Age Constraints and Geochemistry of the Ordovician Tyrone Igneous Complex, Northern Ireland: implications for the Grampian orogeny

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Abstract: The Tyrone Igneous Complex is one of the largest areas of ophiolitic and arc-related rocks exposed along the northern margin of Iapetus within the British and Irish Caledonides. New U-Pb zircon data and regional geochemistry, suggest the Tyrone Plutonic Group represents the uppermost portions of a *c*. 480 Ma suprasubduction zone ophiolite accreted onto an outboard segment of Laurentia prior to 470.3 ± 1.9 Ma. The overlying Tyrone Volcanic Group formed as an island arc which collided with the Laurentian Margin during the Grampian phase of the Caledonidan orogeny. Early magmatism is characterized by transitional to calc-alkaline, light rare earth element-enriched island-arc signatures, with an increasing component of continentally-derived material up sequence. Tholeiitic rhyolites with flat to U-shaped rare earth element profiles and light rare earth element-depleted basalts, located stratigraphically below a *c*. 473 Ma rhyolite of the upper Tyrone Volcanic Group, suggest initiation of intra-arc rifting at *c*. 475 Ma. Metamorphic cooling ages from the Tyrone Central Inlier imply arc-continent collision before 468 ± 1.4 Ma, with the emplacement of the Tyrone Volcanic Group onto the margin. A suite of 470.3 ± 1.9 Ma to 464.3 ± 1.5 Ma calc-alkaline intrusions are associated with the continued closure of Iapetus.

Keywords: Tyrone Igneous Complex, age constraints, geochemistry, Grampian orogenisis, Appalachian-Caledonian.

Supplementary material: geochemical data and petrography are available at www.geolsoc.org.uk/SUP00000

Introduction

The Grampian phase of the Caledonian orogeny records collision between the passive continental margin of Laurentia and a Lower Paleozoic oceanic arc(s) during the Early to Middle Ordovician (Dewey & Shackleton 1984). Predating final closure of the Iapetus Ocean, this was the first orogenic event to affect the southeast margin of Laurentia, broadly equivalent to the Taconic event of the Appalachians (van Staal *et al*. 1998). Widespread *c*. 490-480 Ma ophiolite obduction (Chew *et al*. 2010) was followed by polyphase deformation and metamorphism of thick post-Grenville, Neoproterozoic cover sequences along the Laurentian margin, such as the Dalradian Supergroup (*c*. 475 to 465 Ma; reviewed in Chew 2009). Orogeny was remarkably short-lived due to an associated subduction polarity reversal (Friedrich *et al*. 1999; Dewey 2005).

In Scotland, the colliding volcanic arc (Midland Valley terrane) is separated from the Laurentian margin by the Highland Boundary Fault (**Fig. 1a**), a continuation of the Baie Verte - Brompton Line of Newfoundland and the Fair Head - Clew Bay Line of Ireland (**Fig. 1b**). Ophiolitic rocks are preserved within this fault zone as the Highland Border ophiolite of Scotland, part of the Highland Border Complex, (Tanner 2007) and the dismembered Deer Park ophiolitic mélange of western Ireland, part of the accretionary Clew Bay Complex (Ryan *et al*. 1983). Remnants of the colliding arc(s) are represented within the Irish Caledonides as the Lough Nafooey, Tourmakeady and Charlestown Groups of western Ireland (e.g. Ryan *et al*. 1980; Clift & Ryan 1994; Draut *et al*. 2004), and Tyrone Volcanic Group of Northern Ireland (Cooper *et al*. 2008; Draut *et al*. 2009). The South Mayo Trough represents the fore-arc to post-collisional foreland basin of the colliding Lough Nafooey arc (Dewey & Ryan 1990).

The Dunnage Zone of central Newfoundland and Maritime Canada includes a complex association of Cambro-Ordovician arc and back-arc complexes of both intra-oceanic and continental affinity which were accreted to the Laurentian margin during the Taconic event (van Staal *et al*. 2007) (**Fig. 1b**). Peri-Laurentian tracts of the Notre Dame and Dashwoods Subzones are separated from those of peri-Gondwanan affinity within the Exploits Subzone by the Red Indian Line (Williams *et al*. 1988). Within the Notre Dame Subzone, three distinct phases of the Taconic event are recognized (van Staal *et al.* 2007). Broad correlations have been made between the Caledonides and Newfoundland Appalachians (e.g. van Staal *et al*. 1998), although exact correlations between terranes often remain contentious.

The Tyrone Igneous Complex of Northern Ireland provides one of the most complete sections through an accreted arc within the Grampian belt of the Caledonides. Whole rock geochemical data published by Angus (1977) and Draut *et al*. (2009) detail the evolution of the complex, constrained by four U-Pb zircon dates (Hutton *et al*. 1985; Cooper *et al*. 2008; Draut *et al*. 2009). These data nevertheless only partially characterize the geochronology and geochemistry of the entire complex. This paper presents a total of nine new U-Pb zircon ages, which are combined with existing U-Pb and biostratigraphical age constraints, field relations and new regional geochemistry to shed further light on the Grampian orogenic evolution of the Caledonide – Appalachian orogen (**Fig. 1c**).

Tyrone Igneous Complex

The Ordovician Tyrone Igneous Complex extends over an area of about 350km^2 in the counties of Tyrone and Londonderry, Northern Ireland, and is one of the most extensive areas of ophiolitic and arc-related rocks exposed along the northern margin of Iapetus within the British and Irish Caledonides. Building on the comprehensive survey of Hartley (1933), the Tyrone Igneous Complex was divided into two distinct units: the Tyrone Plutonic Group and the Tyrone Volcanic Group (Cobbing *et al*. 1965; Geological Survey of Northern Ireland 1979, 1983, 1995). The complex overlies sillimanite-grade paragneisses of the Tyrone Central Inlier, which based on detrital zircon age profiling, appears to be of upper Dalradian, Laurentian affinity (Chew *et al*. 2008). Both the Tyrone Igneous Complex and Tyrone Central Inlier are intruded by a suite of arc-related tonalitic to granitic intrusions (Cooper & Mitchell 2004) **(Fig. 2)**.

Tyrone Central Inlier

The Tyrone Central Inlier is composed of a thick sequence of psammitic and semipelitic paragneisses (Hartley 1933) termed the Corvanaghan Formation (GSNI 1995). Metamorphism is characterized by a prograde assemblage of biotite + plagioclase + sillimanite + quartz ± muscovite ± garnet in pelitic lithologies (*c.* 670 ± 113 °C, 6.8 ± 1.7 kbar; Chew *et al.* 2008), with corderite locally observed (Hartley 1933). Recent detrital zircon age profiling suggests an upper Dalradian, Laurentian affinity for these metasediments, with Paleoproterozoic Nd model ages overlapping with those from both the Argyll and Southern Highland groups (Chew *et al.* 2008), while *in situ* Hf isotope analysis of zircon rims from *c.* 470Ma granitoid rocks that cut the Tyrone Central Inlier paragneisses yield negative ε_{Hf}470 values of approximately −39. This isotopic signature requires an Archaean source, suggesting rocks similar to the Lewisian Complex of Scotland occur at depth beneath the Tyrone Central Inlier (Flowerdew *et al.* 2009). The Tyrone Central Inlier is believed to represent part of an outboard segment of Laurentia, most likely detached as a microcontinent prior to arc-continent collision and reattached during the Grampian event (Chew *et al.* 2010).

Tyrone Plutonic Group

The Tyrone Plutonic Group forms the southern, structurally lower portion of the Tyrone Igneous Complex and consists mainly of variably tectonised and metamorphosed, layered, isotropic and pegmatitic gabbros (Cobbing *et al.* 1965; Cooper & Mitchell 2004). Olivine gabbro at Scalp (**Fig. 2**) displays cumulate layering, reflecting textural and compositional variations (see Cooper & Mitchell 2004), with gabbro locally altered to hornblende schist (Cobbing *et al.* 1965). At Black Rock (**Fig. 2**), coarse-grained hornblende gabbro is in contact with, and contains xenoliths of, an early-formed suite of dolerite, itself intruded by younger 1-2 m wide, basalt and dolerite dykes (Cooper & Mitchell 2004). Irregular veins of pegmatitic gabbro are closely associated. In Carrickmore Quarry, parallel NE-SW trending dolerite dykes display two-sided, and more commonly one-sided, chilled margins characteristic of a sheeted dyke complex (Hutton *et al.* 1985). Pillow lavas are scarce within the group, and are present as a roof-pendant within the Craigballyharky intrusion (**Fig. 2**) (e.g. Angus 1977).

Although exposure is poor, this association of rock types and their field relations strongly supports the view of Hutton *et al.* (1985) that the Tyrone Plutonic

Group represents the upper parts of a dismembered ophiolite sequence. Previous geochemistry has shown the sequence to be of suprasubduction affinity (Draut *et al*. 2009). Based on a magma-mixing relationship between gabbro and tonalite at Craigballyharky, Hutton *et al*. (1985) considered the Tyrone Plutonic Group to be contemporaneous with the Tyrone Volcanic Group. A U-Pb zircon 472 $^{+2}/_{-4}$ Ma age determination of a tonalite from Craigballyharky along with magma relationships was taken as evidence for the age of the ophiolite and for the timing of obduction (Hutton *et al*. 1985). However, recent U-Pb zircon dating of gabbro from Craigballyharky yielded a significantly older age of 493 ± 2 Ma for the Tyrone Plutonic Group (Draut *et al*. 2009) which is discussed later.

<u>Tyrone Volcanic Group</u>

The Tyrone Volcanic Group forms the upper part of the Tyrone Igneous Complex and is comprised of basic to intermediate pillow lavas, volcaniclastic tuffs, rhyolites, banded chert, silica-iron exhalite (ironstone) and argillaceous sediment. The predominant "background" lithology within the Tyrone Volcanic Group is a pale-greenish grey, schistose, chlorite-epidote-sericite tuff, which varies from fine-grained ash to coarse-grained lapilli tuff (Cooper & Mitchell 2004). Previous research suggests that there is evidence for at least three volcanic cycles within the Tyrone Volcanic Group; each commencing with basaltic lavas, with cycle tops characterised by the presence of laminated chert and/or mudstone at Tanderagee, Bonnety Bush and Broughderg respectively (Hutton *et al*. 1985; Cooper & Mitchell 2004). The base of the lowest cycle is represented by the Copney Pillow Lava Formation, with rhyolite at Formil Hill (**Fig. 2**) taken as the top of cycle two (Cooper & Mitchell 2004). Biostratigraphical correlation and a robust U-Pb zircon age constraint of 473 ± 0.8 Ma from the Formil Hill rhyolite, suggest an age for the upper Tyrone Volcanic Group within the Australasian Castlemainian (Ca1) Stage of the Arenig (Cooper *et al*. 2008) (**Fig. 3**).

Draut *et al*. (2009) provided the first geochemical study of the Tyrone Volcanic Group. They suggested it formed within an oceanic arc which assimilated considerable detritus from the Laurentian margin and made a correlation with the Lough Nafooey arc of western Ireland. Although Cobbing *et al*. (1965) considered the Tyrone Volcanic Group to unconformably overlie the Tyrone Central Inlier, both

Harley (1933) and more recent work (Cooper & Mitchell 2004; Draut *et al*. 2009) favoured a tectonic contact between the units. Nowhere are contacts exposed with either the Tyrone Plutonic Group or the Tyrone Central Inlier.

Late Intrusive Rocks

Several large granitic to tonalitic intrusions cut the Tyrone Igneous Complex and Tyrone Central Inlier (**Fig. 2**). All show an I-type affinity except an intrusion of muscovite granite at Tremoge Glen. A series of high-level sills and dykes of porphyryitic dacite cut all levels of the complex. Strong large ion lithophile element (LILE) and light rare earth element (LREE) enrichment, coupled with zircon inheritance and strongly negative $\varepsilon Nd_{(t)}$ values, suggest that assimilation of Dalradian-affinity metasediments was an integral part of their petrogenesis (Draut *et al*. 2009).

