Evolution of the Tyrone ophiolite, Northern Ireland, during the Grampian–Taconic orogeny: a correlative of the Annieopsquotch Ophiolite Belt of central Newfoundland?

S. P. HOLLIS1,2*, M. R. COOPER3, S. ROBERTS1, G. EARLS2, R. HERRINGTON2, D. J. CONDON6 & J. S. DALY7

1Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, Waterfront Campus, European Way, Southampton SO14 3ZH, UK
2CSIRO Earth Science and Resource Engineering, 26 Dick Perry Avenue, Kensington, Perth, WA 6151, Australia
3Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Malone Lower, Belfast BT9 5BJ, UK
416 Mill Road, Ballygowan, Newtownards BT23 6NG, UK
5Department of Earth Sciences, Natural History Museum, London SW7 5BD, UK
6NERC Isotope Geosciences Laboratory, British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG, UK
7UCD School of Geological Sciences and National Centre for Isotope Geochemistry, University College Dublin, Belfield, Dublin 4, Ireland

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

Abstract: The Tyrone Plutonic Group of Northern Ireland represents the upper portions of a tectonically dissected suprasubduction-zone ophiolite accreted to the composite Laurentian margin during the Middle Ordovician. Understanding its development and relationship to the Tyrone Central Inlier, an outboard fragment of relatively high-grade, peri-Laurentian continental crust, is essential for reconstructing the closure of the Iapetus Ocean. The Tyrone Plutonic Group is composed of tectonized layered, isotropic and pegmatitic gabbros, sheeted dolerite dykes and rare pillow lavas. New U–Pb zircon thermal ionization mass spectrometry geochronology has yielded an age of 483.68 ± 0.81 Ma from pegmatitic gabbro. Geochemical characteristics, Nd and Sr isotope systematics, and zircon inheritance indicate that the Tyrone Plutonic Group formed above a north-dipping subduction zone, by the propagation of a spreading centre into a microcontinental block. Synkinematic, calc-alkaline tonalitic to granitic material preserved in the contact zone between the Tyrone Plutonic Group and the Tyrone Central Inlier has produced pressure estimates of 2.3–4.0 ± 0.6 kbar and temperatures of 525–610 °C. Coeval arc–ophiolite accretion at c. 470 Ma may explain how sillimanite-grade metamorphic conditions were reached locally in the underlying Tyrone Central Inlier. Strong temporal, geochemical and lithological similarities exist to the Annieopsquotch Ophiolite Belt of Newfoundland.

Supplementary materials: Petrographic photographs, whole-rock, isotopic and mineral geochemical data, and U–Th–Pb isotopic data are available at www.geolsoc.org.uk/SUP18646.

Ophiolites represent fragments of upper mantle and oceanic crust incorporated into continental margins during continent–continent and arc–continent collisions, ridge-trench interactions and/or subduction–accretion events (see references given by Dilek & Furnes 2011). Following the Penrose definition (Anonymous 1972) and establishment of the plate tectonic theory, a paradigm shift occurred for ophiolite genesis between the early 1970s and mid-1980s, when it was recognized that most have geochemical similarities to island arcs (e.g. Miyashiro 1973; Harper 1984). Consequently, the ophiolite concept moved toward a magmatic origin in subduction-zone settings (suprasubduction-zone ophiolites; e.g. Pearce et al. 1984). Suprasubduction-zone ophiolites are interpreted to form in arc–forearc or backarc settings at convergent margins shortly before orogenesis (Dilek & Furnes 2011). Common within many Early Palaeozoic orogens, such as the Caledonian, Appalachian, and Uralian belts, suprasubduction-zone ophiolites often mark the location of subduction suturets within short-lived collision zones and can therefore provide essential information on the closure of ancient ocean basins and their temporal evolution (e.g. Dewey 2005).

The Grampian–Taconic phase (c. 475–465 Ma) of the Caledonian–Appalachian orogen (Fig. 1) resulted from the progressive accretion of a diverse set of arc terranes, ribbon-shaped microcontinental blocks and oceanic tracts to the Laurentian margin during the Early Palaeozoic closure of the Iapetus Ocean (Draut et al. 2004; van Staal et al. 2007; Cooper et al. 2011). In the British and Irish Caledonides, deformed and metamorphosed Neoproterozoic to Early Palaeozoic rocks of the Dalradian Supergroup represent cover sequences of the Laurentian margin (Chew 2009). Recent advances, including new fieldwork, geochemistry, U–Pb zircon and Ar–Ar geochronology (e.g. Chew et al. 2008, 2010; Cooper et al. 2008, 2011; Flowerdew et al. 2009; Hollis et al. 2012, 2013), revealed that the Grampian orogeny was more complex than previously thought. Three main episodes of arc–ophiolite emplacement are recognized within the Newfoundland Appalachians, during the equivalent Taconic orogeny (van Staal et al. 2007). Although potential correlates to each of the c. 510–500 Ma Lushs Bight Oceanic Tract, c. 490–470 Ma Baie Verte Oceanic Tract–Snooks Arm arc, and c. 480–460 Ma Annieopsquotch Accretionary Tract of the Newfoundland Appalachians have been
suggested in the British and Irish Caledonides (e.g. van Staal et al. 1998; Chew et al. 2010; Cooper et al. 2011; Hollis et al. 2012), a number of specific terrane correlations remain contentious.

In the Newfoundland Appalachians, the presence of outriding microcontinental blocks was invoked to explain both (1) discrepancies between the timing of syntectonic sedimentation and tectonic loading on the passive continental margin at c. 475 Ma and ophiolite emplacement prior to c. 488 Ma (see Waldron & van Staal 2001) and (2) the range of ages for Iapetan ophiolites accreted to the Laurentian margin (van Staal 2001). Recent work from the British and Irish Caledonides has similarly demonstrated that subduction and the onset of obduction occurred at least c. 15 Ma before the Grampian orogeny (Chew et al. 2010). Consequently, understanding the relationship between suprasubduction-zone ophiolites and any peri-Laurentian microcontinental blocks within the Caledonides (such as the Tyrone Central Inlier and Sliszwood Division; Flowerdew et al. 2009; Chew et al. 2010; Hollis et al. 2012) is vital for reconstructing the progressive closure of the Iapetus Ocean.

The Tyrone Plutonic Group of Northern Ireland (Fig. 2) represents the upper parts of a tectonically dissected ophiolite sequence (Hutton et al. 1985) accreted onto an outboard segment of Laurentia, the Tyrone Central Inlier, during the Ordovician (Cooper & Mitchell 2004). Opinions on the timing of its formation, emplacement and relationship to both the Tyrone Volcanic Group (a peri-Laurentian island arc) and the Tyrone Central Inlier (a peri-Laurentian microcontinental block; Chew et al. 2008, 2010) have varied (e.g. Angus 1970; GSNI 1979; Hutton et al. 1985; Cooper & Mitchell 2004; Chew et al. 2008; Cooper et al. 2008, 2011; Draut et al. 2009; Hollis et al. 2012). Recent U–Pb zircon geochronology has dated light REE (LREE)-depleted layered olivine gabbro from the Tyrone Plutonic Group to 479.6±1.1 Ma (Cooper et al. 2011), which is significantly younger than previous geochronology from the ophiolite (493±2 Ma; Draut et al. 2009) and other ophiolites preserved in the British and Irish Caledonides. For example, the Deer Park Complex of western Ireland, the Scottish Highland Border Ophiolite and the Shetland Ophiolite have yielded considerably older ages of 514±3 Ma, 499±8 Ma and 492±3 Ma respectively (Spray & Dunning 1991; Chew et al. 2010). Only the Ballantrae Ophiolite Complex of Scotland has produced a similar U–Pb zircon age of 483±4 Ma (Bluck et al. 1980).

Here we present the interpreted results of high-resolution airborne geophysics, whole-rock and mineral geochemistry (including new Nd- and Sr-isotope constraints), and key field relationships across the region, in addition to a new U–Pb zircon age for a pegmatitic gabbro from the Tyrone Plutonic Group. These new data suggest that the c. 484–479 Ma Tyrone Plutonic Group was emplaced relatively late in the Grampian orogeny at c. 470 Ma, coeval with the accretion of the Tyrone arc (= Tyrone Volcanic Group; see Cooper et al. 2011), and is therefore broadly equivalent to the Annieoquotsch Ophiolite Belt of Newfoundland. The relations between the accretion of oceanic rocks and sillimanite-grade metamorphism in the underlying Tyrone Central Inlier will be discussed.

