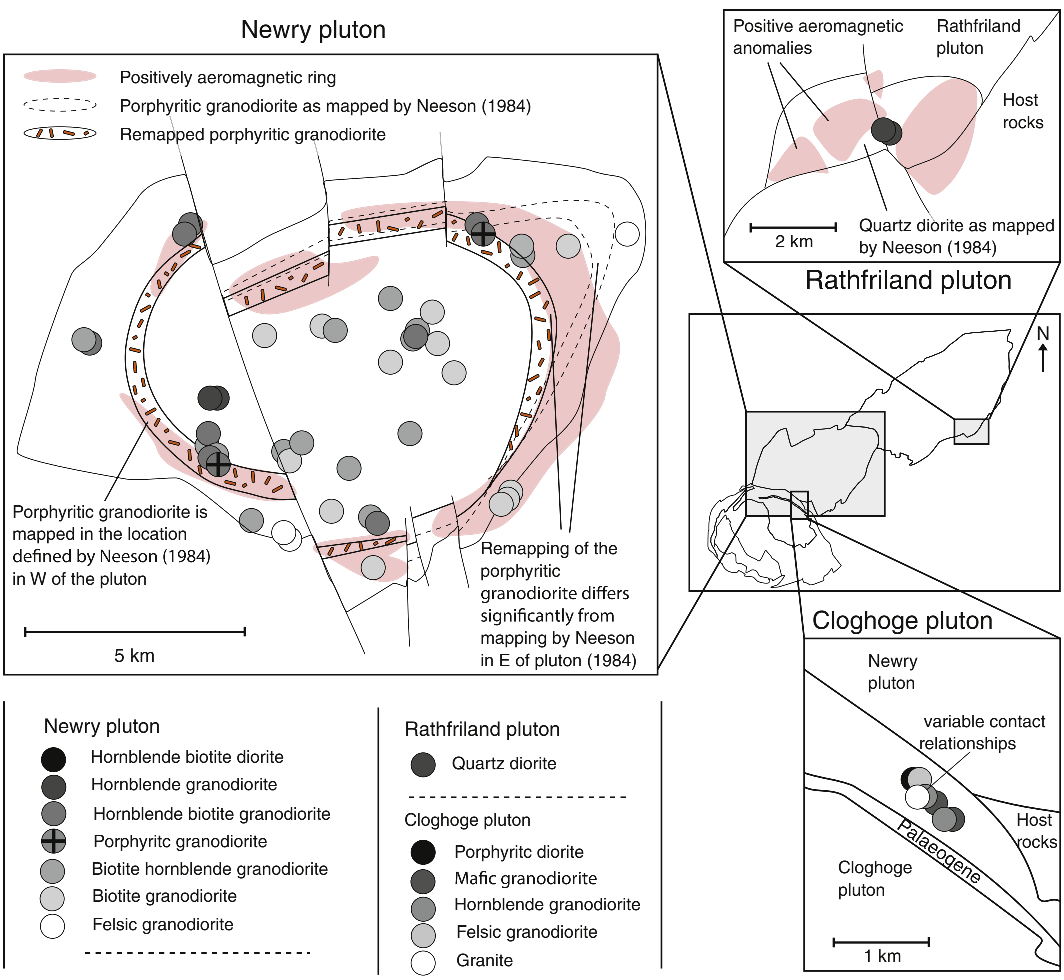


Fig 6. Petrological classifications for three parts of the NIC (the Quartz Diorite of the Rathfriland pluton, the Newry pluton and the eastern Cloghoge pluton margin). Shading of symbols represents the relative evolution of samples (shown in key).