Field relations at Craigballyharky show roof pendants of Ordovician pillow basalt and sheeted dolerite enclosed within tonalite, demonstrating the Tyrone Plutonic Group was in its present structural position prior to intrusion (Cobbing *et al.* 1965; Angus 1977; GSNI 1979). Granodiorite at Craigbardahessiagh contains pendants of Ordovician volcanic rocks and ironstone, and tonalite from Craigballyharky (Cobbing *et al.* 1965; Angus 1977; GSNI 1979). Tonalite from Craigballyharky and Leaghan (i.e. Cashel Rock, **Fig. 2**) has yielded U-Pb zircon ages of 472 $^{+2}/_{-4}$ Ma (Hutton *et al*. 1985) and 475 ± 10 Ma (Draut *et al*. 2009) respectively.

Sampling and Analytical Methods

Geochemistry

A range of stratigraphic levels within the Tyrone Volcanic Group were sampled for geochemical analysis, as were key localities from the Tyrone Plutonic Group and several large tonalitic to granitic intrusions. A total of four Tyrone Plutonic Group, nine Tyrone Volcanic Group, and fifteen arc-related intrusive suite samples were analysed for major, trace and rare-earth elements at the British Geological Survey (BGS) in Nottingham.

Major elements were determined for twenty-eight powdered whole-rock samples on fused glass beads by X-ray Fluorescence Spectrometry (XRF). Samples were dried at 105 °C before loss on ignition (LOI) and fusion. LOI was determined after 1 hour at 1050 °C. Fe_2O_3t represents total iron expressed as Fe_2O_3. SO_3 represents sulphur retained in the fused bead after fusion at 1200 °C. Trace elements were analysed on pressed powder-pellets by XRF. Rare earth elements were determined by inductively coupled plasma mass spectrometry (ICP-MS); samples were subjected to an $HF/HClO_4/HNO_3$ attack with residues fused with NaOH before solutions were combined. Geochemical results are presented in the supplementary publication. Analyses of Draut *et al.* (2009) have also been included in many of the diagrams presented here.

U-Pb Geochronology

Nine samples were dated by U-Pb TIMS geochronology at the NERC Isotope Geoscience Laboratory. Three samples were collected from the Tyrone Plutonic Group – the layered gabbro at Scalp, pegmatitic gabbro at Black Rock and sheeted dykes from Carrickmore Quarry (**Fig. 2**), however only the layered gabbros (JTP207) produced sufficient zircon for successful age dating. Eight samples from the arc-related intrusive suite, including tonalite, granodiorite, granite, porphyritic dacite and quartz-monzodiorite yielded abundant zircon suitable for U-Pb TIMS geochronology.

Heavy mineral concentrates were obtained at the NERC Isotope Geosciences Laboratory using standard crushing techniques, a Gemini™ table, modified superpanner, a Frantz LB1 magnetic separator and heavy liquids. Minerals were selected for analysis by hand picking in alcohol under a binocular microscope and either air-abraded or chemically abraded to improve concordance following Krogh (1982) and Mattinson (2005). Chemically abraded zircons were first annealed at 850 ^{o}C for 48 hours prior to partial dissolution in 29N HF at 180 ^{o}C for 12 hrs (McConnell *et al.* 2009). Dissolutions, spiking and chemical separations follow Krogh (1973) with modifications after Corfu & Noble (1992). Procedural blanks of MRC prefixed samples ranged from c. 20 pg to ≤10 pg Pb and <0.5 pg U, whereas sample JTP prefixed samples had procedural blanks of 2 pg Pb and 0.1pg U.

Correction for common Pb, in excess of the laboratory blank, was made using a Stacey & Kramers (1975) model Pb composition calculated for the $^{207}Pb/^{206}Pb$ age of the analyses, with a 2 % error on the compositions propagated through data reduction calculations. Data were either obtained on a VG354 or Thermo Electron Triton using either a Daly detector or SEM respectively. U-Pb Concordia and upper and lower intercept age calculations followed Ludwig (1998, 2003) using the decay constants and measurement uncertainties of Jaffey *et al.* (1971). Uncertainties quoted for isotope ratios and ages in **Table 1** are at the 2σ level, and all data are plotted with 2σ error ellipses.

Results

All samples examined from the Tyrone Igneous Complex have been subjected to low-grade metamorphism, sub-greenschist to epidote-amphibolite facies and hydrothermal alteration, which has determined the approaches used in the interpretation of the geochemistry. A selection of lithologies identified from the Tyrone Plutonic Group, Tyrone Volcanic Group and late intrusive suite are described in the supplementary publication. Within the upper Tyrone Volcanic Group, volcanogenic base and precious metal mineralization has led to a variety of alteration types, where pervasive chloritic alteration has been overprinted by variably developed sericitic, carbonate and silicic alteration. Intense argillic alteration is well developed within a sub-economic porphyry Cu deposit at Formil Hill (Leyshon & Cazalet 1976) (**Fig. 2**). Primary minerals are rarely well preserved except in late granitic to tonalitic intrusive rocks.

Geochemistry

The hydrothermal alteration and low-temperature metamorphism prevalent across the Tyrone Igneous Complex suggests that the use of mobile elements for whole rock classification and deducing magma affinity will be compromised. In particular, elements such as SiO_2, Na_2O, K_2O, CaO, MgO and FeO, and the low-field strength elements (LFSE: Cs, Rb, Ba, Sr, U), are considered mobile under these conditions (MacLean 1990). By contrast, Al_2O_3, TiO_2, Th, V, Ni, Cr, Co, the high field strength elements (HFSE: Nb, Hf, Ta, Zr, Y, Sc, Ga) and rare earth elements (REE: minus Eu ± Ce) typically remain immobile (e.g. Pearce & Cann 1973; Wood 1980; MacLean 1990; Rollinson 1993; Barrett & MacLean 1999). In light of these results, particular attention is given to the immobile-element geochemistry of the Tyrone Igneous Complex. Although mass change associated with hydrothermal alteration may alter the absolute concentrations of immobile elements, inter-element ratios will remain constant (MacLean 1990).

Tyrone Plutonic Group:

Rocks from the Tyrone Plutonic Group are tholeiitic and basaltic in composition (**Fig. 4a-c**), with positive Pb, negative Nb and modest Ti anomalies (**Fig. 5a**). Geochemical signatures are similar to those previously reported by Draut *et al*. (2009) (**Fig 4 and 5a**) and are typical of basalts generated in a suprasubduction environment (Pearce *et al.* 1984b; **Fig. 4d**). Th concentrations are variable (~1 to 100x primitive mantle), all samples show weak LREE depletion relative to heavy rare earth elements (HREE) (**Fig. 5a**), and HFSE concentrations are generally less than those of normal mid ocean ridge basalt. Aphanitic basaltic rocks (e.g. MRC343 and MRC340) classify as island-arc tholeiitic basalts according to Meschede (1986), Wood (1980), Pearce & Norry (1979) and Pearce & Cann (1973).

Tyrone Volcanic Group:

All basalts analysed from the Tyrone Volcanic Group, except those from Bonnety Bush, are LILE- and LREE-enriched with variable negative Nb anomalies (**Fig. 5b**). Basalts range from subalkaline (transitional to calc-alkaline) to borderline alkalic in composition (**Fig 4a,c**), and plot within the enriched-mid ocean ridge basalt (e-MORB) fields of Wood (1980) and the within-plate/volcanic-arc fields of Meschede (1986) and Pearce & Norry (1979). Samples from around Mountfield are alkalic, of within-plate affinity, and do not display the classic HFSE depletion of suprasubduction zone magmatism (Draut *et al*. 2009). Tholeiitic basalt from Bonnety Bush (MRC349) has Pb and Nb anomalies typical for arc-related volcanism, yet has low LILE concentrations, limited Ti anomalies and is LREE depleted relative to HREE (**Fig. 5c**). Immobile element ratios from this locality (e.g. Sc/Y, Ti/Sc, Ti/V, Sm/Yb, Th/Nb and Zr/Nb) are similar to those from the Tyrone Plutonic Group.

All rocks of andesitic to rhyolitic composition (**Fig. 4a and 4b**), except those from Beaghbeg and Bonnety Bush, are subalkaline and transitional to calc-alkaline in nature (**Fig. 4c**). They are LILE- and LREE-enriched, and have lower HREE concentrations than associated basalts. Consideration of the data within multi-element variation diagrams (**Fig. 5c**) suggests they are typical of arc-related volcanism (e.g. negative Nb anomalies and HFSE depletion). Tholeiitic rhyolitic tuff from Beaghbeg (MRC345) and strongly altered andesitic tuff from Bonnety Bush (MRC348) are unusual within the Tyrone Volcanic Group, in that they display modest LILE enrichment (>10x primitive mantle), and LREE and HREE concentrations around 10x chondrite. Primitive-mantle normalized multi-element variation diagrams show flat to 'U' shaped REE profiles (**Fig. 5c**).

Late arc-related Intrusive Rocks:

Calc-alkaline, arc-related intrusive rocks cut both the Tyrone Igneous Complex and the Tyrone Central Inlier (Fig. 2). These rocks display geochemical affinities similar to the LILE- and LREE-enriched rhyolites and andesites of the Tyrone Volcanic Group (**Fig. 4 and 5b,d**), with granitic rocks classified as volcanic-arc granites according to their Ta-Yb systematics (Pearce *et al*. 1984a).

U-Pb Geochronology

Calculated U-Pb ages for samples analysed are presented in **Table 2**, along with additional information. The U-Pb ages (**Fig. 6**), range in age from 479.6 ± 1.1 Ma to 464.3 ± 1.5 Ma. All samples display evidence of zircon inheritance. Gabbro from the Tyrone Plutonic Group (JTP207) was dated at 479.6 ± 1.1 Ma, with inherited ages of *c*. 1015 Ma and *c*. 2100 Ma. All samples investigated from the arc-related intrusive suite range in age between *c*. 470 Ma and 464 Ma (**Fig. 6**). Granite from Slieve Gallion (MRC92, 466.5 ± 3.3 Ma) and granodiorite from Craigbardahessiagh (MRC91, 464.9 ± 1.5 Ma) both contain Mesoproterozoic inherited zircons. Zircons analysed from quartz porphyry (dacite) from Copney (MRC90, 465 ± 1.7 Ma) and tonalite from Craigballyharky (MRC128, 470.3 ± 1.9 Ma) both contain inherited components dated at *c*. 2100 Ma. Our U-Pb zircon age of the tonalite from Craigballyharky is within error of that proposed by Hutton *et al*. (1985).

Discussion

Using these new U-Pb geochronology and geochemical data we can refine current models for the evolution of the Tyrone Igneous Complex and timing of the Grampian orogeny within Ireland. Our new tectonic model based around the Tyrone Igneous Complex is presented in **Figure 7**.

<u>Development of the Tyrone Plutonic Group</u>

Field relationships and geochemical evidence including negative Nb anomalies and HFSE depletion suggests the Tyrone Plutonic Group represents the uppermost portions of a suprasubduction zone ophiolite which was emplaced onto an outboard segment of Laurentia, the Tyrone Central Inlier, during the Grampian event. Though fault bounded, the Tyrone Plutonic Group and Tyrone Volcanic Group were previously considered contemporaneous based on a magma-mixing relationship between gabbro and $472\ ^{+2}/_{-4}$ Ma tonalite at Craigballyharky (Hutton *et al*. 1985). However, recent work by Draut *et al*. (2009) reported an age of 493 ± 2 Ma for the Craigballyharky gabbro which is too old considering the magma-mixing relationship observed with *c*. 470 Ma tonalite (MRC128 at 470.3 ±1.9 Ma; also $472\ ^{+2}/_{-4}$ Ma of Hutton *et al*. 1985). The zircon age of 493 Ma derived by Draut *et al.* is a $^{206}Pb/^{238}U$ age of three reversely discordant analyses. The reverse discordance is a probable analytical artifact of the SIMS data, possibly attributed to high uranium content of the zircons. The mean $^{207}Pb/^{206}Pb$ age of these same three analyses gives 468 ± 22 Ma (2σ). Draut *et al*. (2009) also presented zircon ages from the Craigballyharky gabbro of approximately 470 Ma, but disregarded them as sample contamination. These three apparently younger zircons give a mean $^{206}Pb/^{238}U$ age of 473.2 ± 1.6 Ma (2σ). We therefore propose that the Craigballyharky gabbro, which is LREE-enriched, is considerably younger than that proposed by Draut *et al*. (2009) and belongs to the arc-related intrusive (*c*. 470-464 Ma) suite. This scenario also agrees with the magma-mixing relationship observed.