Field relationships

The Tyrone Plutonic Group is exposed across c. 95 km² of counties Tyrone and Londonderry, Northern Ireland. It crops out predominantly SE of the Tyrone Central Inlier, and to a lesser extent to the NW around Davagh Forest in faulted contact with the Tyrone Volcanic Group (Fig. 2). The Tyrone Plutonic Group consists mainly of variably tectonized and metamorphosed, layered, isotropic and pegmatitic gabbros, sheeted dolerite dykes and rare pillow lavas, which were thrust over the Tyrone Central Inlier during the Middle Ordovician (Hutton et al. 1985; Cooper & Mitchell 2004; Fig. 2). Primary mineral assemblages in the Tyrone Plutonic Group have been altered to epidote-ambibolite metamorphic assemblages (Merriman & Hards 2000). Mafic minerals have been replaced by hornblende, epidote, actinolite and/or chlorite, with feldspars variably sericitized. Groundmass often comprises a mixture of quartz, amphibole, actinolite, chlorite and epidote, as well as less abundant zircon, titane, sercite, biotite, and locally carbonate. Although the Tyrone Plutonic Group is tectonically dissected and poorly exposed, several key localities preserve a relatively complete upper crustal ophiolite sequence (Hutton et al. 1985). The following zones have been recognized (adapted after GSNI 1979; Hutton et al. 1985).

Layered and isotropic gabbros

Layered and isotropic gabbros form the majority of the Tyrone Plutonic Group and are best exposed at Scalp Hill and eastwards through Cregganconroe and Craigagnagore (Fig. 2). Olivine gabbros at Scalp Hill display cumulate layering, locally differentiated into compositionally distinct bands (centimetre to metre scale) (Cobbing 1969; GSNI 1979). Locally gabbro may be deformed to hornblende schist, with schistosity parallel to mineral layering in surrounding rocks (Cooper & Mitchell 2004). Cooper et al. (2011) reported a
U–Pb zircon age of 479.6±1.1 Ma for layered gabbro from Scalp Hill. Layered magnetite gabbro is common around Scalp and immediately NW of the Craigballyharky Complex (GSNI 1979).

Layered and isotropic gabbros at several localities appear to be younger than an early suite of dolerites (‘Early Dolerites and Gabbros’ of BGS 1986). At Craignagore, a central gabbro intrudes early, fine- to medium-grained amphibolite-facies dolerite (Angus 1970). Exposures of dolerite surrounding the gabbro are generally foliated or schistose amphibolites; with a finely crystalline relic of pyroxene-hornfels exposed at one locality (Angus 1970). The gabbro is largely uniform and porphyritic adjacent to its southern contact, and is itself cut by a later series of dolerite dykes (equivalent to the ‘Ophitic Dolerites of Carrickmore’ of BGS 1986).

**Transition zone**

At Black Rock (Fig. 2), coarse-grained hornblende gabbro intrudes, and contains xenoliths of, an early formed suite of dolerite (the ‘Early Dolerites and Gabbros’ of BGS 1986). This sequence is in turn intruded by younger basalt and dolerite dykes of 1–2 m width (Cooper & Mitchell 2004; Fig. 3a and b). Early basaltic and dolerite dykes are deformed, locally schistose and extensively altered with fine stringers of epidote. Gabbro is extremely coarse grained, ranging from equigranular in nature to pegmatitic. Irregular veins of pegmatitic gabbro contain large hornblende and plagioclase crystals often exceeding 2 cm in length (rarely >8 cm). The youngest suite of basaltic and doleritic dykes at Black Rock are relatively undeformed and less extensively altered. Porphyritic varieties contain 1–2 mm rounded and angular laths of plagioclase in a fine-grained, ophitic or intergranular matrix.

At Oritor (Fig. 2), dolerite dykes intrude gabbro, which contain xenoliths of an earlier foliated dolerite. Dolerite dykes typically trend NW–SE and according to Hartley (1933) can be distinguished from Palaeogene olivine-bearing dykes by their composition and state of alteration. At Slaghtfreeden (Fig. 2), isotropic and pegmatitic gabbro, microgabbro and dolerite also contain xenoliths of foliated basalt. These are intruded by, and present as xenoliths in, late intrusive rocks of quartz and hornblende porphyritic diorite (Fig. 3c). Late ophitic dolerite dykes are also present at Carrickmore, Cregganconnroe and Craignagore (Fig. 2), which cut olivine gabbro and/or poikiloblastic hornblende gabbro.

**Sheeted dykes**

Although the presence of ophitic dolerite at Carrickmore was recognized by Hartley (1933), it was Hutton et al. (1985) who first reported the presence of parallel sheeted dolerite dykes in Carrickmore Quarry (Fig. 2). The sheeted dykes typically average 1 m in thickness, intrude one another forming two-sided chilled margins and more commonly one-sided chilled margins, and can locally constitute 100% of the exposure (Hutton et al. 1985). Dolerite at Carrickmore appears aphanitic in hand specimen, although it may be either intergranular or ophitic in thin section. In Craigballyharky Quarry, dolerite dykes display rare chilled margins and are intruded by relatively undeformed plagiogranite and aplite (Fig. 3d).

**Pillow basalts and volcaniclastic rocks**

Pillow lavas are scarce within the Tyrone Plutonic Group, and are best exposed as a series of roof-pendants within the Craigballyharky complex (Cobbings et al. 1965). Pillow structures at Craigballyharky typically range between 30 and 75 cm in diameter (Fig. 3e). These lavas are aphanitic, subalkaline, tholeiitic, large ion lithophile element (LILE) and LREE depleted and of suprasubduction affinity (Draut et al. 2009; Cooper et al. 2011, see geochemistry). Intermediate and basic lavas have also been reported to occur at Scalp and Oritor (Hartley 1933), with amygdaloidal lavas present.
SW of Scalp Hill. At Slaghtfreeden, Hartley (1933) noted a sheet of gabbro intruding lavas overlain by coarse breccias and tuffs. This sequence was subsequently intruded by a dolerite dyke that contains xenocrysts of hornblende derived from the gabbro.

Craigballyharky complex

The Craigballyharky complex (Cobbing et al. 1965; GSNI 1979) is exposed across c. 3.5 km² (Fig. 2) and is composed of three major units: an intrusion of tonalite representing the summit of Craigballyharky (472 ± 2–4 Ma of Hutton et al. 1985; 470.3 ± 1.9 Ma of Cooper et al. 2011), an intrusion of biotite-granodiorite representing the summit of Craigbardahessiagh (464.9 ± 1.5 Ma of Cooper et al. 2011), and quartz-diorite (see Angus 1962, 1977). A series of roof pendants exposed across the complex include siliceous ironstone possibly derived from the Tyrone Volcanic Group, and isotropic gabbros, dolerites and pillow lavas from the Tyrone Plutonic Group (Cobbing et al. 1965). Siliceous ironstone xenoliths have been recorded in both the Craigbardahessiagh granodiorite and Craigballyharky tonalite (GSNI 1979). Together, these roof pendants, coupled with xenocrystic Proterozoic zircons, imply that both the Tyrone Volcanic Group and Tyrone Plutonic Group were in their present structural position above the Tyrone Central Inlier prior to c. 470 Ma (Cooper et al. 2011). Occurrences of agglomerate, limestone and silicified metasedimentary rocks have also been reported (Cobbing et al. 1965; GSNI 1979), although were not observed during recent fieldwork.

Quartz-diorite is widely regarded to be hybrid in origin (Angus 1962, 1977), produced by magma mixing and mingling between arc-related gabbro and c. 470 Ma tonalite at Craigballyharky (Hutton et al. 1985; Cooper et al. 2011). Although recent dating reported an age of 493 ± 2 Ma for Craigballyharky gabbro (Draut et al. 2009), Cooper et al. (2011) presented a recalculated mean $^{206}\text{Pb}^{238}\text{U}$ age of 473.2 ± 1.6 Ma for this unit, significantly younger and in agreement with field relations and its relatively unaltered and undeformed nature. Consequently, the Craigballyharky gabbro is attributed to the younger c. 470–464 Ma arc-related intrusive suite (see below), consistent with its LILE- and LREE-enriched geochemical characteristics (Draut et al. 2009, fig. 5; Cooper et al. 2011). Late arc-related gabbro also intrudes the c. 475–469 Ma Tyrone Volcanic Group at Beaghbeg and Mweenascallagh (Fig. 2), although the latter is of enriched mid-ocean ridge basalt (E-MORB) affinity (Hollis et al. 2012). At Craigballyharky, magma mixing and mingling within a hybrid quartz-diorite is seen in outcrop where large quartz ocelli are observed to have migrated from the tonalite into gabbro. Contacts are typically diffuse and irregular, though may locally be sharp (Fig. 3f).