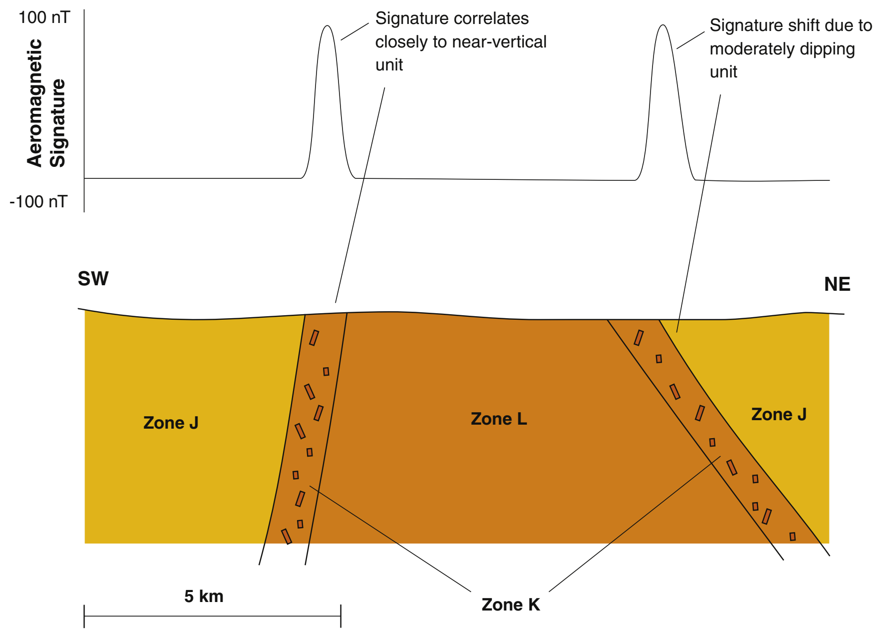


Fig. 7. Schematic NE–SW cross-section of the Newry pluton, accounting for the observed aeromagnetic signature.

granodiorite unit is near-vertical in orientation. Within Fig. 6, the porphyritic granodiorite is remapped according to these new data and interpretations.

5.3. The Cloghoge pluton

Geochemistry confirms the broad separation of the Cloghoge pluton into a silica-poor outer part and a silicic off-centre core inferred by Neeson (1984). This is apparent from mean SiO_2 concentrations of the outer and core parts of the pluton, represented in Table 1 and Fig. 3 by Areas 9 (63.65 wt% SiO_2) and 10 (71.34 wt% SiO_2), respectively. However, mapped concentrations of individual samples reveal an area of anomalously high SiO_2 and low $Fe_2O_{3(t)}$ within the northernmost part of the outer pluton (labelled 'anomalously silicic area' in Fig. 5).

A new area of highly variable geochemisty is also reported here (labelled 'area of variable geochemical concentrations' in Fig. 5). This variation corresponds to the occurrence of a number of steeply orientated sheets of mixed composition. Petrological data show that these sheets consist of granite, felsic granodiorite, hornblende granodiorite, mafic granodiorite, porphyritic diorite, and dolerite (Fig. 6). Some of the rock types resemble those observed within other parts of the Cloghoge pluton, as well as the adjacent Newry pluton. In particular, the granite and mafic granodiorite are similar to the felsic granodiorite and hornblende granodiorite within the Cloghoge pluton, while the porphyritic diorite displays a textural resemblance to the porphyritic granodiorite of the Newry pluton (Fig. 6). The sheets display variable contact relationships, which include straightforward cross-cutting, mixing, and mingling. However, the implied age relationships between the units are inconsistent, suggesting that all were intruded penecontemporaneously.

Mean concentrations of the three radiometric elements, K_2O and Th and U, within the Cloghoge pluton are notably higher (3.89 wt%, 12.6 ppm and 3.0 ppm, respectively) than they are in other parts of the NIC (Fig. 4). These results are consistent with the interpretation of the Cloghoge pluton as an area of 'mixed' K_2O/Th enrichment (Cooper et al., in press), and further suggest that U is also elevated in this area.

6. Discussion

6.1. Zonation of the NIC

Based on current and previous studies, a total of 15 zones are inferred within the NIC (Fig. 7). These are interpreted to have been sequentially emplaced and are named Zones A–O to denote this. U–Pb ages from Cooper et al. (in press) are used to suggest that the zones range in age from ca. 414 to 407 Ma.

6.1.1. The Rathfriland pluton

The Seeconnell Complex is distinguished within the NIC by its unique intermediate–ultramafic composition, as well as its strong positive aeromagnetic anomaly and mixed K- and Th-elevated airborne radiometric signature. Since geochronological data show that the Seeconnell Complex is the oldest part of the NIC (414.02 ± 0.18 Ma), this area is defined as *Zone A* (Fig. 8).

