A U-Pb age for the Late Caledonian Sperrin Mountains minor intrusions suite in the north of Ireland: timing of slab break-off in the Grampian terrane and the significance of deep-seated, crustal lineaments

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Number of words of text: abstract: 188; all text: ~ 10,000

Number of references: 87

Number of tables: 3 (one intended as supplementary material)

Number of figures: 5

Abbreviated title: Sperrin Mountains minor intrusions suite

Abstract: An intrusion of trachy-andesite, representative of a newly discovered suite of high-K-Ba-Sr, calc-alkaline minor intrusions (termed herein the Sperrin Mountains suite), hosted within the Grampian terrane in the north of Ireland, has been dated by U-Pb zircon at 426.69 ± 0.85 Ma (mid-Silurian; Wenlock–Ludlow boundary). Geochemistry reveals a close association to the Fanad, Ardara and Thorrr plutons of the Donegal Batholith and the Argyll and Northern Highlands Suite of Scotland. The deep-seated, Omagh Lineament appears to have limited eastward propagation of the Sperrin Mountains suite from beneath the main centre of granitic magmatism in Donegal. A Hf depleted mantle model age (T_{DMHf}) of *c.* 800 Ma for trachy-andesite zircons indicates partial melting from a source previously separated from the mantle. Whole rock geochemistry of the suite is consistent with a model of partial melting, triggered by slab break-off, following thrusting of Ganderia-Avalonia under the Southern Uplands–Down–Longford accretionary prism (i.e. Laurentian margin). The new age constrains the timing of this event in the north of Ireland and is consistent with the petrogenesis of Late Caledonian high-K granites, appinites and minor intrusions across the Caledonides of northern Britain and Ireland.

Supplementary material: Table 3 geochemical data.

Keywords: Late Caledonian, Sperrin Mountains suite, minor intrusions, trachy-andesite, U-Pb zircon geochronology, slab break-off, Omagh Lineament.

The Caledonian orogenic belt of the British and Irish Caledonides resulted from the progressive closure of the Iapetus Ocean and Tornquist Sea during the early Palaeozoic. Between the late Cambrian and Middle Ordovician, closure of Iapetus was associated with episodic arc-ophiolite accretion to the continental margin of Laurentia and the polyphase deformation and metamorphism of its thick Neoproterozoic cover sequences (Grampian orogeny *c.* 475–465 Ma; see Draut *et al.* 2004; Chew *et al.* 2010; Cooper *et al.* 2011; Hollis *et al.* 2012). Following a subduction polarity reversal, continued ocean closure led to amalgamation of Ganderia, Avalonia, Baltica and a composite Laurentia during the Silurian (see Chew & Stillman 2009). In the Grampian terrane of Scotland, between the Great Glen and Highland Boundary faults, large volumes of intermediate to acid magmatism were generated after cessation of subduction processes at *c.* 430 Ma (Neilson *et al.* 2009; Soper *et al.* 1992). Late Caledonian intrusions of northern Britain and Ireland record

68 the arrival of Ganderia-Avalonia, its underthrusting and slab break-off (Ghani &
69 Atherton 2008). Many of the larger Late Caledonian granitoids, such as the Donegal
70 Batholith, have provided a natural laboratory for generations of geologists to test
71 models of granite emplacement (see Chew & Stillman 2009), as well as the underling
72 petrogenetic processes (i.e. I-, S-, M-, and A-type; e.g. Harmon *et al.* 1984), however
73 the timing of magmatism in the Grampian terrane of Ireland is not well constrained.

74 Rock *et al.* (1988) published a comprehensive account of the petrogenetic and
75 tectonic implications of the distribution and chemical variation of Late Caledonian
76 minor intrusion swarms in northern Britain. The work presented a threefold division
77 of the intrusions based on the traditional definitions of ‘basic’, ‘intermediate’ and
78 ‘acidic’, corresponding to appinitic and lamprophyric variants, microdioritic and
79 andesitic, and variably porphyritic felsitic and microgranitic variants. A spatial,
80 temporal and probable genetic relationship was revealed between these minor
81 intrusions and the contemporaneous “Newer Granites”, including the Newry Igneous
82 Complex of the Down–Longford terrane in Northern Ireland (see Rock *et al.* 1988,
83 Fig. 1). More recent mapping across much of western Northern Ireland (GSNI 1995a,
84 1995b, 2007a, 2008, 2009 and 2013), has revealed the presence of a significant Late
85 Caledonian Sperrin Mountains suite of minor intrusions (Fig. 1).

86 This paper presents the mapped distribution and geochemistry of the Late
87 Caledonian Sperrin Mountains suite in the Grampian terrane, and presents the first U-
88 Pb zircon age and Hf-isotope data for one of these intrusions. The possible role of the
89 deep-seated, Omagh Lineament and the relationship with magmatism and other
90 parallel lineaments are discussed. A magmatic and tectonic model relating genesis of
91 the Sperrin Mountains suite to magmatism elsewhere in the Grampian terrane of
92 Ireland and Scotland is proposed.

93

94 **North of Ireland Late Caledonian intrusions**

95 Late Caledonian minor intrusions are present in all the major basement terranes that
96 form the north of Ireland as defined by Bluck *et al.* (1992), and are exposed where
97 early Palaeozoic and Proterozoic rocks are at surface (Fig. 1).

98 The Southern Uplands–Down–Longford terrane in counties Down and
99 Armagh (Anderson 2004), contains approximately 1300 lamprophyric bodies that
100 occur as dykes and sills in Ordovician and early Silurian sedimentary rocks
101 (Anderson & Oliver 1996). A representative selection of these intrusions from the
102 regional, 1:250,000 scale, bedrock geological map of the north of Ireland (GSNI

1997), is shown on Figure 1b, and, as indicated by Rock *et al.* (1988), a clear, large-scale, spatial relationship with the Newry Igneous Complex is evident. Reynolds (1931) recognised two main phases of minor intrusion: an older suite of deformed dykes, which is restricted to an area south of a line joining Ringburr Point and Ringboy Point on the Ards peninsula, and a later suite of generally undeformed dykes. Deformed and undeformed dyke populations are also described in the vicinity of Clogher Head (Fig. 1a) in County Louth, just north of the surface trace of the Iapetus Suture (Vaughan 1996), whilst in the Southern Uplands a similar suite of intrusions are mostly confined to the Central Belt and have Rb-Sr and K-Ar biotite/hornblende ages for unfoliated lamprophyres in the range 395–418 Ma (Rock *et al.* 1986). From Figure 1b, it can be seen that all of the lamprophyric intrusions associated with the Newry Igneous Complex are found south of the Orlock Bridge Fault in the Central Belt of Down–Longford. A K-Ar age of 415 ± 12 Ma for one of the younger, undeformed dykes, located at Ballyferris in the Down–Longford sector (Anderson & Oliver 1996), is within error of the Southern Uplands suite and also the recently acquired U-Pb zircon age range for the Newry Igneous Complex (c. 414–407 Ma, Condon pers. comm.). The Anderson & Oliver date, if correct, would support lamprophyre intrusion slightly before or overlapping with the main period of pluton formation. Given the error attributed to the Ballyferris K-Ar age and the different dating methods used, caution is required in making this inference and unfortunately there are no mapped, small-scale field relationships to support it, although regionally, lamprophyres are not recorded as occurring within the Newry Igneous Complex (GSNI 1997).

In the Midland Valley terrane, a small number of undated intrusions, described as lamprophyre on the Pomeroy 1:50,000 scale sheet (GSNI 1979), occur northeast of Pomeroy (Fig. 1b) within Upper Ordovician and lower Silurian sedimentary rocks of the Pomeroy Inlier.

The Grampian terrane of Ireland contains by far the greatest volume of Late Caledonian granitic intrusions in the north of Ireland (Fig. 1b). The Donegal granitoids are composed of monzogranites and granodiorites, with lesser monzodiorites, and minor tonalite, quartz diorite and quartz monzonite (Atherton & Ghani 2002). Appinites are commonly associated with the ‘mafic’ Donegal suite (Fanad, Thorra and Ardara), particularly the Ardara pluton (Pitcher & Berger 1972). Despite the Donegal granites being studied and mapped over a number of decades, they have not been systematically dated using robust high-precision geochronological

138 techniques. Existing published radiometric age constraints are based on K-Ar (e.g.
139 Pitcher and Berger, 1972), Ar-Ar (muscovite; Fitch & Millar 1980), Rb-Sr (whole
140 rock; e.g. O'Connor *et al.* 1987), as well as U-Pb (uraninite from pegmatite;
141 O'Connor *et al.* 1984) and give age ranges between 418 and 372 Ma. The younger
142 ages within this range are exclusively K-Ar, Ar-Ar and Rb-Sr ages and may not
143 represent true magmatic ages due to the relatively low closure temperatures of these
144 isotope systems.

145 The dated intrusion featured herein is one of a trachy-andesitic, high-K-Ba-Sr,
146 calc-alkaline suite now recognised to intrude the Dalradian Supergroup of the
147 Grampian terrane in the western Sperrin Mountains and eastern County Donegal (Fig.
148 1b). The intrusions occur mainly within County Tyrone and are not numerous, with
149 less than ten represented on the entire Newtownstewart 1:50,000 sheet (GSNI 2008),
150 a similar number on the Strabane sheet (GSNI 2013), and one each on the Dungiven
151 sheet (GSNI 2007a), Draperstown sheet (GSNI 1995a), and Omagh sheet (GSNI
152 1995b, not identified during its survey). In County Antrim, only two lamprophyres
153 have been mapped intruding Dalradian country rocks on the Ballycastle 1:50,000
154 sheet (GSNI 2002).

