# Episodic arc-ophiolite emplacement and the growth of continental margins: Late accretion in the Northern Irish sector of the Grampian-Taconic orogeny

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## ABSTRACT

**In order to understand the progressive growth of continental margins and the evolution of continental crust, we must first understand the formation of allochthonous ophiolitic and island-arc terranes within ancient orogens and the nature of their accretion. During the early Paleozoic closure of the Iapetus Ocean, diverse sets of arc terranes, oceanic tracts, and ribbon-shaped microcontinental blocks were accreted to the passive continental margin of Laurentia during the Grampian-Taconic orogeny. In the northern Appalachians in central Newfoundland, Canada, three distinct phases of arc-ophiolite accretion have been recognized. New field mapping, high-resolution airborne geophysics, whole-rock and Nd-isotope geochemistry, and U-Pb zircon geochronology within the Tyrone Volcanic Group of Northern Ireland have allowed all three episodes to now be correlated into the British and Irish Caledonides. The Tyrone Volcanic Group (ca. 475–469 Ma) is characterized by mafic to intermediate lavas, tuffs, rhyolite, banded chert, ferruginous jasperoid, and argillaceous sedimentary rocks cut by numerous high-level intrusive rocks. Geochemical signatures are consistent with formation within an evolving peri-Laurentian island-arc/backarc, which underwent several episodes of intra-arc rifting prior to its accretion at ca. 470 Ma to an outboard peri-Laurentian microcontinental block. Outriding microcontinental blocks played a fundamental role within the orogen, explaining the range of ages for Iapetan ophiolites and the timing of their accretion, as well as discrepancies between the timing of ophiolite emplacement and the termination of the Laurentian Cambrian–Ordovician shelf sequences. Accretion of the Tyrone arc and its associated suprasubduction-zone ophiolite represents the third stage of arc-ophiolite emplacement to the Laurentian margin during the Grampian-Taconic orogeny in the British and Irish Caledonides.**

## INTRODUCTION

Understanding the temporal development of allochthonous ophiolitic and island-arc terranes within ancient orogens is an integral part of reconstructing the growth of continental margins (Zagorevski et al., 2009a) and the evolution of continental crust (Draut et al., 2004, 2009). The Caledonian-Appalachian orogen (Fig. 1) is one of the best preserved and most intensely studied examples of a long-lived collision zone within the geologic record. Early Paleozoic closure of the Iapetus Ocean resulted in the accretion of a diverse set of arc terranes, ribbon-shaped microcontinents, and oceanic tracts to the Laurentian margin during Grampian-Taconic orogenesis (e.g., van Staal et al., 1998, 2007; Dewey, 2005). Subsequent collisions with Baltica and Avalonia resulted in the assembly of Euramerica, prior to the construction of Pangaea during the Variscan-Alleghanian-Ouachita orogeny (Nance et al., 2010).

The Canadian Appalachians provide a clear template for the interpretation of segments of the Laurentian margin. Within the analogous British and Irish Caledonides, extensive post-Ordovician cover sequences obscure crucial relationships, and terrane excision and repetition are common. Despite recognized similarities across the orogen (Colman-Sadd et al., 1992; Winchester and van Staal, 1995; van Staal et al., 1998), several specific terrane correlations remain contentious when extended into the British and Irish Caledonides. In contrast with the Grampian orogeny, three main phases of arc-ophiolite accretion have been recognized during the Taconic orogeny (van Staal et al., 2007).

Peri-Laurentian ophiolitic remnants of Iapetus are well documented within the Caledonides and include the Ballantrae Ophiolite Complex (Oliver et al., 2002), Highland Border Ophiolite (Tanner and Sutherland, 2007), Shetland ophiolite (Flinn and Oglethorpe, 2005), Deer Park Complex (Ryan et al., 1983), and Tyrone Plutonic Group (Hutton et al., 1985; Cooper et al., 2011) (Figs. 1 and 2A). Collision between the passive continental margin of Laurentia and the Lough Nafooey arc of western Ireland (and any buried along-strike equivalent in the Midland Valley terrane of Scotland) during the Grampian

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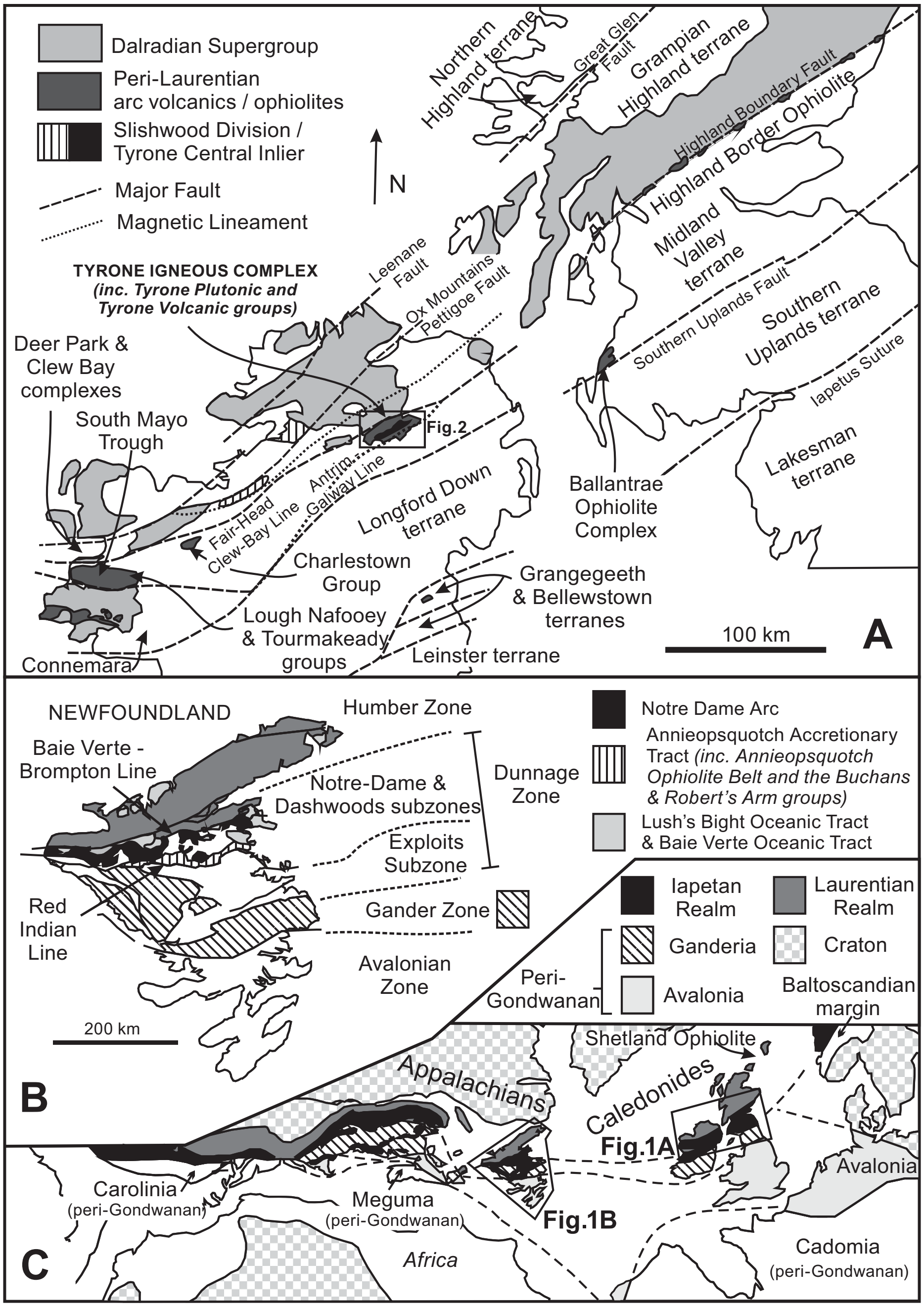

**Figure 1. (A) Setting of the Tyrone Igneous Complex and other comparable ophiolite and volcanic arc associations in Britain and Ireland (after Cooper et al., 2011). (B) Simplified regional geology of Newfoundland (after van Staal et al., 2007). (C) Early Mesozoic restoration of the North Atlantic region and Appalachian-Caledonian orogen (after Pollock et al., 2009).**

orogeny was associated with the polyphase deformation and metamorphism of thick Laurentian sequences, such as the Neoproterozoic Dalradian Supergroup, and the emplacement of suprasubduction-zone ophiolites (Dewey and Shackleton, 1984). Examination of the Lough Nafooey arc and its associated forearc-successor basin, the South Mayo Trough, allows a detailed reconstruction of arc-continent collision in western Ireland (Clift and Ryan, 1994; Dewey and Mange, 1999; Mange et al., 2003, 2010; Draut et al., 2004). Timing of peak metamorphism and regional deformation is constrained by Sm-Nd garnet ages of ca. 473–465 Ma for Barrovian metamorphism in the Scottish Highlands (Baxter et al., 2002) and ca. 475–468 Ma U-Pb zircon ages from synorogenic intrusive rocks in western Ireland (Friedrich et al., 1999a, 1999b). Recent U-Pb zircon geochronology from the Irish Caledonides (e.g., Flowerdew et al., 2005; Chew et al., 2008) is consistent with these interpretations.

The Tyrone Igneous Complex of Northern Ireland consists of a tectonically dissected ophiolite and a relatively complete island-arc sequence, accreted to an outboard segment of Laurentia during the Grampian orogeny. Despite its potential importance, research has been hampered by poor exposure and has therefore focused primarily on graptolite biostratigraphy and U-Pb zircon geochronology (e.g., Hartley, 1936; Hutton and Holland, 1992; Cooper et al., 2008, 2011). Recent work characterized the geochemical affinity of the Tyrone arc (= Tyrone Volcanic Group), its associated suprasubduction ophiolite (= Tyrone Plutonic Group), and a late suite of continental calc-alkaline intrusive rocks (Draut et al., 2009; Cooper et al., 2011; Fig. 2A).

We present the results of new field mapping and high-resolution airborne geophysics, which have enabled the volcanic succession to be placed in a detailed structural and stratigraphic context for the first time. This is complemented by an extensive new whole-rock and Nd-isotopic geochemical data set, which, combined with new and previous U-Pb zircon geochronology, details the evolution of the Tyrone arc during the Grampian phase of the Caledonian orogeny.

## REGIONAL GEOLOGY

Rocks of Grampian age are exposed in the British and Irish Caledonides as inliers that often represent geologically distinct terranes (Fig. 1A). The NE-SW–trending Fair Head–Clew Bay Line of Ireland is generally accepted as the correlative to the Highland Boundary fault of Scotland (Fig. 1A) and the Baie Verte–Brompton Line of the Newfoundland Appalachians (Max and Riddihough, 1975; Max et al., 1983; Fig. 1B). This major tectonic structure separates metamorphosed, Laurentian rift and passive-margin sequences of the Hebridean, Northern Highland, and Southern Highland terranes from lower-grade remnants of the Iapetus Ocean to the south (Park et al., 2002; Strachan et al., 2002). The Midland Valley terrane is bounded by the Highland Boundary fault to the north and the Southern Uplands fault to the south, and it includes a series of allochthonous ophiolitic and island-arc components buried by extensive Upper Paleozoic cover rocks (Oliver et al., 2002). The Southern Uplands and Longford-Down terranes of Scotland and Ireland are widely considered to represent accretionary complexes associated with north-directed

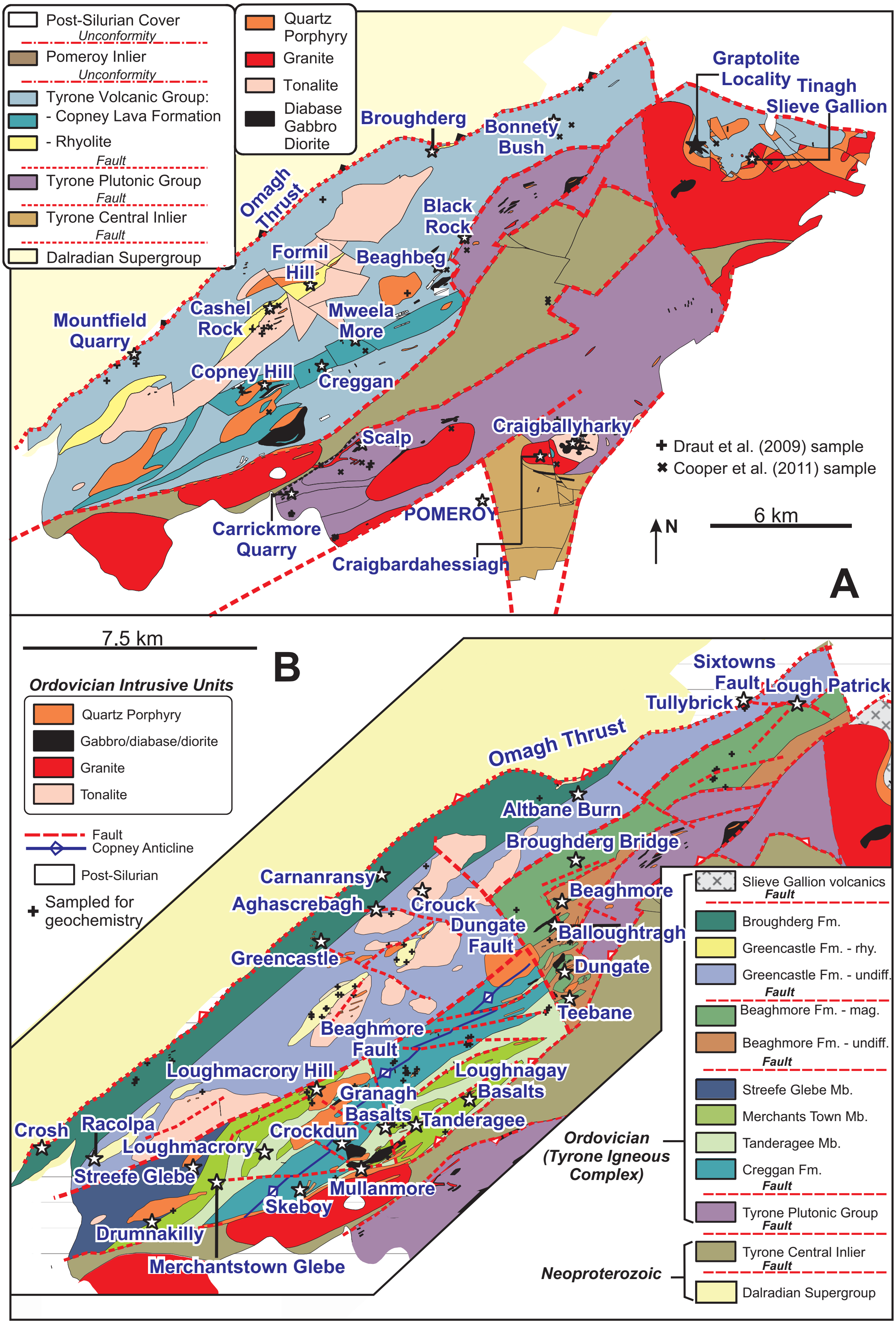

**Figure 2.** (A) Previous geological map of the Tyrone Igneous Complex (after GSNI, 1979, 1983, 1995; Cooper et al., 2011). Crosses and plus symbols mark sample locations of Draut et al. (2009) and Cooper et al. (2011). Copney Pillow Lava Formation and Rhyolite are divisions within the Tyrone Volcanic Group. (B) New geological map of the Tyrone Volcanic Group.

subduction and the post-Grampian closure of the Iapetus Ocean (Graham, 2009).

The Tyrone Igneous Complex underlies ~350 km$^2$ of the Midland Valley terrane and is one of the largest areas of ophiolitic and arc-related rocks exposed along the Laurentian margin of Iapetus within the British and Irish Caledonides (Fig. 1A). It is broadly divisible into the ophiolitic Tyrone Plutonic Group (ca. 480 Ma) and the younger arc-related Tyrone Volcanic Group (ca. >475–469 Ma; Cooper et al., 2008, 2011; Fig. 2A). The northwestern edge of the Tyrone Igneous Complex is bounded by the Omagh Thrust, which has emplaced Neoproterozoic metasedimentary rocks of the Dalradian Supergroup above the Tyrone Volcanic Group (Alsop and Hutton, 1993). Within the central regions of the complex, the structurally underlying metamorphic basement is exposed, termed the Tyrone Central Inlier (Geological Survey of Northern Ireland [GSNI], 1979). A suite of granitic to tonalitic plutons (ca. 470–464 Ma) intrudes both the Tyrone Igneous Complex and Tyrone Central Inlier (Cooper et al., 2011).

