Stratigraphic, geochemical and U–Pb zircon constraints from Slieve Gallion, Northern Ireland: a correlation of the Irish Caledonian arcs

STEVEN P. HOLLIS1,2*, MARK R. COOPER3, STEPHEN ROBERTS1, GARTH EARLS4, RICHARD HERRINGTON5 & DANIEL J. CONDON6

1Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, Waterfront Campus, European Way, Southampton SO14 3ZH, UK
2CSIRO Earth Science and Resource Engineering, 26 Dick Perry Avenue, Kensington, Perth, WA 6151, Australia
3Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Malone Lower, Belfast BT9 5BJ, UK
416 Mill Road, Ballygowan, Newtownards BT23 6NG, UK
5Department of Mineralogy, Natural History Museum, London SW7 5BD, UK
6NERC Isotope Geosciences Laboratory, British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG, UK

*Corresponding author (e-mail: steven.hollis@csiro.au)

Abstract: Recent Ar–Ar and U–Pb zircon geochronology from across the British and Irish Caledonides has revealed a prolonged period of arc-ophiolite formation (c. 514–464 Ma) and accretion (c. 490–470 Ma) to the Laurentian margin during the Grampian orogeny. The Slieve Gallion Inlier of Northern Ireland, an isolated occurrence of the Tyrone Volcanic Group, records the development of a peri-Laurentian island arc–backarc and its obduction to an outboard microcontinental block. Although a previous biostratigraphic age constraint provides a firm correlation of at least part of the volcanic succession to the Cal Stage of the Arenig (c. 475–474 Ma), there is uncertainty on its exact stratigraphic position in the Tyrone Volcanic Group. Earliest magmatism is characterized by light rare earth element (LREE) depleted island-arc tholeiite. Overlying deposits are dominated by large ion lithophile and LREE-enriched, hornblende-phyric and feldspathic calc-alkaline basaltic andesites and andesitic tuffs with strongly negative εNd values. Previously published biostratigraphic age constraints, combined with recent U–Pb zircon geochronology and new petrochemical correlations, suggest that the Slieve Gallon Inlier is equivalent to the lower Tyrone Volcanic Group. Temporal and geochemical correlations between the Slieve Gallion Inlier and Charlestown Group of Ireland suggest that they may be part of the same arc system, which was accreted at a late stage (c. 470 Ma) in the Grampian orogeny. A switch from tholeiitic volcanism to calc-alkaline dominated activity within the Lough Nafooey Group of western Ireland occurred prior to c. 490 Ma, some 15–20 Myr earlier than at Tyrone and Charlestown.

Supplementary materials: Sampling and geochemical results (major elements, loss on ignition, trace elements, REE and Nd isotopes) are available at www.geolsoc.org.uk/SUP18640.

The Caledonian–Appalachian orogen provides a rare window through the mid- to lower-crustal levels of an evolving orogenic belt. Early Palaeozoic closure of the Iapetus Ocean resulted in extensive arc-ophiolite accretion to the Laurentian margin (= Grampian–Taconic orogeny) prior to continent–continent collision (= Acadian orogeny) (Dewey 2005; van Staal et al. 2007; Chew 2009; Cooper et al. 2013). Modern subduction systems, such as the western and SW Pacific, reveal complexities during episodes of large-scale ocean closure, including diachronous and/or oblique arc–continent collision, arc–arc collisions, subduction polarity reversals, subduction rollback, triple junctions, arc interactions with propagating rifts and spreading centres, and the presence of microcontinental blocks and oceanic plateaus. Despite these complexities, forward modelling of collision between Australia and the Asian continent has produced remarkably linear orogenic belts when associated with sinistral oblique convergence (see van Staal et al. 1998). Pseudo-simplified linear orogenic zones can conceal complex histories and geometries, especially if poorly exposed and subjected to terrane excision and strike-slip duplication (van Staal et al. 1998). It is only through detailed study of single terranes, and their interrelationships, that orogens may be understood.

The Grampian–Taconic orogeny resulted from widespread and episodic arc-ophiolite accretion to the Laurentian margin between the Late Cambrian and Middle Ordovician (Dewey & Shackleton 1984; van Staal et al. 2007; Chew et al. 2010). Western Ireland, although not representative of the Grampian orogen as a whole, was a focus for establishing many of the fundamental processes of arc–continent collision owing to its abundant exposure, low metamorphic grade and limited deformation (e.g. Dewey & Shackleton 1984; Dewey & Ryan 1990; Draut et al. 2004; Dewey 2005; Ryan & Dewey 2011). Collision between the Lough Nafooey arc of western Ireland and the passive Laurentian margin was associated with polyphase deformation and metamorphism of thick Neoproterozoic cover sequences such as the Dalradian Supergroup between c. 475 and 465 Ma (Friedrich et al. 1999a,b). The South Mayo Trough, a thick and relatively undeformed accumulation of lavas and volcanoclastic sedimentary rocks, represents the pre-collisional fore-arc and syn- to post-collisional successor basin to the Lough Nafooey arc (Draut et al. 2004; Fig. 1). Within its sedimentary record, the South Mayo Trough preserves the progressive evolution of the Lough Nafooey arc system, its collision with the Laurentian margin, and the unroofing of the orogen (reviewed by Ryan & Dewey 2011). A
younger c. 464 Ma continental arc founded upon the Laurentian margin was associated with subduction polarity reversal following arc–continent collision (Dewey 2005).

Arc-ophiolite formation is now recognized to span c. 514–464 Ma within the peri-Laurentian British and Irish Caledonides (e.g. Chew et al. 2008, 2010; Cooper et al. 2011; Hollis et al. 2012). Early obduction of some ophiolites onto outboard microcontinental blocks (c. 510–490 Ma) may explain discrepancies in the timing between the termination of Laurentian passive margin sedimentation and ophiolite emplacement (Chew et al. 2010). Remnant slices of the accreted volcanic arcs are exposed across the Midland Valley terrane, and include the Bohau Volcanic Formation, Lough Nafaoey Group, Tourmakeady Group and Charlestown Group of Ireland, the Tyrone Volcanic Group of Northern Ireland (Fig. 1), and probably the Games Loup and Mains Hill successions of the Ballantrae Ophiolite Complex, Scotland. Abundant arc-related and ophiolitic detritus in sediments of the Southern Uplands terrane and Middle Ordovician sediments of Girvan also indicate the presence of an extensive arc-ophiolite complex(s) buried within the Midland Valley Terrane (Midland Valley arc) (see Oliver et al. 2002).

The Tyrone Volcanic Group of Northern Ireland occupies an important position in the Caledonides between the well-documented sectors of western Ireland and Scotland (Fig. 1). It records the formation of a peri-Laurentian island arc–backarc during the Early to Middle Ordovician and its accretion to an outboard microcontinental block at c. 470 Ma (see Cooper et al. 2011; Hollis et al. 2012). However, despite its importance, geochemistry from the Tyrone arc is limited to three high-resolution U–Pb zircon dates that shed further light on this enigmatic arc system and the orogen as a whole. Herein we demonstrate that the Tyrone and Lough Nafaoey arcs differ significantly in the timing of their geochemical evolution and accretion. Either arc evolution and accretion was diachronous in the Irish Caledonides, or perhaps more likely the Tyrone and Lough Nafaoey arcs represent distinct arc systems accreted to the Laurentian margin during the Grampian orogeny (after Hollis et al. 2012).

Here we present the results of new field mapping, complemented by high-resolution airborne geophysics, the first detailed geochemical study of the volcanic succession, and two new U–Pb zircon dates that shed further light on this enigmatic arc system and the orogen as a whole. Herein we demonstrate that the Tyrone and Lough Nafaoey arcs differ significantly in the timing of their geochemical evolution and accretion. Either arc evolution and accretion was diachronous in the Irish Caledonides, or perhaps more likely the Tyrone and Lough Nafaoey arcs represent distinct arc systems accreted to the Laurentian margin during the Grampian orogeny (after Hollis et al. 2012).