Arc-related intrusive suite

The arc-related intrusive suite includes a series of high-level plutons, sills and dykes of various compositions, which intrude all levels of the Tyrone Igneous Complex (Fig. 2). Large intrusions of diorite, granodiorite, tonalite, biotite- and hornblende-bearing granite, and quartz ± feldspar porphyry are the most frequent; although minor occurrences of arc-related gabbro and dolerite also occur (Hollis et al. 2012). Field relationships and published U–Pb geochronology (Cooper et al. 2011) are consistent with the intrusions being significantly younger than the Tyrone Plutonic Group (c. 470–464 Ma). For example, diorite at Lough Lily (Fig. 2) contains angular xenoliths of ophiolite-derived dolerite and intrudes the latter as veins (Hartley 1933). At Scalp, coarsely crystalline, pink and grey hornblende-rich tonalite (equivalent to the Golan Burn tonalite of Cooper et al. 2011: 469.9 ± 2.9 Ma) contains xenoliths of gabbro that show all stages of assimilation and the development of hybrid granite (GSNI 1979). At Black
Rock, xenoliths of amphibolite-facies gabbro are present within LREE-enriched arc-related quartz ± biotite ± hornblende porphyry. Diorite at Crooked Bridge displays a magma mixing–milling relationship with hornblende granite and has produced an age of 469.58 ± 0.77 Ma (see Hollis et al. 2013).

Tremoge Glen
Medium- to coarse-grained and pale grey to pink granite exposed at Tremoge Glen is unusual within the Tyrone Igneous Complex as it is extensively altered, intensely sheared and muscovite-bearing. Geological mapping reveals that the granite intrudes gabbros of the Tyrone Plutonic Group and is itself intruded by NE–SW- and NW–SE-trending late Fe–Ti-enriched basaltic or doleritic dykes with ophitic textures (GSNI 1979, Fig. 2). The Tremoge Glen intrusion occurs as a NE–SW-oriented wedge of granite bound on its eastern side by the Tempo–Sixmilecross Fault (Fig. 2). These dykes appear to be related to the younger c. 475–469 Ma Tyrone Volcanic Group (see below).

Ophiolite contact: Blaeberry Rock
A high-strain zone of mylonitic metamorphosed igneous rocks east of Davagh Forest was discovered at the mapped contact between the Tyrone Central Inlier and Tyrone Plutonic Group (Fig. 2). The exposure, known locally as Blaeberry Rock, consists of a 7 m × 6 m × 3 m block and several smaller boulders (Fig. 4a). The main exposure comprises centimetre- to decimetre-sized blocks of amphibolite-facies gabbroic to doleritic material within an intimate mixture of millimetre- to centimetre-scale banded and isoclinally folded synkinematic tonalitic to granitic material, amphibolite and possible Dalradian metasedimentary rocks (Fig. 4b–e). Nearby exposures include smaller angular blocks of gabbro and dolerite that display preserved chilled margins and patchy outcrops of quartzfeldspathic paragneisses of the Tyrone Central Inlier invaded by tonalitic intrusive sheets, leucosomes and pegmatite. Younger moderately deformed tonalitic to granitic veins cut the sheared rocks and are themselves often folded and boudinaged.

Preferential localization of strain appears to be confined to the intrusive sheets, with gabbroic inclusions relatively undeformed except for some alignment of amphibole crystals. Large amphibole crystals up to 3.5 cm in length occur within the melt network and appear to be derived from brecciated bodies of gabbro cut by thin veins. These crystals, along with minor drag folds, show evidence for sinistral shearing (Fig. 4f). Paler grey andesitic (?) clasts (c. 10 cm × 20 cm) also contain a well-developed mineral stretching lineation. Narrow shear zones and late veins of epidote cut the exposure.

Gabbroic and doleritic blocks exposed within the Blaeberry Rock contact are petrologically and geochemically (see below) similar to those from the Tyrone Plutonic Group. These ophiolite-derived lithologies have experienced amphibolite-facies metamorphism and are composed of actinolite (after pyroxene) and plagioclase replaced by white mica, chlorite and epidote. Synkinematic and late tonalitic to granitic veins are composed of quartz, orthoclase, sericitized labradorite with minor muscovite, trace biotite and accessory phases (fluorapatite and titanite). Plagioclase may be internally altered to chloride, epidote and muscovite.

Tellus airborne geophysics
During 2005–2006 the Tellus airborne geophysical survey, part of the Tellus Project (see GSNI 2007), was flown across the entirety of Northern Ireland. Magnetic, radiometric and electromagnetic (EM) data were acquired. Further details on survey specification and geophysical data processing have been provided by Gunn et al. (2008). Interpreted EM and total magnetic intensity (analytic signal) maps over the Tyrone Plutonic Group are shown in Figure 5. Lithologies of the Tyrone Plutonic Group are clearly distinguishable from the non-magnetic units of the Tyrone Central Inlier. Faulted contacts between the Tyrone Plutonic Group, Tyrone Volcanic Group, Tyrone Central Inlier and post-Ordovician cover sequences are best discriminated by EM imagery (Fig. 5a), with boundaries corresponding well to previous mapping (GSNI 1979, 1995). The Tyrone Plutonic Group is characterized by short-wavelength magnetic anomalies (Gunn et al. 2008), with

![Image of Field photographs and petrography from Blaeberry Rock and the Tyrone Plutonic Group. (a) Main Blaeberry Rock exposure. (b) Blocks of amphibolite facies gabbro (right) and andesite (?) (left). (c) Angular block of amphibolite-facies basalt in granitic-tonalitic intrusive material. (d) Late-stage granitic-tonalitic veins crosscutting main fabrics. (e) Isoclinally folded tonalitic to granitic melt and amphibolite. (f) Sinistrally rotated amphibole crystals in melt network.](Fig. 4)
magnetic highs corresponding to areas of magnetite-bearing dolerite and gabbro. Magnetic imagery reveals the Tyrone Plutonic Group to be dissected into thin slices by a series of NE–SW-oriented Caledonian faults (Fig. 5b). Magnetic lows within the Tyrone Plutonic Group are associated with deep-seated granitic plutons of the c. 470–464 Ma arc-related intrusive suite (e.g. Pomeroy granite) and demagnetized zones associated with faulting (e.g. Tempo–Sixmilecross; Fig. 2). Tonalitic and granodioritic plutons at Craigballyharky and Craigbardahessiagh may represent thin laccoliths underlain by highly magnetic material. Along the eastern side of the Tyrone Central Inlier where gneissose psammites and semipelites crop out, highly magnetic lithologies appear to be present. Although it is possible that a portion of the Tyrone Plutonic Group structurally underlies the Tyrone Central Inlier, these magnetic rocks may also represent mafic volcanic rocks associated with the rifting of the Tyrone Central Inlier from the Laurentian margin or buried basement material.

Whole-rock geochemistry

Sampling and analytical techniques

Eighteen samples were collected from key localities across the Tyrone Plutonic Group and Blueberry Rock for whole-rock geochemical analysis. Major elements and trace elements were determined for powdered whole-rock samples on fused glass beads and powder pellets by X-ray fluorescence (XRF) at the University of Southampton. REE (plus Nb, Hf, Ta, Th, U) were determined by inductively coupled plasma mass spectrometry (ICP-MS) on the same samples using HF–HNO₃ digest. Further details have been provided by Hollis et al. (2012). Geochemical analyses of Draut et al. (2009) and Cooper et al. (2011) are also included.