The Tyrone Central Inlier (Corvanaghan Formation; GSNI, 1995; Fig. 2) is a thick sequence of psammitic and semipelitic paragneisses (Hartley, 1933) closely associated with syntectonic leucosomes ($^{207}$Pb-$^{206}$Pb zircon age of 467 ± 12 Ma; Chew et al., 2008), cut by post-tectonic muscovite-bearing pegmatites ($^{40}$Ar-$^{39}$Ar step-heating plateau age of 468 ± 1 Ma; Chew et al., 2008), quartz–K-feldspar porphyritic dikes, and coarse-grained quartzofeldspathic sheets. The rocks of the Tyrone Central Inlier have a prograde metamorphic assemblage of biotite + plagioclase + sillimanite + quartz ± muscovite ± garnet in pelitic lithologies (Chew et al., 2008), with cordierite locally observed (Hartley, 1933). Metamorphic cooling ages imply the Tyrone Central Inlier was metamorphosed and deformed under a thick, hot sequence (~670 ± 113 °C, 6.8 ± 1.7 kbar) prior to 468 ± 1.4 Ma (Chew et al., 2008). Recent detrital zircon age profiling on a sample of psammitic gneiss identified prominent U-Pb age peaks at ca. 1050 Ma, 1200 Ma, and 1500 Ma, with more restricted peaks at ca. 1800 Ma, 2500–2700 Ma, and 3100 Ma (Chew et al., 2008). Deposition must have occurred after 999 ± 23 Ma, the age of the youngest dated zircon (Chew et al., 2008). These ages are consistent with a Laurentian affinity for these Late Neoproterozoic metasedimentary rocks. Paleoproterozoic Nd model ages and a significant ca. 2.5–2.7 Ga U-Pb zircon population may suggest an upper Dalradian Supergroup affinity for the Tyrone Central Inlier (Chew et al., 2008). The Tyrone Central Inlier is interpreted to represent part of an outboard segment of Laurentia, possibly detached as a microcontinent prior to arc-continent collision (Chew et al., 2008). Inherited ca. 2100 Ma zircons derived from the Tyrone Central Inlier, scarce in peri-Laurentian sources, were suggested by Cooper et al. (2011) to signify a different age signature of the basement underlying the region. Extremely negative $\varepsilon_{\mathrm{Hf}_{(t\,=\,470\ \mathrm{Ma})}}$ values within zircon overgrowths imply hidden Archean crust may lie at depth under NW Ireland (Flowerdew et al., 2009).

Since the ophiolitic nature of the Tyrone Plutonic Group (Fig. 2A) was initially recognized by Hutton et al. (1985), a consensus has emerged that the group represents the uppermost portion of a dismembered suprasubduction-zone ophiolite (Chew et al., 2008; Draut et al., 2009; Cooper et al., 2011). The Tyrone Plutonic Group is characterized by layered, isotropic and pegmatitic gabbros, sheeted diabase dikes, and the occurrence of rare pillow lavas (Angus, 1970; Hutton et al., 1985; Cooper and Mitchell, 2004). Layered olivine gabbro has provided a U-Pb zircon age of 479.6 ± 1.1 Ma (Cooper et al., 2011). Accretion to the Tyrone Central Inlier must have occurred prior to the intrusion of a 470.3 ± 1.9 Ma tonalite, which contains inherited Proterozoic zircons and roof pendants of ophiolitic material (Cooper et al., 2011).

The Tyrone Volcanic Group forms the upper part of the Tyrone Igneous Complex and consists of mafic to intermediate pillowed and sheeted lavas, tuffs, rhyolite, banded chert, ferruginous jasperoid (ironstone), and argillaceous sedimentary rocks (Cooper and Mitchell, 2004) (Fig. 2A). The Tyrone Volcanic Group is interpreted to have formed within a peri-Laurentian island arc/backarc, which was accreted to the Tyrone Central Inlier following emplacement of the Tyrone Plutonic Group (Draut et al., 2009; Cooper et al., 2011). A high-precision U-Pb zircon age of 473 ± 0.8 Ma for rhyolite is in close agreement with biostratigraphic age constraints from the Slieve Gallion volcanic succession, which place the upper Tyrone Volcanic Group within the Australasian Castlemainian (Ca1) Stage of the uppermost Floian of the Lower Ordovician (ca. 475–474 Ma: Cooper et al., 2008; Sadler et al., 2009). Large ion lithophile element (LILE) and light rare earth element (LREE) enrichment and strongly negative $\varepsilon_{\mathrm{Nd}_{(t)}}$ values indicate the arc was formed close to or upon the Laurentian margin (either autochthonous margin or microcontinental block) and was contaminated by continental material (Draut et al., 2009; Cooper et al., 2011).

A late suite of I-type, calc-alkalic, tonalitic to granitic plutons intrudes the Tyrone Igneous Complex and Tyrone Central Inlier associated with a syn- to postcollisional continental arc (Draut et al., 2009). Recent U-Pb zircon geochronology indicates these were intruded between ca. 470 and 464 Ma (Cooper et al., 2011). Strong LILE and LREE enrichment coupled with zircon inheritance and strongly negative $\varepsilon_{\mathrm{Nd}_{(t)}}$ values suggest that assimilation of Dalradian-affinity metasedimentary rocks was an integral part of their petrogenesis (Draut et al., 2009; Cooper et al., 2011). Similar plutons intrude Connemara (Cliff et al., 1996; Friedrich et al., 1999a, 1999b; McConnell et al., 2009) and the NE Ox Mountains Slishwood Division (Flowerdew et al., 2005) (Fig. 1A).

## STRATIGRAPHY

Understanding the structural and stratigraphic relationships between and within the Tyrone Igneous Complex and Tyrone Central Inlier has previously been hampered by poor exposure. However, a recently completed regional airborne geophysical survey over Northern Ireland has helped to resolve the crustal structure of the region. Magnetic, radiometric, and electromagnetic (EM) data were acquired over the entirety of Northern Ireland during 2005–2006 as part of the Tellus Project (see GSNI, 2007). Combined with recent geological surveys, the Tellus Geophysical Survey of Northern Ireland has allowed the Tyrone Volcanic Group to be placed in a detailed structural and stratigraphic framework for the first time (see supplementary material[1]). New formations have become apparent, and the Tyrone Volcanic Group has been further subdivided (Fig. 2B). As only one formal stratigraphic unit, the Copney Pillow Lava Formation, was previously recognized (GSNI, 1995), we herein introduced several new formations. Each formation and their type localities are described in detail in the British Geological Survey lexicon. Stratigraphic terminology is according to the International Stratigraphic Guide and the North American Stratigraphic Code. South of the Beaghmore fault, three formations have been recognized within the lower Tyrone Volcanic Group: the Creggan, Loughmacrory, and Beaghmore formations (Fig. 2B). The Dungate fault separates the Creggan and Loughmacrory formations to the west from the Beaghmore formation to the east of this structure (Fig. 2B). This study has redefined the boundaries of the Copney Pillow Lava Formation (GSNI, 1979, 1995) and renamed this unit based on its type locality to the Creggan formation. Consequently, the former name is redundant. North of the Beaghmore fault, the upper Tyrone Volcanic Group is divided into the Greencastle and

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[1] GSA Data Repository item 2012334, Tellus regional geophysical survey of Northern Ireland, methods and whole rock geochemistry of the Tyrone Volcanic Group, is available at http://www.geosociety.org/pubs/ft2012.htm or by request to editing@geosociety.org.

Broughderg formations (Fig. 2B). Formations do not correlate across the major faults, and consequently three distinct structural blocks have been identified: southwestern—Creggan and Loughmacrory formations; eastern—Beaghmore formation; and northwestern—Greencastle and Broughderg formations (Fig. 2B). Each formation is summarized in Figure 3 along with the geochemical affinity of the mafic and felsic units present (discussed later herein). A variety of intrusive units cut the Tyrone Volcanic Group (Figs. 2B and 3).

### Lower Tyrone Volcanic Group

The lower part of the Tyrone Volcanic Group is restricted to south of the Beaghmore fault (southwestern and eastern blocks) and is dominated by basaltic to andesitic lavas and volcaniclastic rocks, with subsidiary agglomerate, layered chert, ferruginous jasperoid (ironstone), finely laminated argillaceous sedimentary rocks, and rare rhyolite breccia, deformed into the SW-NE–trending upright Copney anticline (Fig. 2). Deformation preceded that associated with Dalradian overthrusting. The Creggan formation, exposed along the length of the Copney anticline, is characterized by pillowed, massive, and sheet-flow basalt/basaltic andesite, with lesser layered chert, basaltic agglomerate, and rare mafic volcaniclastic crystal tuff, associated with dikes of diabase and diorite (Fig. 3). The overlying Loughmacrory formation is a diverse succession dominated by basaltic to andesitic lava and thick beds of tuff (often hornblende-bearing), with lesser layered chert, ferruginous jasperoid (ironstone), argillaceous sedimentary rocks (e.g., red siltstone), and rare rhyolite agglomerate breccia (Fig. 3). Intrusions of hornblende-andesite porphyry, quartz-porphyritic microtonalite, diorite, ophitic diabase/gabbro, and microgranite cut the formation. The Beaghmore formation is characterized by crystal, aphyric and lapilli tuff, agglomerate, basalt, and ferruginous jasperoid (ironstone), and it is intruded by bodies of quartz diabase, diorite, and gabbro (Fig. 3). All units in the lower Tyrone Volcanic Group have been subjected to varying degrees of hydrothermal alteration and are characterized by regional subgreenschist- to greenschist-facies metamorphic assemblages. Abundant sills of undeformed quartz ± feldspar porphyritic dacite cut all stratigraphic levels of the Tyrone Volcanic Group.

### Upper Tyrone Volcanic Group

North of the Beaghmore fault, the Greencastle and Broughderg formations of the upper Tyrone Volcanic Group are exposed as a conformable sequence dipping between 35° and 60°NW (Fig.

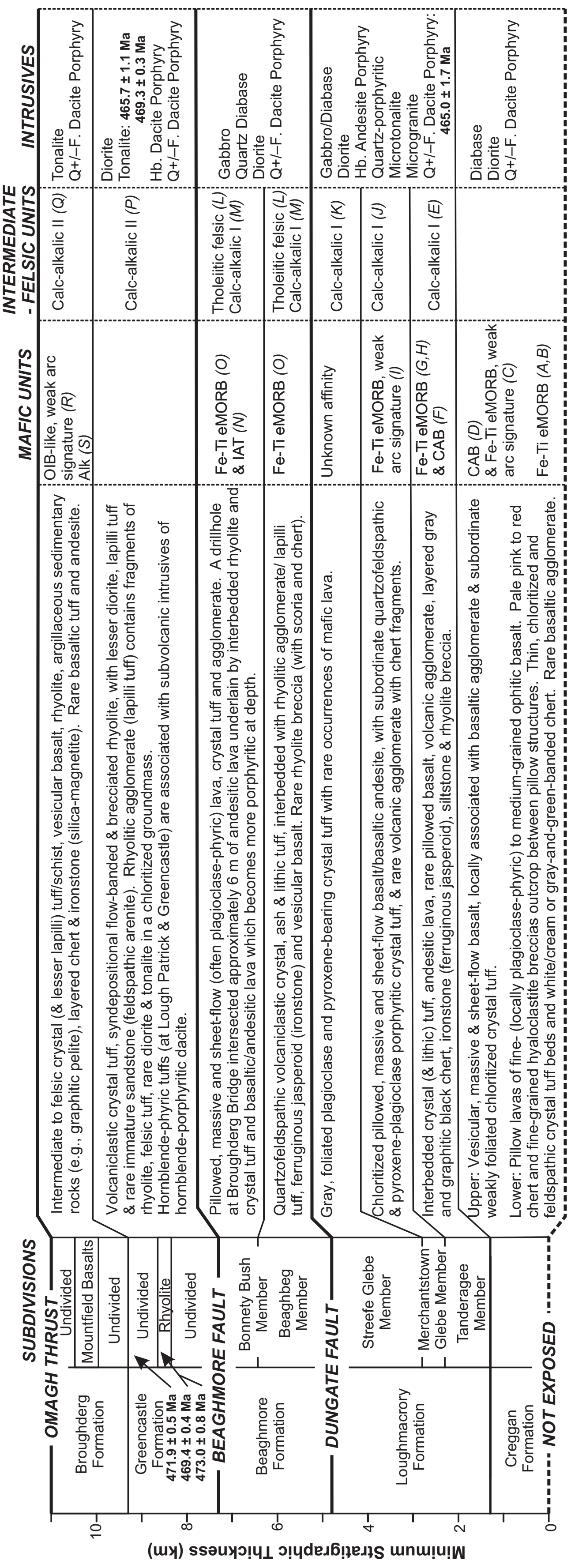


**Figure 3. Stratigraphy of the Tyrone Volcanic Group. All unit thicknesses are minimum values. This study has redefined the boundaries of the Copney Pillow Lava Formation (GSNI, 1979, 1995) and renamed this unit to the Creggan formation. The base of the overlying Loughmacrory formation is marked by the first occurrence of hornblende-porphyritic andesite, ironstone, argillaceous sedimentary rocks, rhyolite breccias, or quartzofeldspathic volcaniclastic tuff. The "Granagh Basalts" have been placed within the Tanderagee member of the Loughmacrory formation and are believed to be broadly equivalent with similar rocks exposed on Copney Hill ("Copney Basalts"). The "Loughnagay Basalts" are believed to be broadly equivalent to the Merchantstown Glebe member. The base of the Broughderg formation is placed at the first occurrence of chert, argillaceous sedimentary rocks, or basalt north of the Beaghmore fault. Mafic and intermediate to felsic petrochemical suites refer to those discussed in geochemistry section. Letters in parentheses refer to geochemical plots of Figure 5. Alk—alkali basalt; Fe-Ti—eMORB; CAI—calc-alkaline lower arc; CAII—calc-alkaline upper arc; CAB—island-arc calc-alkaline basalt; Fe-Ti eMORB—high Fe-Ti enriched mid-ocean-ridge basalt; Hb—hornblende; IAT—island-arc tholeiitic; OIB-like—ocean-island basalt like; Q+/–F—quartz +/– feldspar; TF—tholeiitic felsic.**

2B). Dalradian metasedimentary rocks of the Argyll Group (see McFarlane et al., 2009) overlie the succession along its western edge, separated by the low-angle Omagh Thrust, which dips around 30°NW (Alsop and Hutton, 1993). The crosscutting nature of the Omagh Thrust provides a relatively complete section through the upper part of the Tyrone Volcanic Group, which has been metamorphosed to chlorite-grade greenschist facies. Further south, subgreenschist-facies metamorphic assemblages are preserved around Formil (Fig. 2). Hydrothermal alteration and associated Zn-Pb-Cu(Au) mineralization are widespread within the Greencastle and Broughderg formations. Mineralization is characterized by pyrite-sphalerite-galena-chalcopyrite in locally silicified, sericitic and/or chloritic tuff/rhyolite (Leyshon and Cazalet, 1978; Clifford et al., 1992; Gunn et al., 2008). Between Racolpa and Broughderg, bodies of tonalite and sills of quartz ± feldspar porphyry intrude both formations (Fig. 2).

The Greencastle formation is a relatively thick succession dominated by chloritic, locally sericitized and siliceous quartzofeldspathic crystal tuff, flow-banded and brecciated rhyolite, rhyolitic lapilli tuff, lesser diorite, rare arkosic sandstone, and localized occurrences of hornblende-phyric tuff (Fig. 3). The overlying Broughderg formation is a diverse succession of intermediate to felsic crystal and lesser lapilli tuff/schist, rhyolite (e.g., around Crosh), vesicular basalt, argillaceous sedimentary rocks, layered chert, and black ironstone (silica-magnetite) with bedded pyrite (Fig. 3). Rare occurrences of basaltic tuff and andesite are also associated with the Broughderg formation.

## GEOCHEMISTRY

Volcanic rocks from all major stratigraphic horizons within the Tyrone Volcanic Group were sampled for whole-rock geochemical analysis. Major elements and trace elements were determined by X-ray fluorescence (XRF) analysis using fused glass beads and powder pellets, respectively. Rare earth elements (REEs), plus Nb, Hf, Ta, Th, and U, were determined by inductively coupled plasma–mass spectrometry (ICP-MS) on the same samples following an HF/$HNO_3$ digestion. Neodymium isotope ratios were determined using a VGMicromass Sector 54 thermal ionization mass spectrometer (TIMS). Results and further information are presented as supplementary information (see footnote 1). Geochemical analyses of Draut et al. (2009) and Cooper et al. (2011) are also included where appropriate.