The crescent-shaped area of Th-enriched radiometric signature (Figs. 2B and 4) and relatively basic geochemistry (Figs. 3 and 5) in the eastern part of the Rathfriland pluton is subdivided into Zones B–F on the basis of its internal geochemical variations (Fig. 8). *Zone B* represents the intermediate bodies close to the Seeconnell Complex (Fig. 8). This is due to the compositional similarity between these bodies and the Seeconnell Complex, which indicates a close relationship between the areas (Neeson, 1984; Reynolds, 1934). The extent of this zone is mapped according to the work of Neeson (1984).

All other parts of the eastern Rathfriland pluton are more felsic than Zones A and B, yet are significantly more basic than the inner pluton. *Zone C* represents the area of relatively basic geochemistry in the vicinity of Zones A and B (Fig. 8). The hornblende granodiorite in this area exhibits more basic geochemistry than any of the other granodiorites within the NIC. Hence, this facies is termed basic granodiorite and is thought to reflect evolution of the intermediate magma supplying Zones A and B. Compositionally, Zone C is distinguished from another basic granodiorite (Zone F—see below) through its higher $Fe_2O_{3(t)}$ concentrations.

The area defined as *Zone D* is significantly more silicic than Zone C (Fig. 8). Zone D also exhibits the next oldest U–Pb age (413.44 ± 0.37 Ma) after the Seeconnell Complex (Zones B and C are currently