Our new U-Pb zircon age determination from the layered gabbro at Scalp (JTP207, 479.6 ± 1.1 Ma), suggests that formation of the Tyrone Plutonic Group initiated at *c*. 480 Ma (**Fig. 7a**). Two inherited grains at *c*. 1015 and *c*. 2100 from the Scalp layered gabbro signify that material of this age was present at depth by *c*. 480 Ma. Their occurrence in the ophiolitic Tyrone Plutonic Group may reflect subduction of peri-Laurentian metasediments under the Tyrone ophiolite during formation. Primitive geochemical characteristics presented herein (JTP207) are inconsistent with alternate explanations, which would require intrusion of the Scalp gabbro after ophiolite emplacement with xenocrystic zircons derived during emplacement through the Tyrone Central Inlier. As zircons of *c*. 2100 Ma are not present in abundance in peri-Laurentian sources (Cawood *et al*. 2007), including the Tyrone Central Inlier (Chew *et al*. 2008), their occurrence as xenocrysts may signify a difference in age signature of the basement underlying the region at this time.

Emplacement of the Tyrone Plutonic Group

Obduction of the Tyrone Plutonic Group onto the Tyrone Central Inlier must have occurred prior to *c*. 470 Ma (**Fig. 7b-c**). Two intrusions dated here at *c*. 470 Ma (MRC128, 470.3 ± 1.9 Ma; MRC126, 469.9 ± 2.9 Ma) cut the Tyrone Plutonic Group in its present structural position upon the Tyrone Central Inlier. At Craigballyharky, tonalite (MRC128) contains roof-pendants of LREE-depleted basalt derived from the Tyrone Plutonic Group. Whole rock and isotope geochemistry (see Draut *et al*. 2009) and zircon inheritance from these granitic to tonalitic stitching intrusions suggests they ascended through continental crust. Zircon inheritance (MRC128, MRC126) is compatible with derivation from the underlying Tyrone Central Inlier (Chew *et al*. 2008).

Sillimanite-bearing metamorphic assemblages and leucosomes in paragneisses within the Tyrone Central Inlier are cut by granite pegmatites (Chew *et al*. 2008). The main fabric of the leucosomes yielded a ^{40}Ar–^{39}Ar biotite cooling age of 468 ± 1.4 Ma (Chew *et al*. 2008), which implies the Tyrone Central Inlier was metamorphosed and deformed under a thick, high-temperature succession prior to 468 ± 1.4 Ma (*c*. 670 °C, 6.8 kbar of Chew *et al*. 2008), consistent with ophiolite emplacement prior to *c*. 470 Ma (**Fig. 7c**). The lack of an ultramafic succession within the Tyrone Plutonic Group may be explained by post-obduction excision. In western Ireland, late extensional detachments associated with the Deep Park ophiolitic mélange juxtapose high-pressure, low-temperature blueschist facies rocks alongside lower-pressure Barrovian metasediments (e.g. Chew *et al*. 2010).

Rocks of the South Mayo Trough, western Ireland, the fore-arc to the Lough Nafooey arc, record significant quantities of ophiolite-derived sediment entering the basin from *c*. 478 Ma (Chew 2009); systematic changes in Mg, Cr, Ni (Wrafter &

Graham 1989) and detrital chrome spinel (Dewey & Mange, 1999) suggest the progressive unroofing on a ophiolite prior to the exhumation of the Grampian metamorphic belt (**Fig. 7a**). It is possible that obduction of the Tyrone Plutonic Group was also initiated at or shortly after *c*. 480 Ma. Evidence from certain ophiolites suggests that the timing of magmatism and obduction may be very closely spaced. For instance, age constraints from the Oman-UAE ophiolite indicate that the latest, seafloor, rift-related magmatism occurred less than 1 m.y. prior to obduction (Styles *et al*. 2006; Goodenough *et al*. 2010).

<u>Development of the Tyrone Volcanic Group</u>

Geochemical variation within the Tyrone Volcanic Group is predominantly characterised by transitional to calc-alkaline island-arc signatures, with strong enrichment in the LILE and LREE, high La/Sm and an increasing component of continentally derived material up sequence (see Draut *et al*. 2009). Th/Yb-Nb/Yb systematics imply the magmas were similar to eMORB in composition, but enriched in subduction zone components (e.g. Th, Cs, Rb, Ba, Pb). Draut *et al*. (2009) proposed the observed increase in La/Sm, LILE- and LREE-enrichment, and lowering of $\varepsilon Nd_{(t)}$ values reflects the approach of the arc to the continental margin, subduction of continental detritus and magmatism during arc-continent collision. Although the strongly negative $\varepsilon Nd_{(t)}$ values and LILE- and LREE-enrichment within the Tyrone Volcanic Group are also consistent with formation within an ensialic arc, the occurrence of primitive basalt at several stratigraphic horizons and the absence of zircon inheritance within the *c*. 473 Formil rhyolite (the only the only dated sample which *sensu stricto* belongs to the Tyrone Volcanic Group, Cooper *et al*. 2008), , suggest an oceanic-affinity for the Tyrone arc.

Tholeiitic rhyolite and silicified andesite from Beaghbeg and Bonnety Bush are unusual within the Tyrone Volcanic Group in that they display flat to ‘U-shaped’ chondrite-normalized REE profiles. Although boninite *sensu stricto* was not recorded within the samples analysed, tholeiitic rhyolites with U-shaped REE profiles, which typically form from the melting of mafic (to andesitic) substrates, are present, and are similarly often associated with forearc rifting, intra-arc rifting or rifting during the initiation of back-arc basin activity (see. Piercey 2007). These lavas stratigraphically overly the 473 ± 0.8 Ma rhyolite of Cooper *et al*. (2008) and are closely associated with primitive tholeiitic and LREE-depleted island-arc basalt from Bonnety Bush. If the tholeiitic rhyolites of Beaghbeg mark the initiation of intra-arc rifting, then the LREE-depleted basalts of Bonnety Bush are a likely consequence of the same process, representing eruption onto the floor of the newly formed basin.

Basalt at Mountfield, towards the top of the sequence (Cooper *et al*. 2008), is borderline alkalic, of within-plate affinity, lacks the prominent HFSE depletion of subduction-related magmatism, and displays weakly positive $\varepsilon Nd_{(t)}$ values. Draut *et al*. (2009) suggested this basalt formed at a late stage in the orogen when no strong underthrusting occurred, and is perhaps associated with a reversal in subduction polarity and/or gravitationally induced loss of the lower crust. Although the Mountfield basalts are geochemically consistent with formation in a seamount, their close association with strongly LILE- and LREE enriched rhyolite, argillaceous sediment, abundant volcaniclastic tuff and chert makes this unlikely.

Correlatives across the Grampian – Taconic orogen

In the British and Irish Caledonides, recent work on the Highland Border Ophiolite has demonstrated that generation of oceanic crust in Scotland was underway by 499 ± 8 Ma, with high-grade obduction-related metamorphism constrained to *c.* 490 ± 4 Ma (Chew *et al.* 2010). Similarly, in western Ireland high-grade metamorphism was underway by 514 ± 3 Ma prior to exhumation at 482 ± 1 Ma (Deer Park Complex: Chew *et al.* 2010). Together these dates suggest a correlation between these ophiolites and the *c.* 510-501 Ma Lushs Bight Oceanic Tract of Newfoundland. As the Highland Border and Deerpark Complex ophiolites experienced metamorphism and deformation at least 15 m.y. before the Grampian event (*c*. 475-465 Ma), Chew *et al*. (2010) suggested early obduction may have occurred substantially outboard of the Laurentian margin onto peri-Laurentian microcontinental blocks.

Following obduction, a primitive oceanic-arc, represented locally by the Lough Nafooey and Tourmakeady Groups of western Ireland (Lough Nafooey arc), was active by *c*. 490 Ma (Chew *et al*. 2010) (**Fig. 7a**). Granitoid boulders of this age indicate the assimilation of crustal material ($\varepsilon Nd_{(t)}$ ~0, Chew *et al.* 2007). This ophiolite – oceanic arc complex is preserved within Newfoundland as the *c*. 490 Ma Baie Verte Oceanic Tract and the overlying *c*. 487-476 Ma oceanic Snooks Arm arc/back-arc (see van Staal *et al*. 2007). Collision between the Lough Nafooey arc and the Laurentian margin occurred at *c*. 478 Ma (**Fig. 7b**). The Tourmakeady Group (*c*. 478-470) records volcanism during peak deformation and regional metamorphism within the Dalradian Supergroup (Draut *et al*. 2004).

Similar ages for the Tyrone Plutonic Group (479.6 ± 1.1 Ma) have been reported from the Ballantrae Complex of Scotland (e.g. 483 ± 4 Ma, Bluck *et al*. 1980) and the Annieopsquotch ophiolite belt of Newfoundland (481 to 478 Ma, Dunning & Krogh 1985). Development of the Tyrone Plutonic Group at *c*. 480 Ma outboard of the Tyrone Central Inlier suggests temporal correlation to the Annieopsquotch ophiolite belt, although all components of the Annieospquotch Accretionary Tract were progressively underplated to the Dashwoods microcontinent above a west-dipping subduction zone (Zagorevski *et al*. 2009). As contacts between the Tyrone Plutonic Group, Tyrone Volcanic Group, and Tyrone Central Inlier are unexposed it remains unclear exactly how the Tyrone Igneous Complex was obducted.

Similarly, it is at present unclear whether the Tyrone Volcanic Group (and Tyrone Plutonic Group) developed above a north- or south-dipping subduction zone; both are plausible. In the former case, correlation to the Lough Nafooey arc of western Ireland would be permitted, as suggested by Draut *et al*. (2009) and shown in **Figure 7**. Current geochronology from the Tyrone Volcanic Group, although limited, is consistent with correlation either to the Tourmakeady Group of western Ireland (the syn-collisional stage of the Nafooey arc, also see Draut *et al*. 2009), or the Buchans Group and correlative Roberts Arm Group of the Anniopsquotch Accretionary Tract (see Zagorevski *et al*. 2009). Both the Buchans arc and its continental basement were accreted to the Dashwoods microcontinent prior to *c*. 468 Ma accompanied by the intrusion of dominantly arc-like continental plutons within the Annieopsquotch Accretionary Tract and adjacent Notre Dame Arc (Lissenberg *et al*. 2005). This intrusive suite is comparable in age to those seen in Tyrone (*c*. 470-464 Ma), Connemara (Cliff *et al.* 1996; Friedrich *et al.* 1999; McConnell *et al*. 2009) and also those intruding the NE Ox Mountains Slishwood Division (Flowerdew *et al*. 2005).

Future lithogeochemistry and U-Pb geochronology may shed further light on the development of this enigmatic arc system.

Conclusions

The U-Pb geochronology and geochemistry presented herein refine current models of formation for the Tyrone Igneous Complex and the Grampian orogenic system within the British and Irish Caledonides. Geochemical variation within the Tyrone Plutonic Group is typical for a suprasubduction zone ophiolite and our new U-Pb zircon age of 479.6 ± 1.1 Ma constrains the timing of development of the Tyrone Plutonic Group. Obduction onto the Tyrone Central Inlier must have occurred prior to 470.3 ± 1.9 Ma, although this may have been initiated as early as *c*. 480-478 Ma. The presence of xenocrystic *c*. 2100 and 1500 Ma zircons in the Scalp layered gabbro may signify a difference in age signature of the basement underlying the region.