**Previous work**

The Slieve Gallion Inlier of Northern Ireland is exposed over c. 15 km$^2$ directly NE of the c. 484–479 Ma ophiolitic Tyrone Plutonic Group (Cooper et al. 2011; Hollis et al. 2013), which separates this package of rocks from the main occurrence of the c. 475–469 Ma Tyrone Volcanic Group to the SW (Fig. 2). The Slieve Gallion Inlier is bounded to the north and east by post-Silurian cover and along its southern margin has been intruded by a large body of biotite- or hornblende-bearing granite (Slieve Gallion granite: 466.5 ± 3.3 Ma; Cooper et al. 2011; Fig. 2). The first comprehensive study of the inlier was presented within the seminal work by Hartley (1933) on the ‘Tyrone Igneous Series’ (now Tyrone Igneous Complex). Although no stratigraphy was attempted, Hartley’s map for the complex divided the volcanic succession at Slieve Gallion into (1) andesites, (2) tuffs, and (3) phyllites and chloritic schists. The volcanic rocks have since been resurveyed for the second edition Cookstown and Draperstown sheets of the Geological Survey of Northern Ireland (GSENI 1983, 1995; also see Cameron & Old 1997), which provided the most up-to-date map of the inlier. No division within the volcanic succession was presented at 1:50000, although GSENI field-slips record a variety of lithologies in detail.

Fragmentary graptolites from one locality at Sruhanleanantawey Burn [IGR 27905–38790] have been variably interpreted since their initial discovery by Hartley (1936). A late Llandeilo to early Caradoc age was originally favoured on the presence of specimens...
identified as *Dicranograptus* and *Climacograptus* (Hartley 1936). Re-collection by Hutton & Holland (1992) further identified the presence of *Tetragraptus serra* (Brongniart) and *Sigmagraptus sensu lato*, demonstrating an earlier Arenig to Llanvirn age. Most recently Cooper et al. (2008) collected more than 20 graptolites and a lingulate brachiopod, and re-examined the specimens of Hutton & Holland (1992). They concluded through the presence of *Isograptus victoriae lunatus*, the index fossil of the *Isograptus victoriae lunatus* Zone of the Australasian graptolite succession, that the fauna can be assigned to the lowest Ca1 subdivision of the Castlemainian Stage. This is approximately equivalent to the top of the Whitlandian Stage of the Arenig (c. 475–474 Ma after the age of Sadler et al. 2009).

In addition to their evaluation of the Sruhanleanantawey Burn fauna, Cooper et al. (2008) determined a U–Pb zircon date for a flow-banded rhyolite from Formil Hill from the main sequence of the Tyrone Volcanic Group to the SW (473 ± 0.8 Ma). Rhyolites are common across the upper Tyrone Volcanic Group, exposed from Racolpa through Cashel Rock to Formil (Fig. 2) within the Greencastle Formation (c. 473–469 Ma), and structurally and stratigraphically below the graphitic pelite- and chert-bearing localities around Mountfield and Broughderg (e.g. Crosh; c. 469 Ma Broughderg Formation; Hollis et al. 2012). Cooper et al. (2008) suggested that the chert, thinly bedded tuffaceous siltstone and pyritic mudstones, with greenish grey tuffs and lavas at Slieve Gallion formed synchronously with the succession at Broughderg. At this time, U–Pb geochronology from the Tyrone Volcanic Group *sensu stricto* was restricted to their one high-resolution age from Formil Hill and no detailed stratigraphic or petrochemical account of the Tyrone Volcanic Group existed. Two similar, albeit slightly younger, U–Pb zircon thermal ionization mass spectrometry (TIMS) dates have subsequently been obtained from the Greencastle Formation (469.42 ± 0.79 Ma from rhyolite, 470.37 ± 0.76 Ma from tuff; Hollis et al. 2012).

**Stratigraphy**

The Slieve Gallion Inlier has been re-mapped through the integration of previous geological survey data and new fieldwork, geochemistry (see below) and the Tellus airborne geophysical survey of Northern Ireland. A new map is presented in Figure 3. Magnetic, radiometric and electromagnetic (EM) data were acquired as part of the Tellus Project in 2005–2006 (see GSNI 2007). Details on survey specification and geophysical data processing have been summarized by Beamish et al. (2007). The volcanic succession at Slieve Gallion is hereby divided into three formations: Tinagh, Tawey, and Whitewater (Figs 3 and 4). Each is described below. Major ESE–WNW-oriented faults divide the volcanic succession into three stratigraphic packages. South of the Tirgan Fault, the Tinagh and Tawey formations are exposed; the latter is restricted to the west of Slieve Gallion. North of the Tirgan Fault the structurally overlying Whitewater Formation is exposed. An older set of NW–SE-striking faults cut the formations and are offset by the Tirgan Fault. Several of these NW–SE-striking faults, which are
clear from regional magnetic data (Fig. 3) are directly mappable (e.g. NE of Tinagh; GSNI 1983, 1995). Ordovician intrusive rocks of quartz-porphyry, hornblende- and biotite-granodiorite, aplite and diorite cut the volcanic succession. Units have been metamorphosed to subgreenschist-facies assemblages and consequently the prefix meta- is omitted from all lithologies.

Tinagh Formation

The Tinagh Formation crops out extensively across the southern side of the Slieve Gallion Inlier and includes the following informal stratigraphic units: Derryganard Lavas, Windy Castle Lavas, Letteran Volcanics, Torys Hole Ironstone, and the Mobuy Wood Basalts, each named after their type localities. The Tinagh Formation is dominated by calc-alkaline hornblende porphyritic tuffs and lavas, and non-arc type Fe–Ti-enriched basalt of enriched mid-ocean ridge basalt (E-MORB) affinity (see following sections). Lesser amounts of calc-alkaline, feldspar porphyritic andesite, mafic crystal tuff, ferruginous jasperoid (ironstone), mafic breccias (interpreted as pillow breccias), tholeiitic pillow lavas, and rhodacite are also present. The formation has a maximum exposed thickness of 1.2 km, although the rift-related Mobuy Wood Basalts appear have been erupted locally at different times (Fig. 4) and packages of the Windy Castle Lavas vary considerably in thickness along strike.

Pillow lavas exposed at Derryganard (= Derryganard Lavas) are believed to represent the oldest stage of volcanism within the Slieve Gallion Inlier and are restricted to this area. The succession is at least 130 m thick with pillow structures younging north towards the Windy Castle Lavas. The succession is bounded to the south and east by younger intrusions of c. 465–464Ma quartz-porphyry and a large body of biotite granite, and is succeeded in the NW by the Windy Castle Lavas, which dip NW to NE (Fig. 3). Pillows are generally aphanitic and highly vesicular, and range between 8 and 35 cm in diameter (Fig. 5a and f). Flows become more massive up section, and rare augite phenocrysts occur in some near the base of the sequence. No interpillow chert or sediment was observed. The Derryganard Lavas are non-magnetic and are geochemically distinct from all other units present in the Slieve Gallion Inlier, displaying tholeiitic and light rare earth element (LREE)-depleted geochemical characteristics (see petrochemistry).

Immediately overlying the Derryganard Lavas, the Tinagh Formation is dominated by calc-alkaline tuffs and andesites (Fig. 5b and i), with flows becoming increasingly pillowed and associated with pillow breccias up section. This sequence has been divided into the Windy Castle Lavas and Letteran Volcanics on the basis of the dominant phenocryst type in flows, intensity of magnetic response, and type of associated tuff (i.e. mafic or hornblende-phyric). The contact with the underlying Derryganard Lavas was placed at the first occurrence of hornblende-phyric basaltic andesite or andesite, or tuff. The Windy Castle Lavas are characterized by vesicular hornblende-phyric andesites with lesser mafic crystal tuff; type localities occur at Windy Castle and west of Letteran. Locally the Windy Castle Lavas reach a thickness of 275 m. The Letteran Volcanics are characterized by non-magnetic, calc-alkaline, and feldspar-phyric, massive and...
pilowed andesites (which lack abundant hornblende phenocrysts; Fig. 5i) and sheared hornblende-bearing crystal tuffs (Fig. 4). The Letteran Volcanics locally vary in thickness between c. 275 and 340 m. Packages of the Windy Castle Lavas alternate with the Letteran Volcanics both up sequence and along strike (Fig. 3). This suggests that different areas experienced pyroclastic and effusive activity at different times, most probably associated with rifting (see below). This is further supported by the geochemistry of the closely associated Mobuy Wood Basalts (see the petrochemistry section) and the occurrence of ironstone at Torsys Hole, where a 1 m thick bed is exposed towards the base of the Tinagh Formation. This unit is characterized by a mosaic of quartz and hematite (Cameron & Old 1997).