Two samples were analysed at Southampton for Sr isotopes. Strontium was separated using c. 80 µl columns containing Sr-Spec resin and elution with 3M HNO₃ to remove interfering elements. The purified Sr samples were collected with water and loaded onto a single Ta filament using a Ta activator solution. Samples were analysed by thermal ionization mass spectrometry (TIMS) using a multi-dynamic peak jumping routine on a VG Micromass Sector 54 system at the University of Southampton. Rb and Sr concentrations were obtained by ICP-MS. The ratios were corrected using an exponential fractionation correction relative to ⁸⁶Sr/⁸⁸Sr of 0.1194. NIST-987 was run and its long-term average ⁸⁷Sr/⁸⁶Sr value was 0.710243 ± 18 (2SD, n = 93). An age correction was performed to account for radioactive decay and ingrowth of ⁸⁷Sr; values for that time are reported as ⁸⁷Sr/⁸⁶Sr. Modern CHUR was taken to be 0.7045 and 0.0827 for ⁸⁷Sr/⁸⁶Sr and ⁸⁷Rb/⁸⁶Sr respectively. The decay constant of ⁸⁷Sr is 1.42 × 10⁻¹¹ a⁻¹.

Four samples were analysed for Sm–Nd and Rb–Sr by isotope dilution (ID)-TIMS at University College Dublin (UCD). Samples were weighed and spiked prior to digestion in HF–HNO₃ in Teflon bombs at temperatures up to 180°C, following initial treatment with cold, followed by hot, HCl, to remove any carbonates present. Standard ion chromatography separation procedures used Eichrom ion-specific resins (Sr Resin for Sr, TRU Resin SPS for the REE as nitrates) and a Biorad cation exchange resin (AG 50W-X12 for Rb as chloride). Sm and Nd were separated from one another as chlorides using Eichrom Ln Resin SPS. Sm, Nd and Sr isotopic analyses were carried out by multiple collector (MC)-TIMS on a ThermoScientific Triton system. Analyses were carried out in static multicollection mode, with switching of amplifiers between Faraday collectors to correct for differential amplifier responses. All Nd peaks were measured, along with ¹⁴⁹Sm and ¹⁴⁷Sm to correct for isobaric interference from Sm. In practice, this correction was negligible (e.g. <2 ppm on ¹⁴³Nd/¹⁴⁴Nd ratios). The La Jolla standard yielded a value of ¹⁴⁳Nd/¹⁴⁴Nd = 0.511842 ± 5 (2SD, n = 24) during the period of this work. The uncertainty in ¹⁴⁷Sm/¹⁴⁴Nd is estimated to be 0.1%. Sr aliquots were measured on single Ta filaments using a Ta activator solution. At UCD, the SRM987 standard yielded a value of ⁸⁷Sr/⁸⁶Sr = 0.710247 ± 11 (2SD, n = 25), indistinguishable from that obtained at Southampton. ⁸⁷Rb/⁸⁶Sr ratios were measured by MC-ICP-MS on a ThermoScientific Neptune system on solutions doped with zirconium and corrected for mass bias using the meas-
ured $^{90}Zr/^{91}Zr$ ratio, assuming a natural $^{90}Zr/^{91}Zr$ ratio of 4.588, following Nebel et al. (2005).

**Element mobility**

Various studies have demonstrated that most of the major elements (e.g. SiO$_2$, Na$_2$O, K$_2$O, CaO, MgO) and the low field strength elements (LFSE; Cs, Rb, Ba, Sr, except Th) are mobile during metamorphism and hydrothermal alteration (see references given by Dilek & Furnes 2011). As primary mineral assemblages within the Tyrone Plutonic Group have been metamorphosed to amphibolite-facies conditions only elements demonstrated to be immobile are used to elucidate petrogenesis and tectonic affinities. Comparison of the major and trace element data from the Tyrone Plutonic Group with $Zr$ (assumed immobile) confirms this mobility, with considerable scatter for Na$_2$O, K$_2$O, Sr and Ba in particular (Hollis 2013). TiO$_2$, MgO, P$_2$O$_5$, Th, Nb, V, Cr, Co, Sc, Y, U and the REE appear to have remained immobile. SiO$_2$ appears to have remained relatively immobile, apart from minor silicification in some samples. Al$_2$O$_3$/Na$_2$O ratios vary between 2.3 and 23.9 (Fig. 6a). Sampled lithologies show carbonate–chlorite–pyrite index (CCPI; see Large et al. 2001) values typical of mafic volcanic rocks (41.1–95.4, most >80, Fig. 6b) and Hashimoto alteration index (AI; Ishikawa et al. 1976) values (22.6–5.15) typical of weakly altered rocks. Sericite index values (Saeki & Date 1980; K$_2$O/(K$_2$O + Na$_2$O)) vary between 0.07 and 0.49. Analyses show a weak negative correlation between Na$_2$O and loss on ignition (LOI), suggesting that lower Na$_2$O contents are due to losses associated with alteration (e.g. sericitization).

**Petrochemistry**

**Tyrone Plutonic Group.** Immobile element ratios within the Tyrone Plutonic Group are predominantly subalkaline (Nb/Yb <0.06) and tholeiitic (Zr/Y 0.7–3.8) (Fig. 6c). On multi-element variation diagrams sampled lithologies display slight LREE depletion (La/Sm 0.6–1.2, Fig. 7a) and flat heavy REE (HREE) profiles (Gd/Lu 0.7–3.8) (Fig. 6c). On multi-element variation diagrams (La/Sm to 7.2, La/Yb 4.5–6.8) ratios and ThCN values (154.2–297.0), and pronounced negative Nb anomalies (0.11–0.48) on multi-element variation diagrams (Fig. 7d). These samples geochemically resemble the c. 470–465 Ma tonalites of the Tyrone Igneous Complex (see Cooper et al. 2011) which are characterized by high Zr/TiO$_2$ (154.5–583.8), Zr/Y (5.6–10.5) and La/Sm (4.5–6.8) ratios and Th$_{geo}$ values (154.2–297.0), and pronounced negative Nb anomalies (0.17–0.27, Fig. 7c) (values from Cooper et al. 2011; Hollis et al. 2012; Hollis 2013). Sampled Dalradian-affinity metasedimentary rocks of the Tyrone Central Inlier from Corvanaghan Quarry and Fir Mountain Quarry (adjacent to Blaeberry Rock: Fig. 2) similarly have steep REE profiles (La/Sm to 7.2, La/Yb to 28.7) and can display pronounced negative Nb anomalies (often owing to the presence of melt), but have significantly higher Zr, Rb, Ba, Th$_{geo}$, and REE$_{total}$ concentrations, and higher Ti/V and Nb/Y ratios (to 0.9) (Hollis 2013).

**Tremoge Glen.** S-type muscovite granite from Tremoge Glen shows calc-alkaline characteristics (Zr/Y 13.3) is strongly LREE enriched relative to the HREE (La/Yb 18.2), and strongly LILE enriched (Th$_{geo}$ c. 325). Samples analysed have high K$_2$O/(K$_2$O + Na$_2$O) ratios of c. 0.6 and are strongly peraluminous (after Shand 1943). The S-type geochemical characteristics suggest that it may have been intruded shortly after the emplacement of the Tyrone Plutonic Group from the melting of metasedimentary material of the Tyrone Central Inlier. This is consistent with its high Th$_{geo}$ and LREE enrichment.
A single sample (MRC129) was analysed from the basaltic–doleritic dykes at Tremoge Glen that cut the S-type muscovite granite. This sample is Fe–Ti enriched (Fe$_2$O$_3$T 15.4, TiO$_2$ 2.7), lacks a prominent negative Nb anomaly characteristic of island-arc tholeiites ( Nb anomaly 0.82) and is of ‘within-plate’ or E-MORB affinity (e.g. Wood 1980; Fig. 6b). MRC129 is subalkaline, calc-alkalic, and LILE and LREE enriched (Nb/Y 0.55, Zr/Y 7.2, La/Yb 4.7, Th$_{CN}$ 107.83). Low Cr (c. 50 ppm) and Ni (c. 14 ppm) contents confirm the relatively evolved nature of this sample. High LOI (7.06 wt%), CCPI (87.4), Si (0.31) and Al

(50.9) values are consistent with extensive alteration. The small negative Nb anomaly is indicative of a weak subduction signature or may reflect minor crustal contamination.