155

156 **The significance of deep-seated lineaments**

157 Deep-seated lineaments in the UK and Ireland (see Russel & Hazeldine 1992; Hutton
158 & Alsop 1996) are enigmatic in that they are often rather weak features on both
159 gravity and magnetic anomaly images. An exception to this is the Draperstown
160 Lineament (Fig. 1b) which was investigated by Earls *et al.* (2000) and is clearly
161 visible on the Bouguer anomaly map of Ireland (Readman *et al.* 1997). Such
162 lineaments are more often inferred, for example, through the occurrence of regional
163 strike swing, occurrences of mapped faults, mineral veins and igneous complexes. In
164 Ireland the influence of lineaments on the formation of such features and bodies spans
165 from the Neoproterozoic to the Palaeogene and as such they represent long-lived, pre-
166 Caledonian crustal structures. A striking aspect of the lineaments recognised in this
167 study (Fig. 1b) is their straightness and parallel spacing which ranges from *c.* 10–35
168 km.

169 It is well known and documented that many of the major Late Caledonian
170 granites of Ireland were emplaced in dilational zones associated with major
171 movements on sinistral shear zones and faults (e.g. Donegal: see Chew & Stillman
172 2009; Galway: Crowley & Feely 1997). However, a number of these granites, and

173 associated appinites and lamprophyres, are also associated with crustal lineaments
 174 (Fig. 1b). Examples include the main Donegal granite which is bounded by the Fanad
 175 and Donegal lineaments, and more specifically the Ardara, Thorr, Rosses and Toories
 176 plutons which are located on the latter (see Hutton & Alsop 1996). The Newry
 177 Igneous Complex (Cooper & Johnston 2004a) shows a similar relationship to the
 178 Argyll and Newry lineaments, with the Argyll Lineament passing through the oldest,
 179 north-eastern end of the complex and continuing south, right through the middle of
 180 the Palaeogene Mourne Mountains granites (Cooper & Johnston 2004b). The Newry
 181 Lineament is associated with the youngest, south-western pluton of the Newry
 182 Igneous Complex, but also hosts the Palaeogene Slieve Gullion and Tardree central
 183 complexes (Fig. 1b). At its most northerly projection in Northern Ireland the Newry
 184 Lineament coincides with sparse Late Caledonian lamprophyres in NE County
 185 Antrim (GSNI 2002). The Draperstown Lineament is associated with lamprophyres
 186 that occur within the Pomeroy Inlier (Cooper & Mitchell 2004) and also coincides
 187 with a swing in the Tow Valley Fault that connects it to the Omagh Thrust (GSNI
 188 1997). Two further lineaments are proposed, these are: the Cavan Lineament that
 189 passes through the Late Caledonian Crossdoney Pluton near Cavan (Fig. 1a), County
 190 Cavan (Skiba 1952; Chew & Stillman 2009) and the Curraghinalt gold deposit in
 191 county Tyrone; and the Kingscourt Lineament that defines the western side of the
 192 Kingscourt outlier in County Louth (Fig. 1a).

193 The Omagh Lineament (Fig.1b) is not visible on existing geophysical images,
 194 e.g. Tellus survey geophysics (GSNI 2007b), but is recognised by the location of
 195 mineral veins including the Cavanacaw gold deposit and working mine (Parnell *et al.*
 196 2000), a significant strike swing in Dalradian rocks (GSNI 1997) and the eastern limit
 197 of a prominent Bouguer anomaly known as the Dromore High (Reay 2004). Figure
 198 1b shows that the Sperrin Mountains suite occurs mainly to the west of the Omagh
 199 Lineament, towards the Fanad Lineament and the Donegal Batholith. However, the
 200 intrusions have invaded Dalradian Supergroup strata by up to 5 km to the east of the
 201 lineament. Orientation of the intrusions is variable (NNE–NE with some examples
 202 of NW) but mainly reflects the dominant strike of the country rock. The distribution
 203 of intrusions relative to the Omagh Lineament supports movement of magma from
 204 west to east, whilst the orientation of the bodies supports injection into a block
 205 experiencing sinistral transtension (Leslie pers. Comm.). The field relationships seen
 206 at Ballynamallett Quarry [24815 39915] (Fig. 1b), where a dyke is observed to
 207 intrude along a steeply inclined fault surface and then jump orthogonally across the

208 regional schistosity creating a step (Fig. 2a), is best explained by intrusion of magma
209 into a sinistrally deforming rock mass.

210

211 **Sample selection and petrography**

212 Samples for petrography and geochemistry were collected during geological survey
213 from intrusions located across the Sperrin Mountains. The dated sample (MRC 93)
214 was taken from an intrusion well exposed in Letterbrat Quarry [24715 39235], 1.5 km
215 northwest of Plumbridge, County Tyrone (Fig. 1b). Figure 3 shows that at the time of
216 sample collection, near the floor of the quarry, the intrusion is a 1–2 m thick dyke that
217 cuts steeply through schistose psammites. On the first bench of the quarry the dip
218 flattens and the intrusion thickens to 6–7 m within schistose semipelites that contain
219 numerous thrust surfaces (Fig. 2b). The intrusion cuts across these thrusts and
220 continues to traverse the main regional (S2) schistosity to the top of the quarry.
221 Elsewhere in the Sperrin Mountains the intrusions are emplaced along thrusts and this
222 is so often the case, that they can be used to help locate and map such tectonic
223 discontinuities (GSNI 2008, 2013). At regular positions on the Letterbrat Quarry
224 face, the intrusion is cut by high-angle normal faults with throws of <1 m and
225 associated, localised sulphide mineralisation. A 20 kg sample was taken for U-Pb
226 zircon geochronology, avoiding chilled margins, faults and other discontinuities,
227 mineralised/altered rock and xenoliths of country rock.

228 Sample MRC 93 is a trachy-andesite (Merriman & Hards 2000) composed of
229 feldspar (20%), amphibole (10%), and biotite (5%) phenocrysts in a fine-grained
230 feldspathic groundmass (65%) (Fig. 2c). Large (<10 mm) phenocrysts of zoned,
231 simply twinned plagioclase are heavily altered to white mica with patches and veins
232 of carbonate. Compositionally similar plagioclase also forms microphenocrysts (<1
233 mm). Colourless to pale brown microphenocrysts of clinopyroxene form 1–1.5 mm
234 long subhedral laths and prismatic sections. These and minor amphibole
235 microphenocrysts (<1.5 mm) have been variably replaced by intergrown green clay
236 (chlorite-smectite?), white mica, carbonate and Fe-oxide granules. Biotite flakes (<1
237 mm), many of which enclose unaltered apatite crystals, are partially replaced by white
238 mica, titanite and carbonate. The groundmass consists of intergrown anhedral crystals
239 of feldspar (<0.2 mm), Fe (Ti)-oxide, secondary white mica, carbonate and green clay
240 minerals.

241 Fifteen thin sections from minor intrusions on the Newtownstewart and
242 Strabane 1:50,000 sheets (GSNI 2008, 2013) were also examined. The samples

243 showed some variation in colour, mainly relating to the degree of alteration, but all
244 share a similar overall mineralogy to MRC 93 with the exception of MRC 334. The
245 latter is composed of brown amphibole (52%), plagioclase feldspar (45%) and
246 magnetite (3%) and as such classifies as a hornblende lamprophyre (spessartite).

247

248 **U-Pb zircon geochronology**

249 *Analytical techniques*

250 Heavy mineral concentrates were obtained at the NERC Isotope Geosciences
251 Laboratory (NIGL) using standard crushing techniques, a Gemini™ table, modified
252 superpanner, a Frantz LB1 magnetic separator, and heavy liquids. Minerals were
253 selected for analysis by hand picking in alcohol under a binocular microscope.
254 Zircons were either air-abraded (Krogh 1982), or chemically abraded (Mattinson
255 2005) to improve concordance. The latter method involved annealing zircons at 900
256 °C for 60 hours, followed by partial dissolution at 180 °C for 12 hours in 29N HF and
257 trace 8N HNO₃ to selectively remove the most damaged domains. Zircons containing
258 melt and mineral inclusions were snapped prior to chemical abrasion to permit access
259 for the leaching acids. Grains were washed in 6N HCl and ultrapure water prior to U-
260 Pb chemistry. Chemical procedures followed Krogh (1973) with modifications (Corfu
261 & Noble 1992). Procedural blanks ranged from ~ 20 pg to ≤2 pg Pb and <0.5 pg U.
262 Data were obtained on VG354 and Triton Thermal Ionisation Mass Spectrometers
263 (TIMS).

264 Correction for common Pb in excess of laboratory blank was made using a
265 Stacey & Kramers (1975) model Pb composition based on the zircon ²⁰⁷Pb/²⁰⁶Pb ages,
266 with a 2% error on the common Pb compositions propagated through data reduction
267 calculations. Concordia, and upper and lower intercept age calculations, followed
268 Ludwig (1998, 2003), using the decay constants of Jaffey *et al.* (1971). Uncertainties
269 quoted for isotope ratios and ages in Table 1 are at the 2σ level.

270

271 *Results*

272 MRC 93 zircons display a wide range of morphologies from well rounded to well
273 faceted. The majority are equant to very elongate, and cores were clearly visible in a
274 significant proportion. Figure 4a presents all six U-Pb zircon analyses on a
275 Concordia diagram and illustrates that two air abraded zircon fractions (Z5 and Z6)
276 have inherited components. Figure 4b is an enlargement of the lower part of Figure 4a
277 illustrating four U-Pb zircon analyses comprising multi-grain air abraded fractions

(Z3 and Z4) together with single grain (Z1) and multi-grain (Z2) chemically abraded fractions. Fractions Z3 and Z4 are elongate grains and yield modestly discordant results due to Pb-loss. Fraction Z1 gives a concordant $^{206}\text{Pb}/^{238}\text{U}$ age of 426.69 ± 0.85 Ma, whereas Z2 is slightly discordant due to a minor inherited component. In order to investigate if any of the discordant analyses have a *c.* 427 Ma component, several regressions were attempted. Three separate regressions yield ages of 426.6 ± 2.9 (Z1, Z3 and Z4: MSWD = 0.91), 426.24 ± 0.96 (Z1, Z2 and Z6: MSWD = 0.44) and 427.6 ± 1.3 Ma (Z1, Z2 and Z5: MSWD = 0.97). The three point discordia have low MSWD values and indicate that all analysed zircon fractions have a *c.* 427 Ma aged component. The $^{206}\text{Pb}/^{238}\text{U}$ age of the chemically abraded, concordant, single grain fraction Z1 (426.69 ± 0.85 Ma; mid-Silurian) is taken as the age of the trachy-andesite and straddles the Wenlock–Ludlow boundary (IUGS 2012).