Geochemical analyses of the Tyrone Volcanic Group indicates that it formed within an oceanic volcanic arc receiving an increasing component of continentally derived material from the Laurentian margin. Magmatism associated with the maturing arc is strongly LILE- and LREE-enriched and calc-alkaline in nature. Tholeiitic rhyolites with U-shaped REE profiles and LREE-depleted basalts mark the initiation and formation of an intra-arc basin at *c*. 475 Ma. Arc-continent collision can be constrained to *c*. 470 Ma in Northern Ireland. Eight new U-Pb ages from the arc-related intrusive suite range from 470.3 ± 1.9 to 464.9 ± 1.5 Ma and are associated with continued closure of the Iapetus Ocean.

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Figure Captions

Fig. 1 (a) Setting of the Tyrone Igneous Complex and other comparable ophiolite and volcanic arc associations in Britain and Ireland (after Hutton *et al.* 1985; Parnell *et al*. 2000: Chew *et al.* 2008). (b) Simplified regional geology of Newfoundland (after van Staal *et al*. 2007) (c) Early Mesozoic restoration of North Atlantic region and Appalachian-Caledonian orogen (after Pollock *et al.* 2009).

Fig. 2. Simplified geological map of the Tyrone Igneous Complex showing locations sampled or discussed in this study (after GSNI, 1979, 1983, 1995). Crosses and plus symbols mark sample locations of Draut *et al*. (2009) and the new analyses presented here. Copney Pillow Lava Formation and Rhyolite are divisions within the Tyrone Volcanic Group.

Fig. 3. Tectonostratigraphic evolution of the Tyrone Igneous Complex during the Ordovician. Stratigraphy after Cooper & Mitchell (2004), Cooper *et al.* (2008); Draut *et al*. (2009). The standard British Ordovician stages and the Australian graptolite zones are after Sadler *et al.* (2009). Biostratigraphic and U-Pb zircon ages: 1. Ca1 graptolite age of Cooper *et al.* (2008); 2. Formil Hill rhyolite of Cooper *et al.* (2008); 3. Scalp layered gabbro; 4. Laght Hill tonalite; 5. Pomeroy granite ; 6. Copney quartz porphyry; 7. Craigbardahessiagh granodiorite; 8. Slieve Gallion granite; 9. Golan Burn tonalite; 10. Creggانconroe quartz-monzodiorite; 11. Craigballyharky tonalite.

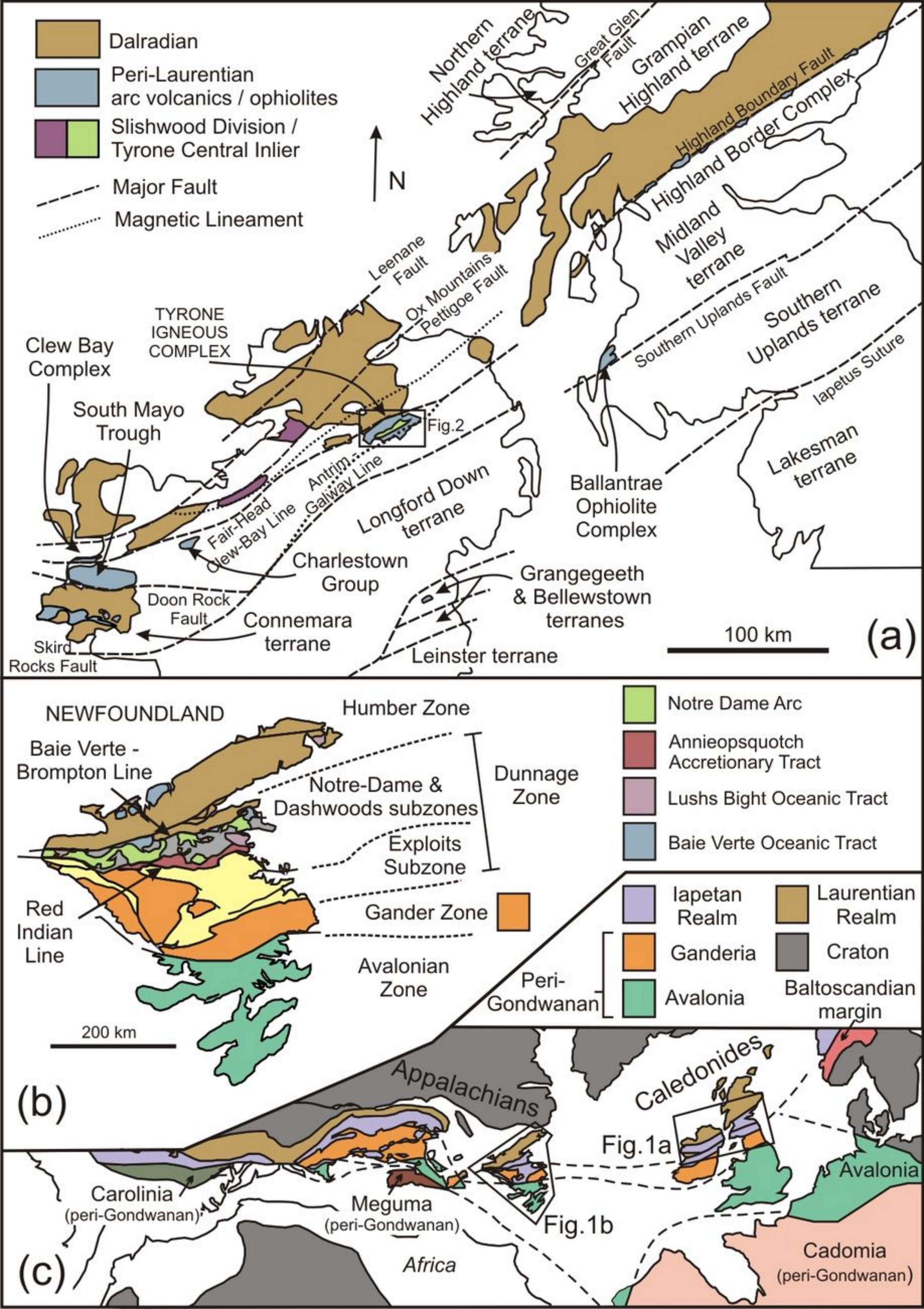
Fig. 4. Geochemical analyses from the Tyrone Igneous Complex; data of Draut *et al*. (2009) also included. Figure 4a Nb/Y v Zr/Ti after Winchester & Floyd (1977) modified by Pearce (1996). Figure 4b Th-Co plot after Hastie *et al*. (2007). Figure 4c Zr v Y after Barrett and MacLean (1999). Figure 4d Th/Yb v Nb/Yb after Pearce (1983). Calc-alk, calc-alkaline; e-MORB, enriched mid-ocean ridge basalt; MORB, mid-ocean ridge basalt; OIB, ocean-island basalt, IAT, island arc tholeiite; SHO, shonshonite.

Fig. 5. Multi-element variation diagrams for samples from the Tyrone Plutonic Group (Fig. 5a), Tyrone Volcanic Group (Fig. 5b,c) and arc-related intrusives (Fig. 5d).

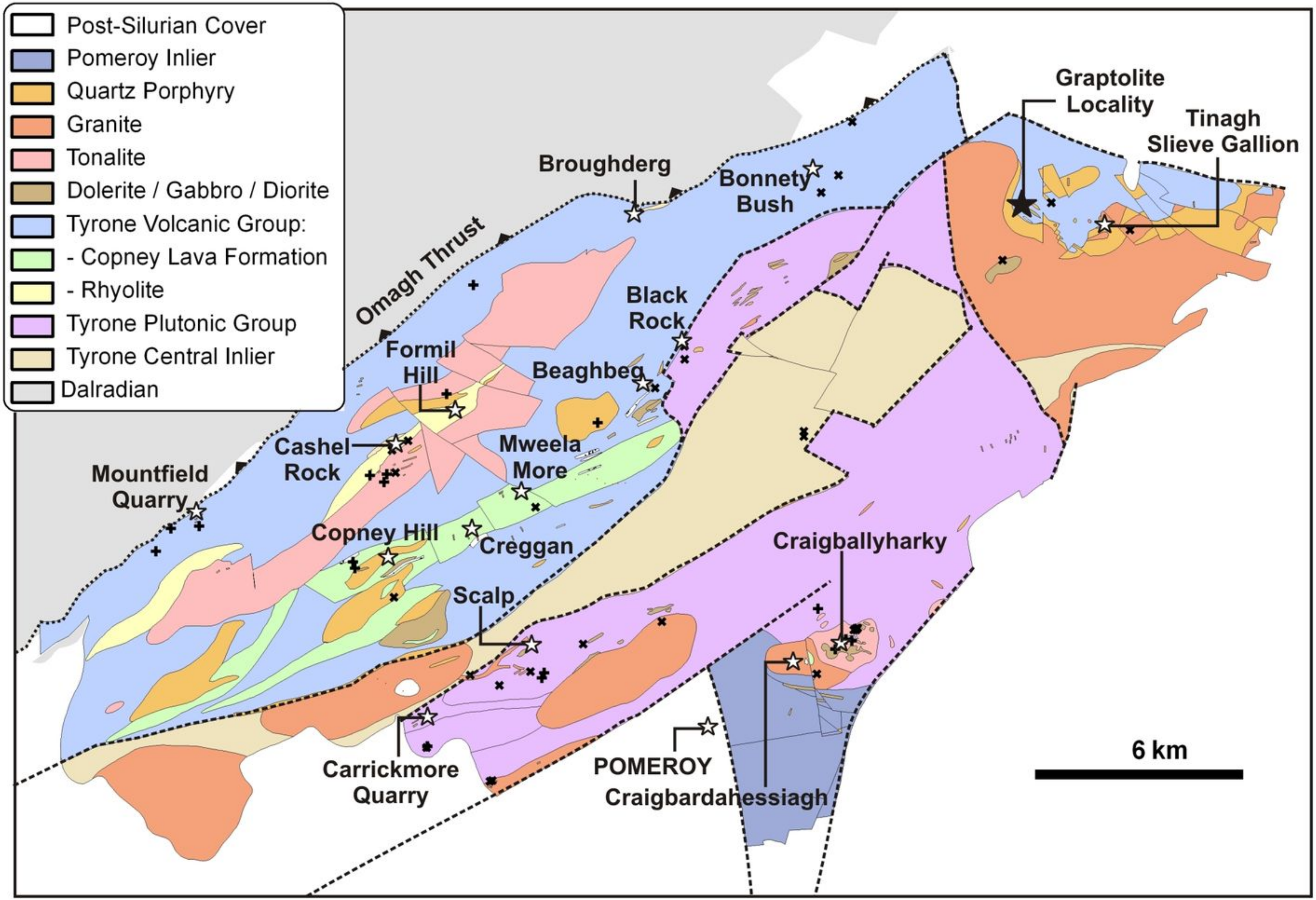
Shading reflects Draut *et al*. (2009) data for each respective group. Primitive mantle normalization values after Sun and McDonough (1989).