Under low-grade metamorphic conditions and during hydrothermal alteration, most major elements (e.g., $SiO_2$, $Na_2O$, $K_2O$, CaO) and the low field strength elements (LFSE: Cs, Rb, Ba, Sr, U, except Th) are mobile (MacLean, 1990). As the primary mineral assemblages within the Tyrone Volcanic Group have been hydrothermally altered and metamorphosed under subgreenschist- to lower-greenschist-facies conditions, the following account is based on demonstrably immobile elements. In addition to $Al_2O_3$, $TiO_2$, Th, V, Co, and Sc, the high field strength elements (HFSE, e.g., Nb, Hf, Ta, Zr, Y), and REEs (minus Eu ± Ce) are herein considered to have been immobile during metamorphism and hydrothermal alteration (e.g., Pearce and Cann, 1973; MacLean, 1990; Jenner, 1996).

Results for lithostratigraphic units identified within the Tyrone Volcanic Group are presented in Figures 4 and 5. Multi-element variation diagrams show a distinction between different petrochemical suites of basalt/basaltic andesite (calc-alkaline basalt [CAB], Fe-Ti–enriched mid-ocean-ridge basalt [eMORB], island-arc tholeiite [IAT], ocean-island basalt [OIB]–like, alkali [Alk]) and intermediate to felsic lavas and volcaniclastics (calc-alkaline lower arc [CA-I], calc-alkaline upper arc [CA-II], tholeiitic felsic [TF]) in each formation (Figs. 3–5). Petrochemical suites identified are summarized here in relation to the newly presented stratigraphy (see Fig. 3) and are described further in Table 1. Several episodes of rifting within the Tyrone Volcanic Group are evident from Figure 4 through a return to more primitive geochemical compositions (e.g., lower $SiO_2$, $Zr/TiO_2$, Zr/Y, and higher Nb/Y) at several stratigraphic levels and the eruption of Fe-Ti–enriched eMORB (see following).

### Lower Tyrone Volcanic Group

#### *Petrochemical Suites*

Three geochemically distinct suites of basalt/basaltic andesite and two geochemically distinct suites of intermediate to felsic lavas and volcaniclastics have been recognized within the lower Tyrone Volcanic Group (southwestern and eastern structural blocks; Fig. 2B).

***Calc-alkaline basalt (CAB).*** Subalkaline, borderline to strongly calc-alkaline, LILE- and LREE-enriched basalt/basaltic andesite (Table 1): These rocks display pronounced negative Nb and HFSE anomalies characteristic of

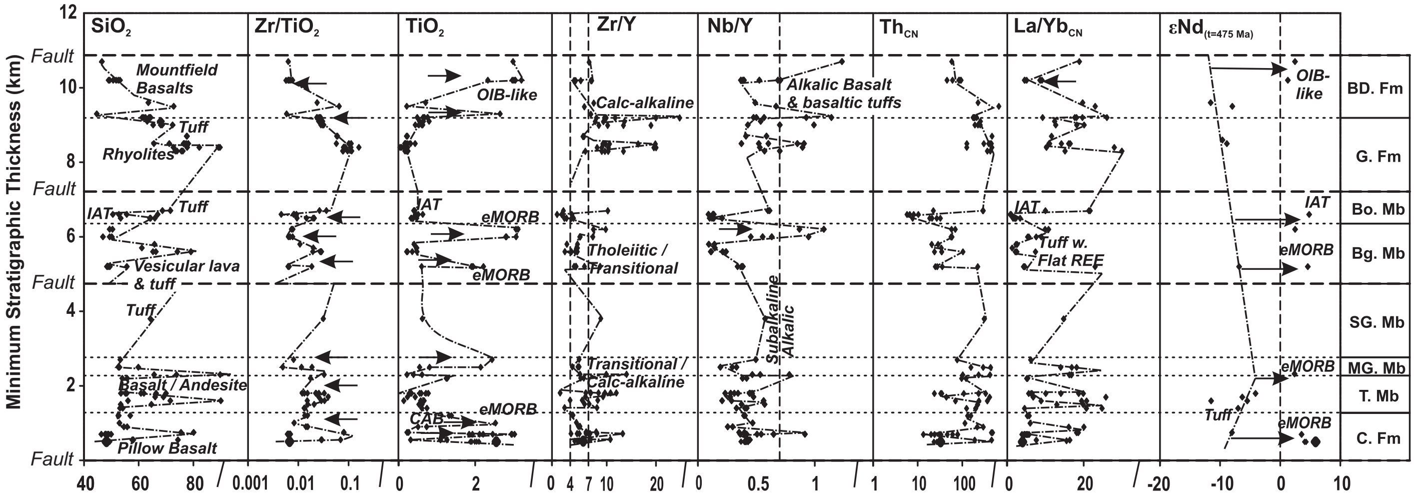


**Figure 4. Geochemical analyses from the Tyrone Igneous Complex; data from Draut et al. (2009) and Cooper et al. (2011) are also included. Arrows indicate episodes of rifting and a return to more primitive geochemical signatures. BD. Fm—Broughderg formation; Bg. Mb—Beaghbeg member; Bo. Mb—Bonnety Bush member; C. Fm—Creggan formation; MG. Mb—Merchantstown Glebe member; SG. Mb—Streefe Glebe member; T. Mb—Tanderagee member. Units: wt% for major elements; ppm for trace elements.**

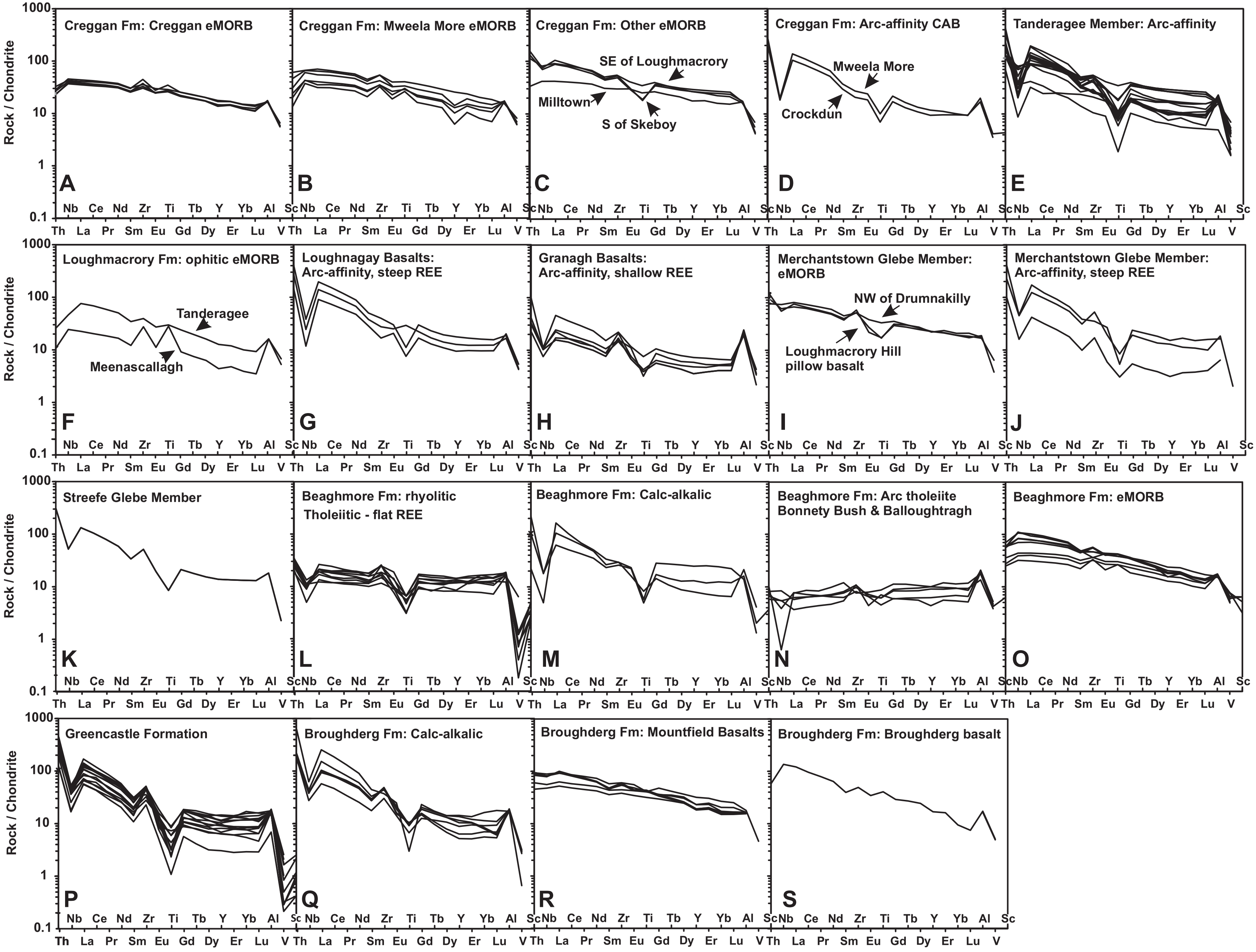


Figure 5. Multi-element variation diagrams for samples from the Tyrone Volcanic Group. Chondrite normalization values are after McDonough and Sun (1995). Analyses of Draut et al. (2009) and Cooper et al. (2011) are also included. Units: wt% for major elements; ppm for trace elements.

TABLE 1. PETROCHEMICAL SUITES IDENTIFIED WITHIN THE TYRONE VOLCANIC GROUP

|  | Composition | Nb/Y | Zr/Y | Enrichment | Arc signature? | $\varepsilon_{Nd(t)}$ | Affinity | Comment |
|---|---|---|---|---|---|---|---|---|
| Lower Tyrone Volcanic Group |  |  |  |  |  |  |  |  |
| CAB | Basalt/basaltic andesite ($SiO_2$ 52.6–61.9 wt%; $Zr/TiO_2$ <0.03) | Subalkaline (Nb/Y 0.19 to 0.47) | Borderline to strongly calc-alkaline (Zr/Y 4.3 to 10.6, most >5) | $Fe_2O_{3T}$ (8.1%–14.0%), $TiO_2$ (0.3%–2.5%), and $P_2O_5$ (0.13%–0.32%), enrichment is variable. LILE and LREE enriched ($La/Yb_{CN}$ 4.3–10.6) | Pronounced negative Nb ($Th/Nb_{CN}$ 1.4–15.0) and HFSE anomalies | No data | Arc-type Calc-alkaline | Further subdivisions can be made between those with steep REE profiles (e.g., Loughnagay Basalts; Fig. 5G) and those with shallower REE profiles (e.g., Granagh Basalts; Fig. 5H). |
| Fe-Ti eMORB | Basalt/basaltic andesite ($SiO_2$ 45.8–56.9 wt%, typically <50 wt%; $Zr/TiO_2$ <0.02) | Subalkaline to alkalic (Nb/Y, 0.36–1.1, most <0.6) | Transitional to calc-alkaline (Zr/Y, 4.1–15.2, most <8) | Strongly Fe-Ti-P–enriched (8.4–16.6 wt% $Fe_2O_{3T}$, 1.1–3.1 wt% $TiO_2$, 0.10–0.44 wt% $P_2O_3$), moderately LILE and LREE enriched ($La/Yb_{CN}$ 2.6–7.6) | Fe-Ti basalts can display either weakly positive or less often negative Nb, Zr, and Ti anomalies on multi-element variation diagrams (e.g., Figs. 8A–8C, 8F, 8I) | Moderately primitive (+2.4 to +5.9) | Non-arc type Fe-Ti eMORB | $Al_2O_3$ concentrations (13.2%–16.3%, most <14.5%) are generally lower than those of CAB. Highest Fe and Ti enrichment occurs in basalts with low $SiO_2$, $Al_2O_3$, and Cr. Samples analyzed from Mweela More display negative Y anomalies (Fig. 5B). Y mobilization may be due to the action of carbonate-rich fluids (e.g., Hynes, 1980). |
| IAT (Beaghmore formation only) | Basalt/basaltic andesite ($SiO_2$ 50.5–60.9 wt%, typically <55 wt%; $Zr/TiO_2$ <0.01) | Subalkaline (Nb/Y <0.15) | Tholeiitic (Zr/Y 1.8–4.5) | Moderately LILE enriched (Th 5.8–10.3× chondrite) and LREE depleted ($La/Yb_{CN}$ 0.54–1.43) | Prominent Nb anomalies (e.g., Th/Nb 1.0–16.6) | +4.8 | Arc-type Tholeiitic | $SiO_2$ (50.5–60.9 wt%) and MgO (1.1–8.6 wt%) concentrations are variable due to extensive chlorite and/or silica-epidote alteration. |
| CA-I (Loughmacrory and Beaghmore formations) | Intermediate to felsic lavas and tuffs | Subalkaline | Calc-alkaline | LILE and LREE enriched (Th ~20–420× chondrite) with steep REE profiles ($LaYb_{CN}$ 3.1–16.9) | Prominent Nb and HFSE anomalies (Figs. 8E, 8J–8K) | –4.1 to –11.5 | Arc-type Calc-alkaline | Quartz-porphyritic rhyolite from Tanderagee produced a $\varepsilon_{Nd(t=475\ Ma)}$ value of –11.5, whereas volcaniclastic tuffs produced $\varepsilon_{Nd(t=475\ Ma)}$ values between –4.1 and –7.0. Feldspar-phyric andesitic tuff from Teebane produced a $\varepsilon_{Nd(t=475\ Ma)}$ value of –6.8. |
| TF (Beaghmore formation only) | Felsic tuffs ($SiO_2$ 61.1–79.1 wt%) | Subalkaline (Nb/Y 0.1–0.4) | Tholeiitic (Zr/Y 1.0–3.6) | Low LILE enrichment (Th ~20–35× chondrite) and flat to U-shaped REE profiles ($La/Yb_{CN}$ 0.9–2.3) | Prominent Nb and HFSE anomalies (Fig. 8L) | No data | Arc-type Tholeiitic | Closely associated with Fe-Ti eMORB and ironstone. |
| Upper Tyrone Volcanic Group |  |  |  |  |  |  |  |  |
| OIB-like (Broughderg formation only) | Basalt ($SiO_2$ 44.7–53.2 wt%) | Subalkaline to borderline alkalic (Nb/Y 0.37–0.70) |  | LILE (Th ~45–100× chondrite) enriched and modest LREE enrichment to HREE | Weak to absent negative Nb ($Th/Nb_{CN}$ 0.95–1.1) and Ti anomalies (Fig. 8R) | +1.3 (Draut et al., 2009) | Weak arc signature, OIB-like, Fe-Ti enriched | Immobile-element variation profiles are similar to ocean-island basalts (Fig. 5R). Samples classify as within-plate basalt and/or e-MORB. $T_{DM}$ ages are ca. 1.4 Ga. |
| Alk (Broughderg formation only) | Basaltic tuff (sample SPH189, $SiO_2$ 46.5 wt%) | Alkalic (Nb/Y 1.2) |  | LILE (~60× chondrite) enriched. LREE enrichment relative to the HREE ($La/Yb_{CN}$ 12.8) | Strongly positive Nb ($Th/Nb_{CN}$ 0.4), Zr, and Ti anomalies (Fig. 8S) | +2.5 | Non-arc type Fe-Ti eMORB, alkalic | This sample produced a $T_{DM}$ age of ca. 2.0 Ga. |
| CA-II | Andesite, flow-banded to brecciated rhyolite and associated volcaniclastic rocks ($SiO_2$ 63.1–89.2 wt%) | Subalkaline (0.4–0.9) and calc-alkaline (Zr/Y 4.6–22.0, most ~6–15) |  | Strongly LILE and LREE enriched (Th ~92–465× chondrite, $La/Yb_{CN}$ 3.4–20.4) | Prominent negative Nb ($Th/Nb_{CN}$ 1.1–11.1) and HFSE anomalies | –8.0 to –11.6 | Arc-type Calc-alkaline | Rhyolite and diorite from the Greencastle have produced $\varepsilon_{Nd(t=475\ Ma)}$ values of –8.9 and –9.2, respectively. Andesite and coarse-grained quartzofeldspathic crystal tuff from Mountfield and Broughderg have produced $\varepsilon_{Nd(t=475\ Ma)}$ values of –8.0 and –11.6, respectively. $T_{DM}$ ages are Proterozoic (1.6–2.2 Ga). |

*Note:* Alk—alkali basalt; CAI—calc-alkaline lower arc; CAII—calc-alkaline upper arc; CAB—island-arc calc-alkaline basalt; Fe-Ti eMORB—high Fe-Ti enriched mid-ocean-ridge basalt; HFSE—high field strength element; IAT—island-arc tholeiitic; LILE—large ion lithophile element; LREE—light rare earth element; OIB-like—ocean-island basalt like; TF—tholeiitic felsic.

island-arc rocks (Pearce and Cann, 1973; Pearce and Norry, 1979; Wood, 1980; Shervais, 1982; Meschede, 1986) (Figs. 5D–5E, 5G–5H, and 5J). Further subdivisions can be made between those that display steep REE profiles (e.g., Loughnagay basalts; Fig. 5G) and those with shallower REE profiles (e.g., Granagh basalts; Fig. 5H).