Non-arc type basalts of E-MORB affinity are restricted to the SW of the Slieve Gallion Inlier, exposed between Sruhanleanantawey Burn and Letteran (Fig. 3), and around Mobuy Wood. These lavas are geochemically distinct from all others analysed from the Slieve Gallion Inlier, having rift-related characteristics (see the petrochemistry section). They are herein termed the Mobuy Wood Basalts. Flows are often highly vesicular (Fig. 5c), and are either massive or display well-developed pillow structures with radial fractures. Basaltic pillow breccias (Fig. 5d) are commonly associated with the latter. Although the Mobuy Wood Basalts are largely aphanitic, some flows contain rare augite phenocrysts, which can display evidence for rounding (Fig. 5g). This suggests that these may be xenocrysts derived from the underlying Derryganard Lavas. The Mobuy Wood Basalts can be distinguished based on their geochemistry and high total magnetic intensity, and differ from underlying flows of the Windy Castle Lavas and Letteran Volcanics by a lack of hornblende phenocrysts. It is not known if the Mobuy Wood Basalts are present on the east side of Slieve Gallion as these lavas were not sampled for geochemistry, although augite-bearing andesites have been reported on GSNI fieldsheets north of Tirgan. A single unit of rhyodacite also occurs at Mobuy Wood near the base of the overlying Tawey Formation. This rhyodacite is extensively sheared and is associated with rare hornblende-phyric lava, tuff and small intrusions of quartz diorite.

Tawey Formation

The overlying Tawey Formation is defined in the section exposed in Sruhanleanantawey Burn (Fig. 3). The formation is at least 1.45 km thick (discounting intrusive units) and is dominated by crystal and lithic tuffs, hornblende-phyric lavas with lesser fine-grained sedimentary rocks (banded chert, pyritic mudstone, banded siltstone and phyllite) (Fig. 4). Poorly exposed, the Tawey Formation is restricted to the western side of Slieve Gallion. It has been broadly divided into sequences dominated by lava (associated with high total magnetic intensity owing to the presence of Fe-oxides; Fig. 3) and those dominated by tuff and sedimentary rocks. The base of the Tinagh Formation was placed at the first occurrence of sedimentary rocks or layered chert, as crystal tuffs and hornblende-phyric lavas occur in both formations. No evidence for faulting between these formations is apparent from field relationships or geophysics. No pilowed or vesicular flows have been recognized in the Tawey Formation, unlike the underlying Tinagh Formation. Way-up criteria in the formation are scarce owing to patchy outcrop. Bedding towards the base of the Sruhanleanantawey Burn dips steeply NW, whereas towards the top bedding dips moderately SE (Fig. 3). It is believed that this variation in the SE is due to localized doming associated with intrusive activity. Intrusions are abundant in the stream section and include quartz-porphyry, a >35 m thick unit of hornblende-rich diorite, and alkali-basalt (see the discussion on sample MRC335 below). A large NW–SE-oriented fault also cuts the upper part of the stream, perpendicular to bedding below the SE-dipping graptolite-bearing succession. Owing to poor exposure combined with structural complications the succession is described as a transverse up Sruhanleanantawey Burn (as was done by Cameron & Old 1997).

Near the base of the Sruhanleanantawey Burn section the formation is characterized by greenish grey hornblende and feldspar-phyric tuff and lava, which have been intruded by sills of reddish and pink weathered quartz porphyritic dacite common throughout the Tyrone Igneous Complex (Figs 2 and 3). Euhedral quartz, plagioclase feldspar and occasional greenish mica phenocrysts occur in a fine-grained pink dacitic matrix (Cameron & Old 1997).
Quartz-porphyritic dacite that intrudes the lower Tyrone Volcanic Group has been dated at 465 ± 1.7 Ma (Cooper et al. 2011). Contacts of alternating exposures between quartz-porphyritic dacite and greenish grey tuff and lava, which contain hornblende and feldspar phenocrysts, are not well exposed, although at Tyrus Hole and Tinagh quartz-porphyry is chilled against tuffs and dark greenish grey dacite respectively. Bedding is clear in coarse tuffs and banded phyllites, although extensive shearing often makes it difficult to distinguish between hornblende-bearing crystal tuffs and lavas.

The upper reaches of Sruhanleanantawey Burn have been mapped and logged in detail by the GSNI (Cameron & Old 1997), as summarized here. Pale grey, chert-like phyllites display faintly visible bedding and are composed of very fine-grained quartz, schistose sericite with weathered-out pyrite porphyroblasts surrounded by limonite haloes (Cameron & Old 1997). Further upstream, phyllites are interbedded with coarse tuffs and dark grey coarse-grained crystal tuff. A horizon of pale grey tuffaceous chert also occurs with bands of crystal-rich material and light grey thinly bedded tuffaceous siltstone. Towards the top of the Sruhanleanantawey Burn section, dark blue–grey pyritiferous mudstones and thin coarse tuff bands are overlain by strongly banded blue–grey siltstones (Fig. 5e). Cooper et al. (2008) obtained a Cal Whitlandian age from a sparse graptolite fauna from this part of the sequence. Coarse crystal tuff further up Sruhanleanantawey Burn is associated with blocks of chert. A thick (>30 m) feldspar-phryic silicified basaltic rock (Fig. 5h) is also present in Sruhanleanantawey Burn downstream from the graptolite-bearing horizon. This unit is non-vesicular and massive, and appears to contain small angular xenoliths of aphanitic basalt or fine-grained silicified sediment. Its contacts with adjacent units are not exposed, although owing to U–Pb zircon geochronology and its unique geochemical characteristics (see below) it is interpreted as intrusive.

Whitewater Formation

Whitewater River and its tributaries provide the most complete section through the Whitewater Formation. The lower part of this formation (>650 m thick) is characterized by thick accumulations of interbedded hornblende-phryic andesite and tuff, and is in faulted contact with the Tinagh and Tawey formations (Fig. 3). Tuffs are often schistose on the northern side of Slieve Gallion and are often chloritic and/or silicified. Lithic and crystal varieties occur with broken crystals of hornblende, augite, epidote, orthoclase and plagioclase set in a feldspathic groundmass with quartz, chlorite and epidote (Hartley 1933). Augite and plagioclase would suggest a mafic source and glass fragments can display a devitrified perlitic structure (Hartley 1933). Rare volcanic breccias containing chert fragments crops out SE of Windy Castle, and at Tirgan a 30 cm thick bed of layered chert occurs that contains intercalated tuff bands (Cameron & Old 1997; Fig. 3). Some of the andesites NE of Slieve Gallion and north of Tirgan display pillow structures with a consistent orientation suggesting younging towards the north. A rare horizon of ironstone (quartz–hematite) is exposed at Drummuck (= Drummuck Ironstone; Fig. 3), with float occurring along strike to the north of Slieve Gallion. The upper part of the Whitewater Formation is best exposed around Straw Mountain and is composed of a >750 m thick sequence of chloritic and silicified lithic and crystal tuff with rare andesite. Locally tuffs in Whitewater River (south of Straw Mountain) can be intensely sericitized and pyritic. Ironstone (quartz–hematite) float is also common around Straw Mountain, suggesting that a second stratigraphically higher unit may be present in the Whitewater Formation above the Drummuck Ironstone (Fig. 3).

Petrochemistry

Volcanic rocks from all major stratigraphic horizons within the Slieve Gallion Inlier were sampled for whole-rock geochemical analysis. All signs of weathering, alteration and veining were removed prior to powdering in a Cr-steel TEMA. Major elements and trace elements were determined for whole-rock samples on fused glass beads and powder pellets, respectively, by XRF (Philips® MagiX-Pro 4KW Rh X-ray tube) at the University of Southampton. REE (plus Nb, Hf, Ta, Th, U) were determined by inductively coupled plasma mass spectrometry (ICP-MSThermo Scientific Xseries 2) on
the same powders following an HF–HNO₃ digest. Accuracy (%RD) and precision (%RSD) were typically <3% for ICP-MS analyses and <5% for XRF analyses based on replicate analyses of a range of international standards (XRF: JR-1, JR-2, JG-3, JB-1a, JA-a; ICP-MS: BHVO-2, JB-1a, JB-3, JGB-1, JR-1) (Hollis 2013). Elements with accuracy and precision >10% (ICP-MS: Ta, Hf; XRF: Cu, Co) are considered poor (Jenner 1996) and were not used. Neodymium was isolated for Nd isotope analysis from ICP-MS mother solutions using 6.5 ml Dowex AG50W-X8 (200–400 mesh) cation columns and Ln-spec reverse phase columns. Nd isotope ratios were measured by TIMS using a VGMicromass Sector 54 instrument at the University of Southampton. ¹⁴⁶Nd/¹⁴⁴Nd was measured in multidynamic mode, exponentially corrected for instrumental fractionation relative to ¹⁴⁶Nd/¹⁴⁴Nd = 0.7219. The JNdI standard gave a value of 0.512091 ± 14 (2SD, n = 20). Further details on methods have been reported by Hollis et al. (2012). Geochemical analyses of Cooper et al. (2011; MRC prefixes) are also included where appropriate. Owing to the extensive hydrothermal alteration and metamorphism across the Tyne Volcanic Group, only elements demonstrated to be immobile are used to elucidate petrogenesis, tectonic affinities and chemostratigraphy (after Cooper et al. 2011; Hollis et al. 2012). These include TiO₂, Th, V, Sc, high field strength elements (HFSE; e.g. Nb, Zr, Y), and the REE.