**Mineral chemistry**

Electron microprobe analyses were completed at the Natural History Museum, London, to determine mineral compositions and establish **P–T** conditions from the Tyrone Plutonic Group and its contact with the underlying Tyrone Central Inlier. Three samples were analysed: one from pegmatitic gabbro from Black Rock within the ‘transition zone’ of the Tyrone Plutonic Group (SPH34), and two from Blaeberry Rock (SPH210, gabbroic clast; SPH215, tonalitic material in the contact). SPH34 from Black Rock is dominated by plagioclase and amphibole. Plagioclase is extensively altered along grain boundaries to secondary minerals: epidote, carbonate, white mica, chlorite and...
residual albite. Amphibole occurs as large anhedral grains of hornblende intergrown with actinolite. Sample SPH210 (gabbroic clast) is similar to SPH34 (collected from Black Rock) and contains amphibole closely associated with epidote and muscovite, and is believed to represent ophiolite-derived material based on mineral chemical and whole-rock geochemistry. In contrast, sample SPH215 comprises a mixture of hornblende, quartz, orthoclase, plagioclase, chlorite, epidote and accessory phases (titanite and fluorapatite) from tonalitic layers in the contact. Spot analyses were performed on a Cameca SX-50 electron microprobe equipped with a wavelength-dispersive system, and were conducted at 20keV and 20nA. Counting times ranged from 10 to 50 s for spot analysis.

Amphiboles analysed from SPH34 (Black Rock) and SPH210 (Blueberry Rock clast) chemically classify as tremolitic actinolite and magnesio-hornblende, whereas those analysed from synkinematic tonalitic intrusive sheets at Blueberry Rock (SPH215) classify as magnesio-hornblende with significantly lower Mg/(Mg + Fe) ratios and Si contents, and higher Ti, Fe and Mn concentrations (Fig. 8a). Low TiO$_2$ (0–0.45 wt%) and Al$_2$O$_3$ (1.74–4.79 wt%) in amphiboles from Black Rock (SPH34) and from the ophiolite-derived clast at Blueberry Rock (SPH210) plot predominantly just off the geothermometer of Ernst & Liu (1998), producing temperature estimates of c. 500°C. Spot analyses from SPH215 amphiboles (tonalite) contain higher TiO$_2$ (0.35–0.65 wt%) and Al$_2$O$_3$ (6.51–8.54 wt%) indicating slightly higher temperatures of 525–610°C. Hammarstrom & Zen (1986) first proposed that solids pressures of intermediate calc-alkaline plutons can be estimated from the Al content of hornblende. Rocks should be near-solidus with the magmatic assemblage hornblende + biotite + plagioclase + quartz + sanidine + titanite + magnetite + ilmenite ± epidote. The Al-in-hornblende geobarometer experimentally calibrated by Schmidt (1992) produces pressure estimates of c. (2.3–4.0) ± 0.6 kbar for tonalite from Blackberry Rock.

Episodes from the Tyrone Plutonic Group typically have lower Fe and Ca, and higher Al, contents than those from Black Berry Rock. Samples SPH210 and SPH215 are chemically similar, except for higher Si content in SPH215.

Alkali feldspar compositions from Blueberry Rock sample SPH215 are restricted to a relatively narrow range between Or$_{16.1}$Ab$_{6.1}$An$_{1.3}$ and Or$_{16.7}$Ab$_{3.7}$An$_{0.6}$ (Fig. 8b). BaO and C$_6$E$_7$O$_3$ concentrations range between 0.46 and 1.4 wt% and 0.17 and 0.53 wt% respectively. FeO$_2$ concentrations vary between 0.03 and 0.43 wt%. The composition of plagioclase from SPH215 varies from andesine to labradorite (Or$_{53.7}$Ab$_{25.3}$An$_{21.0}$ to Or$_{58.3}$Ab$_{27.8}$An$_{14.9}$) (Fig. 8b). FeO$_2$ concentrations range between 0.11 and 0.17 wt%.

Chlorites from the Tyrone Plutonic Group are relatively Mg-rich and classify as pycnochlorite (SPH34), whereas those analysed from Blueberry Rock (SPH215) classify as both pycnochlorite and magnesio-hornblende. Pegmatitic gabbro from Black Rock is in agreement with its more primitive geochemical characteristics. Pegmatitic gabbro from Black Rock is more LILE, LREE and HREE depleted than layered gabbro from Scalp Laboratory (NIGL). Zircons were isolated using conventional mineral separation techniques. Prior to ID-TIMS analyses zircons were subject to a modified version of the chemical abrasion technique (Mattinson 2005). Methods are identical to those reported by Hollis et al. (2012). Errors for U–Pb dates are reported in the following format: ±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 238U decay constant errors of Jaffey et al. (1971).

Results

Six fractions (single grains) were analysed from the Black Rock sample MRC344 (pegmatitic gabbro). All six analyses are concordant when their systematic $\lambda^{238}$U and $\lambda^{235}$U decay constant errors are considered, with five analyses forming a coherent single population yielding a weighted mean $^{206}$Pb/$^{238}$U date of 483.68 ± 0.36(0.60)[0.81] Ma (MSWD = 1.8) (Fig. 9). We interpret this as being the best estimate for the age of this sample. This age is slightly older than that produced for layered gabbro from Scalp (479.6 ± 1.1 Ma: Cooper et al. 2011). No inherited 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 Plutonic Group

The Tyrone Plutonic Group is composed primarily of layered, isotropic and pegmatitic gabbros, sheeted dolerite dykes and rare pillow lavas (Angus 1970; Hutton et al. 1985; Cooper & Mitchell 2004). Geochemical evidence and field relations presented herein are consistent with the Hutton et al. (1985) interpretation that the Tyrone Plutonic Group represents the upper portions of a tectonically dissected ophiolite that was accreted to the Laurentian margin during the Grampian orogeny. Multi-element profiles and Nd-isotope compositions are consistent for basalts generated at an oceanic spreading centre above a subduction zone (Draut et al. 2009). The new U–Pb zircon geochronology presented here (483.68 ± 0.81 Ma) is similar to that of Cooper et al. (2011: 479.6 ± 1.1 Ma) constraining the formation of the Tyrone Plutonic Group to c. 484–479 Ma. The slightly older age presented here for pegmatitic gabbro from Black Rock is in agreement with its more primitive geochemical characteristics. Pegmatitic gabbro from Black Rock is more LILE, LREE and HREE depleted than layered gabbro from Scalp. It is entirely possible that multiple slices of Iapetan ocean floor of slightly varying age occur within the Tyrone Plutonic Group, as the ophiolite is tectonically dissected.

Field relationships across the ophiolite are consistent with several phases of intrusive activity typical of oceanic spreading centres. Poor preservation of the sheeted dyke complex is typical of suprasubduction-zone ophiolites in general, with large well-developed complexes requiring an appropriate balance between spreading and magma supply rates (see references given by Robinson et al. 2008). In contrast to fast-spreading mid-ocean ridges, where these conditions are maintained, suprasubduction-zone spreading rates are not directly controlled by magma supply but are ultimately dependent on slab rollback, which is related to the angle of subduction and the rate of convergence (Robinson et al. 2008). The absence of a thick ultramafic section within the Tyrone Plutonic Group may be explained by post-tectonic excision or more probably by delamination and subduction of
the lower crust during ophiolite emplacement (e.g. Annieopsquotch Ophiolite Belt; Zagorevski et al. 2009). Limited occurrences of ultramafic material may be present around Davagh Forest, where ‘basic and ultrabasic rocks, often pyroxenitic’ have been described (see Gunn et al. 2008), with closely associated elevated platinum group element, Cr and Ni soil anomalies.

Fe–Ti-enriched basaltic dykes that intrude S-type muscovite granite at Tremoge Glen have a within-plate affinity and lack a pronounced island-arc geochemical signature. High LILE and LREE enrichment, coupled with low Cr and Ni, is indicative of their more evolved nature compared with other samples from the Tyrone Plutonic Group. Fe–Ti-enriched basals are defined by >12 wt% FeO, and >2 wt% TiO₂ (e.g. Sinton et al. 1983), and typically display lower concentrations of MgO, CaO and Al₂O₃ than normal MORB. Fe–Ti basals are common in propagating rifts, and occur at several stratigraphic horizons in the structurally overlying c. 475–469 Ma Tyrone Volcanic Group, a peri-Laurussian island arc–backarc (Hollis et al. 2012). Fe–Ti basals of E-MORB to OIB affinity with slight negative Nb anomalies, which are geochemically identical, also occur in the upper Tyrone Volcanic Group as the c. 469 Ma Mountfield Basalts of the Broughderg Formation (see Hollis et al. 2012, 2013). U–Pb zircon TIMS geochronology has also directly dated a geochemically similar unit from Sruhanleanantawey Burn (Fig. 2) to 469.36 ± 0.34 Ma (Hollis et al. 2013). We suggest that the Tremoge Glen Fe–Ti-enriched dykes were emplaced at c. 469 Ma, and may be part of an extensive swarm that fed the Mountfield Basalts (see Hollis et al. 2013).