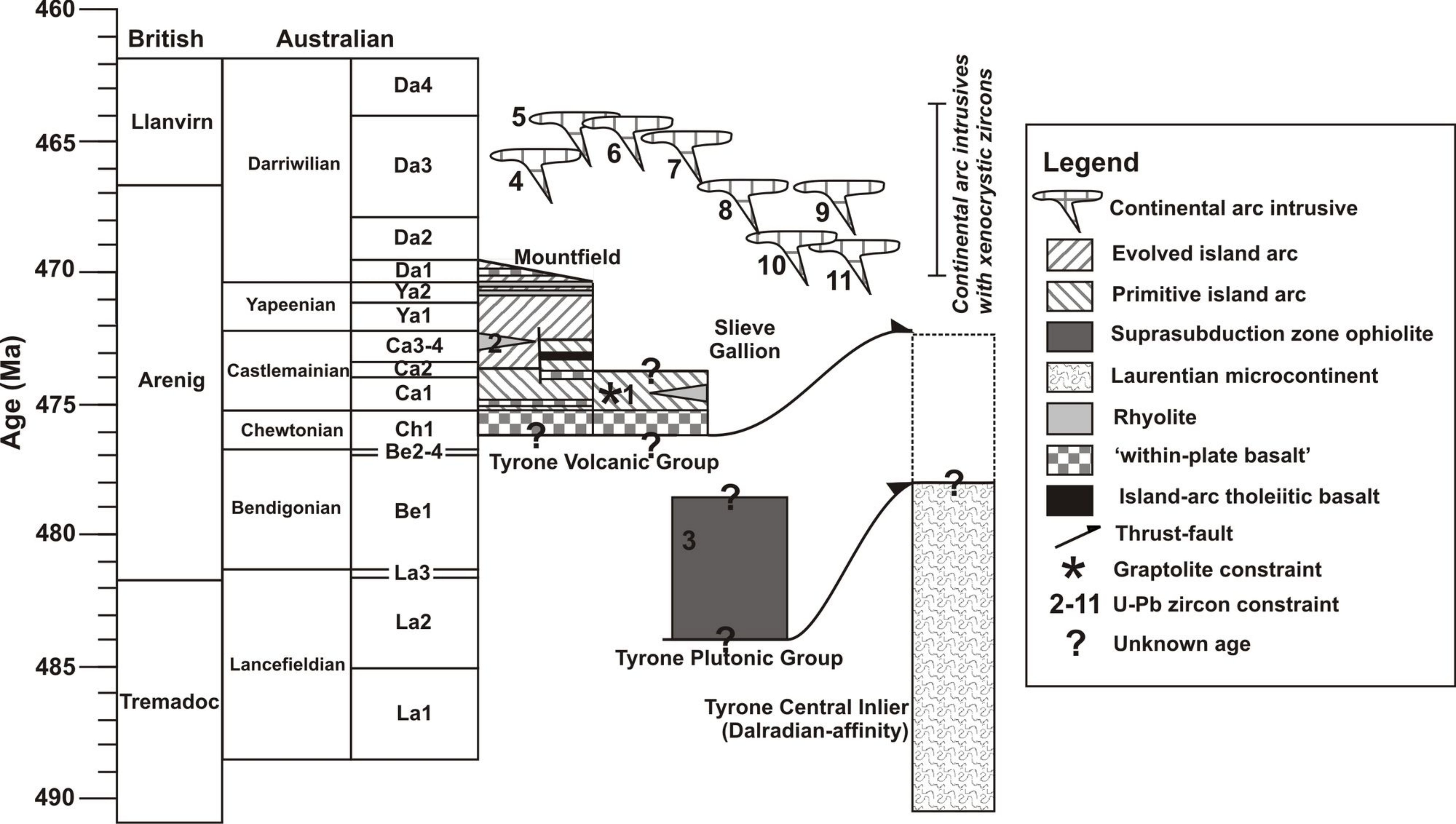
Fig. 6. $^{206}Pb/^{238}U$-$^{207}Pb/^{235}U$ concordia diagrams: (a) JTP207 Scalp layered gabbro. (b) JTP209 Laght Hill tonalite. (c) MRC89 Pomeroy granite. (d) MRC90 Copney quartz porphyry. (e and f) MRC91 Craigbardahessiagh granodiorite. (g and h) Slieve Gallion granite. (i) MRC126 Golan Burn tonalite. (j) MRC127 Cregganconroe quartz-monzodiorite. (k) Craigballyharky tonalite, with data of Hutton *et al*. (1985) also shown. All data-point error ellipses are 2σ.

Fig. 7. Tectonic model for the formation of the Tyrone Igneous Complex during the early Ordovician, illustrating contrasts with the Nafooey-Tourmakedy arc system of western Ireland. (a) Ophiolite exhumation in western Ireland occurs at *c*. 480 Ma, around the same time as maturation of the Nafooey arc and formation of the Tyrone Plutonic Group. (b) Formation of the Tyrone Volcanic Group occurs between >*c*. 475 Ma and 470 Ma, synchronous with arc-continent collision in western Ireland and development of the Tourmakeady Group. (c) Subduction polarity reversal in western Ireland occurs prior to *c*. 464 Ma. In Northern Ireland, arc-continent collision occurs prior to the intrusion of a suite of *c*. 470-464 Ma continental intrusives. Ages after Draut *et al.* (2004). Dewey (2005), Cooper *et al*. (2008), Chew *et al*. (2008, 2010). C.B.C, Clew Bay Complex; L.N.A, Lough Nafooey arc; S.M.T, South Mayo Trough; T.P.G, Tyrone Plutonic Group; T.V.G, Tyrone Volcanic Group.

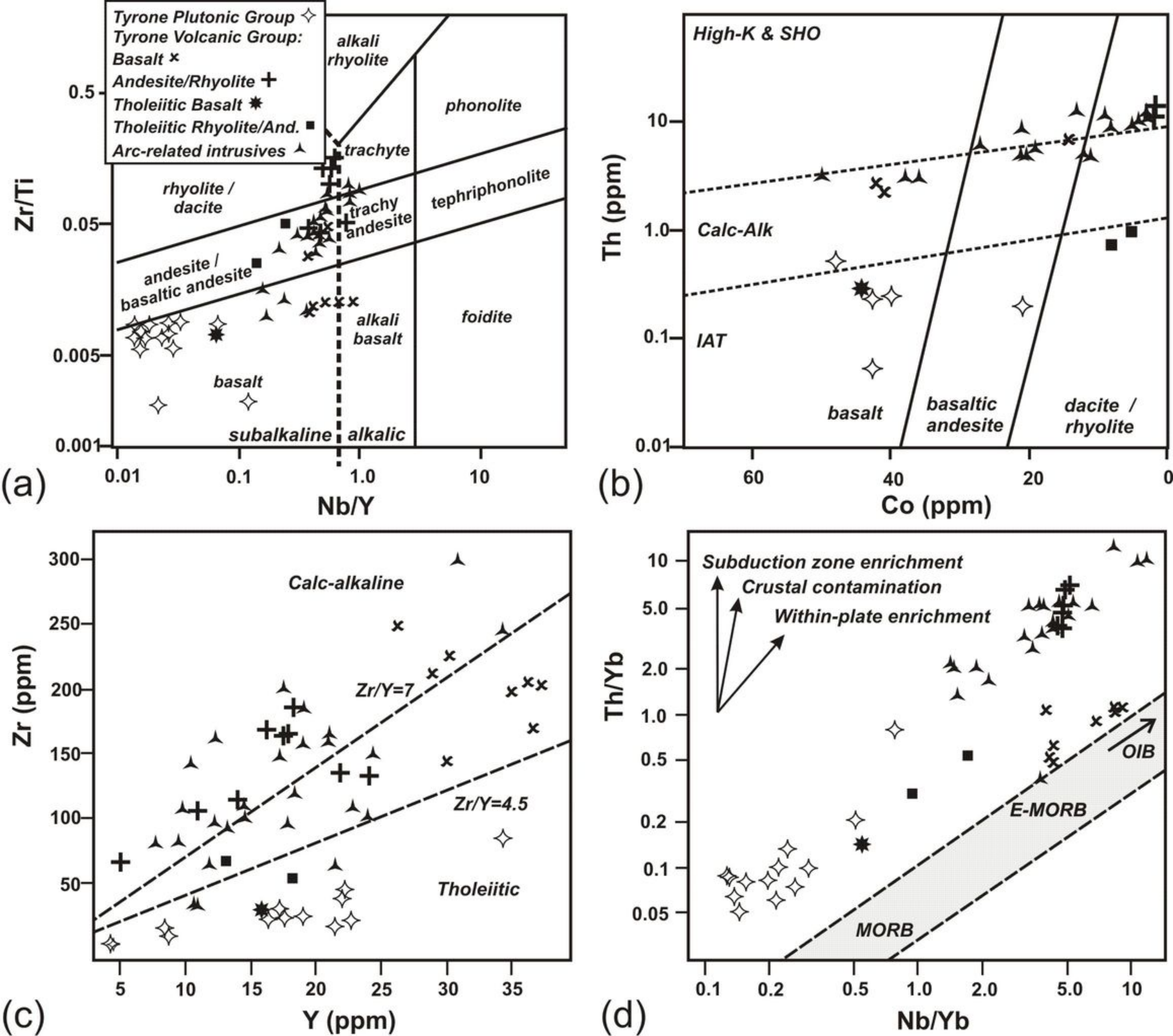


Dalradian
Peri-Laurentian arc volcanics / ophiolites
Slishwood Division / Tyrone Central Inlier
Major Fault
Magnetic Lineament
N
Northern Highland terrane
Great Glen Fault
Grampian Highland terrane
Highland Boundary Fault
Highland Border Complex
Midland Valley terrane
Southern Uplands Fault
Southern Uplands terrane
Iapetus Suture
Lakesman terrane
Leenane Fault
Ox Mountains Pettigoe Fault
TYRONE IGNEOUS COMPLEX
Clew Bay Complex
South Mayo Trough
Fig.2
Antrim - Galway Line
Fair-Head Clew-Bay Line
Longford Down terrane
Ballantrae Ophiolite Complex
Charlestown Group
Grangegeeth & Bellewstown terranes
Doon Rock Fault
Connemara terrane
Skird Rocks Fault
Leinster terrane
100 km
(a)
NEWFOUNDLAND
Humber Zone
Baie Verte - Brompton Line
Notre-Dame & Dashwoods subzones
Dunnage Zone
Exploits Subzone
Red Indian Line
Gander Zone
Avalonian Zone
200 km
Notre Dame Arc
Annieopsquotch Accretionary Tract
Lushs Bight Oceanic Tract
Baie Verte Oceanic Tract
Iapetan Realm
Laurentian Realm
Ganderia
Craton
Peri-Gondwanan
Avalonia
Baltoscandian margin
(b)
Appalachians
Caledonides
Fig.1a
Avalonia
Carolinia (peri-Gondwanan)
Meguma (peri-Gondwanan)
Fig.1b
Africa
Cadomia (peri-Gondwanan)
(c)