290

291 **Geochemistry**

292 *Analytical techniques*

293 Eight samples were analysed for major, trace and rare-earth elements from the
294 Sperrin Mountains suite. Major elements were determined for powdered whole-rock
295 samples on fused glass beads by X-ray Fluorescence Spectrometry (XRF) at the
296 British Geological Survey (BGS) in Nottingham. Samples were dried at 105 °C
297 before loss on ignition (LOI) and fusion. LOI was determined after 1 hour at 1050
298 °C. $\text{Fe}_2\text{O}_3\text{t}$ represents total iron expressed as Fe_2O_3 . SO_3 represents sulphur retained
299 in the fused bead after fusion at 1200 °C. Trace elements were analysed on pressed
300 powder-pellets by XRF. Rare earth elements (REE, plus Nb, Y, Hf, Ta, Th, U) were
301 determined by inductively coupled plasma mass spectrometry (ICP-MS). Samples
302 were subjected to an $\text{HF}/\text{HClO}_4/\text{HNO}_3$ attack with residues fused with NaOH before
303 solutions were combined. Geochemical results (Table 3) are presented as
304 Supplementary Material.

305 Hf-Zr-Y-REE solutions were saved from U-Pb column chemistry washes of
306 single grain zircon fractions. Washes from the most concordant fractions were
307 selected for Hf-isotope analysis on a Nu Plasma MC-ICP-MS at NIGL. Unspiked
308 solutions were dried down and converted to dilute HNO_3 -HF solutions with no further
309 chemical pre-treatment prior to analysis. The isobaric interference correction for
310 ^{176}Yb was determined prior to each analytical session using Yb-doped JMC475 Hf
311 standards. This correction was determined for total Yb/Hf ratios of up to 0.3. These
312 data were used to calculate a true ratio for the $^{176}\text{Yb}/^{173}\text{Yb}$ of 0.79488. The Lu

interference correction used the ratio of 0.02653 for $^{176}\text{Lu}/^{175}\text{Lu}$. During the measurement ^{173}Yb and ^{175}Lu peaks were monitored and a correction applied using these ratios. Spiked and unspiked reference solutions were analysed to monitor instrumental performance and effectiveness of the corrections. The average of standard measurements obtained was used to normalise sample results relative to an assumed $^{176}\text{Hf}/^{177}\text{Hf}$ value of 0.282160 for JMC475. Fifteen determinations of JMC475 yielded a mean of 0.282186 ± 0.000012 (2σ). The average $^{176}\text{Hf}/^{177}\text{Hf}$ value obtained from three measurements of the 91500 zircon standard was 0.282299 ± 20 (2σ), after normalisation to the JMC475 standard measurements. The average non-normalised $^{178}\text{Hf}/^{177}\text{Hf}$ for three 91500 zircon analyses obtained was 1.467303 ± 20 (2σ). Combined internal and external errors are quoted at the 2σ level.

Geochemistry of the Sperrin Mountains suite

The geochemistry of the Sperrin Mountains suite is presented in Figure 5(a–i). All rocks sampled form part of a high-K-Ba-Sr, calc-alkaline series (Fig. 5a) characterised by high total alkali contents (7.13–8.99 wt.% $\text{Na}_2\text{O}+\text{K}_2\text{O}$) and high $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios (0.73–2.47). Most samples are peraluminous apart from MRC 276 and MRC 334 which are metaluminous (Fig. 5b). Samples are slightly enriched in Zr (≤ 167 ppm; Fig. 5c) and are characterised by very high Ba (≤ 1046 ppm) and Sr (≤ 687 ppm); and low Rb (≤ 114 ppm), Th (≤ 9 ppm), U (≤ 2.9 ppm) and Nb (≤ 14 ppm). As the rocks are variably altered element mobility may have occurred. However, in a Zr/Ti-Nb/Y plot featuring ratios of immobile elements (Fig. 5d), the samples fall within the trachy-andesitic field. Rare earth element (REE) profiles are consistent with other Late Caledonian granites and minor intrusions showing LREE enrichment relative to the HREE (Fig. 5e). Immobile multi-element variation diagrams display negative Nb, Y and high field strength element (HFSE) anomalies relative to chondrite (Fig 5e, 5g). Eu anomalies are weak or absent (Fig. 5e). HFSE contents are typically low ($\text{Ta} < \text{detection}_{[2\text{ppm}]}$). All samples show large negative Pb anomalies relative to chondrite (Fig 5g).

Petrographically sample MRC 334 is a hornblende lamprophyre and is geochemically distinct from all other intrusive rocks analysed. This sample plots in the basaltic trachy-andesite field on a Total Alkali–Silica diagram (Fig. 5a) and is strongly metaluminous (Fig. 5b). MRC 334 and MRC 93 were the only analyses to plot in the shoshonite series rather than the high-K calc-alkaline series (Peccerillo & Taylor 1976: not shown). MRC 334 is characterised by higher: TiO_2 , $\text{Fe}_2\text{O}_{3\text{T}}$, MgO ,

348 CaO, P₂O₅, Sr, Nb, Y, V, Cr and Ni concentrations than others samples analysed,
349 and higher Ba than all samples except MRC 276 and MRC 357. SiO₂, Th, U and Rb
350 concentrations are lower. Figure 5e shows MRC 334 has a similar multi-element
351 variation profile to the rest of the Sperrin Mountains suite, but with higher overall
352 REE and HFSE concentrations and a less pronounced negative Nb anomaly due to
353 higher Nb and lower Th (Fig. 5e, 5g). HREE and HFSE concentrations are low (Yb =
354 2.31 ppm, Ta < detection [2ppm]). The more primitive geochemical characteristics of
355 sample MRC 334 (e.g. higher Ba-Sr, Ni, Cr, Co and V, low Th), the only hornblende
356 lamprophyre analysed, has important implications for the petrogenesis of the Sperrin
357 Mountains suite (see below).

358

359 *Zircon Hf- isotopes*

360 Initial ¹⁷⁶Hf/¹⁷⁷Hf values, recalculated as εHf_(T), represent the Hf-isotope
361 composition at the time of zircon crystallization and provide information about the
362 pre-zircon crystallisation evolutionary history of the sources (Amelin *et al.* 1999;
363 Blichert-Toft & Albarède, 1997; Stevenson & Patchett 1990; Vervoort & Patchett
364 1996). The average normalised ¹⁷⁶Hf/¹⁷⁷Hf value obtained from three inheritance free
365 zircon fractions of the trachy-andesite sample MRC 93 is 0.282680 ± 20 (2σ) (Table
366 2). The individual ¹⁷⁶Hf/¹⁷⁷Hf values equate to εHf_(T) of c. +5.0 to +6.0. Lu–Hf model
367 ages are calculated by back extrapolation of crustal evolution paths. Zircons
368 crystallised from a juvenile source will give Hf depleted mantle model ages (T_{DMHf})
369 close to their U-Pb zircon crystallisation age. The T_{DMHf} for three zircon fractions
370 presented here (Z1, Z3 and Z4) are c. 800 Ma. The petrogenetic and tectonic
371 significance of the Hf-isotopes for this sample is discussed below.

372

373 **Geochemistry of Late Caledonian high Ba-Sr suites**

374 *Irish Caledonides*

375 In the Irish Caledonides, major and trace-element geochemical characteristics
376 of the Donegal granitoids have been discussed in detail by Azman & Atherton (2008)
377 and Ghani & Atherton (2008) as summarised below. They all belong to the same
378 high K, calc-alkaline series (Ghani & Atherton 2008). Low ⁸⁷Sr/⁸⁶Sr ratios (< 0.707,
379 typical of an enriched source), and the presence of amphibole and titanite, are
380 consistent with their I-type, metaluminous nature. No geochemical domains are
381 apparent in the Grampian terrane of the Irish Caledonides, where high Ba-Sr plutons
382 can be found with their low Ba-Sr equivalents (Ghani & Atherton 2008). However,

383 two distinct geochemical groupings have been identified (after Ghani & Atherton
384 2008):

385 (i) A 'mafic' suite characterised by quartz monzodiorite, granodiorite and
386 granite is represented by the Ardara (Fig. 1b), Thorra and Fanad plutons. These
387 contain very high Ba, Sr, high Na, P and Zr, and typically low Rb, Th, Nb, Rb/Zr and
388 Rb/Sr (Ghani & Atherton 2008; Tarney & Jones 1994). Hornblende is common in
389 these rocks reaching up to 15 %. This suite appears to be analogous to the Argyll
390 Suite (Stephens & Halliday 1984), now termed the Argyll and Northern Highlands
391 Suite (Stephenson *et al.* 1999), of late granites in the SW Scottish Highlands.
392 Appinites are commonly associated with the 'mafic' Donegal suite (Fanad, Thorra and
393 Ardara), particularly the Ardara pluton. The Fanad pluton also has appinitic
394 affinities, with compositions related to the associated lamprophyric dykes (Pitcher &
395 Berger 1972).

396 (ii) A 'felsic' suite, composed principally of biotite granite with some
397 granodiorite, is represented by the Rosses, Barnesmore and Trawenagh Bay plutons.
398 These intrusive rocks are SiO₂ rich, and contain low Sr and Ba, and high Nb, Rb and
399 Th (Ghani & Atherton 2008). This suite appears to be equivalent to the Cairngorm
400 Suite of the NE Highlands, Scotland (see Stephens & Halliday 1984). Few appinites
401 have been recognised associated with this suite.

402 The geochemical characteristics and the proximity of the Sperrin Mountains
403 suite to the Donegal granitoids, in particular the Ardara pluton and its associated
404 appinitic bodies (Fig. 1b), suggests they may be related by some underlying process.
405 Geochemical data presented herein indicates that the 'mafic' Donegal suite, appinites
406 and trachy-andesite to shoshonitic intrusions are part of a high-K, calc-alkaline series,
407 in the north of Ireland Grampian terrane, characterised by high Ba, Sr and low Nb and
408 Th (Fig. 5c, f–g).