Incorporation of Palaeoproterozoic and Mesoproterozoic xenocrystic zircons (c. 1015 and 2100 Ma) into the Scalp layered gabbros (Cooper et al. 2011) suggests that the Tyrone Plutonic Group formed above a north-dipping subduction zone by the propagation of a spreading centre into a microcontinental block (= Tyrone Central Inlier; see below) (Fig. 10). A similar tectonic scenario was presented for the formation of the c. 480 Ma Annieopsquotch Ophiolite Belt of Newfoundland (Zagorevski et al. 2006; also see Cutts et al. 2012, and the following section). The presence of propagating rifts is consistent with the occurrence of Fe–Ti–P-enriched ‘within-plate’ basalt across the Tyrone Igneous Complex from at least c. 475 Ma to 469 Ma, minor continental contamination in the Tyrone Plutonic Group according to Nd- and Sr-isotope systematics, and zircon inheritance at Scalp. This tectonic scenario may also explain the strong LILE, LREE and negative εNd values in the c. 475–469 Ma Tyrone Volcanic Group (Hollis et al. 2012). The Tyrone Volcanic Group is believed to have formed above a north-dipping subduction zone immediately outboard of the Tyrone Central Inlier (Hollis et al. 2012). These geochemical characteristics may be explained if the arc was in part founded upon a fragment of microcontinental crust that was rifted off the Tyrone Central Inlier during the formation of the Tyrone Plutonic Group (Fig. 10; Hollis et al. 2013). A similar situation has been envisaged for the evolution of the analogous Buchans–Robert’s Arm arc of Newfoundland (Zagorevski et al. 2006, 2012). In situ Hf isotope analysis of zircon rims from c. 470 Ma granitoid rocks that cut the Tyrone Central Inlier paragneisses yield negative εHf values of c. −39 (Flowerdew et al. 2009). This isotopic signature requires an Archaean source, suggesting that rocks similar to the Lewisian Complex of Scotland occur at depth beneath the Tyrone Central Inlier (Flowerdew et al. 2009).

Accretion to the Tyrone Central Inlier

The Tyrone Central Inlier is composed of a thick sequence of psammite and semi-pelitic paragneisses (Hartley 1933) exposed within the central regions of the Tyrone Igneous Complex (Fig. 2), and is cut by a variety of acidic intrusive rocks. A prograde assemblage of biotite + plagioclase + sillimanite + quartz ± muscovite ± garnet is observed in pelitic lithologies (Chew et al. 2010), with cordierite locally observed (Hartley 1933). The high-grade nature of the Tyrone Central Inlier (c. 670 ± 113 Ma, 6.8 ± 1.7 kbar; Chew et al. 2008) and its position SE of the Fair Head–Clew Bay Line (Fig. 1) has led recent workers (e.g. Chew et al. 2008, 2010; Flowerdew et al. 2009; Cooper et al. 2011) to suggest that the Tyrone Central Inlier may represent part of an outboard segment of Laurentia, which detached as a microcontinent during the opening of Iapetus (c. 570 Ma?) and subsequently reattached during the Grampian orogeny (c. 470 Ma). Geochronology of syntectonic leucosomes (207Pb–206Pb zircon age of 468 ± 12 Ma; main fabric 40Ar–39Ar biotite cooling age of 468 ± 11.4 Ma) and post-tectonic muscovite-bearing pegmatites (40Ar–39Ar step heating plateau ages of 466 and 468 ± 1 Ma) suggests a Grampian age (c. 475–465 Ma) for the deformation and metamorphism of the Tyrone Central Inlier (Chew et al. 2008).

Obduction of the Tyrone Plutonic Group onto the Tyrone Central Inlier must have occurred prior to the intrusion of the Craigballyharky tonalite (470.3 ± 1.9 Ma), which contains inherited Proterozoic zircons and roof pendants of ophiolitic and arc-related material (Cooper et al. 2011). All rocks of the arc-related intrusive suite are LILE and LREE enriched with strongly negative εNd values (to −11.8; Hollis et al. 2012, and unpublished data), implying that interaction with continental crust was an integral part of their petrogenesis (Draut et al. 2009). Xenocrystic zircons are consistent with derivation from the structurally underlying Tyrone Central Inlier (Cooper et al. 2011), although the source of the c. 2100 Ma inheritance remains elusive (Hutton et al. 1985; Cooper et al. 2011). Interestingly, plutons of the Notre Dame Arc in Newfoundland, built on an along-strike equivalent of the Tyrone Central Inlier, termed the Dashwoods block (see below), have also yielded xenocrystic components of Palaeoproterozoic age (e.g. upper intercept of 2090 ± 75 Ma; Whalen et al. 1987).

The muscovite granite that cuts layered gabbro at Tremoge Glen is unusual within the arc-related intrusive suite; its S-type
geochemical characteristics, high Th/Cs and LREE enrichment suggest that it may have been intruded shortly after the emplacement of the Tyrone Plutonic Group from the melting of under-thrust peri-Laurentian metasedimentary material (i.e. Tyrone Central Inlier). Attempts to date the Tremoge Glen muscovite granite using U–Pb zircon were not successful and produced large errors (Noble et al. 2004). Although apparently core-free zircons were picked, two analyses showed very significant inheritance, with upper intercepts of c. 1560 and 2351 Ma (Noble et al. 2004). A second attempt to date this unit is in progress.

Although the Tyrone Plutonic Group was emplaced between c. 479 and 470 Ma, the exact timing of this event has remained elusive. At Blaeberry Rock the presence of ophiolite-derived blocks in abundant synkinematic tonalitic to granitic material and amphibolite suggests that the Tyrone ophiolite may have been accreted to the Tyrone Central Inlier at the same time as the Tyrone Volcanic Group at c. 470 Ma. Tonalite intrusions are abundant throughout the Tyrone Igneous Complex and four occurrences have produced U–Pb zircon ages: 470.3±1.9 Ma at Craigallyharky (Cooper et al. 2011), 465.6±1.1 Ma from Laght Hill (Cooper et al. 2011; also 475±10 Ma, Draut et al. 2009), 469.9±2.9 Ma from Golan Burn (Cooper et al. 2011), and 469.29±0.33 Ma from Cashel Rock (Hollis et al. 2012). Emplacement at c. 470 Ma, synchronous with the Tyrone arc (= Tyrone Volcanic Group), may explain how the metamorphic conditions evident within the Tyrone Central Inlier (c. 470±113 °C, 6.8±1.7 kbar; Chew et al. 2008) were generated prior to c. 468 Ma. These conditions cannot have been solely the result of the obduction of the Tyrone Plutonic Group, as it is tectonically dissected and thin, and lacks an ultramafic section. The coeval emplacement of both the arc and the ophiolite would provide a >10–15 km thick, hot crustal sequence, enough to produce the required P–T conditions in the Tyrone Central Inlier.

Amphiboles from synkinematic tonalitic material within the Blaeberry contact (SPIH120; Fig. 8a) produced temperature estimates of 525–610 °C, slightly lower than (but within error of) those produced by Chew et al. (2008) from the Blaeberry Rock (SPIH1210) are again lower than those produced by Chew et al. (2008); however, Hartley (1933) noted that the presence of sillimanite in the Tyrone Central Inlier is restricted to its SE side. As the Tyrone Igneous Complex was emplaced from this direction, the higher temperatures and pressures from Corvanaghan Quarry may simply be restricted to that region, where the accreted succession was thickest. Sillimanite-bearing paragneisses are also preserved across the Notre Dame and Dashwoods subzones of the equivalent Newfoundland Appalachians associated with arc–ophiolite accretion (e.g. Brem et al. 2007; van Staal et al. 2007, 2009; Fig. 1b). In the Dashwoods subzone, large bodies and screens of variably migmatized sillimanite-bearing paragneisses are exposed (see van Staal et al. 2007). Lesser exposures further north in the Notre Dame subzone (e.g. as screens in the Hungry Mountain Complex; Waldron & van Staal 2001) are due to the level of denudation (van Staal et al. 2007).