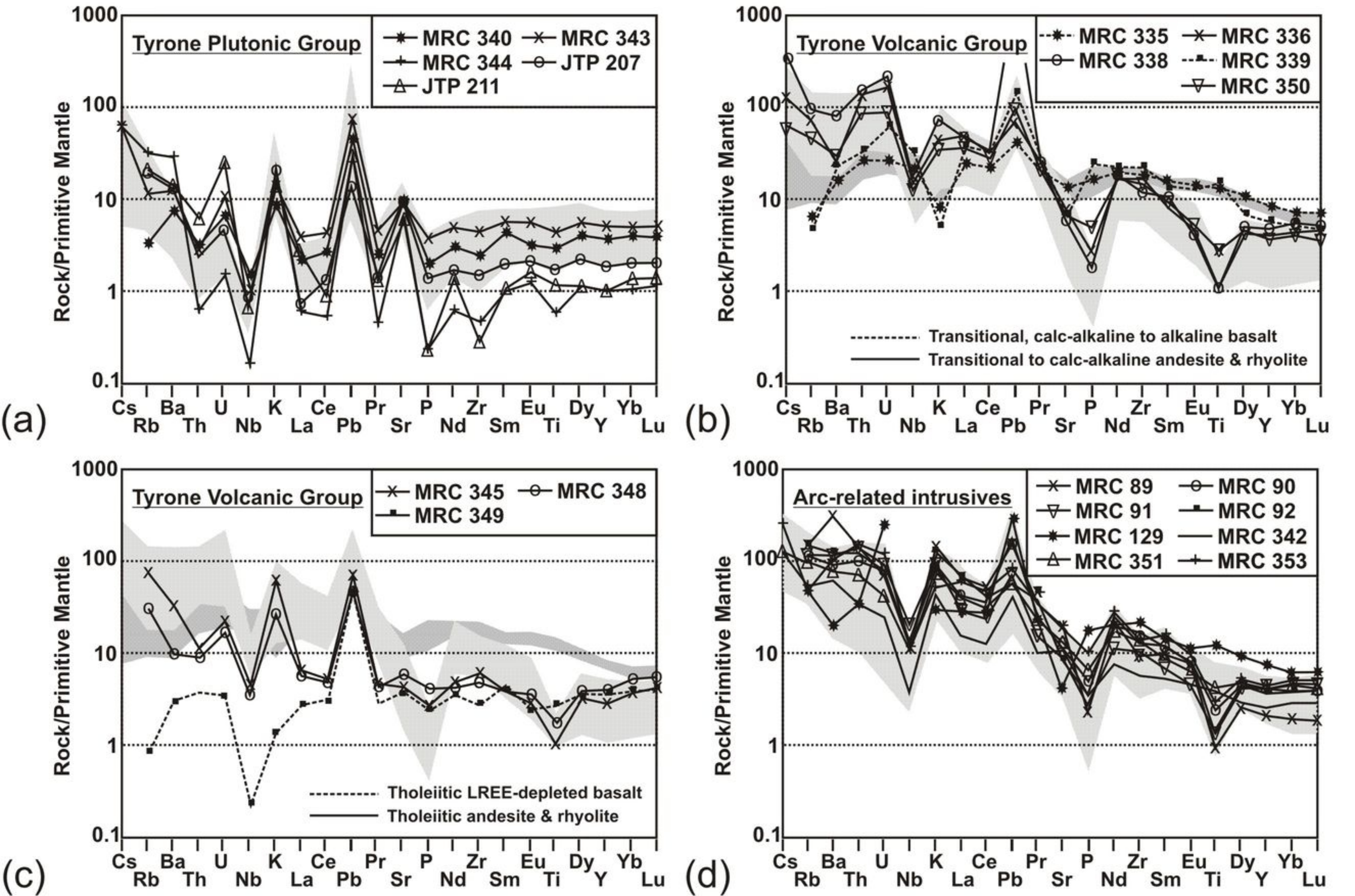

Post-Silurian Cover
Pomeroy Inlier
Quartz Porphyry
Granite
Tonalite
Dolerite / Gabbro / Diorite
Tyrone Volcanic Group:
- Copney Lava Formation
- Rhyolite
Tyrone Plutonic Group
Tyrone Central Inlier
Dalradian
Omagh Thrust
Broughderg
Bonnety Bush
Graptolite Locality
Tinagh Slieve Gallion
Black Rock
Formil Hill
Beaghbeg
Cashel Rock
Mweela More
Mountfield Quarry
Copney Hill
Creggan
Scalp
Craigballyharky
Carrickmore Quarry
POMEROY
Craigbardahessiagh
6 km

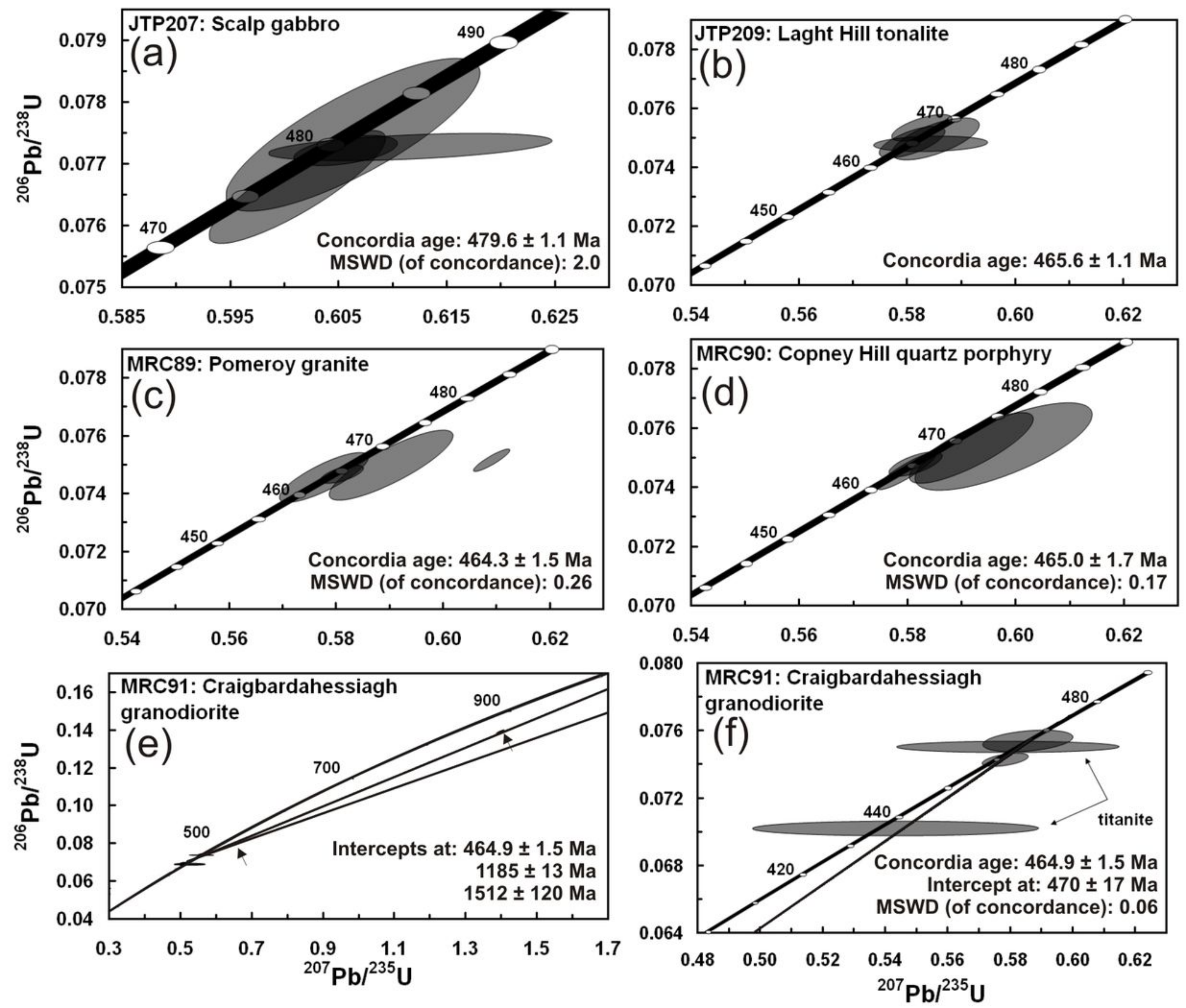


Age (Ma)
460
465
470
475
480
485
490
British
Australian
Llanvirn
Arenig
Tremadoc
Darriwilian
Yapeenian
Castlemainian
Chewtonian
Bendigonian
Lancefieldian
Da4
Da3
Da2
Da1
Ya2
Ya1
Ca3-4
Ca2
Ca1
Ch1
Be2-4
Be1
La3
La2
La1
Mountfield
Slieve Gallion
Tyrone Volcanic Group
Tyrone Plutonic Group
Tyrone Central Inlier (Dalradian-affinity)
Continental arc intrusives with xenocrystic zircons
Legend
Continental arc intrusive
Evolved island arc
Primitive island arc
Suprasubduction zone ophiolite
Laurentian microcontinent
Rhyolite
'within-plate basalt'
Island-arc tholeiitic basalt
Thrust-fault
Graptolite constraint
2-11 U-Pb zircon constraint
? Unknown age

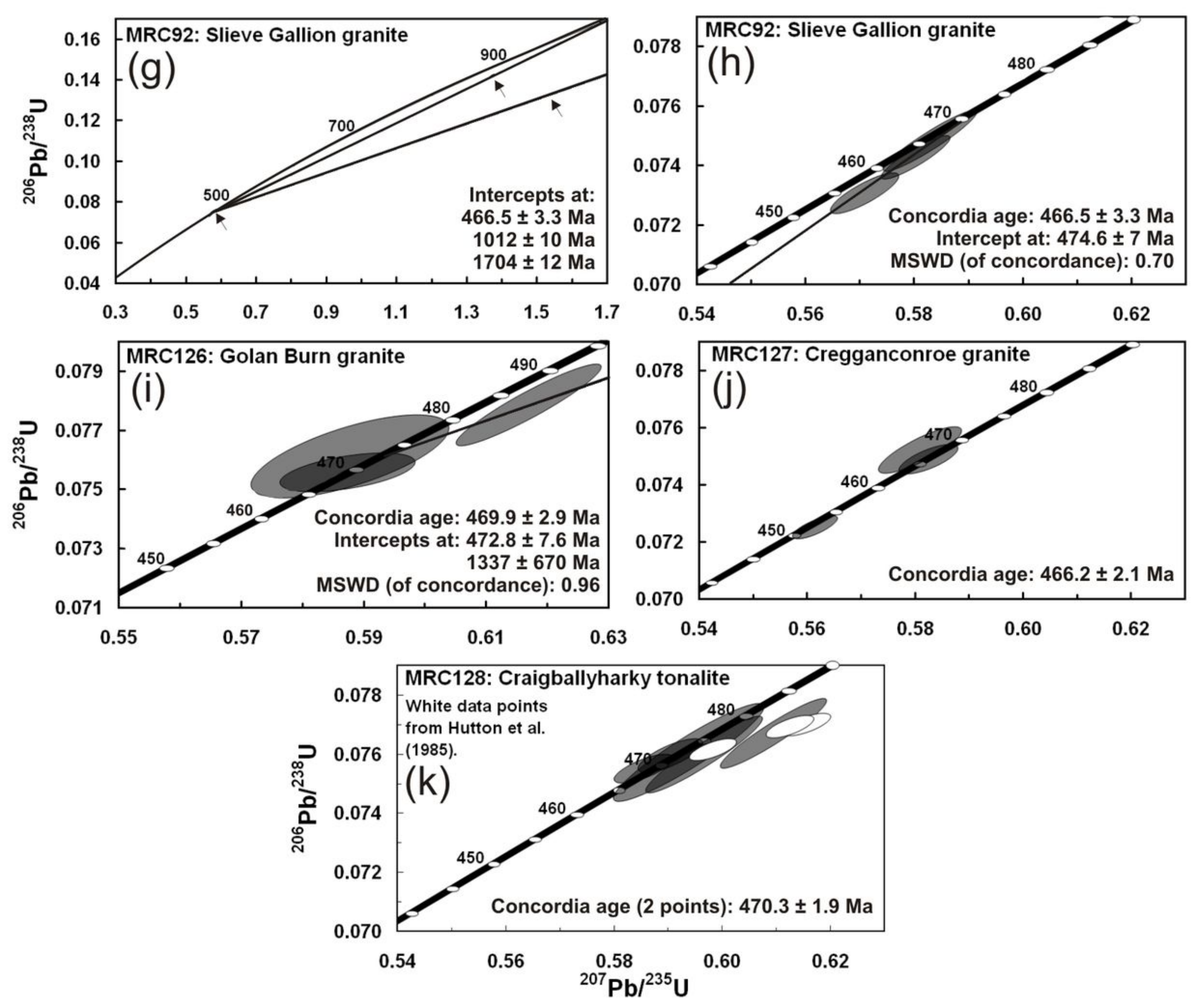


Tyrone Plutonic Group
Tyrone Volcanic Group:
Basalt
Andesite/Rhyolite
Tholeiitic Basalt
Tholeiitic Rhyolite/And.
Arc-related intrusives
alkali rhyolite
phonolite
trachyte
rhyolite / dacite
tephriphonolite
trachy andesite
andesite / basaltic andesite
alkali basalt
foidite
basalt
subalkaline
alkalic
Zr/Ti
0.5
0.05
0.005
0.001
0.01
0.1
1.0
10
Nb/Y
(a)
High-K & SHO
Calc-Alk
IAT
basalt
basaltic andesite
dacite / rhyolite
Th (ppm)
10
1.0
0.1
0.01
60
40
20
0
Co (ppm)
(b)
Calc-alkaline
Zr/Y=7
Zr/Y=4.5
Tholeiitic
Zr (ppm)
300
250
200
150
100
50
5
10
15
20
25
30
35
Y (ppm)
(c)
Subduction zone enrichment
Crustal contamination
Within-plate enrichment
OIB
E-MORB
MORB
Th/Yb
10
5.0
2.0
1.0
0.5
0.2
0.1
0.05
0.1
0.2
0.5
1.0
2.0
5.0
10
Nb/Yb
(d)