**Tinagh Formation**

A single sample was analysed from the Derryganard Lavas. This sample (SPH525) is unusual within the Slieve Gallion Inlier that it displays low Th (ThCN 8.21) and LREE depletion relative to the heavy REE (HREE) (La/YbCN 0.7). Low Zr/Y (2.24), Zr/TiO₂ and Nb/Y (0.03) ratios suggest these lavas are primitive subalkaline basalts of tholeiitic affinity (Figs 6 and 7a). Pronounced negative Nb and Ti anomalies are consistent with formation in an island-arc setting. Sample SPH525 is characterized by high MgO (9.71 wt.%), Cr (650 ppm) and Ni (247 ppm), and low SiO₂ (47.1 wt.%).

Non-pillowed hornblende-phyllic lavas of the Windy Castle Lavas were sampled between Derryganard and Slieve Gallion (SPH506, SPH511, SPH528 and SPH534). These units are strongly calc-alkaline (Zr/Y 6.45–12.1), large ion lithophile element (LILE) enriched (ThCN 201.8–458.6) and display high LREE enrichment relative to the HREE (La/YbCN 9.52–14.00) (Figs 6 and 7b). TiO₂ (0.48–0.61 wt.%) and Cr (59–173) contents are low, and Nb/Y values range between 0.35 and 0.65. Sample SPH532, collected from pillow lavas NE of Letteran, is calc-alkaline (Zr/Y 7.93) and displays extreme LILE enrichment (ThCN 600) and low MgO (0.16 wt.%), TiO₂ (0.24 wt.%), Cr (99 ppm) and V (34 ppm). All units from the Windy Castle Lavas display island-arc geochemical characteristics including pronounced negative Nb anomalies (Figs 6 and 7b). A single sample of feldspathic andesite (SPH530) from the Letteran Volcanics is also strongly calc-alkaline (Zr/Y 10.37) and LILE and LREE enriched (ThCN 237.4, La/YbCN 12.69) (Figs 6 and 7b). This sample yielded a strongly negative εNd value of −9.02 (Fig. 6c) and displayed strong island-arc geochemical characteristics (e.g. negative Nb anomalies).

The Mobuy Wood Basalts are geochemically distinct from all other mafic rocks in the Slieve Gallion Inlier and resemble rift-related lavas of the Tyne Volcanic Group (Hollis et al. 2012). Low Zr–Ti and high Nb/Y (0.36–0.64) classify these lavas as subalkaline basalts, whereas Zr/Y ratios (3.82–6.46) locate them within the calc-alkaline field of Ross & Bédard (2009) (Fig. 6a, d and f). All of the samples analysed are characterized by high FeO(Tot) (11.56–13.07 wt.% and TiO₂ (1.83–2.33 wt.%). εNd values are the most primitive of all samples analysed from the Slieve Gallion Inlier (+0.6–+2.5; Fig. 6c). Th/Yb-Nb/Yb systematics and various discrimination diagrams (e.g. Pearce & Cann 1973; Pearce & Norry 1979; Wood 1980; Meschede 1986) suggest that these lavas are of E-MORB affinity and slightly enriched in subduction zone components (Fig. 7c and d). On multi-element variation diagrams all three samples analysed from the Mobury Wood Basalts show high LILE (ThCN 38.8–155.3) and REE enrichment, and LREE enrichment relative to the HREE (La/YbCN 3.44–4.82) (Fig. 7c and d). Sample SPH533 (vesicular pillowed basalt) displays a small positive Nb anomaly and minor negative Ti anomaly (Fig. 7c), whereas samples SPH508 and SPH517 (unpillowed basalt) show negative Nb and Ti anomalies (Fig. 7d). Sample SPH533 is characterized by slightly lower TiO₂, Th, REE and HFSE, higher Zr/Y, Cr and MgO, and a more primitive εNd value than SPH508 and SPH517 (Fig. 7c).

**Tawey Formation**

Four samples have been analysed from the Tawey Formation: lithic tuff (SPH493), tuff associated with chert (SPH494), chert (SPH52) and siltstone (SPH496). The volcanic samples are subalkaline, transitional to calc-alkaline (Zr/Y 3.94–8.57) and display high ThCN (172.4–275.8) (Fig. 6). Chert is characterized by high ThCN (343.5), K₂O+Na₂O and Al₂O₃ (11.16 wt.%) consistent with both continental- and arc-derived components.

**Whitewater Formation**

All samples analysed from the Whitewater Formation (SPH467 to SPH488, and SPH502) are basaltic andesite or andesite in composition. These rocks are subalkaline (0.45–0.7), strongly calc-alkaline (Zr/Y 5.69–10.57), LILE (ThCN 227.72–310.41) and LREE enriched relative to the HREE (La/YbCN 7.88–10.91), and are characterized by strongly negative εNd values (~12.68 to ~13.86) (Figs 6 and 7f). Cr contents are high (282–405 ppm). All samples show pronounced negative Nb and HFSE anomalies, and positive Zr anomalies, on multi-element variation diagrams (Fig. 7f).

**Sruhanleanantawey Burn alkali basaltic rock**

An extensively altered feldspar-phyllic basaltic rock from the upper portions of Sruhanleanantawey Burn (MRC335 and SPH25) was sampled for geochemistry and U–Pb geochronology downstream of the c. 475–474 Ma graptolite-bearing rocks analysed by Cooper et al. (2008) and previous workers. This unit is characterized by high TiO₂ (3.53–3.84 wt.%), Fe₂O₃(Tot) (17.82–18.28 wt.%), P₂O₅ (0.56–0.62 wt.%), loss on ignition (LOI) (4.51%–4.85%), V (403–463 ppm) and Cr (249–283 ppm), and low Na₂O (0.89) ppm. U–Pb TIMS analysis, zircons were subject to a modified version of the chemical abrasion technique (Mattinson 2005). Methods are identical to those reported by Hollis et al. (2012, 2013). Errors for U–Pb dates are reported in the following format: ±ε(Nd)[2], where ε is the internal or analytical uncertainty in the absence of systematic errors (tracer calibration and decay constants), y includes the quadratic
addition of tracer calibration error (using a conservative estimate of the standard deviation of 0.1% for the Pb/U ratio in the tracer), and z includes the quadratic addition of both the tracer calibration error and additional 238U decay constant errors of Jaffey et al. (1971). All analytical uncertainties are calculated at the 95% confidence interval. Data are presented in Table 1.

Sample MRC351 was collected from the Crooked Bridge diorite, a 1 km long by 400 m wide body exposed within the Slieve Gallion granite (Fig. 2). At its northern margin, c. 400 m north of Crooked Bridge [2750 3859], the transition from granite to diorite is observed over less than 5 m. In places, the granite includes irregular patches of hornblende-rich diorite that are sometimes diffuse, suggestive of magma mingling and mixing. In thin section, diorite from this marginal location contains mainly early euhedral hornblende and plagioclase crystals with late interstitial quartz that encloses smaller sub-anhedral plagioclase. The texture is that of a granite–diorite hybrid and indicates syn-magmatic crystallization. Seven zircon fractions (single grains and fragments) were analysed from MRC351. All seven analyses are concordant when the systematic $\lambda_{238U}$ and $\lambda_{235U}$ decay constant errors are considered. Six form a coherent single population yielding a weighted mean 206Pb/238U date of 469.58 ± 0.32 (0.57)[0.77]Ma (MSWD = 1.4), which we interpret as being the age of the sample (Fig. 8a). One older analysis (z7; Fig. 8a) is considered to reflect incorporation of older material (c. 473 Ma) derived from the Tyrone Volcanic Group into the magmatic system.