***High Fe-Ti enriched mid-ocean-ridge basalt (Fe-Ti eMORB).*** Subalkaline to alkalic, moderately LILE- and LREE-enriched, and strongly Fe-Ti-P–enriched basalt/basaltic andesite (Table 1): These rocks are of "within-plate" and/or eMORB affinity on various discrimination diagrams and lack a distinctive island-arc signature (Figs. 5A–5C, 5F, 5I, and 5O). The $\varepsilon_{\mathrm{Nd}(t = 475\ \mathrm{Ma})}$ values are moderately primitive (+2.4 to +5.9).

***Island-arc tholeiite (IAT).*** Tholeiitic, moderately LREE-depleted basalt/basaltic andesite, with a distinctive island-arc signature (Fig. 5N; Table 1): Basalt from Bonnety Bush has a moderately primitive $\varepsilon_{\mathrm{Nd}(t = 475\ \mathrm{Ma})}$ value of +4.8.

***Calc-alkalic evolved (CA-I).*** Intermediate to rhyolitic lavas and tuffaceous rocks present within the Loughmacrory and Beaghmore formations are transitional to calc-alkaline, LILE and LREE enriched, and display steep REE profiles, strongly negative $\varepsilon_{\mathrm{Nd}(t)}$ values, and island-arc geochemical characteristics (see Figs. 5E and 5J–5K; Table 1).

***Tholeiitic felsic (TF).*** Intermediate to rhyolitic tuffaceous rocks present within the Beaghmore formation at Beaghbeg and Bonnety Bush can be geochemically distinguished from those of the Loughmacrory formation. These rocks are tholeiitic, with low LILE enrichment and flat to U-shaped REE profiles, and they display strong arc-like geochemical characteristics (Figs. 5L–5M; Table 1).

### *Petrochemical Stratigraphy*

The lower part of the Creggan formation is dominated by pillowed Fe-Ti–enriched within-plate basalt/basaltic andesite (Fe-Ti eMORB) associated with rare agglomerate and layered chert. Strongly LILE- and LREE-enriched, island-arc calc-alkaline basalt/basaltic andesite (CAB) occurs only within the upper part of the formation (e.g., Mweela More, Crockdun; Figs. 5C–5D). Although contacts across the lower Tyrone Volcanic Group are typically poorly exposed, at Mweela More island-arc basalt (CAB) and within-plate basalt (Fe-Ti eMORB) are clearly nontectonic. Pillowed flows of Fe-Ti eMORB affinity are interlayered with, or intruded by, massive and nonpillowed CAB. Cherts associated with both suites in the Creggan formation display LREE-enriched arc-like signatures (e.g., Fig. 5E). High $Al_2O_3$, steep REE profiles, and negative Ti and Nb anomalies in these cherts suggest the presence of arc-derived components, whereas strongly negative $\varepsilon_{\mathrm{Nd}(t = 475\ \mathrm{Ma})}$ values (–8.0 from Mweela More) and Proterozoic $\tau_{\mathrm{DM}}$ ages (1.7 Ga) imply the presence of continentally derived components.

In the overlying Loughmacrory formation, mafic lavas are characterized by both strongly LILE- and LREE-enriched, island-arc calc-alkaline basalt/basaltic andesite (CAB, e.g., Tanderagee, Granagh, Merchantstown Glebe; Figs. 5E, 5G–5H, and 5J), and Fe-Ti eMORB (e.g., Tanderagee, Mweenascallagh). The latter is present at several stratigraphic horizons within the Tanderagee (Fig. 5F) and Merchantstown Glebe members (Fig. 5I). Fe-Ti eMORB lavas, LREE-enriched calc-alkaline tuffs (CA-I), and layered cherts of island-arc affinity are interbedded within the Loughmacrory formation. At Mweenascallagh, ophitic Fe-Ti eMORB intrudes a sequence of calc-alkaline volcanics (CA-I), which characterize the rest of the formation.

The Beaghmore formation is characterized by abundant Fe-Ti eMORB (e.g., Teebane and north of Beaghbeg), tholeiitic island-arc basalt/basaltic andesite (IAT) (Bonnety Bush and Balloughtragh), tholeiitic rhyolite and volcaniclastic rocks with flat to U-shaped REE profiles (TF), and rare LREE-enriched volcaniclastic tuffs (CA-I). Within the Beaghbeg member, calc-alkaline LREE-enriched, island-arc feldspar-phyric andesitic tuff is interbedded with Fe-Ti eMORB, which is in turn overlain by tholeiitic felsic rocks that display flat to U-shaped REE profiles (TF) and ferruginous jasperoid (ironstone). Strongly LILE- and LREE-enriched volcanic and tuffaceous rocks (CA-I) are restricted to three samples from Teebane (SPH195), Beaghbeg (SPH19), and Bonnety Bush (SPH184). Within the overlying Bonnety Bush member, CA-I–affinity tuffs overlie tholeiitic and LREE-depleted basalts (IAT) and ferruginous jasperoid (ironstone).

## Upper Tyrone Volcanic Group

Within the upper Tyrone Volcanic Group, basalt and extensively altered basaltic tuff are restricted to the Broughderg formation. Two geochemically distinct suites have been recognized (OIB and Alk, summarized in the following sections), both of which are interbedded with strongly LILE- and LREE-enriched intermediate to felsic island-arc volcaniclastic rocks (CA-II). Chert from Carnanransy Burn (upper Tyrone Volcanic Group: Broughderg formation) has high $Al_2O_3$ (15.24%) and $Fe_2O_{3T}$ (7.66%) and steep REE profiles ($La/Yb_{CN}$ 12.0), and displays calc-alkaline, arc-like geochemical characteristics.

### *OIB-Like (OIB)*

Around Mountfield, basalt is subalkaline to borderline alkalic, is LILE and Fe-Ti-P enriched, and displays weak to absent negative Nb and Ti anomalies on multi-element normalized diagrams (Fig. 5R). Chondrite-normalized REE profiles show modest LREE enrichment relative to the heavy (H) REEs. Immobile-element variation profiles are similar to ocean-island basalts (Fig. 5R). Samples classify as within-plate basalt and/or e-MORB (Pearce and Cann, 1973; Pearce and Norry, 1979; Wood, 1980; Shervais, 1982; Meschede, 1986). The $\varepsilon_{\mathrm{Nd}(t = 475\ \mathrm{Ma})}$ values are less primitive than within the lower Tyrone Volcanic Group (+1.3; Draut et al., 2009), and $\tau_{\mathrm{DM}}$ ages are ca. 1.4 Ga.

### *Alkalic (Alk)*

Basaltic tuff (SPH189) from Broughderg is alkalic and LILE and Fe-Ti-P enriched. This sample displays strongly positive Nb, Zr, and Ti anomalies on multi-element variation diagrams (Fig. 5S), and has produced a $\varepsilon_{\mathrm{Nd}(t = 475\ \mathrm{Ma})}$ value of +2.5 and a $\tau_{\mathrm{DM}}$ age of ca. 2.0 Ga. Chondrite-normalized REE profiles show steeper LREE enrichment relative to the heavy (H) REEs and are similar to eMORB.

### *Calc-Alkalic (CA-II)*

All nonbasaltic samples analyzed from the Greencastle and Broughderg formations are in many respects geochemically similar (Figs. 4 and 5P–5Q). Andesite, flow-banded to brecciated rhyolite, and associated volcaniclastic rocks are predominantly calc-alkaline, are strongly LILE and LREE enriched, and display prominent negative Nb and HFSE anomalies characteristic of formation within an island-arc environment. The $\varepsilon_{\mathrm{Nd}(t = 475\ \mathrm{Ma})}$ values are strongly negative, indicating contamination by continental crust or such detritus (–8 to –11.6; Table 1).

## GEOCHRONOLOGY

Three samples were selected for U-Pb (zircon) geochronology at the Natural Environment Research Council (NERC) Isotope Geosciences Laboratory. Two samples were analyzed from the Tyrone Volcanic Group, both from within the Greencastle formation: rhyolite from Cashel Rock (MRC336) and silicified feldspathic tuff from Tullybrick (MRC350). A sample of tonalite from Cashel Rock (MRC337) was also dated. Zircons were isolated using conventional mineral separation techniques. Prior to isotope dilution–thermal ionization mass spectrometry (ID-TIMS), zircons were subject to a modified version of the chemical abrasion technique (Mattinson, 2005). Errors for U-Pb dates are reported in the following format: $\pm X(Y)[Z]$, where

*X* 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 $^{238}$U decay constant errors of Jaffey et al. (1971). Further analytical information is provided as supplementary material (see footnote 1). Calculated U-Pb ages for samples analyzed herein are presented in Table 2 and Figure 6, along with additional information. All published U-Pb geochronology from the Tyrone Igneous Complex is summarized in Table 3.

Five zircon fractions (single grains) were analyzed from samples MRC336 (Cashel Rock rhyolite) and MRC337 (Cashel Rock tonalite). Five analyses from each are concordant when their systematic $\lambda^{238}$U and $\lambda^{235}$U decay constant errors are considered. Analyses from MRC336 (Cashel Rock rhyolite) form a coherent single population yielding a weighted mean $^{206}$Pb/$^{238}$U date of 469.42 ± 0.38 (0.60)[0.79] Ma (mean square of weighted deviates [MSWD] = 2.2). Analyses from sample MRC 337 (Cashel Rock tonalite) form a coherent single population yielding a weighted mean $^{206}$Pb/$^{238}$U date of 469.29 ± 0.33 (0.58)[0.77] Ma (MSWD = 1.7).

The calculated U-Pb ages for rhyolite (MRC336: 469.42 ± 0.38 Ma) and tonalite (MRC337: 469.29 ± 0.33 Ma) from Cashel Rock are within error at ca. 469 Ma, and both are younger than rhyolite along strike at Formil (473.0 ± 0.8 Ma; Cooper et al., 2008), and significantly older than a previously dated sample of tonalite from Cashel Rock (JTP209 465.66 ± 1.1 Ma; Cooper et al., 2011). Field relations and U-Pb zircon geochronology imply that several generations of tonalite occur within the succession. At Cashel Rock, at least two generations can be identified; early tonalite (ca. 469 Ma) is foliated and present as xenoliths within both a younger unfoliated tonalite (ca. 465 Ma) and syndepositional rhyolite (ca. 473–469 Ma). Both are in turn intruded by sills of quartz ± feldspar porphyritic dacite.

For sample MRC350 (silicified feldspathic tuff from Tullybrick), six fractions (single grains) were analyzed. Each analysis is concordant; however, there is dispersion, with $^{206}$Pb/$^{238}$U dates ranging from 469.8 ± 0.9 Ma to 471.9 ± 0.5 Ma. The younger age is defined by a cluster of three equivalent $^{206}$Pb/$^{238}$U dates (z6A, z6B, and z15), yielding a weighted mean $^{206}$Pb/$^{238}$U date of 470.37 ± 0.31 (0.56)[0.76] Ma (MSWD = 1.7), which we interpret as being the best estimate for the age of sample. As this sample was taken from near the top of the

TABLE 2. U-Th-Pb ISOTOPIC DATA

| | Compositional parameters | | | | | | Radiogenic isotope ratios | | | | | | | | Isotopic ages | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample* | $\frac{\mathrm{Th}}{\mathrm{U}^{\dagger}}$ | $^{206}$Pb* (×$10^{-13}$ mol)§ | mol % $^{206}$Pb*§ | $\frac{\mathrm{Pb}^*}{\mathrm{Pbc}^{\S}}$ | Pbc (pg)§ | $\frac{^{206}\mathrm{Pb}}{^{204}\mathrm{Pb}^{\#}}$ | $\frac{^{208}\mathrm{Pb}}{^{206}\mathrm{Pb}^{**}}$ | $\frac{^{207}\mathrm{Pb}}{^{206}\mathrm{Pb}^{**}}$ | % err†† | $\frac{^{207}\mathrm{Pb}}{^{235}\mathrm{U}^{**}}$ | % err†† | $\frac{^{206}\mathrm{Pb}}{^{238}\mathrm{U}^{**}}$ | % err†† | Corr. coef. | $\frac{^{207}\mathrm{Pb}}{^{206}\mathrm{Pb}^{\S\S}}$ | ±†† | $\frac{^{207}\mathrm{Pb}}{^{235}\mathrm{U}^{\S\S}}$ | ±†† | $\frac{^{206}\mathrm{Pb}}{^{238}\mathrm{U}^{\S\S}}$ | ±†† |
| MRC 336 | | | | | | | | | | | | | | | | | | | | |
| z2 | 0.387 | 15.6011 | 99.90% | 307 | 1.23 | 19160 | 0.121 | 0.05651 | 0.08 | 0.5880 | 0.17 | 0.075469 | 0.085 | 0.981 | 471.96 | 1.88 | 469.59 | 0.63 | 469.11 | 0.38 |
| z2 | 0.456 | 25.3823 | 99.88% | 239 | 2.62 | 14594 | 0.143 | 0.05648 | 0.09 | 0.5877 | 0.18 | 0.075466 | 0.106 | 0.944 | 470.85 | 1.92 | 469.39 | 0.68 | 469.09 | 0.48 |
| z3 | 0.384 | 8.6931 | 99.93% | 451 | 0.47 | 28270 | 0.120 | 0.05646 | 0.09 | 0.5880 | 0.17 | 0.075543 | 0.087 | 0.966 | 469.89 | 1.92 | 469.61 | 0.63 | 469.55 | 0.39 |
| z6 | 0.380 | 5.9321 | 99.87% | 230 | 0.62 | 14458 | 0.119 | 0.05645 | 0.13 | 0.5883 | 0.20 | 0.075585 | 0.090 | 0.813 | 469.55 | 2.95 | 469.76 | 0.74 | 469.81 | 0.41 |
| z7 | 0.326 | 4.7533 | 99.48% | 56 | 2.05 | 3523 | 0.102 | 0.05642 | 0.12 | 0.5876 | 0.20 | 0.075531 | 0.093 | 0.895 | 468.69 | 2.75 | 469.35 | 0.75 | 469.48 | 0.42 |
| MRC 337 | | | | | | | | | | | | | | | | | | | | |
| z1 | 0.528 | 5.3096 | 99.85% | 208 | 0.64 | 12539 | 0.165 | 0.05642 | 0.10 | 0.5878 | 0.18 | 0.075557 | 0.086 | 0.936 | 468.56 | 2.27 | 469.45 | 0.67 | 469.63 | 0.39 |
| z2 | 0.601 | 16.4755 | 99.94% | 505 | 0.84 | 29864 | 0.188 | 0.05649 | 0.09 | 0.5876 | 0.17 | 0.075444 | 0.086 | 0.965 | 471.32 | 1.94 | 469.35 | 0.63 | 468.95 | 0.39 |
| z3 | 0.479 | 2.3702 | 99.13% | 33 | 1.77 | 1995 | 0.150 | 0.05651 | 0.16 | 0.5884 | 0.25 | 0.075521 | 0.106 | 0.880 | 471.92 | 3.62 | 469.84 | 0.94 | 469.42 | 0.48 |
| z6 | 0.747 | 8.7411 | 99.95% | 637 | 0.37 | 36381 | 0.234 | 0.05643 | 0.08 | 0.5875 | 0.17 | 0.075508 | 0.087 | 0.981 | 469.15 | 1.82 | 469.30 | 0.62 | 469.33 | 0.39 |
| z7 | 0.473 | 1.9337 | 99.80% | 152 | 0.32 | 9284 | 0.148 | 0.05650 | 0.10 | 0.5879 | 0.18 | 0.075477 | 0.088 | 0.947 | 471.52 | 2.28 | 469.56 | 0.68 | 469.16 | 0.40 |
| MRC 350 | | | | | | | | | | | | | | | | | | | | |
| z1 | 0.735 | 0.9068 | 99.62% | 86 | 0.28 | 4915 | 0.230 | 0.05654 | 0.13 | 0.5915 | 0.20 | 0.075886 | 0.095 | 0.884 | 473.11 | 2.83 | 471.85 | 0.77 | 471.59 | 0.43 |
| z6A | 0.738 | 1.0059 | 99.17% | 38 | 0.69 | 2218 | 0.231 | 0.05643 | 0.19 | 0.5889 | 0.26 | 0.075687 | 0.097 | 0.817 | 469.12 | 4.16 | 470.19 | 0.97 | 470.40 | 0.44 |
| z6B | 0.644 | 0.2892 | 98.56% | 22 | 0.35 | 1283 | 0.202 | 0.05645 | 0.30 | 0.5883 | 0.40 | 0.075586 | 0.193 | 0.704 | 469.71 | 6.65 | 469.78 | 1.52 | 469.80 | 0.87 |
| z11 | 0.719 | 0.4301 | 99.11% | 36 | 0.32 | 2069 | 0.225 | 0.05653 | 0.22 | 0.5908 | 0.30 | 0.075796 | 0.124 | 0.758 | 473.01 | 4.83 | 471.39 | 1.12 | 471.05 | 0.56 |
| z15 | 0.773 | 0.9928 | 99.05% | 34 | 0.78 | 1941 | 0.242 | 0.05647 | 0.22 | 0.5894 | 0.29 | 0.075707 | 0.115 | 0.749 | 470.43 | 4.85 | 470.50 | 1.10 | 470.52 | 0.52 |
| z20 | 0.821 | 0.5847 | 99.29% | 46 | 0.34 | 2605 | 0.257 | 0.05645 | 0.18 | 0.5911 | 0.26 | 0.075938 | 0.107 | 0.826 | 469.88 | 3.95 | 471.56 | 0.97 | 471.90 | 0.48 |

*Note:* Dates in bold are those included in weighted mean calculations. See text for discussion.