409 It is noteworthy that Ba-Sr enriched lamprophyres, syenites, trachy-andesites
410 and microgranites also occur in eastern Ireland in the Longford–Down terrane
411 (Vaughan 1996), which further supports the absence of “domaining” in the Irish
412 Caledonides. Many of Longford–Down terrane intrusions display similar
413 geochemical characteristics to those presented herein (e.g. Fig. 5i), except Na₂O+K₂O
414 contents which are typically higher in the Grampian terrane. Average total alkali
415 contents of lamprophyres and trachy-andesites of eastern Ireland are 4.60 and 6.16
416 wt.% Na₂O+K₂O respectively (Vaughan 1996), compared to 6.40 and 8.17 wt.% of
417 the rocks analysed herein.

418

419 *Scottish Caledonides*

420 In the Scottish Caledonides, Stephens and Halliday (1984) recognised three
 421 magmatic suites with contrasting geochemistry and geographic distribution. The
 422 Grampian terrane hosts the Argyll and Cairngorm suites. The former is restricted to
 423 the SW Highlands and characterized by high Ba-Sr, low Nb, Th and Rb and calc-
 424 alkalic, high Na geochemical compositions (Fig. 5i). Intrusive rocks are
 425 predominantly biotite granites with abundant appinites. By contrast, the Cairngorm
 426 suite, restricted to the NE Highlands, is a highly silicic and metaluminous group of
 427 diorites and granodiorites (with few appinites), characterised by high Nb, Rb, Th, and
 428 low Ba and Sr. A third suite, predominantly occurring in the Southern Uplands
 429 terrane, but with some intrusions in the Grampian and Midland Valley terranes, was
 430 referred to as the ‘South of Scotland suite’ (Stephens & Halliday 1984). This is
 431 characterised by calc-alkalic diorites and granodiorites with low La, Ce, Ba and Sr.

432 In the SW Grampian Highlands the Lorn lava pile, dated at *c.* 425–426 Ma, is
 433 composed of andesitic and dacitic lavas many of which exhibit high Ba and Sr
 434 (Neilson *et al.* 2009). Although some authors have suggested that the appinite suite of
 435 the W Highlands of Scotland preceded intrusion of granitic magmas in the region
 436 (e.g. Rogers & Dunning 1991), Neilson *et al.* (2009) demonstrated that for the
 437 Glencoe region appinitic melts were generated over an extended period of at least 15
 438 m.y. between *c.* 430 and 415 Ma. An appinitic magma however, typically fractionates
 439 to yield a syenite-trachyte, rather than a trachy-andesite (e.g. Fowler & Henney
 440 1996), so it is unlikely there is a direct petrogenetic link between the two magma
 441 types. Any petrogenetic model explaining the genesis of these intrusive rocks must
 442 account for a separate source for the intermediate andesite to trachy-andesite magmas
 443 in comparison to other broadly contemporaneous magma types.

444

445 **Source of magmatism**

446 The source of the high-K, high Ba-Sr Late Caledonian magmas has been a
 447 contentious topic for a number of decades (e.g. Rock & Hunter 1987; Fowler &
 448 Henney 1996; Fowler *et al.* 2008; Ghani & Atherton 2008). The significance of high-
 449 K small melt fractions from the lithospheric mantle was first recognised by McKenzie
 450 (1989) who stated that such melts generally crystallise at depth and may form a
 451 metasomatic layer within the lithosphere. Re-melting of this geochemically
 452 distinctive layer may occur during heat conduction or decompression by extension

453 and can be triggered by a substantially smaller change to the lithospheric thermal
454 structure than that which is required to produce “dry melting”. More recently, it has
455 been suggested that because the high-K and Ba-Sr signature persists through the
456 fractionation of this Late Caledonian suite, and is traceable to the most mafic rocks,
457 these magmas are mantle derived (e.g. Fowler & Henney 1996; Canning *et al.* 1996;
458 Fowler *et al.* 2001). Specifically, partial melting of enriched sub-continental
459 lithospheric mantle would give rise to appinite-lamprophyre magmas with the
460 observed composition (Neilson *et al.* 2009). Appinites, which are the plutonic
461 equivalents of hornblende-rich and calc-alkaline lamprophyres, have been interpreted
462 as small degree partial melts of metasomatised subcontinental lithospheric mantle or
463 melts of metasomatic veins within it (Ghani & Atherton 2008). High-K and
464 shoshonitic affinities together with the alkali rich nature of the mafic rocks, highly
465 fractionated REE patterns with small Eu anomalies and low HFSE, may also suggest
466 equilibration with amphibole in the source (Canning *et al.* 1998) and the presence of
467 K-amphibole or phlogopite as residual phases (Canning *et al.* 1998; Ghani &
468 Atherton 2008).

469

470 **Slab breakoff model**

471 Slab breakoff was defined by Davies and von Blanckenburg (1994) as “the
472 buoyancy-driven detachment of subducted oceanic lithosphere from the light
473 continental lithosphere that follows it during continental collision”. Once initiated in
474 locally thermally weakened crust, lateral migration of slab breakoff is a rapid process
475 resulting in a linear trace of magmatism. Petrogenetic characteristics of magmatism
476 produced in this manner may include: (i) small degrees of partial melting of
477 lithospheric mantle, (2) compositionally diverse magmatism possibly reflecting
478 source heterogeneity and / or partial melting at differing depths, (3) voluminous
479 silicic magmatism produced by further heating and decompression. Ghani & Atherton
480 (2008) and Neilson *et al.* (2009) proposed models for the Grampian terrane whereby
481 slab breakoff following underthrusting of Avalonia (or more likely Ganderia) led to
482 the rise of hot asthenosphere. Their models explain the close spatial, temporal and
483 geochemical characteristics observed in Late Caledonian intrusions across the British
484 and Irish Caledonides. The rise of asthenosphere most likely occurred through the
485 break between the oceanic and continental lithosphere. As the thick metasomatised
486 and veined lithosphere underwent partial melting, the base of the crust would have
487 been underplated with lamprophyric magma. We would contend that some of this

488 ascended through deep-seated, crustal lineaments (e.g. the Omagh Lineament) to
489 produce the high level Late Caledonian lamprophyre dykes (e.g. MRC 334) and
490 appinite complexes within the crust. Sinistral transtension, acting upon the crust at
491 this time, provided the spaces into which the magma could flow and be
492 accommodated. Continued uplift resulted in melting first at the base of the crust and
493 then at shallower levels. As the sites of partial melting moved through the crust they
494 became progressively more contaminated with continental material, but due to mixing
495 of magmas from different sources they retained a mantle component. Decreasing Ba-
496 Sr enrichment (an indicator of the mantle component) with time is also reflected in
497 the 'mafic' and 'felsic' Donegal plutons (Ghani & Atherton 2008). The close spatial
498 association between appinite–lamprophyre and intermediate–silicic magmas indicates
499 that both magma types ascended to the upper crust along the same pathways even
500 though the magma types are genetically unrelated. It is envisaged that the trachy-
501 andesite intrusions also formed during this partial melting event as these share some
502 geochemical characteristics with the Donegal 'mafic' granitoids.

503 Atherton & Ghani (2002) suggested that progressive slab detachment from the
504 earlier Laurentia-Baltica collision produced a linear uplift belt with a singular, peaked
505 pulse of magmatism related to migration of the heat source from northeast to
506 southwest (i.e. from Scotland towards Donegal). Although slab break-off does follow
507 a linear trend, the resulting heat flux and magmatism is considered to be of local (10s
508 of km) rather than regional significance (Davies & von Blanckenburg 1994). The
509 significance of this is that a slab break-off event generating magmatism in the SW
510 Scottish Highlands would be unlikely to result in magmatism >200 km along strike to
511 the west in Donegal. Also, the predominant spatial distribution of the Sperrin
512 Mountains suite west of the Omagh Lineament, suggests that it acted to limit
513 eastward propagation of magma. We therefore propose a separate slab break-off event
514 centred under the Donegal granites which propagated eastwards. An implication of
515 such a scenario is that this east-wards migrating heat flow and magma generation
516 model is more compatible with slab break-off subsequent to collision of Ganderia-
517 Avalonia and Laurentia, rather than the Laurentia-Baltica collision suggested by
518 Atherton & Ghani (2002). Further robust U-Pb zircon age constraints will be needed
519 for the Donegal granites and related intrusions to ascertain if they display a similar
520 age range to the magmatism of Glencoe and Lorn (Neilson *et al.* 2009). This will help
521 to determine if a model of progressive, short-lived slab detachment (Atherton &

522 Ghani 2002) or one of long-lived heat flow from upwelling mantle asthenosphere
523 associated with this slab-detachment process is supported.

524 Moore and Kokelaar (1998) suggested that central volcanoes may have
525 formed above the Donegal granites but have since been removed by uplift and
526 erosion. This may account for the absence of *large* volumes of intermediate magmas
527 in the north of Ireland Grampian terrane. In Scotland, andesites or eroded remnants of
528 andesitic volcanic rocks can be found in Lorn, Kerrera, Glencoe and Ben Nevis
529 (Browne *et al.* 2002; Kokelaar & Moore 2006), indicating that large volumes of
530 intermediate volcanic rocks were being extruded and eroded in the Grampian Terrane
531 from at least *c.* 426 Ma.