Sample MRC335 represents a silicified, feldspar porphyritic Fe–Ti-enriched alkali basaltic rock that crops out towards the top of Sranhleanantawey Burn. As detailed above, this unit is non-vesicular and massive, and appears to contain angular xenoliths of aphanitic basalt or silicified sediment. Its contacts with adjacent units are not exposed. Five zircon fractions (single grains) were analysed from MRC335. One grain yielded a Proterozoic age (c. 1033 Ma) indicating incorporation of older basement material. Within the remaining population all of the analyses are concordant; however, there is dispersion with 206Pb/238U dates ranging from 467.43 ± 0.48 to 470.38 ± 0.40 Ma (Fig. 8). The youngest 206Pb/238U date (z1; Fig. 8a) we interpret to reflect minor Pb loss. The age of the sample is approximated by the population of three equivalent 206Pb/238U dates (z6, z11 and z14) to 469.36 ± 0.34 (0.58)[0.78] Ma (MSWD 0.42).

Visual inspection, and limited CL imaging, of the zircons (including ones dated) indicates that they are typical of magmatic zircons (including other samples dated in this study) based upon their external morphology and internal concentric zonation (Fig. 8b).

### Discussion

#### Petrochemical evolution

Earliest magmatism within the Slieve Gallion Inlier (Tinagh Formation) is characterized by the eruption of tholeiitic pillow basalt
of island-arc affinity (= Derryganard Basalts). These lavas are the most primitive of all samples analysed (low SiO₂ and Zr/Y, high MgO). Low La/YbCN and ThCN suggest that magmatism at this stage was not contaminated by continental material. Overlying deposits within the Tinagh Formation (= Letteran Volcanics & Windy Castle Lavas) are dominated by LILE- and LREE-enriched hornblende-pyric and feldspathic calc-alkaline basaltic andesites and andesitic tuffs. Strongly negative εNd values, high ThCN and La/YbCN suggest that a sudden and significant input of continental crust and/or detritus occurred at this time into the arc system, or that the Derryganard basalts represent an episode of volcanism associated with extensive back-arc rifting, such as the Beaghmore Formation of the lower Tyrone Volcanic Group (see Hollis et al. 2012). Mafic tuffs and lavas become increasingly replaced by those of andesitic composition up sequence. The proportion of pillow breccias and pyroclastic deposits also increases towards the top of the Tinagh Formation.

Primitive, non-arc type Fe–Ti–P enriched basalt of E-MORB affinity recognized around Mobuy Wood (= Mobuy Wood Basalts) are typical of rift-related lavas present within the Tyrone Volcanic Group (see references given by Hollis et al. 2012). Although εNd values of Fe–Ti E-MORB are the most primitive of all samples analysed within the Slieve Gallion Inlier (+0.6 to +2.5), they are less so than those described by Hollis et al. (2012) from main exposures of the lower Tyrone Volcanic Group to the SW (+2.4 to +5.9).

Hollis (2013) noted a systematic geochemical variation in Fe–Ti-enriched basalts of the Tyrone Volcanic Group, with increasing Fe and Ti associated with increasing Zr, Th, V, La and Nb, decreasing MgO, CaO, Al₂O₃, Ni and Cr, and more negative εNd values. These lavas may have formed through the interaction between an island arc and a propagating rift (Hollis et al. 2012).

The occurrence of 1–5 m thick beds of ironstone (or ironstone float) within all formations of the Slieve Gallion Inlier also suggests that rifting was episodic. Ironstones are common within the Tyrone Volcanic Group, where they occur as laterally continuous beds in the Loughmacrory, Beaghmore and Broughderg formations (Fig. 2a; Hollis et al. 2012). Clasts of ironstone are also found in some basalitic breccias of the Creggan Formation and in tuffs of the aforementioned formations (Hollis et al. 2012). Ironstones in the Tyrone Volcanic Group are temporally and spatially associated with rift-related lavas (e.g. Fe–Ti-enriched E-MORB, OIB, island-arc tholeiite), synvolcanogenic faults, hydrothermal alteration and in some instances base-metal mineralization (Hollis 2013). Whole-rock geochemical ratios and small positive Eu anomalies at Torrys Hole (and Tanderagee of the Loughmacrory Formation) are comparable with
Table 1. U–Pb zircon geochronology from Slieve Gallion

<table>
<thead>
<tr>
<th>Sample</th>
<th>Compositional parameters</th>
<th>Radiogenic isotope ratios</th>
<th>Isotopic ages (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Th/U²</td>
<td>²⁰⁶Pb* (× 10⁻¹³ mol)³</td>
<td></td>
</tr>
<tr>
<td>z₁</td>
<td>0.745</td>
<td>2.4430</td>
<td>98.43%</td>
</tr>
<tr>
<td>z₂</td>
<td>0.510</td>
<td>3.9679</td>
<td>99.65%</td>
</tr>
<tr>
<td>z₆</td>
<td>1.006</td>
<td>4.4897</td>
<td>99.62%</td>
</tr>
<tr>
<td>z₁₁</td>
<td>0.738</td>
<td>0.3981</td>
<td>99.19%</td>
</tr>
<tr>
<td>z₄</td>
<td>1.011</td>
<td>0.4433</td>
<td>97.90%</td>
</tr>
<tr>
<td>z₁₅</td>
<td>1.365</td>
<td>5.9864</td>
<td>99.83%</td>
</tr>
<tr>
<td>z₂</td>
<td>1.216</td>
<td>4.0148</td>
<td>98.97%</td>
</tr>
<tr>
<td>z₃</td>
<td>1.139</td>
<td>8.6618</td>
<td>98.86%</td>
</tr>
<tr>
<td>z₆</td>
<td>1.108</td>
<td>1.8259</td>
<td>99.79%</td>
</tr>
<tr>
<td>z₇</td>
<td>0.992</td>
<td>0.6754</td>
<td>97.96%</td>
</tr>
<tr>
<td>z₈</td>
<td>0.936</td>
<td>1.0390</td>
<td>99.11%</td>
</tr>
<tr>
<td>z₉</td>
<td>0.910</td>
<td>1.5808</td>
<td>99.19%</td>
</tr>
</tbody>
</table>

1z₁, z₂, etc. are labels for fractions composed of single zircon grains or fragments; all fractions annealed and chemically abraded after Mattinson (2005).
2Model Th/U ratio calculated from radiogenic ²⁰⁸Pb/²⁰⁶Pb ratio and ²⁰⁶Pb/²³⁵U age.
3Pb* and Pbc represent radiogenic and common Pb, respectively; mol % ²⁰⁶Pb* with respect to radiogenic, blank and initial common Pb.
4Measured ratio corrected for spike and fractionation only.
5Corrected for fractionation, spike, and common Pb, up to 2 pg of common Pb was assumed to be procedural blank: ²⁰⁶Pb/²³⁸U = 18.60 ± 0.80%; ²⁰⁷Pb/²⁰⁶Pb = 15.69 ± 0.32%; ²⁰⁸Pb/²⁰⁶Pb = 38.51 ± 0.74% (all uncertainties 1σ). Excess over blank was assigned to initial common Pb.
6Errors are 2σ, propagated using the algorithms of Schmitz & Schoene (2007).
7Calculations are based on the decay constants of Jaffey et al. (1971). ²⁰⁶Pb/²³⁵U and ²⁰⁷Pb/²⁰⁶Pb ages are corrected for initial disequilibrium in ²⁰⁶Th/²³⁵U using Th/U [magma] = 3, using the algorithms of Schärer (1984). Dates in bold are those included in weighted mean calculations.
Correlations with the Tyrone Volcanic Group

Using recently published U–Pb zircon geochronology and geochemistry (Cooper et al. 2008, 2011; Draut et al. 2009; Hollis et al. 2012) and the work presented herein, we can refine possible correlations across the Tyrone Volcanic Group. Stratigraphic divisions established within the main occurrence of the Tyrone Volcanic Group, exposed to the SW of the Slieve Gallion Inlier, have been presented by Hollis et al. (2012) and are summarized in Figure 9. Although the volcanic succession at Slieve Gallion was initially suggested to correlate with the Broughderg Formation of the upper Tyrone Volcanic Group (Cooper et al. 2008), recent geological mapping (Hollis et al. 2012) has identified the presence of similar lithologies (e.g. hornblende-phryic lavas, thinly bedded argillaceous sedimentary rocks, sheared-rhyolitic tuff, layered chert and greenish grey tuffs) within the Loughmacrory Formation (Fig. 2) of the lower Tyrone Volcanic Group (Fig. 9). In addition, the occurrence of ferruginous jasper (ironstone) at Slieve Gallion would argue against a correlation with the Broughderg Formation (c. 469 Ma), where ironstones are characterized by magnetite–silica–pyrite and graphitic pelite is abundant (Hollis et al. 2012). Only at Crosh in the Broughderg Formation has quartz–hematite ironstone been recognized (Fig. 2), where it replaces a tuffaceous horizon in a thick sequence of graphitic pelite (Hollis 2013). Pillow lavas of calc-alkaline affinity are also absent within the upper Tyrone Volcanic Group, but are present in the Creggan, Loughmacrory and Beaghmore formations of the lower Tyrone Volcanic Group (Hollis et al. 2012).