Tyrone Plutonic Group
MRC 340
MRC 343
MRC 344
JTP 207
JTP 211
Rock/Primitive Mantle
1000
100
10
1
0.1
Cs Rb Ba Th U Nb K La Ce Pb Pr Sr P Nd Zr Sm Eu Ti Dy Y Yb Lu
(a)
Tyrone Volcanic Group
MRC 335
MRC 336
MRC 338
MRC 339
MRC 350
Transitional, calc-alkaline to alkaline basalt
Transitional to calc-alkaline andesite & rhyolite
(b)
Tyrone Volcanic Group
MRC 345
MRC 348
MRC 349
Tholeiitic LREE-depleted basalt
Tholeiitic andesite & rhyolite
(c)
Arc-related intrusives
MRC 89
MRC 90
MRC 91
MRC 92
MRC 129
MRC 342
MRC 351
MRC 353
(d)



JTP207: Scalp gabbro
(a)
490
480
470
Concordia age: 479.6 ± 1.1 Ma
MSWD (of concordance): 2.0
JTP209: Laght Hill tonalite
(b)
480
470
460
450
Concordia age: 465.6 ± 1.1 Ma
MRC89: Pomeroy granite
(c)
480
470
460
450
Concordia age: 464.3 ± 1.5 Ma
MSWD (of concordance): 0.26
MRC90: Copney Hill quartz porphyry
(d)
480
470
460
450
Concordia age: 465.0 ± 1.7 Ma
MSWD (of concordance): 0.17
MRC91: Craigbardahessiagh granodiorite
(e)
900
700
500
Intercepts at: 464.9 ± 1.5 Ma
1185 ± 13 Ma
1512 ± 120 Ma
MRC91: Craigbardahessiagh granodiorite
(f)
480
440
420
titanite
Concordia age: 464.9 ± 1.5 Ma
Intercept at: 470 ± 17 Ma
MSWD (of concordance): 0.06
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$



MRC92: Slieve Gallion granite
(g)
900
700
500
Intercepts at:
466.5 ± 3.3 Ma
1012 ± 10 Ma
1704 ± 12 Ma
MRC92: Slieve Gallion granite
(h)
480
470
460
450
Concordia age: 466.5 ± 3.3 Ma
Intercept at: 474.6 ± 7 Ma
MSWD (of concordance): 0.70
MRC126: Golan Burn granite
(i)
490
480
470
460
450
Concordia age: 469.9 ± 2.9 Ma
Intercepts at: 472.8 ± 7.6 Ma
1337 ± 670 Ma
MSWD (of concordance): 0.96
MRC127: Cregganconroe granite
(j)
480
470
460
450
Concordia age: 466.2 ± 2.1 Ma
MRC128: Craigballyharky tonalite
White data points from Hutton et al. (1985).
(k)
480
470
460
450
Concordia age (2 points): 470.3 ± 1.9 Ma
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$

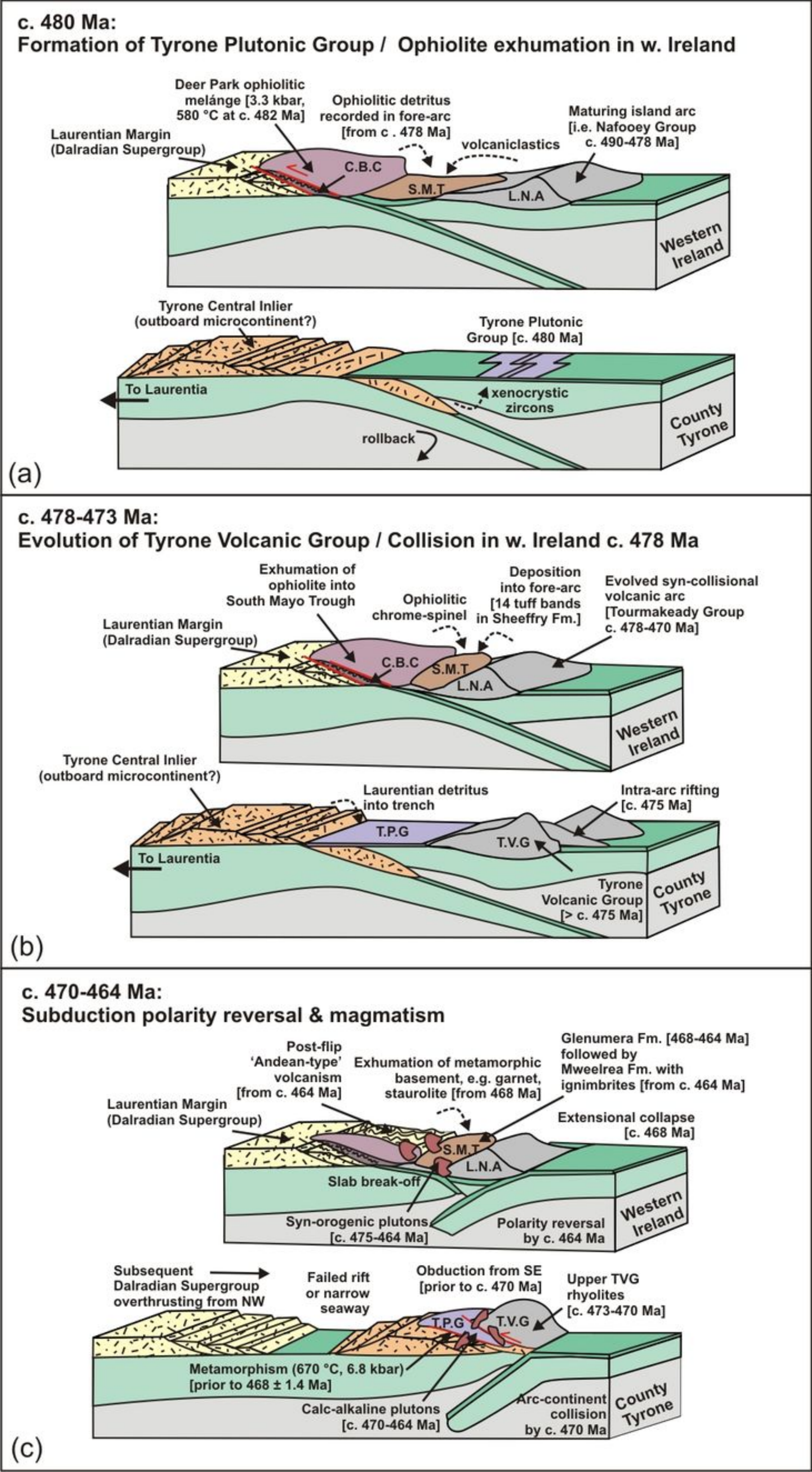

c. 480 Ma:
Formation of Tyrone Plutonic Group / Ophiolite exhumation in w. Ireland
Deer Park ophiolitic melánge [3.3 kbar, 580 °C at c. 482 Ma]
Ophiolitic detritus recorded in fore-arc [from c . 478 Ma]
Maturing island arc [i.e. Nafooey Group c. 490-478 Ma]
Laurentian Margin (Dalradian Supergroup)
volcaniclastics
C.B.C
S.M.T
L.N.A
Western Ireland
Tyrone Central Inlier (outboard microcontinent?)
Tyrone Plutonic Group [c. 480 Ma]
To Laurentia
xenocrystic zircons
rollback
County Tyrone
(a)
c. 478-473 Ma:
Evolution of Tyrone Volcanic Group / Collision in w. Ireland c. 478 Ma
Exhumation of ophiolite into South Mayo Trough
Ophiolitic chrome-spinel
Deposition into fore-arc [14 tuff bands in Sheeffry Fm.]
Evolved syn-collisional volcanic arc [Tourmakeady Group c. 478-470 Ma]
Laurentian Margin (Dalradian Supergroup)
C.B.C
S.M.T
L.N.A
Western Ireland
Tyrone Central Inlier (outboard microcontinent?)
Laurentian detritus into trench
Intra-arc rifting [c. 475 Ma]
T.P.G
T.V.G
To Laurentia
Tyrone Volcanic Group [> c. 475 Ma]
County Tyrone
(b)
c. 470-464 Ma:
Subduction polarity reversal & magmatism
Post-flip 'Andean-type' volcanism [from c. 464 Ma]
Exhumation of metamorphic basement, e.g. garnet, staurolite [from 468 Ma]
Glenumera Fm. [468-464 Ma] followed by Mweelrea Fm. with ignimbrites [from c. 464 Ma]
Laurentian Margin (Dalradian Supergroup)
Extensional collapse [c. 468 Ma]
S.M.T
L.N.A
Slab break-off
Syn-orogenic plutons [c. 475-464 Ma]
Polarity reversal by c. 464 Ma
Western Ireland
Subsequent Dalradian Supergroup overthrusting from NW
Failed rift or narrow seaway
Obduction from SE [prior to c. 470 Ma]
Upper TVG rhyolites [c. 473-470 Ma]
T.P.G
T.V.G
Metamorphism (670 °C, 6.8 kbar) [prior to 468 ± 1.4 Ma]
Calc-alkaline plutons [c. 470-464 Ma]
Arc-continent collision by c. 470 Ma
County Tyrone
(c)

Table 1. *U-Pb data for zircons and titanites from the intrusive suite, Tyrone Igneous Complex, Northern Ireland*