*z1, z2, etc., are labels for fractions composed of single zircon grains or fragments; all fractions were annealed and chemically abraded after Mattinson (2005).

†Model Th/U ratio calculated from radiogenic $^{208}$Pb/$^{206}$Pb ratio and $^{207}$Pb/$^{235}$U age.

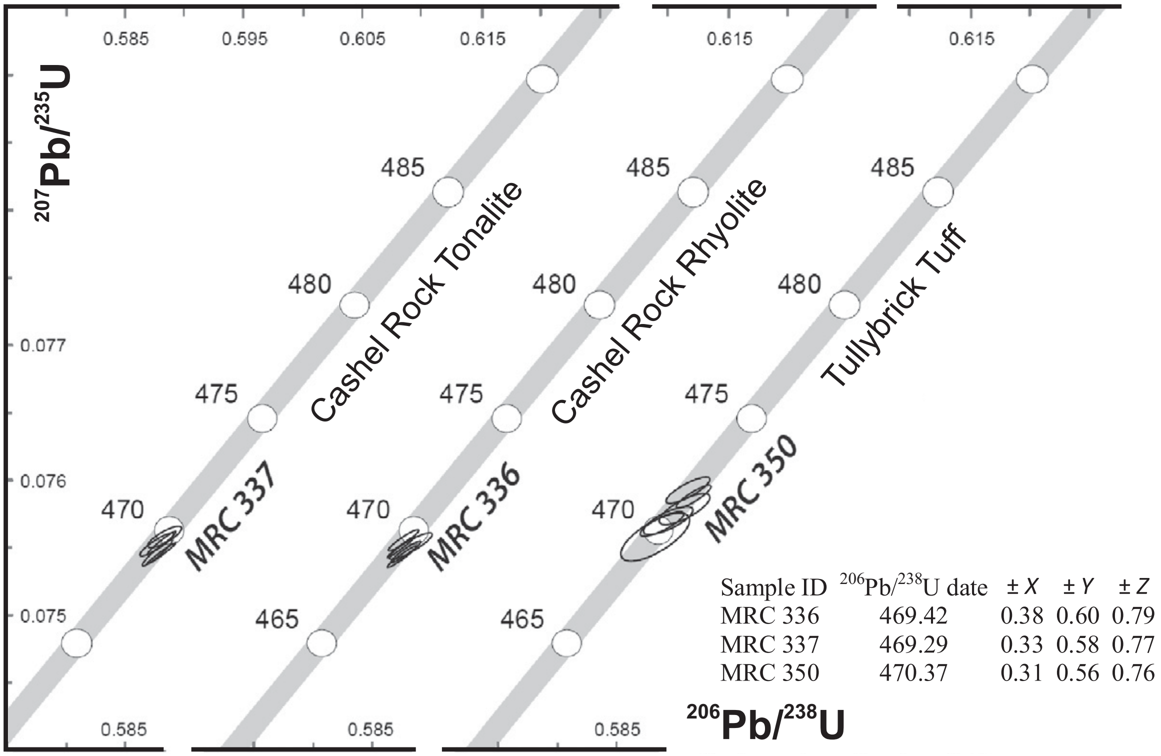
§Pb* and Pbc represent radiogenic and common Pb, respectively; mol % $^{206}$Pb* with respect to radiogenic, blank, and initial common Pb.

#Measured ratio corrected for spike and fractionation only.

**Corrected for fractionation, spike, and common Pb; up to 2 pg of common Pb was assumed to be procedural blank: $^{206}$Pb/$^{204}$Pb = 18.60% ± 0.80%; $^{207}$Pb/$^{204}$Pb = 15.69% ± 0.32%; $^{208}$Pb/$^{204}$Pb = 38.51% ± 0.74% (all uncertainties 1σ). Excess over blank was assigned to initial common Pb.

††Errors are 2σ, propagated using the algorithms of Schmitz and Schoene (2007).

§§Calculations are based on the decay constants of Jaffey et al. (1971). $^{206}$Pb/$^{238}$U and $^{207}$Pb/$^{206}$Pb ages were corrected for initial disequilibrium in $^{230}$Th/$^{238}$U using Th/U [magma] = 3, using the algorithms of Schärer (1984).



| Sample ID | $^{206}Pb/^{238}U$ date | ± *X* | ± *Y* | ± *Z* |
|---|---|---|---|---|
| MRC 336 | 469.42 | 0.38 | 0.60 | 0.79 |
| MRC 337 | 469.29 | 0.33 | 0.58 | 0.77 |
| MRC 350 | 470.37 | 0.31 | 0.56 | 0.76 |

**Figure 6. U-Pb zircon concordia and summary of interpreted U-Pb zircon dates.**

Greencastle formation, a maximum age of ca. 470.37 ± 0.31 Ma is consistent with underlying rhyolites dated at ca. 473–469 Ma. No Proterozoic ages were derived from any of the dated zircon fractions, although zircon selection was biased to avoid morphologies that may have contained inherited cores.

## DISCUSSION

### Evolution of the Tyrone Arc

The new stratigraphic, geochemical, and geochronological data presented here suggest that the evolution of the Tyrone Volcanic Group is more complex than the trifold cyclicity proposed by Cooper and Mitchell (2004), although an apparent cyclicity is recognized in the occurrence of Fe-Ti eMORB at several stratigraphic levels and through the repeated occurrence of ferruginous jasperoid (ironstone). In addition, the stratigraphic chart of Draut et al. (2009) is reevaluated, as this was constructed primarily using geochemical data.

Early magmatism within the lower Tyrone Volcanic Group is characterized by subalkaline (transitional to calc-alkaline) basalt and basaltic andesite with subordinate crystal and lapilli tuff. Cherts associated with pillowed, massive, and sheet-flow basalt display geochemical characteristics consistent with both continentally derived and evolved island-arc components (Fig. 5E). High LILE and LREE enrichment and Proterozoic $\tau_{DM}$ ages suggest that the lower Tyrone Volcanic Group formed close to the Laurentian margin or upon a fragment of peri-Laurentian microcontinental crust and was contaminated by such material. The presence of mafic breccias that contain rare felsic clasts (and interbedded rhyolite, rhyolitic tuff and breccias, and mafic lavas) indicates effusive mafic volcanism was coeval with silicic activity. Collectively, these data argue for an early history in the Tyrone Volcanic Group characterized by subaqueous arc magmatism in a peri-Laurentian realm.

The evolution of the lower Tyrone Volcanic Group is recorded by the progressive replacement of transitional to calc-alkalic island-arc vesicular basalt (of the Creggan and Loughmacrory formations) by porphyritic-andesite, and finally flow-banded rhyolite and rhyolitic volcaniclastic tuff in the Beaghmore formation. This evolution was coeval with the replacement of plagioclase-pyroxene crystal tuff (Creggan formation) by hornblende-bearing and quartzofeldspathic crystal tuffs (Loughmacrory and Beaghmore formations). This lithostratigraphic evolution is reflected by increasing $SiO_2$, $Zr/TiO_2$, Zr/Y, $Th_{CN}$, and $La/Yb_{CN}$ and more negative $\varepsilon_{Nd_{(t)}}$ values (Fig. 4). However, several returns to more primitive geochemical compositions, associated with episodes of rifting, are evident in Figure 4.

The occurrence of interbedded LILE- and LREE-enriched island-arc volcanic rocks, with Fe-Ti eMORB, and LREE-depleted island-arc tholeiite (IAT) implies a history of intra-arc rifting within the Tyrone Volcanic Group. Fe-Ti ± P–enriched lavas of eMORB affinity occur throughout the group at several stratigraphic levels (Figs. 3 and 4) and are typically interbedded with or overlie island-arc basalt and/or tuff. Primitive $\varepsilon_{Nd_{(t)}}$ values and high Nb/Y ratios imply an association with rifting and the upwelling of asthenosphere. Intermittent rifting of the arc system and the eruption of Fe-Ti eMORB may have been due to slab rollback and/or the interaction between the arc system and a propagating rift (see following).

An episode of rifting at ca. 475 Ma, represented by the occurrence of tholeiitic rhyolitic agglomerate and tuff with flat REE profiles (TF), Fe-Ti eMORB, and tholeiitic LREE-depleted basalt (IAT), in the Beaghmore formation led to the formation of an intra-arc/backarc basin (Cooper et al., 2011). Early volcanic activity within the Beaghmore formation, exposed around Teebane, is characterized by LILE- and LREE-enriched tuffs (CA-I) interbedded with vesicular Fe-Ti eMORB. Overlying deposits at Beaghbeg are characterized Fe-Ti eMORB interbedded with ferruginous jasperoids (ironstone) and tholeiitic rhyolite breccias with flat to U-shaped REE profiles (TF). Continued rifting led to the eruption of further Fe-Ti eMORB and LREE-depleted IAT, capped by LILE- and LREE-enriched tuff (CA-I) and ironstone at Bonnety Bush.

Collision between the Tyrone arc and Tyrone Central Inlier is typically placed at ca. 470 Ma (Cooper et al., 2011) during deposition of the Greencastle formation of the upper Tyrone Volcanic Group (ca. 473–469 Ma; Table 3). At this time, an abundance of rhyolite (e.g., Cashel Rock; Fig. 2) and thick quartzofeldspathic crystal tuff dominate the succession. An absence of xenocrystic zircons within a ca. 473 Ma rhyolite (Cooper et al., 2008) and their occurrence in ca. 470–464 Ma intrusive rocks (Cooper et al., 2011) suggest that arc accretion occurred between ca. 473 and 470 Ma. All lithostratigraphic units sampled within the Greencastle formation are strongly LILE and LREE enriched, implying continental material contaminated this phase of volcanism. Increasingly negative $\varepsilon_{Nd(t)}$ values suggest the Tyrone Central Inlier occupied a lower-plate setting during arc accretion, due to the progressive underthrusting of Laurentian-affinity continental material and obduction of the Tyrone Volcanic Group.

Normal arc magmatism ceased shortly after collision. Thin rhyolite flows of the Broughderg formation (e.g., at Crosh; Fig. 4) may mark this transition. The Broughderg formation is predominantly characterized by volcaniclastic tuff, chert, and argillaceous sedimentary rocks. A late stage of rifting is recorded by the presence of alkali OIB-like Fe-Ti-P–enriched basalts with weakly oceanic $\varepsilon_{Nd(t)}$ values (Mountfield basalts; Fig. 2). Late-stage rifting may have formed the deeper-water conditions in which layered cherts and argillaceous sedimentary rocks of the upper Broughderg formation were deposited.

## Petrogenesis of Fe-Ti Basalts

Fe-Ti basalts are defined by >12 wt% $FeO_T$ and >2 wt% $TiO_2$ (e.g., Sinton et al., 1983), and typically display lower concentrations of MgO, CaO, and $Al_2O_3$ than normal MORB. They are interpreted to form by high degrees of closed-system fractional crystallization maintained by low $fO_2$ (references in Harper, 2003; Raveggi et al., 2007). These conditions are necessary to delay the saturation of Ti-magnetite in the melt and allow Fe-Ti enrichment in the most evolved fractionates. Fe-Ti basalts are confined to extensional settings and have been reported from: continental and oceanic rifts (e.g., Afar Rift of Ethiopia, Red Sea Rift, mid-ocean ridges); on tips of propagating rifts; on intersections of mid-ocean ridges and transform faults; in triple

TABLE 3. CALCULATED U-Pb ZIRCON AGES AND PREVIOUSLY PUBLISHED U-Pb GEOCHRONOLOGY FOR TYRONE IGNEOUS COMPLEX*

| Lithological unit | From | Age (Ma) | Ref. | Calculated on | Additional information |
|---|---|---|---|---|---|
| Scalp Layered Gabbro | TPG | 479.6 ± 1.1 | 2 | Three concordant zircon analyses | U-Pb zircon ID-TIMS. Two zircon fractions gave inherited ages of ca. 1015 Ma (concordant) and 2100 Ma (upper intercept anchored at 479.6 Ma). |
| Craigballyharky Gabbro | TPG? | 493 ± 2 | 3 | Three concordant zircon analyses | U-Pb zircon SHRIMP. The weighted mean $^{238}U/^{206}Pb$ age of the oldest three concordant ages from the gabbro was 493 ± 2 Ma. Three younger zircons with ages around ca. 470 Ma were attributed to contamination. Age refuted by Cooper et al. (2011). |
| Cashel Rock Rhyolite | TVG | 469.42 ± 0.38 | 1 | Five concordant zircon analyses | U-Pb zircon ID-TIMS. No inheritance noted. |
| Tullybrick Tuff | TVG | 470.37 ± 0.31 | 1 | Cluster of three equivalent $^{206}Pb/^{238}U$ dates | U-Pb zircon ID-TIMS. Dispersion with $^{206}Pb/^{238}U$ dates ranging from 469.8 ± 0.9 to 471.9 ± 0.5 Ma. |
| Formil Rhyolite | TVG | 473.0 ± 0.8 | 4 | Three concordant zircon analyses | U-Pb zircon ID-TIMS. No inheritance noted by authors. |
| Cashel Rock Tonalite | ARIS - tonalite | 469.29 ± 0.33 | 1 | Five concordant zircon analyses | U-Pb zircon ID-TIMS. No inheritance noted. |
| Cashel Rock Tonalite | ARIS - tonalite | 475 ± 10 | 3 | Ten zircon analyses | U-Pb zircon SHRIMP. Archean cores identified in three zircon grains using SHRIMP and LA-MC-ICP-MS. |
| Laght Hill Tonalite | ARIS - tonalite | 465.6 ± 1.1 | 2 | Four concordant analyses | U-Pb zircon ID-TIMS. This tonalite provided a low yield of inheritance-free zircon. |
| Golan Burn Tonalite | ARIS - tonalite | 469.9 ± 2.9 | 2 | Two concordant zircon analyses | U-Pb zircon ID-TIMS. Zircons separated from this sample were generally free from inheritance but contained melt and mineral inclusions. Three zircon analyses yielded concordant to near-concordant analyses. Third analysis showed a small degree of inheritance. |
| Craigballyharky Tonalite | ARIS - tonalite | 470.3 ± 1.9 | 2 | Two concordant zircon analyses | U-Pb zircon ID-TIMS. These new data are consistent with those of Hutton et al. (1985) for the same sample site. Plotting these new U-Pb data with those of Hutton et al. gives a lower-intercept age of 471.2 $^{+2.0}/_{-2.3}$ Ma and an upper intercept of 2101 $^{+400}/_{-350}$ Ma, indicating an inherited component at ca. 2100 Ma. |
| Craigballyharky Tonalite | ARIS - tonalite | 471+2/–4 | 5 | Three zircon size fractions | U-Pb zircon ID-TIMS. Analyses are moderately discordant and define a discordia line with an upper intercept of 2030 $^{+630}/_{-500}$ Ma and lower intercept of 471$^{+2}/_{-4}$ Ma. |
| Cregganconroe Quartz-monzodiorite | ARIS - monzodiorite | 466.2 ± 2.1 | 2 | Two concordant zircon analyses | U-Pb zircon ID-TIMS. A small proportion of zircons from this sample displayed visible inherited components, and these were avoided. A third point was discordant along a shallow Pb-loss trajectory. |
| Craigbardahessiagh Granodiorite | ARIS - granodiorite | 464.9 ± 1.5 | 2 | One analysis each of titanite and zircon are concordant | U-Pb zircon ID-TIMS. Zircons showed both inheritance and Pb loss, while some titanites analyzed exhibited Pb loss. Most data plot near 465 Ma on the concordia diagram, but two zircon analyses show a significant Mesoproterozoic (ca. 1185–1512 Ma) inherited component. |
| Pomeroy Granite | ARIS - granite | 464.3 ± 1.5 | 2 | Two concordant zircon analyses. | U-Pb zircon ID-TIMS. The zircons analyzed are predominantly acicular neocrystalline with rare visible inherited cores. |
| Slieve Gallion Granite | ARIS - granite | 466.5 ± 3.3 | 2 | One concordant analysis | U-Pb zircon ID-TIMS. This granite contains both core-free zircons and those with clearly visible cores. Two analyses of inherited zircons have Mesoproterozoic ages from ca. 1000 Ma to 1700 Ma. Three analyses of core-free grains are concordant to slightly discordant and yield an upper-intercept age of 474.6 $^{+7.1}/_{-6.9}$ Ma. The most concordant analysis has an age of 466.5 ± 3.3 Ma, and this is considered to be the best estimate of the intrusion age. |
| Copney Quartz Porphyry | ARIS - quartz porphyry | 465.0 ± 1.7 | 2 | Two concordant zircon analyses | U-Pb zircon ID-TIMS. Zircons recovered are very similar to those described for the Pomeroy granite. A discordia yields a lower-intercept age of 464.6 ± 2.3 Ma and an upper intercept of ca. 2150 Ma. |

*Note:* ARIS—arc-related intrusive suite; TPG—Tyrone Plutonic Group; TVG—Tyrone Volcanic Group. SHRIMP—sensitive high-resolution ion microprobe; LA-MC-ICP-MS—laser ablation–multicollector–inductively coupled plasma–mass spectrometry; ID-TIMS—thermal ionization mass spectrometry.