532

533 **Implications for crustal structure of NW Ireland**

534 For the SW Grampian Highlands, Neilson *et al.* (2009) suggested an earlier
535 mafic LILE enriched (subduction related) mantle derived underplating event occurred
536 at *c.* 1.8 Ga (i.e. the age of the Rhinns Complex; Lowey *et al.* 2003, Muir *et al.* 1992)
537 and that re-melting of this material by intrusion and interaction of the lamprophyre-
538 appinite series generated intermediate magmas. Such a model is compatible with
539 whole-rock Sr-Nd-Pb isotope evidence for Scottish Grampian magmatism (e.g.
540 Thirlwall 1981, 1986). It is unclear however, if a juvenile melt at *c.* 1.8 Ga also
541 underlies the Grampian terrane in Ireland. Inherited Palaeoproterozoic zircons are
542 known from the Tyrone Igneous Complex (Cooper *et al.* 2011), but these may be late-
543 stage contaminants, rather than reflecting a Palaeoproterozoic age component in the
544 source. Based on U-Pb ages and Hf-isotope systematics of zircon, Flowerdew *et al.*
545 (2009) suggested that Archean (Lewisian or Lewisian derived) and juvenile
546 Palaeoproterozoic (Rhinns or Annagh Gneiss) basement sources occur at depth
547 beneath different parts of NW Ireland. Partial melting of these Archean or
548 Palaeoproterozoic sources at *c.* 427 Ma (i.e. the time of intrusion of the Sperrin
549 Mountains suite) would result in a zircon ϵHf_{427} of *c.* -25 to -37 or *c.* 0 to -19
550 respectively. Partial melting from a depleted mantle source with no re-melting of
551 previously formed zircon would yield a zircon ϵHf_{427} of *c.* +16. None of these
552 scenarios match with an ϵHf of +5 to +6 derived from the trachy-andesite zircons in
553 this study. It is apparent therefore that single component partial melting of any of
554 these sources was not responsible for producing the trachy-andesite suite. A zircon
555 ϵHf of +5 to +6 is consistent a number of possible petrogenetic models, including
556 partial melting of supra-subduction (i.e. metasomatised) mantle together with crustal

assimilation and partial melting of pre-existing zircon in the source. The exact nature of this pre-existing source is not clear. Whereas partial melting of a Palaeoproterozoic source involving partial dissolution of Rhinns or Annagh Gneiss zircon coupled with partial melting directly from the mantle at 427 Ma could yield the observed ϵ_{Hf} for the trachy-andesite zircons, other possible source mixtures cannot be ruled out. It is noted that 800 Ma ages ($T_{\text{DM}}^{\text{Hf}}$ obtained herein) are not typical of Eastern Laurentia. Ganderia, however has a c. 550 to 800 Ma detrital zircon signature (van Staal *et al.* 1996) and Nd model ages of some felsic volcanic and plutonic rocks from Avalonia and Ganderia (e.g. Barr & Hegner 1992; Kerr *et al.* 1995) overlap with the Hf model ages of zircons in this study. It is more likely however that rather than reflecting the age of the source, these model ages reflect mixtures of different sources (i.e. partial melting from heterogeneous lithospheric mantle and compositionally and temporally distinct crustal components). No zircon Hf data exist for the Donegal granites, but a similar argument can be proposed on the basis of whole rock Nd model ages (Dempsey *et al.* 1990). The Ardara pluton gives the youngest Nd model age (c. 500 Ma), the Thorr, Rosses and Barnesmore granites give intermediate Nd model ages (c. 700 to 1100 Ma) and Main Donegal granites yields older Nd model ages (c. 1200 to 1500 Ma). This apparent “age” trend may reflect an increasing crustal/decreasing mantle component mixture. The Ardara pluton, which features the highest ϵ_{Nd} values (-1.2) and youngest Nd model age for the Donegal granites is also associated with a large number of appinitic intrusions, so the whole rock Nd isotope systematics may be reflecting a more dominant mantle-derived component compared to the other Donegal granites, rather than a different aged crustal contribution.

580

581 **Summary**

The identification of a Sperrin Mountains suite of trachy-andesite dykes in the north of Ireland is significant in that it demonstrates the presence of intermediate magma compositions over a wider area of the Grampian terrane than previously recognised. A U-Pb zircon age of 426.69 ± 0.85 Ma constrains intrusion of the Sperrin Mountains suite to the mid-Silurian (straddling the Wenlock–Ludlow boundary). This agrees with a growing number of c. 425–427 Ma ages for Late Caledonian magmatic activity in the Grampian and Northern Highlands terranes (e.g. Neilson *et al.* 2009; Kocks *et al.* 2006; Fraser *et al.* 2004; Stewart *et al.* 2001; Rogers & Dunning 1991) and permits re-appraisal of previously correlated magmatic and tectonic events across a broad area of Ireland and Scotland.

592 It is proposed that the Omagh Lineament and other similarly orientated
593 structures have played a significant role in the emplacement and location of plutons
594 and swarms of minor intrusions, whereby, the transfer of magma occurs from deep-
595 seated, crustal lineaments into accommodation spaces at higher levels that are
596 provided by faults and blocks undergoing strike slip tectonics. The distribution of the
597 Sperrin Mountains suite, predominantly west of the Omagh Lineament, supports
598 eastward migration of melt.

599 Geochemical comparison of the Sperrin Mountains suite with Late Caledonian
600 intrusions from across the Scottish and Irish Caledonides reveals a close association
601 to the 'mafic' suite of Donegal (particularly the Ardara and Fanad plutons), and the
602 Argyll and Northern Highlands Suite (see Figs. 5c, 5f-h). All are characterised by
603 high K, Na, Ba and Sr, and low Rb, Th and Nb (Fig. 5c&f). Although the various
604 Late Caledonian magma types from the north of Ireland are spatially and temporally
605 associated and share some geochemical attributes (i.e. high-K-Ba-Sr), some
606 geochemical differences do exist between the hornblende lamprophyre (MRC 334)
607 and trachy-andesites (Fig. 5). The same geochemical disparity also holds true for
608 appinite-lamprophyre and intermediate magma types elsewhere in the Grampian
609 terrane. Bi-variate trace element variations (e.g. Ba-Sr, Zr-Nb, V-Cr, Y-Zr) indicate
610 that lamprophyric and trachy-andesite magma types represented by samples analysed
611 in this study cannot be related through simple fractional crystallisation. It is likely
612 that the different magma types were generated by partial melting of different sources
613 and at different depths.

614 Zircon Hf-isotope data for the Sperrin Mountains minor intrusion suite do not
615 support a simple petrogenetic model involving partial melting of a single component
616 of typical depleted mantle, or pre-existing Palaeoproterozoic or Archean sources.
617 Instead, we suggest that partial melting of metasomatised lithospheric mantle and
618 some recycling of heterogeneous crustal components occurred. Importantly,
619 Grampian terrane magmatism in general has contributions from both juvenile mantle
620 derived magmas (high Ni and Cr appinites, basalts and basaltic-andesites; Neilson *et al.*
621 2009; Thirlwall 1981) and older pre-existing crustal material (inherited zircons,
622 depleted mantle model ages older than crystallisation ages).

623 The timing of magmatism precludes a direct link with subduction processes,
624 as subduction of Iapetus oceanic lithosphere beneath Laurentia is considered to have
625 ceased by *c.* 430 Ma in this part of the Caledonide belt (Soper *et al.* 1992). Whereas
626 slab break-off has previously been proposed to explain the timing and composition of

627 Late Caledonian magmatic events across the Grampian terrane of Scotland and
628 Donegal (Atherton & Ghani 2002; Neilson *et al.* 2009), our U-Pb zircon age for the
629 Sperrin Mountains suite is the first robust age constraint for this phase of magmatism
630 in the north of Ireland. The geochemical attributes of this Late Caledonian
631 magmatism are consistent with the magmas being generated by slab break-off, which
632 we suggest followed the closure of Iapetus by subduction of Ganderia-Avalonia under
633 the Laurentian margin.

634 Robust geochemical and geochronological evidence for the presence or
635 absence of Avalonia or Ganderia affinity crust at depth under the Laurentian
636 lithosphere of the Grampian terrane of Ireland and the possibility of other sources
637 within this lithosphere (e.g. Archean Lewisian Complex or Palaeoproterozoic Rhinns
638 Complex) would require a systematic U-Pb and Hf-isotope study of magmatic and
639 any inherited zircon components to fully resolve this question.

640

641 **Acknowledgements.** This work and publication was made possible through
642 Northern Ireland Department of Enterprise Trade and Investment funding. We thank
643 Garth Earls, Ian Mitchell (Geological Survey of Northern Ireland), Dan Condon
644 (NIGL), Martin Gillespie and Graham Leslie (BGS) and external reviewers Mike
645 Fowler, Alan Vaughan and Bernard Bingen for reviewing and improving the
646 manuscript. Dee Flight is thanked for assistance during sampling. MRC publishes
647 with permission of the Executive Director of the British Geological Survey (NERC).
648 SPH is supported by the BGS University Funding Initiative (BUFI), Dalradian
649 Resources, GSNI, University of Southampton, Metallum Resources and Natural
650 History Museum, London.

651

652 **References**

653

- 654 AMELIN, Y., LEE, D.-C., HALLIDAY, A.N. & PIDGEON, R.T. 1999. Nature of the Earth's
655 earliest crust from hafnium isotopes in single detrital grains. *Nature*, **399**, 252–
656 255.
- 657 ANDERSON, T.B. 2004. Southern Uplands–Down–Longford Terrane. *In*: MITCHELL,
658 W.I. (ed.) *The Geology of Northern Ireland - Our Natural Foundation, second*
659 *edition*. Geological Survey of Northern Ireland, Belfast, 41–60.