The Loughmacrory Formation is amongst the most diverse succession in the Tyrone Volcanic Group and was divided by Hollis et al. (2012) into three members (Figs 4 and 9). The oldest, the Tanderagee Member, is characterized by a thick succession of crystal and lithic tuff, pillowed calc-alkaline basalt or basaltic andesite, hornblende-and feldspar-phryic andesites, and pillow breccias, associated with lesser ironstone, Fe–Ti E-MORB, layered chert and sedimentary rocks (including siltstone and rare mudstone). The overlying Merchantstown Glebe Member is characterized by pillowed, massive and sheet-flow Fe–Ti-enriched basalt or basaltic andesite of E-MORB affinity associated with lesser crystal tuff and pillow breccias. The youngest, the Streep Glebe Member, is characterized by a thick sequence of calc-alkaline LILE- and LREE-enriched crystal tuff with rare occurrences of lava (of unknown affinity). The Loughmacrory Formation bears a striking resemblance to the volcanic succession exposed in the Slieve Gallion Inlier, with the Tinagh and Tawey formations equivalent to the Tanderagee Member, and the Whitewater Formation broadly equivalent to the Streep Glebe Member (Fig. 9). Fe–Ti E-MORB lavas of the Mobuy Wood Basalts are present both in the Tanderagee and Merchantstown Glebe members and in the underlying Creggan Formation (Figs 4 and 9). Although a number of these lithologies can also be found in the Beaghmore Formation of the lower Tyrone Volcanic Group, which is restricted to the east of the Dungate Fault (Fig. 2), this backarc assemblage is dominated by bimodal tholeiitic volcanism and Fe–Ti E-MORB, with few lavas of calc-alkaline affinity (Hollis et al. 2012).

Geochemical data from both the Slieve Gallion Inlier and all formations of the Tyrone Volcanic Group are plotted together in Figures 6 and 7. Multi-element variation profiles allow little distinction between calc-alkaline tuffs of the Tyrone Volcanic Group (Fig. 7b and f). Although samples analysed herein overlap with lavas and tuffs from both the lower and upper Tyrone Volcanic Group, the most evolved samples from the latter are characterized by much higher Zr/Y contents, and Nb/Y ratios toward strongly alkaline compositions (Fig. 6f). For example, c. 469 Ma rhyolites of the Broughderg Formation display A-type affinities and are characterized by high Nb and Zr (Hollis 2013), which have not been recognized at Slieve Gallion.

Mafic lavas of the Tyrone Volcanic Group perhaps provide better discrimination between formations, as many units are geochemically distinct. In the lower Tyrone Volcanic Group mafic flows are characterized by calc-alkaline basalt, Fe–Ti-enriched E-MORB

Fig. 8. (a) U–Pb zircon concordia for samples analysed from the Slieve Gallion Inlier and arc-related intrusive suite. The \(^{206}\text{Pb}/^{238}\text{U}\) axis has been duplicated. (b) Representative CL images of zircons from MRC335.
Fig. 9. Stratigraphy, petrochemistry and absolute ages for the Ordovician succession of South Mayo, Charlestown and the Tyrone Igneous Complex. Diagram after Ryan & Dewey (2011). The standard British Ordovician stages, those of the IUGS and the Australian Ordovician graptolite zones are assigned to absolute ages after Sadler et al. (2009). Absolute ages for events are represented by stars with error bars. References: 1, Formil rhyolite (Cooper et al. 2008); 2, Tullybrick tuff and Cashel Rock rhyolite of Greencastle Formation, and Cashel Rock tonalite (Hollis et al. 2012); 3, clasts in Silurian conglomerate derived from Finny Formation (Chew et al. 2007); 4, ignimbrite of Mweelrea Formation (Dewey & Mange 1999); 5, arc-related intrusive rocks of Cooper et al. (2011). Stratigraphy of the Tyrone Volcanic Group from (Hollis et al. 2012, and unpublished data). North and south limbs refer to the Mweelrea syncline (South Mayo Trough).
and island-arc tholeiite. In the upper Tyrone Volcanic Group mafic units are restricted to the Broughderg Formation, where they are borderline to strongly alkaline and display OIB-like characteristics (Hollis et al. 2012). Pillowed lava sampled from the Mobuy Wood Basalts (SPH533) has an identical multi-element variation profile to Fe–Ti pillow lavas from the lower Creggan, Loughmacrory (Tanderagee Member) and Beaghmore formations of the lower Tyrone Volcanic Group, with positive Nb anomalies, and similar LILE and REE concentrations (Fig. 7e). Similarly, massive and vesicular, non-pillowed flows of the Mobuy Wood Basalts (SPH508, SPH517) display slight negative Nb anomalies, and Ti anomalies. These flows are geochemically identical to Fe–Ti lavas from the upper Creggan Formation and Merchantstown Glebe members of the lower Tyrone Volcanic Group (Fig. 7d; see Hollis et al. 2012).

Island arc tholeiite, exposed at Derrycarney, is present only in the lower Tyrone Volcanic Group in the Beaghmore Formation (Hollis et al. 2012). Although these lavas display similar multi-element profiles to sample SPH525 (Derrycarney Lavas; Fig. 7a), they contain higher Nb/Yb, Zr/Y and Nb/Y (Fig. 4a, b, d and e) consistent with backarc volcanism in the Beaghmore Formation following intra-arc rifting (Hollis et al. 2012). Tholeiitic tuffs and rhyolitic agglomerates of the Beaghmore Formation that display flat REE profiles and low Zr/Y and Nb/Yb also appear to be unrepresented in the Slieve Gallion Inlier, although rhyodacite from Mobuy Wood was not analysed.

Nd isotope constraints of samples from Slieve Gallion are shown together with samples from the Tyrone Volcanic Group in Figure 6c. Tuffs and lavas of the Loughmacrory Formation are slightly more primitive (εNd, −4.1 to −7.0) than the Tinagh Formation (Letteran Volcanics: εNd, −9.0), although chert from the underlying Creggan Formation has produced a similar value (εNd, −8.0) (Hollis et al. 2012). No Nd isotope constraints have been carried out on tuffs of the Streefe Glebe Member, which would equate to the Whitewater Formation (εNd, −12.7 to −13.9). It is possible that the upper part of the Whitewater Formation records the onset of arc-accretion (= lower Greencastle Formation), as similar εNd values have also been produced from the syncollisional upper Tyrone Volcanic Group (e.g. −8.9 for rhyolite from Greencastle; −11.6 for tuff associated with graphitic pelite at Broughderg). An alternative explanation is that the Slieve Gallion volcanic rocks may have been founded upon a portion of thicker continental crust and experienced a greater degree of crustal contamination. This latter scenario is consistent with the geochemistry of the Mobuy Wood Basalts, which display less primitive εNd and higher Th/Yb values (Fig. 6d and e) than similar units of the Loughmacrory Formation.

In summary, new stratigraphic and petrochemical data from Slieve Gallion suggest that the succession at Slieve Gallion is more analogous to the lowermost parts of the Tyrone Volcanic Group, specifically the Loughmacrory Formation (Figs 6 and 7). This is also consistent with U–Pb zircon dating of the upper Tyrone Volcanic Group at c. 473–469 Ma (Cooper et al. 2008; Hollis et al. 2012), and an age of c. 475–474 Ma from the graptolite-bearing succession of Sruhanleanantawey Burn (Cooper et al. 2008).