*References: 1—This study, 2—Cooper et al. (2011), 3—Draut et al. (2009), 4—Cooper et al. (2008), 5—Hutton et al. (1985).

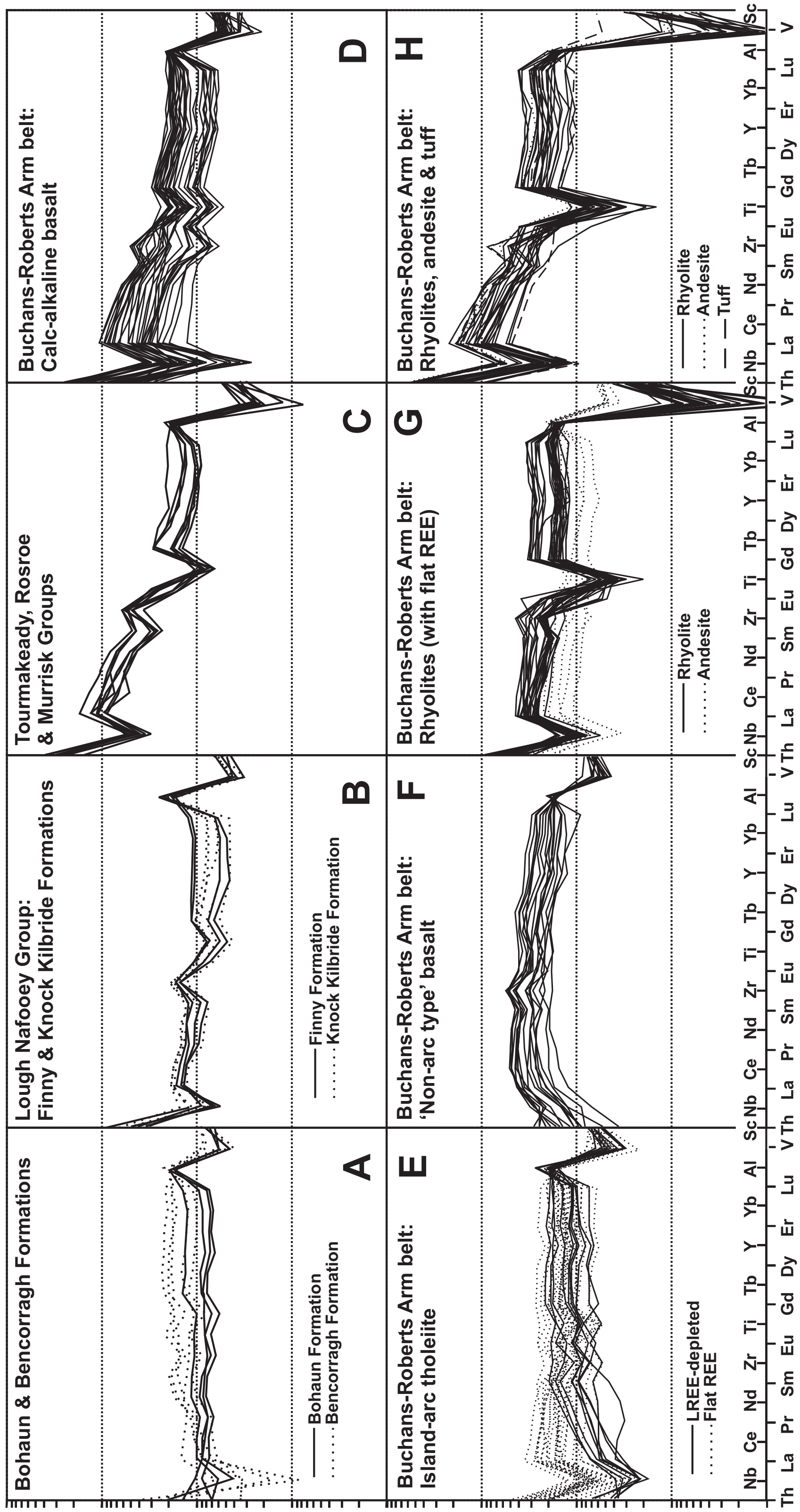


**Figure 7. Multi-element variation diagrams for samples from western Ireland (data from Draut et al., 2004) and the Buchans–Robert's Arm belt (data from Zagorevski, 2008). Chondrite normalization values are after McDonough and Sun (1995). REE—rare earth element; LREE—light rare earth elements.**

junctions; and also in ophiolites (references within Raveggi et al., 2007). Propagating spreading centers are common in many backarc basins (references within Harper, 2003), with Fe-Ti basalt having been erupted in the tip of the Central Lau Basin spreading center (Pearce et al., 1994).

The repeated occurrence of Fe-Ti ± P–enriched basalt within the Tyrone Volcanic Group suggests intermittent rifting may have been caused by the propagation of a rift into the Tyrone arc/backarc. High Fe-Ti basaltic rocks from the Paleoproterozoic Broken Hill block of New South Wales, Australia, show some similarities with samples reported herein. Fe-Ti amphibolites with La/Sm$_{CN}$ ~1.5–3 and Gd/Lu$_{CN}$ ~1 display eMORB-like geochemical compositions (Raveggi et al., 2007). Similarly, Mattsson and Oskarsson (2005) recorded a progression within the Eastern volcanic zone of Iceland from tholeiitic basalt, through Fe-Ti–rich lavas interlayered with silicic lavas, to alkalic compositions at the southernmost tip of the propagating ridge. Some Fe-Ti–enriched basalts from the Heimaey volcanic center of the Eastern volcanic zone have similar La/Sm ratios to eMORB, displaying LREE enrichment and positive Nb anomalies (Mattsson and Oskarsson, 2005). Fe-Ti–enriched basalt has also been recognized within the Annieopsquotch Accretionary Tract of Newfoundland (Zagorevski, 2008; see following), and the peri-Gondwanan–affinity Bathurst Mining Camp of the Tetagouche-Exploits backarc basin (Rogers and van Staal, 2003), Port aux Basques Gneiss of Newfoundland (Schofield et al., 1998), and from several peri-Gondwanan ensialic arc sequences of the British and Irish Caledonides (e.g., Leat et al., 1986; McConnell et al., 1991).

## Correlations across the Grampian–Taconic Event

Direct correlations between Newfoundland Appalachians and the British and Irish Caledonides have previously proven difficult due to poor exposure and the excision of key terranes along strike, such as the Southern Uplands (Colman-Sadd et al., 1992; Winchester and van Staal, 1995; van Staal et al., 1998). New and recently published geochronology and geochemistry (Cooper et al., 2008, 2011; Draut et al., 2009; Chew et al., 2010) allow refinement of previous correlations with the Tyrone Igneous Complex and across the orogen as a whole.

Although previous workers have correlated the Tyrone Igneous Complex with the Lough Nafooey arc system of western Ireland (e.g., Draut et al., 2009; Fig, 7), the data presented herein demonstrate that the Tyrone Igneous Complex represents a distinct arc-ophiolite complex accreted to the composite Laurentian margin during the Grampian orogeny. Consequently, we present a revised model for the evolution of the British and Irish Caledonides where outboard microcontinental blocks play a crucial role (after Chew et al., 2010). Their involvement within the Newfoundland Appalachians help to explain (1) discrepancies between the timing of syntectonic sedimentation and tectonic loading on the passive continental margin at ca. 475 Ma and ophiolite emplacement prior to 488 Ma (see Waldron and van Staal, 2001); and (2) the range of ages for Iapetan ophiolites accreted to the Laurentian margin (see van Staal et al., 2007). Three phases of arc-ophiolite emplacement to the Laurentian margin have been recognized within central Newfoundland during the equivalent Taconic orogeny (van Staal et al., 2007; see Figs. 8–9). Most of the major terranes recognized in Newfoundland bear strong temporal, lithological, and geochemical resemblances to those now identified within the British and Irish Caledonides (see Chew et al., 2010).

### *Early Ophiolite Emplacement*

Early obduction in central Newfoundland is recorded by the emplacement of the ca. 510–501 Ma Lush's Bight Oceanic Tract (Fig. 9A) onto the Dashwoods peri-Laurentian microcontinental block (Waldron and van Staal, 2001) between ca. 500 and 493 Ma (van Staal et al., 2007; Fig. 9B). The Lush's Bight Oceanic Tract consists of an ophiolitic association of pillow basalts, sheeted dikes, gabbro, and rare ultramafic rocks (Kean et al., 1995). Abundant boninite, primitive island-arc tholeiite ($\varepsilon_{Nd[t]}$ of 0 to +2.8; Swinden, 1996; Swinden et al., 1997), and the presence of large intrusions of juvenile trondhjemite and diorite (Fryer et al., 1992) imply that the tract represents an infant arc terrane that formed close to Laurentia (van Staal et al., 1998; Fig. 9A).

Although the Lush's Bight Oceanic Tract occupied an upper-plate setting during its accretion, it is currently unclear whether it formed inboard or outboard of the Dashwoods Block (Zagorevski and van Staal, 2011). Recently, Zagorevski and van Staal (2011) suggested the Lush's Bight Oceanic Tract may have developed inboard of the Dashwoods Block and was obducted from the west (as in Fig. 9). This model removes the requirement for the Dashwoods Block to have been completely subducted under the Lush's Bight Oceanic Tract. Formation inboard of the Dashwoods microcontinental block is also supported by the presence of Lush's Bight remnants in a forearc position during the final closure of the Taconic Seaway (references in Zagorevski and van Staal, 2011).

Recent work on the Deer Park (514 ± 3 Ma: Ar-Ar hornblende of metabasite) and Highland Border (499 ± 8 Ma: U-Pb zircon amphibolite) ophiolites of the British and Irish Caledonides demonstrated that subduction and the onset of obduction occurred at least 15 m.y. before Grampian orogenesis (Chew et al., 2010). Early obduction may have occurred outboard of the Laurentian margin onto ribbon-shaped microcontinental blocks, consistent with the evolution of the Lush's Bight Oceanic Tract (van Staal et al., 2007). Metadiabase blocks that preserve ophitic textures and chilled margins within the Deer Park Complex are tholeiitic, juvenile ($\varepsilon_{Nd[t = 500 Ma]}$ of +6), and display similar suprasubduction-zone geochemical characteristics (Ryan et al., 1983; Chew et al., 2007). Mafic rocks within the Highland Border Ophiolite also include primitive suprasubduction tholeiites (see Henderson and Robertson, 1982; Robertson and Henderson, 1984; Dempster and Bluck, 1991). The Mount-Orford Ophiolite (504 ± 3 Ma; Fig. 8A) of the Quebec Appalachians is of mixed boninitic, tholeiitic, and transitional-alkaline affinity (references in Tremblay et al., 2011) and may also be a potential correlative to the Lush's Bight Oceanic Tract.

Possible microcontinental blocks within the British and Irish Caledonides may include the Tyrone Central Inlier (e.g., Chew et al., 2008, 2010), Slishwood Division (Flowerdew et al., 2009), and Connemara (Chew et al., 2010). The Chain Lakes Massif of western Maine may also represent a possible outboard microcontinental block (Waldron and van Staal, 2001; Fig. 8A), although it has recently been suggested that the high-grade metasedimentary sequence may have been originally deposited in a forearc setting to a peri-Laurentian island arc adjacent to or upon a microcontinental block (Gerbi et al., 2006). Similar metasedimentary rocks are also preserved structurally underneath the ca. 480 Ma Thetford Mines ophiolite of the Quebec Appalachians (see Tremblay et al., 2011; Fig. 8A).

Early obduction outboard of the Laurentian margin may also explain discrepancies between the timing of obduction in the British and Irish Caledonides and the termination of the Laurentian Cambrian–Ordovician shelf sequences of NW Scotland (see Chew et al., 2010). Deposition of the Ardvewck and Durness Groups of the Hebridean terrane, NW Scotland, was not terminated until at least the late Arenig–early Llanvirn (ca. 470–465 Ma; Huselbee and Thomas, 1998), yet the onset of obduction and metamorphism in Scotland occurred some ~15 m.y. earlier (Chew et al., 2010). Emplacement of the Deer Park Complex and Highland Border Ophiolites outboard of these shelf sequences may also explain (after Chew et al., 2010) differences in detrital zircon signatures between the Cambrian–Ordovician passive margin of NW Scotland and its temporal equivalents in the Dalradian Supergroup (Cawood et al., 2007), and why there is an absence of Grampian terrane detritus in the Laurentian passive margin (Bluck, 2007).

### *Nafooey–Baie Verte–Notre Dame Arc System*

Following the emplacement of the Lush's Bight Oceanic Tract, eastward-directed subduction in the Humber Seaway led to the formation and emplacement of the ca. 489–487 Ma Baie Verte Oceanic Tract coeval with both the first-phase activity within the continental Notre Dame arc (ca. 489–477 Ma), and the development of the ca. 476–467 Ma Snooks Arm arc/backarc complex along strike (van Staal et al., 2007; Skulski et al., 2010; Fig. 9B). The Baie Verte Oceanic Tract includes low-Ti and intermediate-Ti boninite, and younger island-arc tholeiitic mafic crust that formed between ca. 489 and 487 Ma (Skulski et al., 2010). In the Irish Caledonides, the Baie Verte Oceanic Tract is represented by the ca. <490–476 Ma Lough Nafooey Group (Lough Nafooey arc; see Ryan et al., 1980; Fig. 1A), which collided with the Laurentian margin ca. 476 Ma (see Ryan and Dewey, 2011; time scales after Sadler et al., 2009).

The Lough Nafooey Group (ca. <490–476 Ma) is of primitive island-arc affinity near its base (Ryan et al., 1980; Clift and Ryan, 1994) and shows an increasing proportion of Laurentian-derived melt up section (Draut et al., 2004). LREE depletion and the strongly positive $\varepsilon_{Nd(t)}$ values of tholeiitic basalts in the lower Lough Nafooey Group suggest an origin far from Laurentia (Draut et al., 2004). By ca. 490 Ma, it is likely that the arc was incorporating some crustal material, as granitoid boulders of this age yield $\varepsilon_{Nd(t)}$ values of ~0 (Chew et al., 2007). Younger volcanic rocks exhibit a trend toward higher $SiO_2$ and $K_2O$, increasing LREE enrichment (Ryan et al., 1980), calc-alkaline affinities, and lower $\varepsilon_{Nd(t)}$ values, associated with continental material entering the subduction channel (Draut et al., 2004). Boninitic-affinity rocks recognized by Clift and Ryan (1994) from the Bohaun Volcanic Formation are of unknown age but are typically placed below, or at the base of, the Lough Nafooey Group (e.g., Draut et al., 2004; Ryan and Dewey, 2011).