- 660 ANDERSON, T.B. & OLIVER, G.J.H. 1996. Xenoliths of Iapetus suture mylonites in
661 County Down lamprophyres, Northern Ireland. *Journal of the Geological*
662 *Society, London*, **153**, 403–407.
- 663 ATHERTON, M.P. & GHANI, A.A. 2002. Slab break-off: a model for Caledonian, Late
664 Granite syncollisional magmatism in the orthotectonic (metamorphic) zone of
665 Scotland and Donegal, Ireland. *Lithos*, **62**, 65–85.
- 666 AZMAN, A. G. & ATHERTON, M.P. 2008. The chemical character of the Late
667 Caledonian Donegal Granites, Ireland, with comments on their genesis.
668 *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **97**, 437–454.
- 669 BARR, S.M. & HEGNER, E. 1992. Nd isotopic composition of felsic igneous rocks in
670 Cape Breton Island, Nova Scotia. *Canadian Journal of Earth Sciences*, **29**, 650–
671 657.
- 672 BLICHERT-TOFT, J. & ALBARÈDE, F. 1997. The Lu–Hf isotope geochemistry of
673 chondrites and the evolution of the mantle–crust system. *Earth and Planetary*
674 *Science Letters*, **148**, 243–258.
- 675 BLUCK, B.J., GIBBONS, W. & INGHAM, J.K. 1992. Terranes. In: COPE, J. C. W.,
676 INGHAM, J. K. AND RAWSON, P. F. (eds) *Atlas of Palaeogeography and*
677 *Lithofacies, Geological Society of London, Memoirs*, **13**, 1–4.
- 678 BROWNE, M.A.E., SMITH, R.A. & AITKEN, A.M. 2002. Stratigraphical framework for
679 the Devonian (Old Red Sandstone) rocks of Scotland south of a line from Fort
680 William to Aberdeen. *British Geological Survey Research Report*, RR/01/04.
681 67pp.
- 682 CANNING, J.C., HENNEY, P.J., MORRISON, M.A. & GASKARTH, J.W. 1996.
683 Geochemistry of late Caledonian minettes from northern Britain: implications
684 for the Caledonian sub-continental lithospheric mantle. *Mineralogical*
685 *Magazine*, **60**, 221–236.
- 686 CANNING, J.C., HENNEY, P.J., MORRISON, M.A., VAN CALSTEREN, P.W.C.,
687 GASKARTH, J.W. & SWARBRICK, A. 1998. The Great Glen Fault: a major
688 vertical lithospheric boundary. *Journal of the Geological Society, London*, **155**,
689 425–428.
- 690 CHEW, D. & STILLMAN, C.J. 2009. Late Caledonian orogeny and magmatism. In:
691 HOLLAND, C. H. & SANDERS, I. S. (eds) *The Geology of Ireland: Second edition*.
692 143–173.

- 693 CHEW, D.M., DALY, J.S., MAGNA, T., PAGE, L.M., KIRKLAND, C.L., WHITEHOUSE,
694 M.J. & LAM, R. 2010. Timing of ophiolite obduction in the Grampian orogen.
695 *Geological Society of America Bulletin*, **122**, 1787–1799.
- 696 COOPER, M.R. AND JOHNSTON, T.P. 2004a. Late Palaeozoic Intrusives. *In*:
697 MITCHELL, W.I. (ed) *The Geology of Northern Ireland - Our Natural*
698 *Foundation, second edition*. Geological Survey of Northern Ireland, Belfast,
699 61–68.
- 700 COOPER, M.R. AND JOHNSTON, T.P. 2004b. Palaeogene Intrusive Igneous Rocks. *In*:
701 MITCHELL, W.I. (ed) *The Geology of Northern Ireland - Our Natural*
702 *Foundation, second edition*. Geological Survey of Northern Ireland, Belfast,
703 179–198.
- 704 COOPER, M.R., AND MITCHELL, W.I. 2004. Midland Valley Terrane. *In*: MITCHELL,
705 W.I. (ed) *The Geology of Northern Ireland - Our Natural Foundation, second*
706 *edition*. Geological Survey of Northern Ireland, Belfast, 25–40.
- 707 COOPER, M. R., CROWLEY, Q. G., HOLLIS, S. P., NOBLE, S. R., ROBERTS, S., CHEW,
708 D. M., MERRIMAN, R. J., EARLS, G. & HERRINGTON, R. 2011. Age constraints and
709 geochemistry of the Ordovician Tyrone Igneous Complex, Northern Ireland:
710 implications for the Grampian orogeny. *Journal of the Geological Society*,
711 *London*, **168**, 837–850.
- 712 CORFU, F. & NOBLE, S.R. 1992. Genesis of the southern Abitibi greenstone belt,
713 Superior Province, Canada: Evidence from zircon Hf-isotope analyses using a
714 single filament technique. *Geochimica et Cosmochimica Acta*, **56**, 2081–2097.
- 715 CROWLEY, Q.G. & FEELY, M. 1997. New perspectives on the order and style of
716 granite emplacement in the Galway Batholith, western Ireland. *Geological*
717 *Magazine*, **134** (4), 539–548.
- 718 DAVIES, J.H. & VON BLANCKENBURG, F. 1995. Slab breakoff: A model of lithosphere
719 detachment and its test in the magmatism and deformation of collisional
720 orogens. *Earth and Planetary Science Letters*, **129**, 85–102.
- 721 DEMPSEY, C.S., HALLIDAY, A.N. & MEIGHAN, I.G. 1990. Combined Sm-Nd and Rb-
722 Sr isotope systematics in the Donegal granitoids and their petrogenetic
723 implications. *Geological Magazine*, **127**, 75–80.
- 724 DRAUT, A.E., CLIFT, P.D., CHEW, D., COOPER, M.J., TAYLOR, R.N., & HANNIGAN, R.
725 E. 2004. Laurentian crustal recycling in the Ordovician Grampian Orogeny: Nd
726 isotopic evidence from western Ireland. *Geological Magazine*, **144**, 195–207.

- 727 EARLS, G., HUTTON, D., WILKINSON, J. AND BOYCE, A. 2000. The Mineral Potential
728 of the Draperstown Lineament. CSA(NI) Report No. 007.002236.
- 729 FITCH, F.J. & MILLER, J.A. 1980. On the age of the Donegal granite. *Scottish Journal*
730 *of Geology*, **16**, 315–320.
- 731 FLOWERDEW, M.J., CHEW, D.M., DALY, J.S. & MILLAR, I.L. 2009. Hidden Archaean
732 and Palaeoproterozoic crust in NW Ireland? Evidence from zircon Hf isotopic
733 data from granitoid intrusions. *Geological Magazine*, **146**, 903–916.
- 734 FOWLER, M.B. & HENNEY, P.J. 1996. Mixed Caledonian appinite magmas:
735 implications for lamprophyre fractionation and high Ba-Sr granite genesis.
736 *Contributions to Mineralogy and Petrology*, **126**, 199–215.
- 737 FOWLER, M.B., HENNEY, P.J., DARBYSHIRE, D.P.F. & GREENWOOD, P.B. 2001.
738 Petrogenesis of high Ba-Sr granites: the Rogart pluton, Sutherland. *Journal of*
739 *the Geological Society, London*, **158**, 521–534.
- 740 FOWLER, M.B., KOCKS, H., DARBYSHIRE, D.P.F. & GREENWOOD, P.B. 2008.
741 Petrogenesis of high Ba-Sr plutons from the Northern Highland Terrane of the
742 British Caledonian Province. *Lithos*, **105**, 129–148.
- 743 FRASER, G.L., PATTISON, D.R.M. & HEAMAN, L.M. 2004. Age of the Ballachulish
744 and Glencoe Igneous Complexes (Scottish Highlands), and paragenesis of
745 zircon, monazite and baddeleyite in the Ballachulish Aureole. *Journal of the*
746 *Geological Society, London*, **161**, 447–462.
- 747 GEOLOGICAL SURVEY OF NORTHERN IRELAND 1979. Pomeroy, Northern Ireland
748 Sheet 34. Solid Geology. 1:50 000. (Keyworth, Nottingham: British Geological
749 Survey).
- 750 GEOLOGICAL SURVEY OF NORTHERN IRELAND 1995a. Draperstown, Northern Ireland
751 Sheet 26. Solid Geology. 1:50 000. (Keyworth, Nottingham: British Geological
752 Survey).
- 753 GEOLOGICAL SURVEY OF NORTHERN IRELAND 1995b. Omagh, Northern Ireland
754 Sheet 33. Solid Geology. 1:50 000. (Keyworth, Nottingham: British Geological
755 Survey).
- 756 GEOLOGICAL SURVEY OF NORTHERN IRELAND 1997. Northern Ireland. Solid Geology
757 (second edition). 1:250 000. (Keyworth, Nottingham: British Geological
758 Survey).
- 759 GEOLOGICAL SURVEY OF NORTHERN IRELAND 2002. Ballycastle, Northern Ireland.
760 Sheet 8. Solid Geology. 1:50 000. (Keyworth, Nottingham: British Geological
761 Survey).

- 762 GEOLOGICAL SURVEY OF NORTHERN IRELAND 2007a. Dungiven, Northern Ireland
 763 Sheet 18. Solid Geology. 1:50 000. (Keyworth, Nottingham: British Geological
 764 Survey).
- 765 GEOLOGICAL SURVEY OF NORTHERN IRELAND, 2007b. The Tellus project:
 766 *Proceedings of the end-of-project conference,*
 767 *Belfast*, <http://www.bgs.ac.uk/gsni/tellus/conference/index.html>.
- 768 GEOLOGICAL SURVEY OF NORTHERN IRELAND 2008. Newtownstewart, Northern
 769 Ireland Sheet 25. Solid Geology. 1:50 000. (Keyworth, Nottingham: British
 770 Geological Survey).
- 771 GEOLOGICAL SURVEY OF NORTHERN IRELAND 2013. Strabane, Northern Ireland
 772 Sheet 17. Solid Geology. 1:50 000. (Keyworth, Nottingham: British Geological
 773 Survey).
- 774 GHANI, A.A. & ATHERTON, M.P. 2008. The chemical character of the Late
 775 Caledonian Donegal granites, Ireland, with comments on their genesis.
 776 *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **97**, 437–454.
- 777 GRIFFIN, W.L., PEARSON, N.J., BELOUSOVA, E., JACKSON, S.E., VAN ACHTERBERGH,
 778 E., O'REILLY, S.Y., SHEE, S.R. 2000. The Hf isotope composition of cratonic
 779 mantle: LAM-MC-ICPMS analysis of zircon megacrysts in kimberlites.
 780 *Geochimica et Cosmochimica Acta*, **64**, 133–147.
- 781 HARMON, R.S., HALLIDAY, A.N., CLAYBURN, J.A.P. & STEPHENS, W.E. 1984.
 782 Chemical and isotopic systematics of the Caledonian Intrusions of Scotland and
 783 Northern England: A guide to magma source region and magma-crust
 784 interaction. *Philosophical Transactions of the Royal Society of London. Series*
 785 *A, Mathematical and Physical Science*, **310**, 709–742.
- 786 HOLLIS, S.P., ROBERTS, S., COOPER, M.R., EARLS, G., HERRINGTON, R., CONDON,
 787 D.J., COOPER, M.J., ARCHIBALD, S.M. & PIERCEY, S.J. 2012. Episodic arc-
 788 ophiolite emplacement and the growth of continental margins: Late accretion in
 789 the Northern Irish sector of the Grampian-Taconic orogeny. *Geological Society*
 790 *of America Bulletin*, **124**, 1702–1723.
- 791 HUTTON, D.W.H., ALSOP, G.I. 1996. The Caledonian strike-swing and associated
 792 lineaments in NW Ireland and adjacent areas: sedimentation, deformation and
 793 igneous intrusion patterns. *Journal of the Geological Society, London*, **153**,
 794 345–360.
- 795 IUGS 2012. International Chronostratigraphic Chart. International Commission on
 796 Stratigraphy. <http://www.stratigraphy.org/column.php?id=Chart/Time%20Scale>