**Intrusive rocks**

The Fe–Ti-enriched alkali basaltic rock of E-MORB to OIB-like affinity from Sruhanleanantawey Burn dated herein to c. 469 Ma is geochemically similar to the Fe–Ti-enriched basalts exposed at Mountfield Quarry (Fig. 5c) and Broughderg, both of which are stratigraphically above c. 473–469 Ma rhyolites of the Greencastle Formation. The Sruhanleanantawey Burn and Broughderg Formation basalts plot in similar positions along the mantle array, at higher Nb/Yb than E-MORB (Fig. 6d and e). Zr/Y ratios are slightly lower in the Mountfield Basalts, although the Sruhanleanantawey Burn samples follow the same trend of increasing alkalinity with Zr/Y (Fig. 4f). Sample MRC335 also shows a similar slight negative Nb anomaly, and positive Zr and Ti anomalies (Fig. 7e). We interpret the Sruhanleanantawey Burn alkali basaltic rock as a late intrusive rock and representative of a suite that fed the rift-related lavas of the uppermost Tyrone arc. The inherited zircon fraction dated at 1033 Ma is consistent with the assimilation of continental material into the magmatic arc at this time. Accretion of the Tyrone arc onto the peri-Laurentian, Dalradian-affinity, Tyrone Central Inlier (Chew et al. 2008) is placed at c. 470 Ma, coeval with widespread tonalite emplacement (Cooper et al. 2011; see also Hollis et al. 2012). Undated Fe–Ti-enriched dykes similar to MRC335 also intrude S-type muscovite granite at Tromoge Glen (SPH129; see Hollis et al. 2013).

The Crooked Bridge diorite, dated herein to 469.8±0.32 (0.57) [0.77] Ma, displays a clear magma mixing–mingling relationship with hornblende-granite. Biotite-granite dated by Cooper et al. (2011) from the eastern side of Slieve Gallion yielded a U–Pb zircon age of 466.5±3.3 Ma, within error of that presented herein for the Crooked Bridge diorite. Although the biotite- and hornblende-bearing granites of Slieve Gallion may represent distinct magmas, the latter may have been simply contaminated from the underlying Tyrone Plutonic Group, as highly magnetic material of the Tyrone Plutonic Group is restricted to the southwestern side of Slieve Gallion where hornblende-bearing granite crops out. Both the Slieve Gallion granite and Crooked Bridge diorite belong to the c. 470–464 Ma arc-related intrusive suite of Cooper et al. (2011), which stitches the Tyrone Volcanic Group in its present structural position following arc-accretion.

**A correlation for the Irish Caledonide arcs**

Through the study of fossil and modern orogens, and the use of geodynamic models (e.g. Afonso & Zlotnik 2011; Boutelier & Chemenda 2011; Gerya 2011), it is evident that there is no paradigm that uniquely defines arc–continent collision (reviewed by Brown et al. 2011). Natural complexities in key first-order parameters such as the nature of the continental margin (e.g. shape, thickness, presence of re-entrants, hydration, composition) and arc–trench complex (e.g. shape of trench, arc thickness, nature of the basement), result in considerable variation between and within orogens (see Brown et al. 2011), along with their interactions with spreading centres, oceanic plateaux and microcontinental blocks. Arc and ophiolite complexes may be obducted (e.g. Lushis Bight, Bay of Islands; Van Staal et al. 2007) or underplated to continental margins (e.g. Anniespquotch Accretionary Tract; Zagorevski et al. 2009) depending on their relative age at the time of accretion and tectonic position. Fore-arc systems may be preserved or completely lost owing to the location of failures in the overriding plate, which are determined by sites of lithospheric weakness (Boutelier & Chemenda 2011). Accretion may also be diachronous across the margin, with implications for the timing of subduction reversal (Brown et al. 2011).

Using recently presented stratigraphic, geochemical and U–Pb zircon constraints from the Tyrone Volcanic Group (Cooper et al. 2011; Hollis et al. 2012; and those in the present study) we can refine possible correlations between the Irish Caledonian arcs that were accreted to the Laurentian margin during the Grampian orogeny. Geochemical correlations are presented in Figure 9, which is modified after Ryan & Dewey (2011) according to the time scale of Sadler et al. (2009). Although previous work has suggested that arc–continent collision during the Grampian orogeny was short-lived and not markedly diachronous (Soper et al. 1999; Dewey et al. 2008), the Grampian orogeny involved significant crustal accretion (e.g. Annieopsquotch Accretionary Tract; Zagorevski et al. 2009) depending on their relative age at the time of accretion and tectonic position. Fore-arc systems may be preserved or completely lost owing to the location of failures in the overriding plate, which are determined by sites of lithospheric weakness (Boutelier & Chemenda 2011). Accretion may also be diachronous across the margin, with implications for the timing of subduction reversal (Brown et al. 2011).
2005), the data presented herein along with recently published geo-
chronology from the Tyro de Igneus Complex (Cooper et al. 2011; 
Hollis et al. 2012) clearly demonstrate that either the evolution of 
arc volcanism and to some extent arc accretion was diachronous in 
the peri-Laurentian Irish Caledonides or multiple arc systems of 
different age are preserved (e.g. Hollis et al. 2012).

In western Ireland, the generation of supra-subduction zone 
affinity oceanic crust began prior to c. 514 Ma, the age of high-
grade metamorphism and deformation of the Deer Park ophiolitic 
mélange (514 ± 3 Ma 40Ar–39Ar hornblende; Chew et al. 2010). Early 
obduction may have occurred to an outboard block of peri-Laurentian 
affinity oceanic crust (Chew et al. 2010), as in the 
Newfoundland Appalachians (= Taconic phase 1 of van Staal 
et al. 2007). Blocks of muscovite-bearing schist within the Deer 
Park mélange contain detrital zircon spectra similar to the 
Dalradian Supergroup and have produced an 40Ar–39Ar age of 
482 ± 1 Ma (Chew et al. 2010). An age of c. 482 Ma for ophiolite 
exhumation is consistent with heavy mineral studies from western 
Ireland, which record significant quantities of ophiolite-derived 
sediment entering the fore-arc (South Mayo Trough) of the Lough 
Nafooey arc from c. 478 to 476 Ma (Dewey & Mange 1999; 
Letterbrook Formation; Fig. 9). Together, the South Mayo Trough, 
Lough Nafooey arc and Tourmadea Group record the develop-
ment of the colliding Lough Nafooey arc prior to and during its 
collision with Laurentia (Ryan et al. 1980; Cliff & Ryan 1994; 
Dewey & Mange 1999; Draut et al. 2004; Fig. 9). LREE depletion 
and the strongly positive εNd values of the Lower Nafooey arc in 
the lower Lough Nafooey Group suggest an origin far from Laurentia. 
A switch from the eruption of island-arc tholeiites (and boninitic 
lavas of the Bohua Volcanic Formation) to calc-alkaline lavas 
occurs prior to c. 490 Ma (Fig. 9). Increasing SiO2, LILE and 
LREE enrichment and more negative εNd values, with strati-
graphic height in the Lough Nafooey arc reflect an increasing con-
tribution of subducted material into the arc system as it approach-
ed the Laurentian margin (Draut et al. 2004; Chew et al. 2007). The 
overlying syn-collisional Tourmadea Group (c. 476–470 Ma) 
formed synchronously with peak metamorphism and regional 
deformation within the Dalradian Supergroup. The timing of 
‘hard’ collision in western Ireland (= base of the Tourmadea Group. 
Draut et al. 2004) occurred between c. 484 Ma (= graptolite 
contraint on Lough Nafooey Group) and c. 476 Ma (= age of the 
Mt. Partry Formation) (Fig. 9). This phase of arc-accretion is 
equivalent to Taconic phase 2 of the Newfoundland Appalachians 
(van Staal et al. 2007; see discussion by Hollis et al. 2013).