The Tourmakeady Group (ca. 476–470 Ma; Ryan and Dewey, 2011) of the Irish Caledonides records volcanism during peak deformation and regional metamorphism of the Dalradian Supergroup, and it is characterized by a diverse succession of rock types, including: rhyolitic tuffs, breccias, and lavas, green and red cherts, graptolitic mudstones, siltstones, limestones,

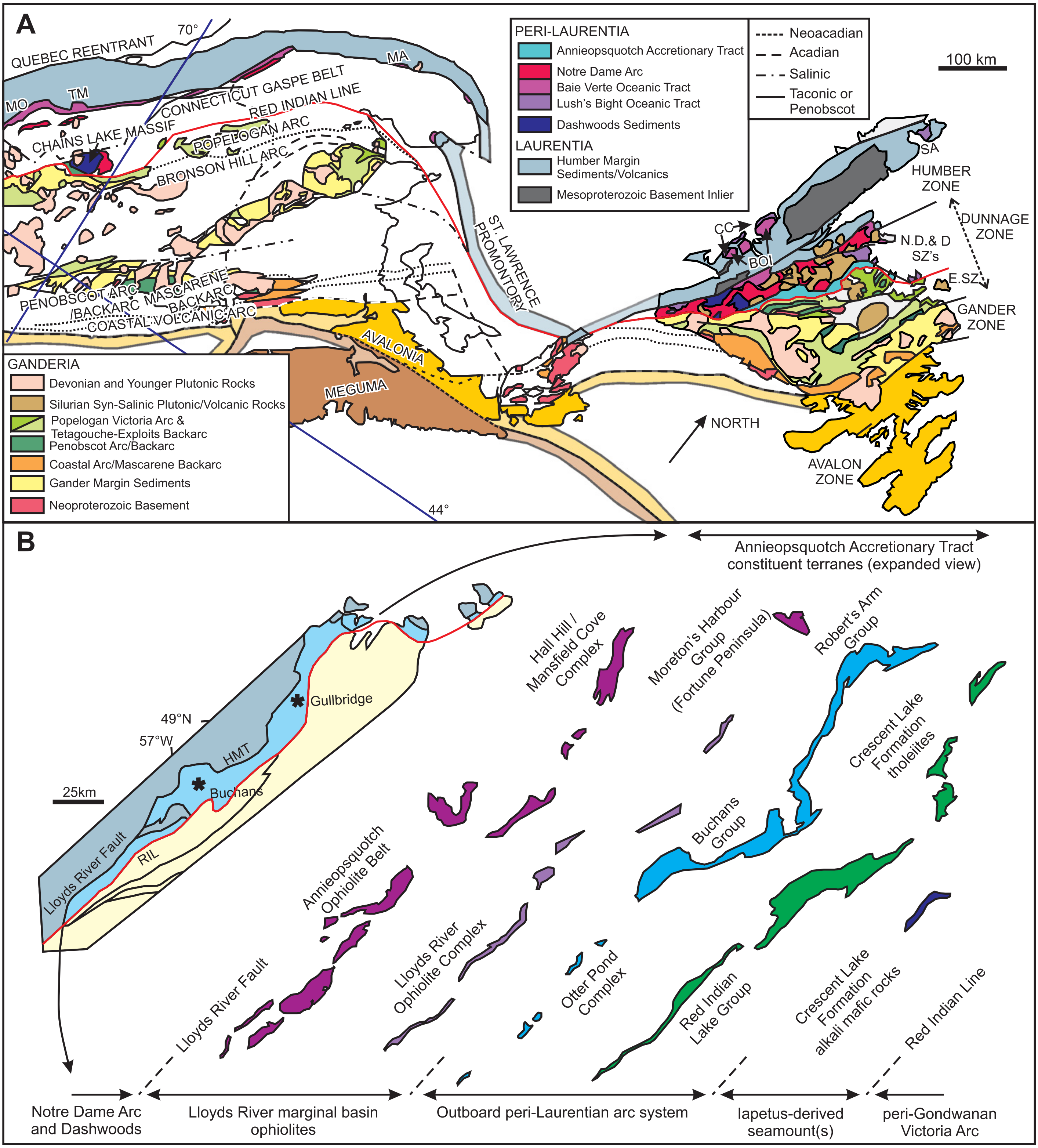


**Figure 8. (A) Geology of the Canadian and adjacent New England Appalachians and the geographical distribution of the major tectonic elements discussed in text (modified after van Staal et al., 2009). (B) Tectono-stratigraphic subdivisions of the Annieopsquotch Accretionary Tract (expanded view: modified after Zagorevski et al., 2009a; Zagorevski and van Staal, 2011). BOI—Bay of Islands; CC—Coastal complex; E.SZ—Exploits subzone; N.D and D. SZ's—Notre Dame and Dashwoods subzones; MA—Mont Albert ophiolite; MO—Mount Orford Ophiolite; SA—St. Anthony complex; TM—Thetford Mines ophiolite.**

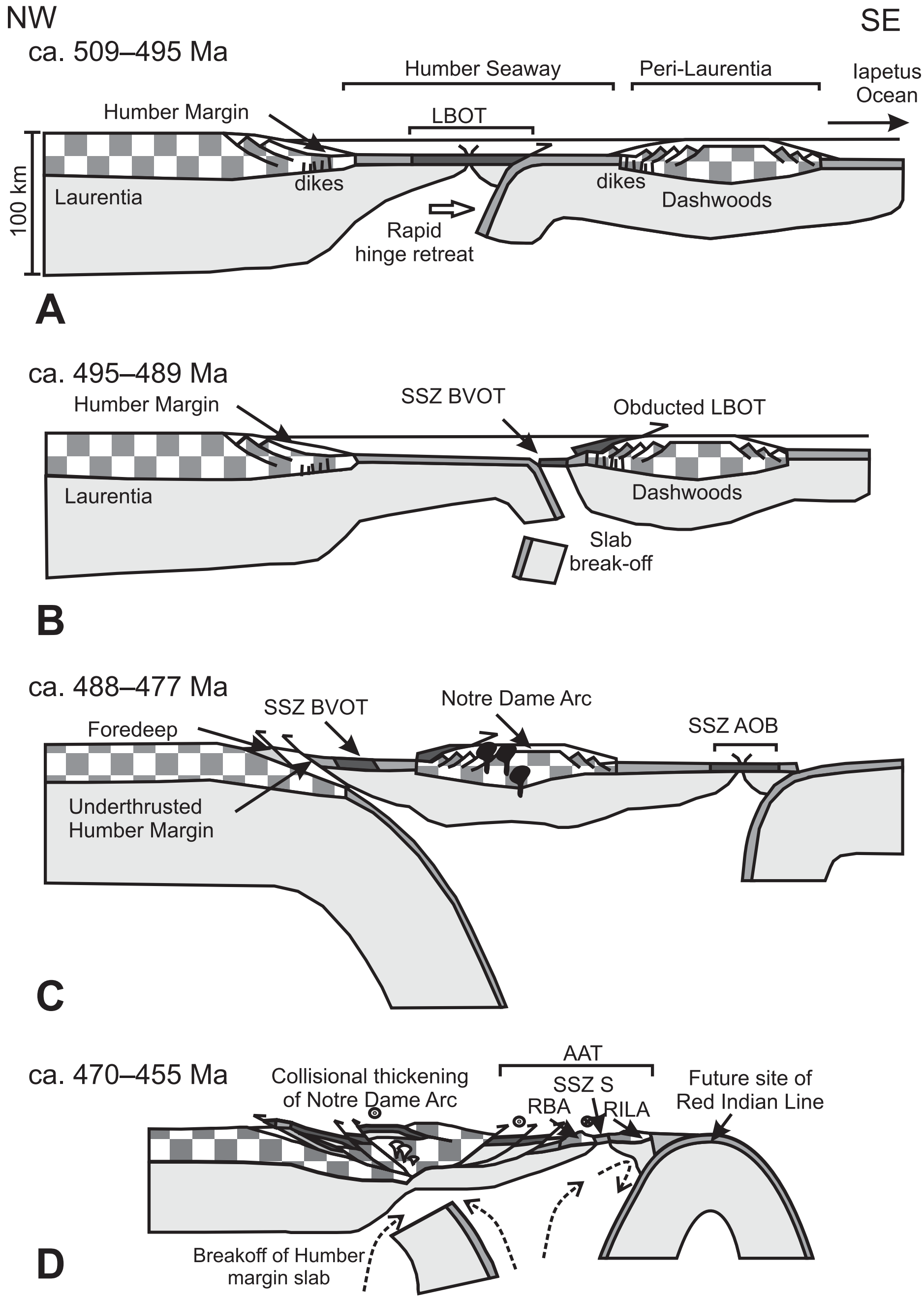


**Figure 9. Evolution of the Laurentian margin during the Taconic event (after van Staal et al., 2007; Zagorevski and van Staal, 2011). (A) Formation of the Lush's Bight Oceanic Tract (LBOT) inboard of the Dashwoods microcontinent. (B) Development of the Baie Verte Oceanic Tract (BVOT) and the Snooks Arm and Notre Dame arcs (NDA) following collision of the Lush's Bight Oceanic Tract. (C) Collision between the Humber margin and Dashwoods Block leads to the initiation of west-dipping subduction and formation of the Annieopsquotch Ophiolite Belt (AOB). (D) Collisional thickening of the Notre Dame arc, slab breakoff, and the accretion of the Annieopsquotch Ophiolite Belt, remnant Buchans arc (RBA), Skidder basalts (S), and Red Indian Lake arc (RILA) to the Laurentian margin. AAT—Annieopsquotch Accretionary Tract; BOI—Bay of Islands ophiolite; SSZ—suprasubduction-zone affinity.**

and conglomerates (Draut et al., 2004; Graham, 2009). $SiO_2$, LILE, and LREE enrichment and strongly negative $\varepsilon_{Nd(t)}$ values for volcanic rocks imply the assimilation of old continental material associated with the continental margin entering the subduction channel (Draut et al., 2004). The Tourmakeady Group appears to be equivalent to the Snooks Arm arc/backarc complex of Newfoundland, which is characterized by similar lithologies (ca. 476–467 Ma; Skulski et al., 2010; Zagorevski and van Staal, 2011). Both groups formed syncollisionally, associated with the accretion of a ca. 490 Ma oceanic arc/tract that developed above a south-dipping subduction zone (i.e., Lough Nafooey Group and Baie Verte Oceanic Tract; Draut et al., 2009; Zagorevski and van Staal, 2011).

The Snooks Arm Group (ca. 476–467 Ma), and its equivalents (e.g., upper Pacquet Harbour Group, Flat Water Pond Group, Point Rousse sequence), includes a diverse succession of rock types, including many of those described from the Tourmakeady Group (e.g., rhyolitic domes, tuff, tuff breccia, siltstone, chert, conglomerate, mudstone, limestone). Mafic rocks are dominated by tholeiitic basalt, with calc-alkaline basalt forming a relatively minor component of the Snooks Arm arc (Skulski et al., 2010). Although eMORB and OIB were not described by Skulski et al. (2010) from the Snooks Arm Group sensu stricto, these rock types form a relatively minor component in regional equivalents (see Skulski et al., 2010). The intrusive syntectonic metagabbros and orthogneisses of Connemara (474.5 ± 1–467 ± 2 Ma; Friedrich et al., 1999a, 1999b), Ireland, may be correlatives to the continental Notre Dame arc.

### *Phase 3: Development of the Tyrone Igneous Complex?*

Using recently published U-Pb zircon geochronology (Cooper et al., 2008, 2011) and the geochemistry and geochronology presented herein, we can refine possible correlatives to the Tyrone Igneous Complex.

Correlation of the Tyrone Volcanic Group (ca. 475–469 Ma) is inconsistent with both the older Lough Nafooey Group (ca. <490–476 Ma) as originally proposed by Draut et al. (2009), and the Baie Verte Oceanic Tract (ca. 489–487 Ma), based on the stratigraphy, geochemistry, and geochronology presented herein (Figs. 7A–7B). LILE- and LREE-enriched island-arc signatures present within the syncollisional Tourmakeady Group (ca. 476–470 Ma; Fig. 7C), and parts of the Snooks Arm Group (ca. 476–467 Ma), are comparable to sections of the Tyrone Volcanic Group (also see Cooper et al., 2011), although a direct correlation seems unlikely. The Tourmakeady Group contains no mafic units, which dominate most formations of the Tyrone Volcanic Group, and it is characterized by felsic and sedimentary rocks. Sedimentary rocks are scarce within the Tyrone Volcanic Group, restricted to rare beds of siltstone and chert in the lower Tyrone Volcanic Group, and graphitic pelite and layered chert in the uppermost Tyrone Volcanic Group. The Snooks Arm arc is dominated by tholeiitic basalt, which makes up a minor component of one member in the Tyrone Volcanic Group, and similar sedimentary units to the Tourmakeady Group. Furthermore, the Tyrone Volcanic Group is believed to have formed outboard a microcontinental block, whereas the Snooks Arm arc formed inboard of the Dashwoods Block (Zagorevski and van Staal, 2011).

As there is no evidence for obduction of the Tyrone Volcanic Group onto the Tyrone Central Inlier until ca. 470 Ma, correlation to the Tourmakeady Group would require arc-continent collision to be diachronous from ca. 476 Ma to 470 Ma across the Irish Caledonides (Draut et al., 2004; Cooper et al., 2011). This scenario predicts a continuation of collision into the Scottish Caledonides associated with a delay in the timing of peak metamorphism and deformation. However, Sm-Nd garnet ages of ca. 473–465 Ma for Barrovian metamorphism in the Scottish Highlands (Baxter et al., 2002) are equivalent to U-Pb zircon ages from synorogenic intrusives in western Ireland. Syn-D2 to early-D3 basic intrusions from western Ireland give ages of 474.5 ± 1 Ma and 470.1 ± 1.4 Ma (Friedrich et al., 1999a), whereas analysis of late D3 quartz diorite gneisses produced an age of 467 ± 2 Ma (Friedrich et al., 1999b). This demonstrates that Grampian orogenesis was under way by ca. 475 Ma across the British and Irish Caledonides with no clear evidence for diachronous collision along this section of the Laurentian margin. The ca. 470 Ma timing in County Tyrone appears to suggest that arc accretion here was associated with an outboard microcontinental block (Tyrone Central Inlier; see Cooper et al., 2011). Although we cannot unequivocally rule out a correlation with the Tourmakeady–Snooks Arm deposits, we believe the Tyrone Igneous Complex more closely correlates with elements incorporated into the Annieopsquotch Accretionary Tract of Newfoundland in terms of its temporal, geochemical, and stratigraphic evolution (see following).

***Annieopsquotch Ophiolite Belt.*** The Annieopsquotch Accretionary Tract of central Newfoundland is composed of a thrust stack of Lower to Middle Ordovician arc and backarc terranes accreted to the composite Laurentian margin (van Staal et al., 2009) during the Middle to Upper Ordovician (Zagorevski et al., 2009a) (see Fig. 8B). Stratigraphic, geochemical, and geochronological similarities have previously been identified between the Annieopsquotch Ophiolite Belt and Tyrone Plutonic Group (Cooper et al., 2011). The ca. 480 Ma Annieopsquotch Ophiolite Belt (Dunning and Krogh, 1985) includes several suprasubduction-zone ophiolite complexes, which formed during west-directed (= north-dipping in Ireland) subduction outboard of the peri-Laurentian Dashwoods Block (Lissenberg et al., 2005; Zagorevski et al., 2006; Fig. 9). Recent geochronology presented by Cooper et al. (2011: 479.6 ± 1.1 Ma) from the Tyrone Plutonic Group, primitive $\varepsilon_{Nd_{(t)}}$ values (+4.5 to +7.5; Draut et al., 2009), tholeiitic suprasubduction geochemical characteristics, and its development outboard of a microcontinental block (Tyrone Central Inlier) are all consistent with the correlation to the Annieopsquotch Ophiolite Belt (Lissenberg et al., 2004). Xenocrystic Mesoproterozoic zircons present within the Tyrone Plutonic Group are consistent with $\tau_{DM}$ ages of 1200–1800 Ma from the Moreton's Harbour Group of Newfoundland (part of the Annieopsquotch Ophiolite Belt; Cutts et al., 2012). The presence of xenocrystic zircons within the Tyrone Plutonic Group suggests it may have formed above a north-dipping subduction zone by the propagation of a spreading center into a microcontinental block (= Tyrone Central Inlier). A similar tectonic scenario was presented for the formation of the Annieopsquotch Ophiolite Belt by Zagorevski et al. (2006). Fe-Ti-P–enriched basalt (to 2.9 wt% $TiO_2$), common at propagating rifts, also occurs within the Tyrone Plutonic Group.