- 797 JAFFEY, A.H., FLYNN, K.F., GLENDENIN, L.E., BENTLEY, W.C., & ESSLING, A.M.
798 1971. Precision measurements of half-lives and specific activities of ^{235}U and
799 ^{238}U . *Physics Reviews*, **C4**, 1889–1906.
- 800 KERR, A., JENNER, G.A., & FRYER, B.J. 1995. Sm-Nd isotopic geochemistry of
801 Precambrian to Palaeozoic granitoid suites and the deep-crustal structure of the
802 southeastern margin of the Newfoundland Appalachians. *Canadian Journal of*
803 *Earth Sciences*, **32**, 224–245.
- 804 KOCKS, H., STRACHAN, R.A. & EVANS, J.A. 2006. Heterogeneous reworking of
805 Grampian metamorphic complexes during Scandian thrusting in the Scottish
806 Caledonides: insights from the structural setting and U-Pb geochronology of the
807 Strath Halladale Granite. *Journal of the Geological Society, London*, **163**, 525–
808 538.
- 809 KOKELAAR, B.P. & MOORE, I. 2006. Classical areas of British geology: Glencoe
810 caldera volcano, Scotland. British Geological Survey, Keyworth, Nottingham.
- 811 KROGH, T.E. 1973. A low contamination method for the hydrothermal decomposition
812 of zircon and extraction of U and Pb for isotopic age determinations.
813 *Geochimica et Cosmochimica Acta*, **37**, 485–94.
- 814 KROGH, T.E. 1982. Improved accuracy of U-Pb zircon ages by the creation of more
815 concordant systems using an air-abrasion technique. *Geochimica et*
816 *Cosmochimica Acta*, **46**, 637–49.
- 817 LOEWY, S.L., CONNELLY, J.N., DALZIEL, I.W.D. & GOWER, C.F. 2003. Eastern
818 Laurentia in Rodinia: constraints from whole-rock Pb and U/Pb geochronology.
819 *Tectonophysics*, **375**, 169–197.
- 820 LUDWIG, K.R. 1998. On the treatment of concordant uranium-lead ages. *Geochimica*
821 *et Cosmochimica Acta*, **62**, 665–676.
- 822 LUDWIG, K.R. 2003. Isoplot/Ex version 3.0. A Geochronological toolkit for
823 Microsoft Excel. *Berkeley Geochronology Center Special Publication No.4*,
824 70p.
- 825 MCKENZIE, D. 1989. Some remarks on the movement of small melt fractions in the
826 mantle. *Earth and Planetary Science Letters*, **95** (1–2), 53–72.
- 827 MATTINSON, J.M. 2005. Zircon U-Pb chemical abrasion (“CA-TIMS”) method:
828 Combined annealing and multi-step partial dissolution analysis for improved
829 precision and accuracy of zircon ages. *Chemical Geology*, **220**, 47–66.

- 830 MERRIMAN, R.J. & HARDS, V.L. 2000. Petrographic notes on igneous and
831 metamorphic rocks from Northern Ireland. *British Geological Survey Short*
832 *Report MPSR/00/7*.
- 833 MOORE, I. & KOKELAAR, P. 1998. Tectonically controlled piecemeal caldera collapse:
834 A case study of Glencoe volcano, Scotland. *Geological Society of America*
835 *Bulletin*, **11**, 1448–1466.
- 836 MUIR, R.J., FITCHES, W.R. & MALTMAN, A.J. 1992. Rhinns complex: A missing link
837 in the Proterozoic basement of the North Atlantic region. *Geology*, **20**, 1043–
838 1046.
- 839 NEILSON J. C., KOKELAAR, B. P., CROWLEY, Q. G. 2009. Timing, relations and cause
840 of plutonic and volcanic activity of the Siluro-Devonian post-collision
841 magmatic episode in the Grampian Terrane, Scotland. *Journal of the Geological*
842 *Society, London*, **166**, 545–561.
- 843 NOWELL, G.M., KEMPTON, P.D., NOBLE, S.R., FITTON, J.G., SAUNDERS,
844 A.D., MAHONEY, J.J., TAYLOR, R.N. 1998. High precision Hf isotope
845 measurements of MORB and OIB by thermal ionisation mass spectrometry:
846 insights into the depleted mantle. *Chemical Geology*, **149**, 211–233.
- 847 O’CONNOR, P.J., LONG, C.B., BASHAIN, I.R., SWAINBANK, I.S. & STEPHENS, B. 1984.
848 Age and geological setting of uranium mineralisation associated with the Main
849 Donegal Granite, Ireland. *Transactions of The Institution of Mining and*
850 *Metallurgy*, **93**, B190–B194.
- 851 O’CONNOR, P.J., LONG, C.B. & EVANS, J.A. 1987. Rb-Sr whole-rock isochron studies
852 of the Barnesmore and Fanad plutons, Donegal, Ireland. *Geological Journal*, **22**,
853 11–23.
- 854 PARNELL, J., EARLS, G., WILKINSON, J.J., HUTTON, D.H.W., BOYCE, A.J., FALICK, A.
855 E., ELLAM, R.M., GLEESON, S.A., MOLES, N.R., CAREY, P.F. & LEGG, I. 2000.
856 Regional Fluid Flow and Gold Mineralization in the Dalradian of the Sperrin
857 Mountains, Northern Ireland. *Economic Geology*, **95**, 1389–1416.
- 858 PECCERILLO, A. & TAYLOR, S.R. 1976. Geochemistry of Eocene calc-alkaline
859 volcanic rocks from the Kastamonu area, Northern Turkey. *Contributions to*
860 *Mineralogy and Petrology*, **58**, 63–81.
- 861 PITCHER, W.S. & BERGER, A.R. 1972. The Geology of Donegal: A Study of Granite
862 Emplacement and Unroofing. Wiley Interscience, New York. 448p.

- 863 READMAN, P.W., O'REILLY, B.M. & MURPHY, T. 1997. Gravity gradients and upper
864 crustal tectonic fabrics, Ireland. *Journal of the Geological Society, London*,
865 **154**, 817–828.
- 866 REAY, D.M. 2004. Geophysics and Concealed Geology. In: MITCHELL, W.I. (ed) *The*
867 *Geology of Northern Ireland - Our Natural Foundation, second edition*.
868 Geological Survey of Northern Ireland, Belfast. 227–248.
- 869 REYNOLDS, D.L. 1931. The dykes of the Ards Peninsula, Co. Down. *Geological*
870 *Magazine*, **68**, 97–111 and 145–165.
- 871 ROCK, N.M.S., GASKARTH, J.W. & RUNDLE, C.C. 1986. Late Caledonian dyke
872 swarms in southern Scotland: a regional zone of primitive K-rich lamprophyres
873 and associated vents. *Journal of Geology*, **94**, 505–522
- 874 ROCK, N.M.S., GASKARTH, J.W., HENNEY, P.J. & SHAND, P. 1988. Late Caledonian
875 dyke-swarms of northern Britain: Some preliminary petrogenetic and tectonic
876 implications of their province-wide distribution and chemical variation.
877 *Canadian Mineralogist*, **26**, 3–22.
- 878 ROCK, N.M.S. & HUNTER, R.H. 1987. Late Caledonian dyke-swarms of northern
879 Britain: Spatial and temporal intimacy between lamprophyric and granitic
880 magmatism around the Ross of Mull Pluton, Inner Hebrides. *Geologische*
881 *Rundschau*, **76**, 805–826.
- 882 ROGERS G. & DUNNING G.R. 1991. Geochronology of appinitic and related granitic
883 magmatism in the W Highlands of Scotland: constraints on the timing of
884 Transcurrent fault movement. *Journal of the Geological Society, London*, **148**,
885 17–27.
- 886 RUSSEL, M.J. & HAZELDINE, R.S. 1992. Accounting for geofractures. In: BOWDEN, A.
887 A., EARLS, G., O'CONNOR, P. G. & PYNE J. F. (eds.) *The Irish Minerals Industry*
888 1980–1990. Irish Association for Economic Geology, Dublin, 135–142.
- 889 SKIBA, W. 1952. The contact phenomena on the north-west of the Crossdoney
890 complex, County Cavan. *Transactions of the Edinburgh Geological Society*,
891 **15**, 322–345.
- 892 SÖDERLUND, U., PATCHETT, P.J., VERVOORT, J.D., ISACHSEN, C.E. 2004. The ¹⁷⁶Lu
893 decay constant determined by Lu–Hf and U–Pb isotope systematics of
894 Precambrian mafic intrusions. *Earth Planetary Science Letters*, **219**, 311–324.
- 895 SOPER, N.J., STRACHAN, R.A., HOLDSWORTH, R.E., GAYER, R.A. & GREILING, R.O.
896 1992. Sinistral transpression and the Silurian closure of Iapetus. *Journal of the*
897 *Geological Society, London*, **149**, 871–880.