Whereas the Lough Nafooey arc clearly shows an increasing 
contribution of subducted material into the arc system as it 
approached the Laurentian margin (Draut et al. 2004), no such sys-
tematic trend is evident in the Tyro de Igneus Complex (Hollis 
et al. 2012). Both the syn-collisional upper Tyro de Igneus Complex and 
the pre-collisional basal formations of the lower Tyro de Igneus 
Group display strongly negative εNd values and evidence for 
strong LILE and LREE enrichment (Figs 6c, f and 7b, f; Draut 
et al. 2009; Cooper et al. 2011; Hollis et al. 2012). Two possible 
scenarios may explain these geochemical characteristics. In the 
first scenario, the Tyro de Igneus Complex may have developed 
above a SE-dipping subduction zone and is part of the Lough 
Nafooey arc system (after Draut et al. 2009; also see Cooper et al. 
2011). In this instance, extensive crustal contamination would 
result from subducted sediment derived from the Laurentian 
marg. Increased contamination may have occurred if the Tyro arc 
was founded upon a segment of peri-Laurentian outriding conti-
nental crust. Arc–continent collision would have been diachronous 
from c. 480 Ma in western Ireland to c. 470 Ma in Co. Tyro. 
Similarly, the geochemical evolution of the arc must have also been 
strongly diachronous (Fig. 9), with a switch from tholeiitic volcani-
sm from <490 Ma in western Ireland (Draut et al. 2004) to 
c. 475 Ma in the Tyro de Igneus Group (Cooper et al. 2011). In 
the second scenario, the Tyro de Igneus Complex may have de-
veloped above a north-dipping subduction zone in a manner similar to 
the Anniepsquaque Accretionary Tract of Newfoundland 
(Zagorevski et al. 2009), and records the evolution of a younger, 
separate arc system that collided with the composite Laurentian 
margin at c. 470 Ma (Hollis et al. 2012, 2013). In this model, the 
Tyro de Igneus Complex formed immediately outboard of the 
Tyro Central Inlier, a peri-Laurentian microcontinental block 
(Dewey et al. 2008). At c. 484–479 Ma, spreading outboard of this 
microcontinental block gave rise to the formation of the ophiolitic Tyro 
Plutonic Group (Hollis et al. 2013). This c. 480 Ma rifting may be 
related to the onset of ‘hard’ collision in Ireland (i.e. Taconic phase 
2). If this model is correct, continental contamination of the Tyro 
arc would be a direct result of the arc being constructed upon the 
rifted-off fragment of microcontinental crust.

The Charlestown Group, exposed across c. 45 km2 of Co. Mayo, 
is an important link between western Ireland and the Tyro de 
Volcanic Group of Northern Ireland. Although it is typically attrib-
uted to the syn-collisional stage of the Lough Nafooey arc system 
and is believed to broadly correlate with the Tourmadey Group 
(e.g. Chew 2009), it remains one of the most understudied compo-
ents of the orogen. Charlesworth (1960) provided the first detailed 
structure and stratigraphy of the Charlestown Group. New ex-
plore allowed O’Connor (1987) to reassess the stratigraphy and 
re-divide the succession into three formations, renamed by Long 
et et al. (2005) as follows: (1) Horan Formation, around 630 m thick, 
characterized by minor sediments, extrusive basalts, siltites and 
mixed tuffs; (2) Carracastle Formation, around 290 m thick, domi-
nated by andesitic tuffs and flows, with coarse volcanic breccias; 
(3) Tawnynah Formation, around 300 m thick, dominated by more 
silicic lithologies. A gradual change was noted from tholeiitic 
arc–continent siltites at the base with associated tuffs, into calc-alka-
line tuffs and resedimented tuffs of the Carracastle Formation, 
passing into more felsic tuffs with accompanying intrusions of 
ryolite and dacite near the top (O’Connor & Poustie 1986; 
O’Connor 1987).

This lithological and petrochemical change is similar to that 
observed from both the Tyro de Volcanic Group (e.g. island arc 
tholeiites into calc-alkaline basalts of the Tinagh Formation to 
syndepositional rhyolites of the upper Tyro arc) and the Lough 
Nafooey arc (e.g. Draut et al. 2004), although the timing differs 
significantly from the latter (Fig. 9). In the Charlestown Group, 
Cummins (1954) obtained an Arenig age from a graptolite-bearing 
sequence near the top of the Horan Formation. This was later veri-
fied by Dewey et al. (1970) specifically to British Didymograptus 
hirundo biozone and Isograptus caduceus biozone of North 
America. Cooper & Lindholm (1990) equated the 
Didymograptus hirundo biozone with the Da1 zone of the Darrilvilan Australasian 
stage; and it was subsequently renamed to the 
Undulograptus austrodenatus biozone (= Da1) and lower part of the 
Undulograptus intersitus biozone (= lower Da2) (see Zalasiewicz 
et al. 2009). The Da1 stage has been calculated by Sadler et al. 
et al. (2009) to 470.54–469.57 Ma, and the upper boundary of Da2 to 
467.94 Ma. Although further work is needed on the Charlestown 
Group, particularly high-resolution U–Pb zircon geochronology, 
trace element geochemistry and Nd isotope constraints, this 
sequence appears to have many temporal, lithological and geo-
chemical similarities to the Tyro de Volcanic Group (Fig. 9) 
despite being separated by some distance. We suggest that both 
may belong to the same arc system (possibly different eruptive
centres), which was subsequently juxtaposed with the Lough Nafooey arc during dextral (Harris 1993) or later sinistral strike-slip activity (Dewey & Strachan 2003). Pb isotope work on galena from Charleton and mineral deposits directly NW of (and structurally overlying) the Tyrone Volcanic Group has also suggested a correlation between the two arc terranes (Parnell et al. 2000).

In summary, if the Lough Nafooey, Tourmakeady, Charleton and Tyrone Volcanic groups formed within the same arc system, the geochemical evolution of this arc must have been strongly diachronous within the Irish Caledonides (Fig. 9) from c. 490 to 475 Ma, with diachronous arc-accretion to Laurentia from c. 480–478 Ma to c. 470 Ma. If correct, this model suggests that a continuation of arc-diacrony into the Scottish Caledonides can be expected. However, as Tremadocian to Early Arenig (c. 490–480 Ma) rocks have also been recognized from the Scottish Caledonides this seems unlikely. Chew et al. (2010) obtained a U–Pb zircon age of 490±4 Ma from a mica-schist (interpreted as a volcaniclastic rock) intercalated within the c. 499±8 Ma (U–Pb zircon) Highland Border Ophiolite, an along-strike equivalent of the Deer Park Complex. Similar ages have also been obtained from Ballantrae (Sm-Nd 501±12 Ma, 476±14 Ma; Thirlwall & Bluck 1984; K–Ar 487±8 Ma; Harris et al. 1965), suggesting that a volcanic arc may have been associated with the Ballantrae Ophiolite Complex (483±4 Ma U–Pb zircon; Bluck et al. 1980) at this time. We suggest that the absence of a volcanic arc in Tyrone prior to c. 475 Ma combined with strong temporal, petrochemical and stratigraphic correlations to ophiolites and arc successions in the Newfoundland Appalachians along strike (Cooker et al. 2011; Hollis et al. 2012, 2013), and the development of the Tyrone Igneous Complex outboard of the Tyrone Central Inlier, together suggest that the complex formed within a separate arc system to the Lough Nafooey Group.

Conclusions

The Slieve Gallion Inlier of Northern Ireland, an isolated fragment of the Tyrone Volcanic Group, records the development of a peri-Laurentian island-arc–backarc and its obduction to an outboard microcontinental block (= Tyrone Central Inlier) at c. 470 Ma. Earliest magmatism is characterized by LREE-depleted island-arc tholeiite. Overlying deposits are dominated by LILE- and LREE-enriched, hornblende-phycic andfeldspathic calcalkaline basaltic andesites and andesitic tuffs with strongly negative εNd values implying substantial contamination by continental crust and/or detritus. Fe–Ti-enriched rift-related basalts of E-MORB affinity may be associated with propagation of a rift into the island arc. Biostratigraphic age constraints and petrochemical correlations suggest that the Slieve Gallion Inlier formed c. 475–474 Ma and is equivalent to the lower Tyrone Volcanic Group. Later c. 469 Ma intrusive rocks of Fe–Ti-enriched alkali basalt appear to have fed the post-collisional rift-related lavas of the uppermost Tyrone arc (= Broughderg Formation). Preliminary temporal, geochemical and stratigraphic correlations between the Slieve Gallion Inlier (Tyrone Volcanic Group) and Charleton Group of Ireland suggest that they may be part of the same arc system. A switch from tholeiitic volcanism to calc-alkaline-dominated activity within the Lough Nafooey arc occurred prior to c. 490 Ma, c. 15–20 Myr earlier than at Charleton (c. 470 Ma) and Tyrone (c. 475 Ma).

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