Another possible fragment of microcontinental crust in the Irish Caledonides is the Slishwood Division (Flowerdew et al. 2005; Chew et al. 2010; Fig. 1a). This metasedimentary sequence is exposed in three inliers of NW Ireland (NE Ox Mountains, Lough Derg and Rosses Point) and is composed predominantly of migmatitic psammatic gneisses with minor pelites, semipelites, calc-silicates, metabasites and serpentinites (Sanders 1979; Flowerdew & Daly 2005; Daly 2009). All three inliers have been suggested on the basis of magnetic and gravity data to form one basement block, which acted as a rigid indenter during the Grampian orogeny (Fig. 1a; see references given by Daly 2009). The Grampian histories of the Slishwood Division and the Tyrone Central Inlier are very similar, both having undergone leucosome generation during orogenesis, and subsequently being intruded by pegmatites that cut the high-level fabrics (Flowerdew et al. 2005; Chew et al. 2008). The NE Ox Mountains Inlier was also intruded by several tonalite and granite bodies between c. 471 and 467 Ma (Flowerdew et al. 2005) with magmas contaminated by the host rocks. This is identical to the late Grampian evolution of the Tyrone Central Inlier (see Cooper et al. 2011). Final imbrication of the Slishwood Division with the Central Ox Mountains Dalradian Supergroup occurred during D3 regional thrusting (between c. 476 and 463 Ma; Flowerdew et al. 2005), equivalent in Country Tyrone to the emplacement of the Dalradian Supergroup above the Tyrone Igneous Complex and Tyrone Central Inlier (Omagh Thrust; Fig. 2).
Clear differences between the Slishwood Division and Tyro Central Inlier are primarily related to their pre-Grampian histories. These include the presence of calc-silicates, metabasites and serpentinites in the former (Daly 2009), although possible metabasites have been recognized in the Tyro Central Inlier during GSNI fieldwork. Metabasites in the Slishwood Division record pre-Grampian high-pressure granulite- and earlier eclogite-facies metamorphic events (Sanders et al. 1987; Flowerdew & Daly 2005) not observed within the Dalradian Supergroup or Tyro Central Inlier. Sm–Nd garnet–plagioclase whole-rock isochrons from the granulite-facies assemblages have yielded ages ranging between 605 ± 37 and 539 ± 11 Ma; with $P$–$T$ estimates of c. 15 kbar and 860°C (Sanders et al. 1987; Flowerdew & Daly 2005; see discussion by Daly 2009). Although this early history is pre-Grampian, Daly (2009) has suggested that the metamorphism cannot be much older, as U–Pb detrital zircon ages (Daly et al. 2004) demonstrate a post-Grenville age of deposition of the protolith, and a pre-tectonic metabasite body that preserves original gabbroic textures has produced a Sm–Nd mineral isochron age of 580 ± 36 Ma. This Sm–Nd age is consistent with magmatism related to the opening of the Iapetus Ocean between c. 570 and 535 Ma (Cawood et al. 2001). Detrital zircon analysis from the Slishwood Division has also revealed differences compared with the Tyro Central Inlier. A significant population between c. 2.5 and 2.7 Ga is present in the Appin, Argyll and Southern Highland groups of the Dalradian Supergroup (Cawood et al. 2003) and Tyro Central Inlier (Chew et al. 2008), but is absent in the Slishwood Division (Daly et al. 2004, cited by Flowerdew et al. 2005) and the Grampian Group of the Dalradian (Cawood et al. 2003). $T_{DM}$ model ages are also significantly younger in the Tyro Central Inlier than in the Slishwood Division (references in Chew et al. 2008).

A correlative of the Annieopsquotch Ophiolite Belt of Newfoundland?

Recent fieldwork, U–Pb zircon geochronology and geochemistry from across the Tyro Igneous Complex has highlighted the close similarities between (1) the Tyro Plutonic Group and the Annieopsquotch Ophiolite Belt of Newfoundland (Cooper et al. 2011), (2) the Tyro Volcanic Group and the Buchans and Robert’s Arm groups of central Newfoundland (Hollis et al. 2012), and (3) a late suite of c. 470–464 Ma calc-alkaline intrusive rocks and the second phase of the Notre Dame arc (van Staal et al. 2007), which also invade the Annieopsquotch Accretionary Tract (Lissenberg et al. 2005; Lissenberg & van Staal 2006). The work presented herein adds further weight to these correlations, indicating that the Tyro Igneous Complex represents the third stage of arc–ophiolite emplacement in the peri-Laurentian British and Irish Caledonides at c. 470 Ma, following the accretion of early c. 510–500 Ma oceanic tracts (Chew et al. 2010), and the Lough Nafooey arc at c. 480 Ma (see Hollis et al. 2012).

The Annieopsquotch Ophiolite Belt of central Newfoundland comprises several suprasubduction-zone ophiolite complexes (e.g. King George IV, Annieopsquotch, Star Lake), which formed during west-directed subduction outboard of the Dashwoods peri-Laurentian microcontinent (Dunning et al. 1987; Whalen et al. 1997; Lissenberg et al. 2005; Zagorevski et al. 2006). Two U–Pb zircon ages from a pegmatitic and medium-grained trondhjemite (481.4 ± 0.6/−1.9 and 477.5 ± 2.6/−2.0 Ma) constrain the age of the Annieopsquotch Ophiolite Belt to c. 481–478 Ma (Dunning & Krogh 1985). The Annieopsquotch Ophiolite Complex is the largest and most studied ophiolite within the belt, and consists of suprasubduction-zone affinity layered to isotopic gabbros, sheeted dykes and pillow basalts (Lissenberg et al. 2005). The lower gabbro zone contains enclaves of troctolite inferred to have formed from boninitic melts (Lissenberg et al. 2004). The youngest basalts are of MORB-type affinity and are cut by sheeted dykes with back-arc geochemical characteristics (Lissenberg et al. 2005). εNd values within the Annieopsquotch Ophiolite Belt range from +7.6 to +8.4 (Zagorevski et al. 2006). The ophiolite lacks an upper mantle section apart from rare occurrences of dunite and pyroxenite (Lissenberg & van Staal 2006).

The age of formation for the Tyro Plutonic Group between 484 and 479 Ma (including the new date of 483.68 ± 0.81 Ma for the pegmatitic gabbro at Black Rock), primitive εNd values ranging from +4.40 to +7.73 (Draut et al. 2009; Cooper et al. 2011), tholeiitic suprasubduction geochemical signatures, preserved ophiolite sequences, and development outboard of a possible microcontinental block (i.e. Tyro Central Inlier) support both a correlation with the Annieopsquotch Ophiolite Belt and formation at an oceanic spreading centre above a subduction zone (see Draut et al. 2009; Cooper et al. 2011). Xenocrystic Mesosproterozoic zircons present within the Tyro Plutonic Group are consistent with $T_{DM}$ ages of 1200–1800 Ma from felsic intrusive rocks of the Moretons Harbour Group (part of the Annieopsquotch Ophiolite Belt of Newfoundland; Cutts et al. 2012) indicating a significant amount of contamination from Mesoproterozoic or older continental crust.

Furthermore, the Lloyds River Fault Zone, which separates the Annieopsquotch Ophiolite Belt from the Dashwoods microcontinental block, bears a striking resemblance to Blaeberry Rock (Lissenberg & van Staal 2002). The Lloyds River Fault at its type locality is a complex shear zone having a central high-strain zone (mainly characterized by mafic and felsic tectonites), which is bounded by less-strained moderately foliated amphibolite and orthogneiss dissected by narrow shear zones (Lissenberg & van Staal 2002). The central high-strain zone is composed of an intimate mixture of banded amphibolite and metapyroxenite (probably of ophiolitic origin) and strongly foliated quartz-diorite and tonalite. Moderately deformed, late-kinematic, folded and boudinaged tonalitic to granodioritic veins that cut sheared rocks suggest that these are magmas were intruded synkinematically (Lissenberg & van Staal 2006). The outer zone of the Lloyds River Fault consists of gabbro and diabase cut by diorite and tonalite, with weakly deformed mafic rocks alternating with strongly sheared amphibolite and orthogneiss. Preferential localization of shear zones occurs in intrusives sheets rather than the ophiolite-derived gabbro, as at Blaeberry Rock. Shear-sense indicators imply that both the Lloyds River Fault and Blaeberry Rock contacts accommodated oblique motion with a sinistral component. Abundant metamorphic hornblende at both sites also suggests that the fault zones formed at amphibolite-facies conditions (with subsequent retrograde overprint) (Lissenberg & van Staal 2006). Abundant synkinematic tonalitic material at Blaeberry Rock implies that the Tyro Plutonic Group was accreted at the same time as the Tyro Volcanic Group at c. 470 Ma. This again is remarkably similar to the age of accretion of the Annieopsquotch Ophiolite Belt, which occurred prior to c. 468 Ma (Lissenberg et al. 2005; Zagorevski et al. 2006).