***Buchans–Robert's Arm Arc.*** The Buchans Group and correlative Robert's Arm Group of Newfoundland are composed of peri-Laurentian ensialic island-arc volcanics that formed above a west-dipping subduction zone (= north-dipping in the Caledonides) (Fig. 9). The Robert's Arm Group (ca. 473–464 Ma) includes several imbricated belts of bimodal to mafic, calc-alkaline–dominated, arc volcanic rocks (Kerr, 1996; O'Brien, 2007; Zagorevski, 2008). The Buchans Group (ca. 473 Ma) is a bimodal to felsic-dominated calc-alkalic succession with strong isotopic and zircon inheritance suggesting interaction with old continental crust (Swinden et al., 1997; Rogers, 2004; Zagorevski, 2008); $\varepsilon_{Nd_{(t)}}$ values from the Buchans Group range between +1 and –10 (Zagorevski et al., 2006). The geochemistry of the Buchans and Robert's Arm groups is presented within Zagorevski (2008) and summarized in Figure 7 here. These data are consistent with correlation to the Tyrone Volcanic Group (Figs. 5 and 7), and Fe-Ti–enriched non-arc-type basalts are also present within the Annieopsquotch Accretionary Tract (to 15.9 wt% $Fe_2O_{3T}$ and 2.5 wt% $TiO_2$) (Fig. 7F; Zagorevski, 2008). The presence of Fe-Ti–enriched non-arc-type basalt at many stratigraphic levels within the Tyrone Volcanic Group is consistent with propagation of a rift into the arc/backarc system. A similar situation was invoked to explain the continental portion of the Robert's Arm–Wiley's Brook arc, which rifted off the Dashwoods Block, leading to the opening of the Lloyds River backarc (see Zagorevski et al., 2006). The Lloyds River ophiolite (ca. 473 Ma) is coeval with the oldest members of the Robert's Arm arc and its chemistry suggests that, at this stage, the rift had evolved into an oceanic backarc basin (Fig. 8B).

Lithologies present within the Robert's Arm (e.g., Kerr, 1996; O'Brien, 2007) and Buchans Groups (stratigraphy of Zagorevski et al., 2009b; Zagorevski et al., 2010) are also consistent with correlation to the Tyrone Volcanic Group. The Robert's Arm Group includes a diverse succession of calc-alkaline mafic flows, felsic pyroclastic rocks, volcaniclastic turbidites, and "chert-jasperoid" sediments (O'Brien, 2007). Massive and pillowed basalt, porphyritic andesite, volcanic breccia (agglomerate) lithic-crystal tuff, argillite, laminated chert, oxide-facies iron formations, and tuffaceous sandstone of the Gullbridge Tract (see O'Brien, 2007; Fig. 8B) are all present within the Tyrone Volcanic Group (Fig. 3). Within the correlative Buchans Group, the Buchans River Formation is composed mainly of calc-alkaline massive to flow-banded rhyolite to rhyodacite, pyroclastic rocks, dacite, volcanogenic conglomerate, granite-bearing conglomerate, sandstone, and turbiditic wacke (Zagorevski et al., 2009b), and it is similar to the Greencastle formation of the Tyrone Volcanic Group. By contrast, the Ski Hill and Sandy Lake formations of the Buchans Group closely resemble the Creggan, Loughmacrory, and Broughderg formations, in that they contain abundant mafic lava, breccias, and tuff with subordinate sedimentary rocks, chert, "jasperoid sediments," rhyolite, and felsic tuff (Zagorevski et al., 2009b). The Mary March Brook Formation of the Buchans Group is a tholeiitic bimodal volcanic succession, interpreted to represent a rifted-arc environment (Zagorevski et al., 2010), which closely resembles the Beaghmore formation.

***Accretion to Laurentia.*** Accretion of the Annieopsquotch Ophiolite Belt, Lloyds River ophiolite complex, and Buchans–Robert's Arm arc system to the Dashwoods microcontinent occurred between ca. 473 and 468 Ma (see Lissenberg et al., 2005; Zagorevski et al., 2006). Similar ages were determined from the ca. 470 Ma tonalite suite within the Tyrone

Igneous Complex, which stitches the Tyrone Plutonic and Tyrone Volcanic Groups to the Tyrone Central Inlier (Cooper et al., 2011). Biotite- and hornblende-bearing granitic plutons from the Tyrone Igneous Complex (ca. 467 Ma; Cooper et al., 2011) also occur within central Newfoundland (see Zagorevski et al., 2009b). Following accretion of the ca. 465–460 Ma Red Indian Lake Group (Zagorevski et al., 2008), continued closure of Iapetus was accompanied by the accretion of seamount fragments to the Laurentian margin, such as the Crescent Lake Formation (Fig. 8B). The South Connemara Group of western Ireland consists of an accretionary volcanic and sedimentary sequence separated from the Dalradian rocks of Connemara by the Skird Rocks fault, a possible continuation of the Southern Uplands fault (Hutton and Murphy, 1987). Ryan and Dewey (2004) identified part(s) of an accreted seamount within the succession.

### Diachronous Collision and Accretion Style

Although we present a model whereby the major terranes and tracts of the Newfoundland Appalachians correlate across the orogen into the British and Irish Caledonides (also see Chew et al., 2010), there are several important differences associated with arc-ophiolite accretion along the Laurentian margin that need to be addressed. Features of particular importance are: (1) the diachronous accretion of ophiolites from first-order promontories to adjacent reentrants; (2) the presence of several terranes that appear to have no direct analogs (e.g., Red Indian Lake Group, Southern Uplands–Longford Down terrane); and (3) the underplating of the arc-ophiolite terranes of the Annieopsquotch Accretionary Tract to the composite Laurentian margin, whereas in Northern Ireland, arc-ophiolite obduction occurred.

#### *Diachronous Collision, Promontories, and Reentrants*

It has been suggested that first- and second-order reentrants and promontories along the Laurentian margin may be responsible for the variable preservation of Iapetan ophiolites and their diachronous accretion (Zagorevski and van Staal, 2011). Suprasubduction-zone ophiolites generated in deep reentrants occur where mainly Mediterranean-style subduction continued as a result of rollback, while convergence slowed significantly at promontories (Zagorevski and van Staal, 2011). These pericollisional ophiolites formed close to the Laurentian margin and were emplaced shortly after formation, occupying an upper-plate setting. Most contain well-preserved metamorphic soles and conform to the classic Penrose stratigraphy (see Zagorevski and van Staal, 2011).

In the Quebec Appalachians, the Thetford Mines (479.2 ± 1.6 Ma), Asbestos (478–$480\ ^{+3}/_{-2}$ Ma), and Lac-Brompton ophiolites (references in Tremblay et al., 2011; Fig. 8A) are interpreted to be of similar age to the Annieopsquotch Ophiolite Belt and Tyrone Plutonic Group. However, these ophiolites most likely formed as a result of syncollisional spreading in reentrants, while obduction of other segments of the Baie Verte Oceanic Tract was ongoing at adjacent promontories (van Staal et al., 2007; Fig. 8A). Emplacement of the ca. 480 Ma Thetford Mines ophiolite of the Quebec Appalachians onto the Laurentian margin occurred prior to ca. 470 Ma (see Tremblay et al., 2011). Younger ages in Quebec for constituents of the Baie Verte Oceanic Tract are consistent with diachronous collision expected when moving from a first-order promontory to an adjacent reentrant (Zagorevski and van Staal, 2011).

The Ballantrae Ophiolite Complex of Scotland (483 ± 4 Ma U-Pb zircon age; Bluck et al., 1980; Fig. 1A) is unusual in the British and Irish Caledonides in that it contains a well-preserved metamorphic sole that gives a relatively young K-Ar age of 478 ± 8 Ma (Bluck et al., 1980). The $\varepsilon_{\mathrm{Nd}(t)}$ values are between +4.9 and +7.9, and geochemical signatures (including the presence of boninite) are consistent with a suprasubduction-zone origin (Smellie and Stone, 2001, and references therein). Indication of a suprasubduction-zone origin for the Ballantrae ultramafics includes the abundance of harzburgite over lherzolite, wehrlite over troctolite, chrome-spinel chemistry, and Cr-$TiO_2$ geochemistry of harzburgite (see Oliver et al., 2002). Evidence supporting a correlation between the Tyrone Igneous Complex and the Ballantrae Ophiolite Complex includes: (1) similar U-Pb zircon ages of ca. 484–480 Ma from Ballantrae and the Tyrone Plutonic Group; (2) their suprasubduction-zone characteristics (Cooper et al., 2011); (3) a close association among ophiolites, island-arc volcanics, and within-plate lavas at both; and (4) the occurrence of early to late Arenig graptolitic faunas (Floian to early Darriwilian; Sadler et al., 2009) and tuffs dated at ca. 470 Ma (with large analytical errors) from Ballantrae (see Oliver et al., 2002; Sawaki et al., 2010). However, despite these similarities, the Ballantrae Ophiolite Complex may also represent a young ophiolite of the Lough Nafooey–Baie Verte arc system associated with a reentrant along the Laurentian margin that was emplaced ca. 480 Ma. This could explain the preservation of its metamorphic sole and mantle sequence. Older, albeit unreliable, K-Ar and Sm-Nd ages have also been produced from the Ballantrae Ophiolite Complex for: (1) within-plate–affinity gabbro (K-Ar age of 487 ± 8 Ma; Harris et al., 1965), (2) island-arc lavas (whole-rock Sm-Nd ages of 476 ± 14 Ma and 501 ± 12 Ma; Thirlwall and Bluck, 1984), and (3) garnet metapyroxenite (Sm-Nd age of 505 ± 11 Ma; Hamilton et al., 1984). Furthermore, northwestward-directed duplexes within the Ballantrae Ophiolite Complex are consistent with southeast-directed subduction (Sawaki et al., 2010), whereas the Tyrone Plutonic Group appears to have formed outboard of a peri-Laurentian microcontinental block above a north-dipping subduction zone.

#### *Obduction or Underplating?*

Preferential obduction of ophiolites, as opposed to their dismemberment and accretion (and possible underplating), is dependent on a number of factors directly related to tectonic setting, and consequently the lithologies involved; these include: (1) the age, hydration, and temperature of the crust being emplaced, (2) the nature of the crust (i.e., type of ophiolite; see Dilek and Furnes, 2011), (3) the presence of topographic highs (e.g., oceanic plateaus or seamounts), (4) the nature, thickness, and effect of the overlying sediment pile, (5) whether the oceanic crust is deformed prior to obduction or accretion, (6) presence of transform faults, and (7) the presence and nature of any microcontinental blocks (shape, composition, and/or thickness). Underplating of the Annieopsquotch Accretionary Tract to the composite Laurentian margin was associated with the accretion of thin (<5 km) but large slabs of supracrustal arc rocks and ophiolitic crust with high aspect ratios (Zagorevski et al., 2009a). Transfer of these arc terranes to an upper-plate setting was in part controlled by the proximity to the brittle-ductile transition in hydrated crust. Terranes were partially hydrated and cold at the time of their accretion (Zagorevski et al., 2009a). By contrast, the Tyrone Volcanic Group was still hot at the time of its accretion (Cooper et al., 2011) and may have been obducted at the same time as the Tyrone Plutonic Group ca. 470 Ma. Other possible explanations for the obduction of the Tyrone Plutonic and Tyrone Volcanic groups include: (1) the nature of the microcontinental block onto which they were accreted; and (2) the arrival of a seamount and temporary jamming of the north-dipping subduction zone, facilitating obduction.

Several lines of evidence now suggest that there is basement material underneath the Tyrone Central Inlier: (1) Highly magnetic material underlying the Tyrone Central Inlier is clear from Tellus geophysical imagery; (2) inherited ca. 2100 Ma zircons derived from the Tyrone Central Inlier are scarce in peri-

Laurentian sources (Cooper et al., 2011); and (3) extremely negative $\varepsilon_{\mathrm{Hf}_{(t = 470\ \mathrm{Ma})}}$ values within zircon overgrowths may imply the presence of hidden Archean crust (Flowerdew et al., 2009). An exotic relic of Archean basement material under a consequently thickened microcontinental block may explain why the Tyrone Plutonic Group was obducted rather than underplated.

Temporary jamming of the subduction channel may be supported by the presence of the South Connemara Group of western Ireland (Ryan and Dewey, 2004). The tectonically disrupted South Connemara Group includes: part(s) of an accreted seamount (Gorumna Formation); oceanic deep-sea cherts, with upper levels diluted with distal continentally derived detritus (Golam Formation); and conglomerate containing abundant detrital almandine from a recycled orogen provenance, and igneous and metamorphic clasts (Lettermullen Formation) (see Ryan and Dewey, 2004). Together with structural data, this argues for formation in a subduction-accretion complex above a north-dipping subduction zone (Ryan and Dewey, 2004). Clasts of the Lettermullen Formation imply a post- or syn-Grampian age for the Group. Limited paleontological constraints place the Golam Formation within the Floian-Darriwilian (Lower-Middle Ordovician; Graham, 2009; Sadler et al., 2009). Along the Northern Belt of the Southern Uplands terrane and along the northern edge of the Longford Down terrane, tectonic slices of alkali and tholeiitic basalt of within-plate affinity occur; these may be equivalent to tectonically accreted fragments of seamount(s) and island-arc volcanoes (Dewey and Ryan, 2004). Temporary jamming of the subduction zone by the arrival of a large seamount(s) or island-arc volcano may have facilitated obduction at ca. 470 Ma. Extensive post-Ordovician cover sequences obscure most of the Midland Valley terrane SE of the Tyrone Igneous Complex.

The occurrence of the Red Indian Lake Group in the Newfoundland Appalachians and the Southern Uplands–Longford Down accretionary prism in the British and Irish Caledonides may reflect the geometry and along-strike extent of the colliding Red Indian Lake arc system or the nature of sediment supply to the subduction trench (e.g., sediment starved, erosive). Recently, Zagorevski and McNicoll (2011) have suggested the Laurentian margin was sediment starved along the Newfoundland sector during the Ordovician. In stark contrast to the rapidly exhuming Grampian orogen, low relief of the Taconic orogen in Newfoundland may have resulted in low sediment supply (see Zagorevski and McNicoll, 2011). Although there is evidence for a buried arc in the Southern Uplands–Longford terrane, this sector of the Laurentian margin was predominantly characterized by the progressive accretion of Iapetan ocean floor and sedimentary material to the composite Laurentian margin (Graham, 2009).

## CONCLUSIONS

The Tyrone Igneous Complex of Northern Ireland is an integral part of the Grampian-Taconic phase of the Caledonian-Appalachian orogen. A new geological survey has enabled the Tyrone Volcanic Group to be placed within a detailed structural and stratigraphic context. Extensive new geochemistry details the progressive evolution of a short-lived peri-Laurentian island arc/backarc (ca. <475–469 Ma) that developed outboard of a microcontinental block (Tyrone Central Inlier) prior to its accretion at ca. 470 Ma. Episodic arc rifting is recorded by the occurrence of Fe-Ti–enriched basalts of eMORB affinity at several stratigraphic levels, alkali basalt, LREE-depleted island-arc tholeiite, and tholeiitic rhyolite with flat to U-shaped REE profiles.

Broad correlations can be made across the Grampian-Taconic orogeny. Three major phases of arc-ophiolite accretion identified in the Newfoundland Appalachians are now recognized within the Caledonides. Early ophiolite obduction within the Caledonides is recorded by the emplacement of the Deer Park (ca. 514 Ma) and Highland Border (ca. 500 Ma) Ophiolites onto possible outboard microcontinental blocks, broadly equivalent to the emplacement of the Lush's Bight Oceanic Tract (ca. 510–501 Ma) of Newfoundland onto the Dashwoods microcontinental block at ca. 500–493 Ma. Continued closure of the Iapetus Ocean led to the formation and accretion of the ca. <490–476 Ma Lough Nafooey arc (= buried Midland Valley arc?) to the Laurentian margin. This phase of arc-ophiolite accretion is recorded in Newfoundland by the development and emplacement of the Baie Verte Oceanic Tract (ca. 489–487 Ma). The syncollisional stage of the Lough Nafooey arc (Tourmakeady Group; ca. 476–470 Ma) appears to be broadly equivalent to the development of the Snooks Arm Group (ca. 476–467 Ma) of Newfoundland. The Tyrone Igneous Complex (ca. 480–464 Ma) closely resembles elements incorporated within the Annieopsquotch Accretionary Tract of Newfoundland, specifically the ca. 480 Ma Annieopsquotch Ophiolite Belt and Buchans–Robert's Arm groups (ca. 473–464 Ma).

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