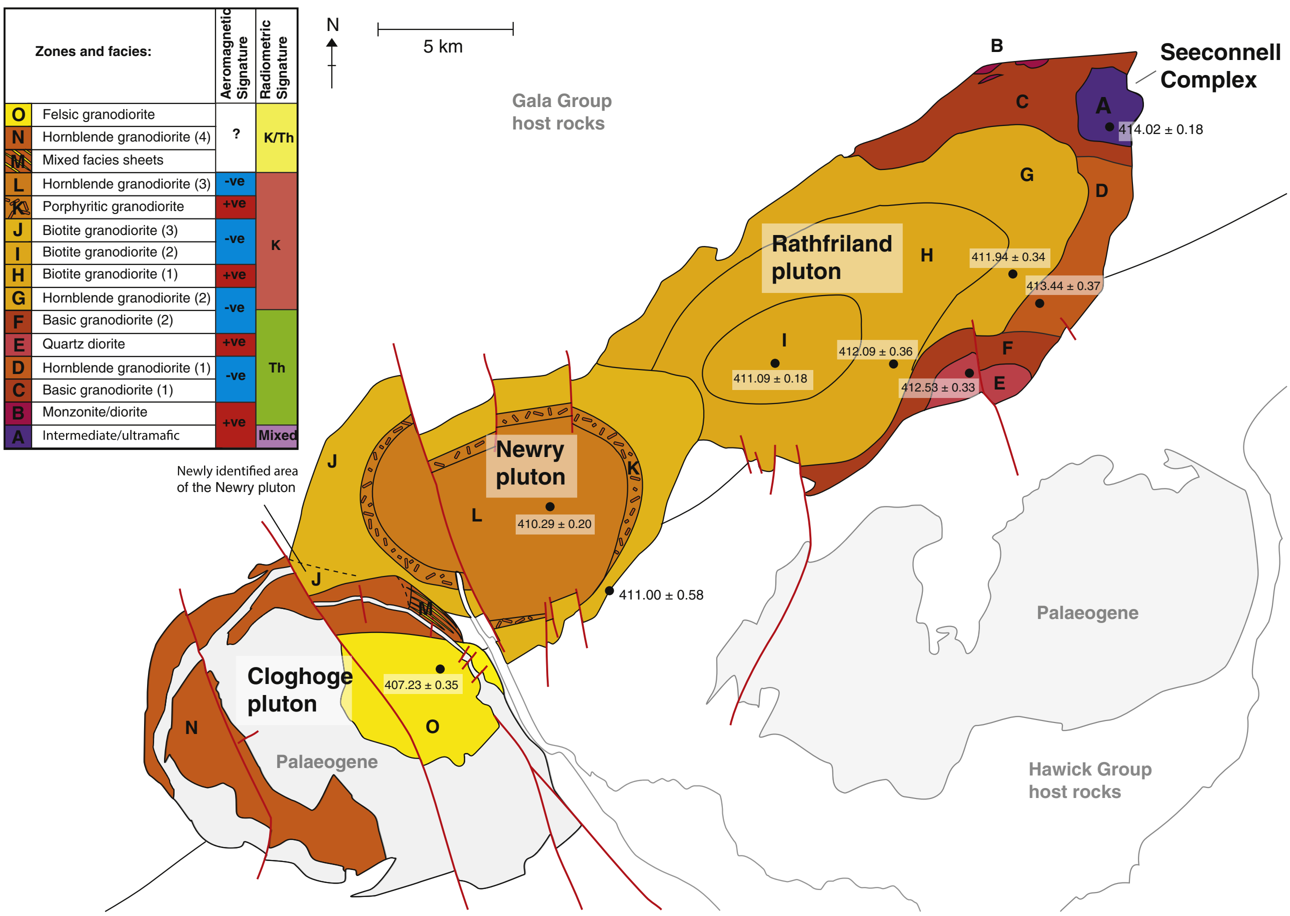


Fig. 8. Derived zonation of the NIC, shown in relation to recent U–Pb dates of Cooper et al. (in press).

undated) and consists of hornblende granodiorite. Therefore, Zone D may represent further evolution of the magma supplying Zones A to C.

Zone E is defined as the quartz diorite in the south of the Rathfriland pluton. This is more basic than the Zone D granodiorite, although its geochronological age (412.53 ± 0.33 Ma) clearly suggests that it is the younger of the two facies (Fig. 8). Hence, straightforward evolution of a single source by fractional crystallisation does not account for the variation between these zones, and mixing of more basic magma is thought to have produced the Zone E composition. The quartz diorite (Zone E) is also distinguished by a prominent positive aeromagnetic anomaly (Fig. 2A). Together with Neeson's (1984) mapping, this anomaly is used to determine the extent of Zone E.

Zone E is surrounded by another area of granodiorite displaying relatively basic geochemistry (Fig. 8). Xenoliths of quartz diorite have been observed within this adjacent basic granodiorite (Neeson, 1984), which is thus suggested to be younger than Zone E. The area is defined as *Zone F* and is referred to as a second basic granodiorite (Fig. 8), which may represent evolution of the magma supplying Zone E. Zone F is distinguished from the other basic granodiorite (Zone C) by its lower $Fe_2O_{3(t)}$ concentrations.

The inner (including the southwestern), younger (ca. 412 to 411 Ma), more silicic parts of the Rathfriland pluton (Zones G–I) show comparatively little geochemical variation (Fig. 8). Thus, the entire area is thought to consist of biotite granodiorite, showing little or no inward change in composition. This is consistent with the interpretation by Neeson (1984) that the Rathfriland pluton broadly consists of an outer hornblende granodiorite and inner biotite granodiorite, although the current study suggests that the boundary between these facies is abrupt.

Due to the consistent geochemistry of the inner Rathfriland pluton, the zonal divisions here are made according to aeromagnetic data. *Zone G* represents the area outside of the Rathfriland pluton positive aeromagnetic ring, *Zone H* represents the positive aeromagnetic ring itself, and *Zone I* represents the area inside of this anomaly (Fig. 8). Fabrics in the inner part of the pluton are steep to vertical (Fig. 1), hence aeromagnetic signature is thought to closely reflect surface extent of facies. Radiometric dates for Zones G, H, and I (411.94 ± 0.34, 412.09 ± 0.36, and 411.09 ± 0.18 Ma, respectively) broadly suggest that this part of the pluton becomes younger towards the centre.

6.1.2. The Newry pluton

Geochemistry is consistent with Neeson's (1984) divisions of the Newry pluton, showing that this pluton becomes more basic towards its centre (Fig. 5A and B). Since cross-cutting relationships and U–Pb geochronology demonstrate that the Newry pluton is slightly younger than the Rathfriland pluton (GSNI, 1997; Neeson, 1984), the three main divisions within the Newry pluton are defined as Zones J, K, and L (Fig. 8).