- 898 STACEY, J.S. & KRAMERS, J.D. 1975. Approximation of terrestrial lead isotope
899 evolution by a two-stage model. *Earth and Planetary Science Letters* **26**, 207–
900 221.
- 901 STEPHENS, W.E. & HALLIDAY, A.N. 1984. Geochemical contrasts between Late
902 Caledonian granitoid plutons of northern, central and southern Scotland.
903 *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **75**, 259–273.
- 904 STEPHENSON, D., BEVINS, R.E., MILLWARD, D., HIGHTON, A.J., PARSONS, I., STONE, P.
905 & WADSWORTH, W.J. 1999. Caledonian igneous rocks of Great Britain.
906 *Geological Conservation Review Series*, **17**, Peterborough, UK, Joint Nature
907 Conservation Committee, 648 p.
- 908 STEVENSON, R.K., PATCHETT, P.J. 1990. Implications for the evolution of continental
909 crust from Hf isotope systematics of Archean detrital zircons. *Geochimica et*
910 *Cosmochimica Acta*, **54** (6), 1683–1697.
- 911 STEWART, M., STRACHAN, R. A., MARTIN, M. W. & HOLDSWORTH, R. E. 2001.
912 Constraints on early sinistral displacements along the Great Glen Fault Zone,
913 Scotland: structural setting, U-Pb geochronology and emplacement of the syn-
914 tectonic Clunes tonalite. *Journal of the Geological Society, London*, **158**, 821–
915 830.
- 916 TARNEY, J. & JONES, C.E. 1994. Trace element geochemistry of orogenic igneous
917 rocks and crustal growth models. *Journal of the Geological Society, London*,
918 **151**, 855–868.
- 919 THIRLWALL, M.F. 1981. Implications for Caledonian plate tectonic models of
920 chemical data from volcanic rocks of the British Old Red Sandstone. *Journal of*
921 *the Geological Society, London*, **138**, 123–138.
- 922 THIRLWALL, M.F. 1986. Lead isotope evidence for the nature of the mantle beneath
923 Caledonian Scotland. *Earth and Planetary Science Letters*, **80**, 55–70.
- 924 VAN STAAL, C.R., SULLIVAN, R.W. & WHALEN, J.B. 1996. Provenance and tectonic
925 history of the Gander Margin in the Caledonian / Appalachian Orogen:
926 implications for the origin and assembly of Avalonia. In: NANCE, R.D. &
927 THOMPSON, M.A. (eds) *Avalonian and Related Peri-Gondwanan Terranes of the*
928 *Circum-North Atlantic*. Geological Society of American, Special Papers, **304**,
929 347–367.
- 930 VAUGHAN, A.P.M. 1996. A tectonomagmatic model for the genesis and emplacement
931 of Caledonian calc-alkaline lamprophyres. *Journal of the Geological Society*,
932 *London*, **153**, 613–623.

933 VERVOORT, J.D. & PATCHETT, P.J. 1996. Behavior of hafnium and neodymium
 934 isotopes in the crust: constraints from Precambrian crustally derived granites.
 935 *Geochimica et Cosmochimica Acta*, **60**, 3717–3733.

936

937 **Explanation of figures**

938

939 Fig. 1(a) Map of UK and Ireland showing study area and locations outside of study
 940 area mentioned in the text. (b) Outline geological map showing major basement
 941 terranes, bounding structures, lineaments and pertinent geological features. Key
 942 localities mentioned in text also shown. The outline of GSNI 1:50 000 scale maps
 943 considered in this study are shown.

944

945 Fig. 2 (a) Photograph of stepped intrusion on fault surface in Ballynamallaght Quarry
 946 (tyre is 1 m diameter). F = fault plane, S2 = regional schistosity and dashed lines
 947 highlight edge of minor intrusion. (b) Photograph of the intrusion at Letterbrat Quarry
 948 cutting Dalradian semipelites and pelites and thrust package of Grampian age (person
 949 for scale). (c) Thin section photomicrograph of Letterbrat trachy-andesite showing a
 950 porphyritic rock composed of feldspar (F), amphibole (A), and biotite (B)
 951 phenocrysts in a fine-grained feldspathic groundmass (field of view is 11 mm).

952

953 Fig. 3 Details of Letterbrat Quarry sample location and geological relationships.

954

955 Fig. 4 U-Pb concordia diagram for Letterbrat trachy-andesite (MRC 93).

956

957 Fig. 5. Geochemistry of the Late Caledonian high-K minor intrusive suite of County
 958 Tyrone and eastern County Donegal. Also shown is the geochemistry of the Donegal
 959 granitoids for comparison (Ghani & Atherton 2008), the Argyll and Northern
 960 Highlands Suite of Scotland (Stephenson *et al.* 1999) and the eastern Ireland
 961 lamprophyres, syenites, microgranites and trachy-andesites of the Down–Longford
 962 terrane (Vaughan 1996).

963

964 Table 1. U-Pb zircon data from trachy-andesite sample MRC 93, Letterbrat Quarry.

965

966 **Notes:** * Zircon grain characteristics specified as: x°N = non-magnetic, at specified tilt angle on a
 967 Frantz LB-1 Separator at 1.7 amps; X:1 = aspect ratios of grains; lengths of grains in μm , number
 968 of grains analysed in (). AA = air abrasion, CA = chemical abrasion. † Maximum errors are

969 ±20% for air-abraded grains, ±40% for chemically abraded grains. Weights were measured on a
 970 Cahn C32 microbalance (AA) or estimated from grain size (CA). § Measured ratio corrected for
 971 fractionation and spike Pb. # Corrected for fractionation, spike, laboratory blank Pb and U, and
 972 initial common Pb estimated from Stacey and Kramers, 1975. Laboratory blank Pb composition is
 973 $^{206}\text{Pb}/^{204}\text{Pb} : ^{207}\text{Pb}/^{204}\text{Pb} : ^{208}\text{Pb}/^{204}\text{Pb} = 18.19:15.58:38.50$. Quoted errors are 2σ (% for atomic ratios,
 974 absolute for ages). ** $^{207}\text{Pb}/^{235}\text{U} - ^{206}\text{Pb}/^{238}\text{U}$ error correlation coefficient calculated following
 975 Ludwig (2003).

976

977 Table 2. Lu-Hf zircon data from trachy-andesite sample MRC93, Letterbrat Quarry.
 978 $^{176}\text{Hf}/^{177}\text{Hf}$ is corrected for Lu and Yb interference and normalised to 0.282160 for
 979 JMC 475 Hf.
 980

981 Table 3. Whole rock geochemical data for Sperrin Mountains suite. – For
 982 supplementary publication.
 983

**Palaeogene
Intrusions**

**Ardara Pluton /
Appinitic Bodies**

Dromore High

Minor Intrusions

S

N

Vertical
Scale 10m

	Trachy-andesite		Sample Location
(MRC 93)		Lithological boundary
/ S2 Schistosity
	Semipelites / pelites		Faults		Sulphide
Mineralisation
	Psammites		Thrusts		

Zircon Fractions*	Weight (μg) [†]	U (ppm) [†]	Pb (ppm) [†]	Common Pb (ppm) [†]	²⁰⁶ Pb/ ²⁰⁴ Pb [§]	²⁰⁸ Pb/ ²⁰⁶ Pb [#]	²⁰⁶ Pb/ ²³⁸ U [#]	% err (2 σ)	²⁰⁷ Pb/ ²³⁵ U [#]
1. -2NM, CA, 2:1, 80 μm (1)	0.5	2393	165	1.4	3556	0.1106	0.06843	0.19	0.5223
2. -2NM, CA, 2:1, 100 μm (3 frags)	1.7	1373	93	1.7	5800	0.07862	0.06925	0.13	0.5328
3. -2NM, AA, 2:1, 150 μm , (1)	1.5	719	46	8.8	518	0.05694	0.06551	0.97	0.4997
4. -2NM, AA, 2:1, 150 μm , (1)	2	327	23	11.4	255	0.05729	0.06699	1.40	0.5091
5. -2NM, AA, 2:1, 200 μm , (1)	2.6	178	22	3.2	4903	0.135	0.11935	0.32	1.1512
6. -2NM, AA, 2:1, 150 μm , (2)	4.6	563	63	4.7	6717	0.0753	0.11348	0.32	1.1644

% err (2δ)	$^{207}\text{Pb}/^{206}\text{Pb}^\#$	% err (2δ)	$^{206}\text{Pb}/^{238}\text{U}$	abs err (2δ)	$^{207}\text{Pb}/^{235}\text{U}$	abs err (2δ)	$^{207}\text{Pb}/^{206}\text{Pb}$	abs err (2δ)	ρ**
			Age (Ma)		Age (Ma)		Age (Ma)		
0.20	0.05536	0.12	426.69	0.81	426.69	0.85	426.60	2.80	0.84
0.10	0.05581	0.05	431.64	0.56	433.67	0.43	444.60	1.20	0.93
1.10	0.05532	0.48	409.05	3.97	411.50	4.53	425.40	11.00	0.89
1.70	0.05512	0.80	418.00	5.85	417.84	7.10	417.20	18.00	0.88
0.35	0.06996	0.15	726.84	2.33	777.83	2.72	927.10	2.99	0.89
0.36	0.07442	0.16	692.92	2.22	784.01	2.82	1052.82	1.68	0.89

	$^{176}\text{Hf}/^{177}\text{Hf}^a$	$\pm 1\sigma$ abs	$^{176}\text{Lu}/^{177}\text{Hf}$	$\pm 1\sigma$ abs	$^{176}\text{Hf}/^{177}\text{Hf}_i$	εHf_i	$\pm 2\sigma$ abs	$T_{\text{DM}}\text{Hf (Ma)}$	$\pm 2\sigma$ abs
Z1	0.282691	0.000012	0.001242	0.000014	0.282681	6.2	0.1	770	34
Z3	0.282671	0.000010	0.001464	0.000001	0.282658	5.3	0.1	802	42
Z4	0.282679	0.000008	0.002275	0.000003	0.282660	5.1	0.2	809	69

Values for $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR}}$ (0.282772) and $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}}$ (0.0332) are from (Blichert-Toft and Albarede, 1997).

εHf values calculated using a Lu decay constant of $1.867 \cdot 10^{-11} \text{a}^{-1}$ (Soderlund et al., 2004).

The $^{176}\text{Lu}/^{177}\text{Hf}$ ratios of the average crust (TDMC) ($^{176}\text{Lu}/^{177}\text{Hf} = 0.015$; Griffin et al., 2000), the initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of the zircons and the depletor (present-day $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of the depleted mantle = 0.28325; Nowell et al., 1998) and the U-Pb age were used to calculate Hf model ages.

d mantle