Zircon Fractions*	Wt (μg)†	U (ppm)†	Pb (ppm)†	Cm Pb (ppm)†	$^{206}Pb/^{204}Pb$§	$^{208}Pb/^{206}Pb$#	$^{206}Pb/^{238}U$#	$^{207}Pb/^{235}U$#	$^{207}Pb/^{206}Pb$#	$^{206}Pb/^{238}U$ age (Ma)	$^{207}Pb/^{206}Pb$ age (Ma)	ρ**
JTP207: Scalp Layered Gabbro												
1. 173-2 0NM, 1:1, 45 μm (1)	0.4	239.0	30.25	1	144.4	0.0462	0.1704±2.1	1.716±2.1	0.07305±0.84	1014.4±20.8	1015.2±17.1	0.92
2. 173-3 0NM, 2:1, 100 μm (1)	0.8	273.2	22.48	1	208.7	0.3326	0.07747±1.3	0.6063±1.6	0.05676±0.93	481.0±6.3	482.3±20.4	0.81
3. 173-4 0NM, 2:1, 80 μm (3)	1.9	301.1	27.65	1	293.5	0.4120	0.07662±0.98	0.6012±1.1	0.05691±0.55	475.9±4.7	487.8±12.2	0.86
4. 173-5 0NM, 2:1, 100 μm (1)	0.9	239.4	28.03	6	139.1	0.4796	0.07727±0.23	0.6116±1.7	0.05740±0.66	479.8±1.1	507.1±14.6	0.46
5. 173-6 0NM, 2:1, 80 μm (1)	0.6	173.7	65.03	1	258.7	0.3002	0.3279±1.1	5.743±1.1	0.1270±0.28	1828.3±20.1	2056.9±4.9	0.97
JTP209: Laght Hill Tonalite												
6. 209-2 0NM, 2:1, 80 μm (5)	23.2	235.5	21.11	7.3	352.9	0.1481	0.07478±0.28	0.5844±1.5	0.05668±1.5	463.6±1.3	479±33.5	0.18
7. 209-4 0NM, 2:1, 60-80 μm (9)	16.2	151.3	12.30	16	710.6	0.1568	0.07533±0.50	0.5828±0.80	0.05611±0.60	465.9±2.3	456.7±13.4	0.67
8. 209-6 0NM, 2:1-4:1, 50-70 μm (20)	2.8	561.7	47.76	15	501.8	0.1890	0.07484±0.58	0.5810±0.86	0.05630±0.63	462.6±2.6	464.4±14.0	0.67
9. 209-7 0NM, 2:1-4:1, 80-100 μm (7)	4.0	283.5	24.27	15	368.7	0.1681	0.07496±0.77	0.5853±1.2	0.05663±0.85	462.5±3.5	477.1±18.9	0.67
MRC89: Pomeroy Granite												
10. 89-1 0NM, 5:1, 100 μm (2)	3.2	380.1	35.31	15	391.2	0.3256	0.07458±0.95	0.5778±1.2	0.05619±0.69	459.4±4.3	459.8±15.4	0.81
11. 89-2 0NM, 5:1, 80 μm (2)	1	854.6	83.49	15	278.8	0.3608	0.07501±1.3	0.5904±1.6	0.05709±0.86	460.3±5.9	494.9±19.1	0.85
12. 89-6 0NM, 2:1, 60 μm (6)	8.3	292.9	24.86	9	1256	0.2265	0.07517±0.41	0.6092±0.46	0.05878±0.20	465.4±1.9	558.9±4.4	0.90
13. 89-7 0NM, cl, 3:1, 40-60 μm (10)	4.3	348.8	30.47	7	1006	0.2677	0.07469±0.35	0.5811±0.56	0.05642±0.42	462.8±1.6	469.1±9.3	0.66
MRC90: Copney Quartz Porphyry												
14. 90-1 0NM, 3:1, 60-70 μm (5)	5.3	127.6	13.52	18	193.9	0.3909	0.07545±1.6	0.5978±2.2	0.05747±1.5	461.7±7.2	509.4±33.3	0.73
15. 90-2 0NM, 3:1, 60-70 μm (5)	6.4	135.6	13.34	16	278.5	0.3588	0.07540±1.3	0.5918±1.6	0.05693±0.90	462.7±5.9	488.9±20.0	0.82
16. 90-4 0NM, 3:1, 80 μm (3)	5.1	135.1	12.73	5	666.8	0.3496	0.07485±0.45	0.5815±0.68	0.05635±0.50	463.3±2.0	466.1±11.1	0.67
17. 90-5 0NM, 3:1, 80 μm (3)	5.3	162.3	14.75	6	747.3	0.3493	0.07462±0.69	0.5799±0.78	0.05636±0.34	460.8±3.1	466.8±7.5	0.90
MRC91: Craigbardahessiagh Granodiorite												
18. 91-3 0NM, mi, 5:1, 70-100 μm (5)	9	185.5	16.69	7	1080	0.3351	0.07395±0.44	0.5760±1.0	0.05650±0.89	458.0±2.0	471.9±19.8	0.52
19. 91-4 0NM, 5:1, 70-100 μm (5)	11	150.1	15.26	35	240.1	0.2862	0.07503±0.69	0.5831±2.0	0.05636±1.8	463.3±3.1	466.6±40.4	0.35
20. 91-5 0NM, 1:1-2:1, 60-80 μm (6)	5.4	219.1	31.92	13	817.4	0.1260	0.1390±0.55	1.405±0.60	0.07334±0.23	834.7±4.3	1023.2±4.7	0.93
21. 91-6 Titanite	138	256.0	35.42	1420	130.5	0.4523	0.07471±0.37	0.5769±4.9	0.05600±4.9	462.8±1.7	452±112	0.02
22. 91-7 Titanite	47.1	190.4	28.35	490	98.50	0.5466	0.06999±0.49	0.5417±6.8	0.05614±6.8	434.0±2.1	458±158	0.02
23. 91-8 0NM, 3:1, 80 μm (6)	3.3	216.2	21.17	6	578.9	0.2883	0.08112±0.59	0.6759±0.85	0.06042±0.59	500.0±2.9	618.8±12.8	0.72
MRC92: Slieve Gallion Granite												
24. 92-1 0NM, 2:1, 100 μm (1)	7	347.0	47.92	12	1869	0.0582	0.1417±0.33	1.374±0.36	0.07031±0.15	851.6±2.6	937.4±3.1	0.92
25. 92-2 0NM, 2:1, 80 μm (2)	6.3	228.7	20.03	13	510.6	0.2745	0.07434±0.81	0.5804±0.91	0.05662±0.40	458.6±3.6	476.8±8.9	0.90
26. 92-3 0NM, 4:1, 80 μm (3)	4.7	213.3	18.50	12	409.6	0.2596	0.07490±1.1	0.5830±1.2	0.05645±0.42	460.6±4.9	470.1±9.3	0.94
27. 92-4 0NM, 2:1, 60-80 μm (5)	4.8	321.9	28.35	15	473.0	0.2861	0.07313±0.77	0.5710±0.91	0.05663±0.49	451.6±3.4	477.1±10.9	0.84
28. 92-6 0NM, 1:1-2:1, 70-100 μm (8)	11.6	253.7	36.69	14	1749	0.1639	0.1326±0.30	1.538±0.36	0.08410±0.20	800.4±2.3	1294.9±3.9	0.84
29. 92-7 0NM, 1:1-2:1, 60-80 μm (12)	14.3	227.7	22.11	19	937.2	0.2107	0.08719±0.49	0.8022±0.54	0.06673±0.22	536.4±2.5	829.5±4.6	0.92
MRC126: Golan Burn Tonalite												
30. 126-1 0NM, 2:1-3:1, 80-100 μm (5)	5.2	103.2	10.73	14	196.2	0.3392	0.07607±1.5	0.5977±2.3	0.05603±1.7	465.8±6.8	453.5±38.2	0.68
31. 126-4 0NM, i, 5:1, 100 μm (6)	12.4	91.5	8.47	17	351.4	0.3044	0.07781±1.5	0.6169±1.6	0.05750±0.56	476.1±7.0	510.9±13.4	0.93

32. 126-5 0NM, i, 5:1, 100 µm (6)	13.8	87.8	8.4	15	537.9	0.3207	0.07554±0.70	0.5874±1.5	0.05640±1.3	466.3±3.2	468±29.1	0.53
MRC127: Cregganconroe Quartz-monzodiorite												
33. 127-2 0NM, 1:1-2:1, 40-60 µm (12)	7.4	207.3	18.71	14	537.9	0.2788	0.07497±0.56	0.5827±0.77	0.05637±0.52	463.5±2.5	467.1±11.6	0.73
34. 127-3 0NM, i, f, 6:1, 150-200 µm (5)	6.4	310.6	26.52	12	742.1	0.2706	0.07259±0.46	0.5617±0.60	0.05612±0.38	449.7±2.0	457.0±8.5	0.77
35. 127-4 0NM, i, f, 6:1, 150-200 µm (6)	8	242.1	22	21	450.1	0.2986	0.07529±0.89	0.5811±1.1	0.05598±0.60	463.9±4.0	451.5±13.4	0.83
MRC128: Craigballyharky Tonalite												
36. 128-1 0NM, 1:1-2:1, 70-90 µm (4)	15.2	92.5	8.65	11	614.4	0.3332	0.07598±0.61	0.5905±0.83	0.05637±0.54	469.3±2.8	466.8±12.0	0.76
37. 128-2 0NM, 1:1-2:1, 40-60 µm (12)	12	77.6	7.17	20	240.5	0.2778	0.07608±1.8	0.5939±1.9	0.05661±0.72	464.5±8.2	476.6±16.0	0.93
38. 128-3 0NM, i, f, 4:1, 200 µm (3)	14.9	81.8	7.43	17	358.8	0.3078	0.07601±1.4	0.5967±1.5	0.05693±0.49	465.9±6.4	488.9±10.9	0.94
39. 128-4 0NM, i, 4:1 200 µm (3)	16.8	97.4	8.61	12	643.5	0.2580	0.07553±0.54	0.5856±0.76	0.05623±0.52	466.9±2.5	461.3±11.6	0.73
40. 128-5 0NM, i, f, 5:1, 100-150 µm (6)	15.1	95.2	8.93	19	382.7	0.3222	0.07674±1.3	0.6096±1.3	0.05761±0.43	470.7±6.0	515.0±9.5	0.94

Notes: ***** Zircon grain characteristics specified as: x°N = non-magnetic, at specified tilt angle on a Frantz LB-1 Separator at 1.7 amps; mi = abundant melt inclusions, i = opaque inclusions: X:1 = aspect ratios of grains; lengths of grains in µm, number of grains analysed in ( ). **†** Maximum errors are ±20%. Weights were measured on a Cahn C32 microbalance. § Measured ratio corrected for fractionation and spike Pb. **#** Corrected for fractionation, spike, laboratory blank Pb and U, and initial common Pb estimated from Stacey & Kramers, 1975. Laboratory blank Pb composition is $^{206}Pb/^{204}Pb:^{207}Pb/^{204}Pb:^{208}Pb/^{204}Pb$ = 18.19:15.58:38.50. Quoted errors are 2σ (% for atomic ratios, absolute for ages). ****** $^{207}Pb/^{235}U$ – $^{206}Pb/^{238}U$ error correlation coefficient calculated following Ludwig (2003).

Table 2. *Calculated U-Pb zircon ages and additional information for analysed samples. Previously published U-Pb geochronology for Tyrone Igneous Complex also included.*

Lithological Unit	Age (Ma)	Calculated On	Additional Information
Scalp Layered Gabbro (JTP207)	479.6 ± 1.1	Three concordant zircon analyses	Two zircon fractions gave inherited ages of *c*. 1015 Ma (concordant) and 2100 Ma (upper intercept anchored at 479.6 Ma).
Laght Hill Tonalite (JTP209)	465.6 ± 1.1	Four concordant analyses	This tonalite provided a low yield of inheritance free zircon.
Golan Burn Tonalite (MRC126)	469.9 ± 2.9	Two concordant zircon analyses	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 shows a small degree of inheritance.
Cregganconroe Quartz-monzodiorite (MRC127)	466.2 ± 2.1	Two concordant zircon analyses	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.
Craigballyharky Tonalite (MRC128)	470.3 ± 1.9	Two concordant zircon analyses	These new data are consistent with that 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 *c*. 2100 Ma.
Pomeroy Granite (MRC89)	464.3 ± 1.5	Two concordant zircon analyses.	The zircons analysed are predominantly acicular neocrystalline with rare visible inherited cores.
Copney Quartz Porphyry (MRC90)	465.0 ± 1.7	Two concordant zircon analyses.	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 *c*. 2150 Ma.
Craigbardahessiagh Granodiorite (MRC91)	464.9 ± 1.5	One analysis each of titanite and zircon are concordant	Zircons show both inheritance and Pb-loss, while some titanites analysed exhibit Pb loss. Most data plot near 465 Ma on the concordia diagram, but two zircon analyses show a significant Mesoproterozoic (*c*. 1185 - 1512 Ma) inherited component.
Slieve Gallion Granite (MRC92)	466.5 ± 3.3	One concordant analysis	This granite contains both core-free zircons and those with clearly visible cores. Two analyses of inherited zircons have Mesoproterozoic ages from *c*. 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.
Previous Geochronology:			
Leaghan tonalite of Draut *et al*. (2009)	475 ± 10	Ten zircon analyses	U-Pb zircon SHRIMP. Archaean cores identified in three zircon grains using SHRIMP and LA-MC-ICP-MS.
Craigballyharky Gabbro of Draut *et al*. (2009)	493 ± 2	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 *c*. 470 Ma were attributed to contamination.
Formil Rhyolite of Cooper *et al*. (2008)	473.0 ± 0.8	Three concordant zircon analyses.	U-Pb zircon TIMS. No inheritance noted by authors.
Craigballyharky Tonalite of Hutton *et al*. (1985)	471+2-4 Ma	Three zircon size fractions.	U-Pb zircon 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.