In the Newfoundland Appalachians, three distinct phases of deformation and metamorphism have been recognized during the Taconic orogeny, owing to arc and ophiolite accretion (van Staal et al. 2009; Zagorevski & van Staal 2011). Early obduction of the Lushs Bight Oceanic Tract onto the peri-Laurentian Dashwoods microcontinental block resulted in Taconic phase 1 at c. 495 Ma (van Staal et al. 2009). Evidence for ductile deformation and metamorphism at this time is relatively cryptic (van Staal et al. 2009) as in the British and Irish Caledonides (e.g. 514 ± 3 Ma 40Ar–39Ar hornblende age from Deer Park ophiolite mélangé: Chew et al. 2010).
Taconic phase 2 is largely regarded as the main orogenic phase of the Appalachians, and is broadly equivalent to the main episode of Grampian deformation in the British and Irish Caledonides (c. 475–465 Ma) (e.g. van Staal et al. 2009). In the Newfoundland Appalachians this resulted from the dextral oblique collision of an Early Ordovician west-facing peri-Laurentian arc (containing ensimatic and ensialic segments) with the passive Laurentian margin, and the obduction of super-subduction affinity crust of the intervening seaways (van Staal et al. 2007, 2009). It has been suggested that chaking of the A-subduction channel during Taconic phase 2 may have been the main cause for the initiation of subduction at c. 480 Ma, immediately outboard of the accreted Notre Dame arc-Dashwoods Block, which led to the formation of the Annieopsquotch Accretionary Tract (van Staal et al. 2009). This timing is identical to that in the Irish Caledonides, where the Lough Nafooey arc are collinear with the Laurentian margin between c. 484 and 476 Ma (Draut et al. 2004), coeval with the early development of the Tyrone Igneous Complex outboard of the Tyrone Central Inlier (Hollis et al. 2013). The rapid accretion of the Tyrone and Buchans–Robert’s Arm arc systems to the composite Laurentian margin occurred at c. 470–468 Ma during the peak of Taconic phase 2 deformation (van Staal et al. 2009; Cooper et al. 2011). It is at present unclear why the Tyrone Igneous Complex was obducted whereas the Annieopsquotch Accretionary Tract was underplated (Hollis et al. 2012). Late orogenesis in Newfoundland (Taconic phase 3) is related to the accretion of a late peri-Gondwanan arc system to the leading edge of Laurentia along the Red Indian Line (Fig. 1b; van Staal et al. 2007).

Other potential correlatives?

The Ballantrae Ophiolite Complex of Scotland is a structurally imbricated assemblage of ophiolitic, ocean-island and island-arc rocks exposed over c. 75 km² immediately north of the Southern Uplands Fault (Fig. 1). A U–Pb zircon date of 483 ± 4 Ma from trondhjemite constrains the genesis of the ophiolite, and a K–Ar hornblende cooling age of 478 ± 4 Ma from its metamorphic sole constrains the timing of its emplacement (Bluck et al. 1980). Although it is possible that the Ballantrae Ophiolite Complex is an along-strike equivalent of the Tyrone Igneous Complex, current age constraints are not sufficient for reconstructing the petrochemical evolution of the exposed sequences across tectonic blocks (discussed by Hollis et al. 2012). Although grabiptolite-bearing sedimentary units are Early to Late Arenig in age (Stone & Strachan 1981; Stone & Rushton 1983; Rushton et al. 1986), considerably older ages have also been produced from gabbro of within-plate affinity (K–Ar age of 487 ± 8 Ma; Harris et al. 1965), and island-arc lavas (e.g. whole-rock Sm–Nd age of 501 ± 12 Ma: Thrillwall & Bluck 1984). Post-obduction dykes of the Ballantrae Ophiolite Complex are similarly divisible into those of island-arc and withinplate affinity (Holub et al. 1984).

The Norwegian (Scandinavian) Caledonides consist of four major allochthonous nappe complexes, referred to as the Lower, Middle, Upper and Uppermost allochthons, which overlie parautochthonous and autochthonous Baltic rocks (Roberts & Gee 1985). The Uppermost Allochthon is of interest here as it is considered to represent an Ordovician Taconic orogenic event on the Laurentian margin, similar to that preserved in the British and Irish Caledonides (e.g. Slagstad et al. 2011). Although U–Pb ages similar to those from the Tyrone Plutonic Group have been obtained in the Norwegian Caledonides from trondhjemite of the Karmoy ophiolite (485 ± 2 Ma) and a cross-cutting arc-related tonalite of the Gullfjellet ophiolite (482 ± 6–4 Ma), both ophiolites also record earlier magmatism at c. 490 Ma (Dunning & Pedersen 1988). Although it is clear that ocean basin development occurred along the Laurentian margin at this time (published U–Pb ages summarized by Slagstad et al. 2011), it is not clear how these units relate to those preserved in the Irish Caledonides.

Conclusions

The Tyrone Plutonic Group is composed of variably tectonized and metamorphosed, layered, isotropic and pegmatitic gabbros, sheeted dolerite dykes and rare pillow lavas. New and previously published geochronology constrains the formation of the Tyrone Plutonic Group to c. 484–479 Ma, within error of U–Pb zircon dating from the Annieopsquotch Ophiolite Belt of Newfoundland. Whole-rock Sr-isotopic constraints from the upper parts of the ophiolite are comparable with the ⁸⁷Sr/⁸⁶Sr composition of Early to Middle Ordovician seawater and range to slightly more radiogenic values. In contrast, gabbro from Scalp yielded a significantly less radiogenic ⁸⁷Sr/⁸⁶Sr value suggesting somewhat lesser interaction with seawater, consistent with its probably deeper original position within the ophiolite. High ⁸⁷Sr/⁸⁶Sr values in the upper ophiolite, Sm–Nd isotopic constraints (εNd = +4.4 to +7.7) and the presence of inherited zircons in layered gabbros are consistent with minor crustal contamination into the source region. Together these data suggest that the Tyrone Plutonic Group formed above a north-dipping subduction zone, by the propagation of a spreading centre into a microcontinental block. S-type, peraluminous muscovite granite, generated from the partial melting of Laurentian-affinity metasedimentary material, contains inherited Proterozoic zircons and appears to have been intruded after ophiolite emplacement. Ophiolite obduction onto the Tyrone Central Inlier must have occurred prior to the intrusion of a c. 470 Ma tonalite that contains roof pendants of ophiolitic and arc material and xenocrystic Proterozoic zircons. Late Fe–Ti basaltic dykes of E-MORB affinity are consistent with formation at a propagating rift following obduction. Geochemically identical lavas are present in the upper Tyrone Volcanic Group (Mountfield Basalts) and at Slieve Gallion, constrained by U–Pb zircon geochronology to c. 469 Ma. The presence of synkinematic, calc-alkaline tonalite to granitic material within the contact between the Tyrone Central Inlier and Tyrone Plutonic Group suggests that the latter may have been emplaced relatively late within the orogen at c. 470 Ma synchronous with the Tyrone arc. In the absence of an ultramafic section, the coeval obduction of the ophiolite and volcanic arc may explain how metamorphic conditions within the sillimanite-grade Tyrone Central Inlier were reached prior to c. 468 Ma.

Strong temporal, geochemical and lithological similarities to the Annieopsquotch Ophiolite Belt of Newfoundland indicate that these ophiolites may have a shared origin and evolution. This adds to a growing body of evidence that the Tyrone Igneous Complex represents the third stage of arc–ophiolite emplacement in the peri-Laurentian British and Irish Caledonides at c. 470 Ma, following the accretion of early c. 510–500 Ma ophiolites (Highland Border and Deer Park), and the Lough Nafooey arc at c. 480 Ma.

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