The outermost biotite granodiorite represents *Zone J* (Fig. 8), as it has the older of the two U–Pb ages obtained from the pluton (411.00 ± 0.58 Ma). Although the adjacent porphyritic (hornblende–biotite) granodiorite ring is undated, it has been observed to crosscut the outer biotite granodiorite (Neeson, 1984); hence, the porphyritic granodiorite represents *Zone K* (Fig. 8).

The original location of the porphyritic granodiorite (Zone K) inferred by Neeson (1984) has been modified in this study through consideration of aeromagnetic data as discussed previously. The relationship of the porphyritic granodiorite to the positive aeromagnetic ring allows for more accurate mapping of the Newry pluton than what has previously been possible (Fig. 8). As a result, the porphyritic granodiorite in the east of the pluton is now shown to be less marginal than it is suggested to be by Neeson (1984) (compare Figs. 1 and 8). The inner hornblende granodiorite generated the younger of the two U–Pb ages obtained from the Newry pluton (410.29 ± 0.20 Ma) and is, therefore, designated *Zone L*.

6.1.3. The Cloghoge pluton

The single U–Pb age from the Cloghoge pluton (407.23 ± 0.35 Ma) and the cross-cutting relationship between this and the adjacent Newry pluton (Neeson, 1984) shows that the Cloghoge pluton is the youngest part of the NIC. Consequently, the zones within the Cloghoge pluton are defined as M, N, and O (Fig. 8). The notably basic geochemistry (low SiO_2)of the outer Cloghoge pluton and the silicic geochemistry of its off-centre core (Fig. 5) is consistent with the broad division of this pluton into an outer (albeit relatively basic) hornblende granodiorite and a felsic granodiorite core (Neeson, 1984; Reynolds, 1943).

Part of the outer Cloghoge pluton as mapped by the GSNI (1997) is now thought to represent the outer Newry pluton (Fig. 8). This area (labelled 'anomalously silicic area' in Fig. 5) exhibits high SiO_2 and low $Fe_2O_{3(t)}$ concentrations that are similar to those observed within the Newry pluton. Furthermore, the area was originally mapped as part of the Newry pluton by Neeson (1984).

The previously unrecognised area of steeply orientated sheets in the northeast of the Cloghoge pluton is defined as *Zone M* (Fig. 8). This area is thought to predate other parts of the Cloghoge pluton due its marginal location. Of the sheets in the area, those consisting of porphyritic diorite show similarity to the Newry pluton porphyritic granodiorite (Zone K), while those consisting of mafic granodiorite and granitic sheets show similarity to the remaining outer part and core area of the Cloghoge pluton, respectively. Hence, it is possible that the sheeted margin of the Cloghoge pluton (Zone M) represents magmas that also supplied other parts of the NIC.

The outer hornblende granodiorite of the Cloghoge pluton is defined as *Zone N* (Fig. 8). Although this area is undated, it is tentatively assumed to be older than the pluton core due to the general inward younging relationships observed across the NIC. Finally, the off-centre felsic granodiorite core of the Cloghoge pluton is defined as *Zone O* (Fig. 8). U–Pb geochronology yields a significantly younger age for this area (407.23 ± 0.35 Ma). The time gap between this and the next youngest age (for Zone L of the Newry pluton) is consistent with Zone O being the youngest part of the NIC.

6.2. Incremental emplacement

We suggest that the NIC was emplaced as a series of distinct magma pulses, which are represented by the inferred zones (Farina et al., 2012; Pitcher, 1997; Richey, 1928; Stevenson et al., 2007). Evidence for this incremental emplacement is provided by the abrupt changes in geochemical, aeromagnetic, and radiometric signatures between the various zones. Understanding the mechanism through which these pulses were emplaced, and the siting of the NIC as a whole, will require further structural study of the complex and its host rocks.

6.3. Parental magma

Geochemical results show that zones within the NIC become broadly more silicic with younging, possibly reflecting evolution of the parental magma. However, exceptions are observed between Zone D (hornblende granodiorite) and Zone E (quartz diorite) of the Rathfriland pluton, between Zone J (biotite granodiorite/) and Zones K/L (porphyritic granodiorite/hornblende granodiorite) of the Newry pluton, and between the Zone L (hornblende granodiorite) and Zone N (more basic hornblende granodiorite) of the adjacent Newry and Cloghoge pluton (Fig. 8). We suggest that these compositional patterns were produced by variations in the parental magma, with fractional crystallisation causing evolution towards more silicic compositions, and with mixing of more basic magmas causing interruptions in this trend.

6.4. The reliability of Tellus data in determining zonation

Aeromagnetic data for the NIC (see Fig. 2A) corresponds in places to changes in facies at the surface. This is apparent from the prominent positive aeromagnetic anomalies located at the Seeconnell Complex, the quartz diorite in the Rathfriland pluton, and the porphyritic granodiorite in the Newry pluton (Fig. 2A). However, the correlation between aeromagnetic signature and composition in other parts of the NIC is inconsistent (Fig. 5). This is clearest from the positive aeromagnetic ring within the Rathfriland pluton, which shows no obvious relationship to geochemistry (Fig. 5). Hence, the origin of aeromagnetic anomalies within the NIC is not always clear.

The aeromagnetic anomalies that are linked to facies at the surface do not consistently correlate with these facies in terms of boundary locations. This occurs for the anomalies corresponding to the quartz diorite in the Rathfriland pluton and the porphyritic granodiorite in the Newry pluton (Fig. 6). Schetselaar et al. (2000) suggest that such inconsistencies between aeromagnetic and surface data reflect aeromagnetic detection of facies at depth. This is thought to be the case for the porphyritic granodiorite, which shows an outward-shifted aeromagnetic signature in the east of the Newry pluton (Fig. 7).

Airborne radiometric data for the NIC (Fig. 2B) correspond to surface zonation more precisely. For example, radiometric Th elevation in the eastern NIC can be correlated to distinct geochemical concentrations of various elements (Figs. 2B, 4 and 5). The Seeconnell Complex also corresponds to an area of K elevation (Figs. 2B and 4). The only apparent inconsistency between radiometric data and surface composition occurs to the east of the Rathfriland pluton, where an elevated Th signature characteristic of the pluton itself is observed for the host rocks, which are predominantly greywackes (Fig. 2B). Cooper et al. (in press) suggest that glacial transport of rock material from the Rathfriland pluton occurs in this area and likely accounts for the anomaly.

7. Conclusions

The following four main conclusions are drawn from this study:

1. The NIC can be divided into 15 distinct zones (Fig. 8). These are largely defined compositionally by current geochemistry results. Zones are also distinguished by Tellus aeromagnetic and radiometric data. Aeromagnetic data are particularly key to distinguishing zones within the central Rathfriland pluton, within which no compositional variation has been observed. A thorium-elevated radiometric signature additionally helps to distinguish the more basic eastern part of the Rathfriland pluton. Zones are concentric within the three plutons, excluding the eastern part of the Rathfriland pluton, where several zones are distributed within the more basic crescent-shaped rim, and within the Cloghoge pluton, which exhibits a significantly off-centre core and a single sheeted margin. Zones show a general evolution from intermediate (with associated ultramafic) to felsic throughout the NIC, although there are exceptions where this evolutionary trend is reversed.
2. The 15 derived zones are likely to have been emplaced incrementally via at least this number of distinct magma pulses. However, the mechanism of emplacement of these pulses and the siting of the NIC remains poorly understood and will require further structural study.
3. The general evolutionary trend shown within the NIC is consistent with a magma supply that has undergone substantial fractional crystallisation (see Meighan and Neeson, 1979), together with occasional mixing of more basic magma.

4. Aeromagnetic and radiometric data broadly resolve much of the zonation of the NIC. However, the boundaries of some aeromagnetic zones are inconsistent with surface exposure of the corresponding facies and are interpreted to reflect dipping facies margins. Radiometric data are thought to represent surface composition more reliably, although the southwestern boundary of the Rathfriland pluton is not accurately resolved, due to glacial transport of material from the NIC. Therefore, there would be a number of caveats associated with exclusive use of aeromagnetic and radiometric data to constrain zonation. As has been previously suggested (e.g., Schetselaar et al., 2000), it is clear that field work and sampling is also required to obtain accurate interpretations of zonations within large igneous plutonic bodies.

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