The tectonothermal evolution and provenance of the Tyrone Central Inlier, Ireland: Grampian imbrication of an outboard Laurentian microcontinent?

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Abstract: The Tyrone Central Inlier is a metamorphic terrane of uncertain affinity situated outboard of the main Dalradian outcrop (south of the Fair Head–Clew Bay Line) and could represent sub-arc basement to part of the enigmatic Midland Valley Terrane. Using a combination of isotopic, structural and petrographic evidence, the tectonothermal evolution of the Tyrone Central Inlier was investigated. Sillimanite-bearing metamorphic assemblages (c. 670 °C, 6.8 kbar) and leucosomes in paragneisses are cut by granite pegmatites, which post-date two deformation fabrics. The leucosomes yield a weighted average 207Pb/206Pb zircon age of 467 ± 12 Ma whereas the main fabric yields a 40Ar–39Ar biotite cooling age of 468 ± 1.4 Ma. The pegmatites yield 457 ± 7 Ma and 458 ± 7 Ma Rb–Sr muscovite–feldspar ages and 40Ar–39Ar step-heating plateaux of 466 ± 1 Ma and 468 ± 1 Ma, respectively. The metasedimentary rocks yield Palaeoproterozoic Sm–Nd model ages and laser ablation inductively coupled plasma mass spectrometry detrital zircon U–Pb analyses from a psammitic gneiss yield age populations at 1.05–1.2, 1.5, 1.8, 2.7 and 3.1 Ga. Combined, these data permit correlation of the Tyrone Central Inlier with either the Argyll or the Southern Highland Group of the Dalradian Supergroup. The inlier was thus part of Laurentia onto which the Tyrone ophiolite was obducted.

The Grampian (= Taconian) orogeny resulted from the Early to Middle Ordovician collision of the Laurentian passive margin with an outboard volcanic arc terrane and an associated suprasubduction-zone ophiolite (e.g. Williams & Stevens 1974; Dewey & Shackleton 1984). Recent structural and geochronological studies relating to this orogenic episode have emphasized the role that microcontinental indenters play in arc–continent collisions. Examples include the Sliedrecht Division in western Ireland (Flowerdew et al. 2005), the Dashwoods block in Newfoundland (Waldron & van Staal 2001; Cawood et al. 2001) and elements of the Helgeland nappe complex in central Norway (Yoshinobu et al. 2002). In each of these examples, the microcontinental indenter was incorporated into an outboard arc terrane prior to final accretion onto the Laurentian margin.

In this study, the provenance and tectonic evolution of the Tyrone Central Inlier (Hartley 1933), a high-grade metasedimentary terrane of hitherto uncertain affinity, is investigated using a combination of petrography, mineral chemical analyses and isotopic evidence. We suggest that it may represent an outboard segment of the Laurentian passive margin, which was incorporated into an outboard volcanic arc terrane prior to accretion onto the Laurentian margin during Grampian orogenesis. This model could also imply that the Tyrone Central Inlier represents sub-arc basement to the along-strike continuation of this volcanic arc terrane, the cryptic Midland Valley Terrane of Scotland.

The Grampian orogeny and the Midland Valley Terrane in Ireland

The orthotectonic Caledonides (Dewey 1969) of Scotland consist of a series of pervasively deformed metasedimentary rocks (the Moine and Dalradian Supergroups; Fig. 1a) and associated basement inliers. The Moine Supergroup and the lower portions of the Dalradian Supergroup have been interpreted as Neoproterozoic intracratonic rift basins (e.g. Dalziel & Soper 2001) or successor basins to the Grenville orogen (Kirkland et al. 2007), with the younger parts of the Dalradian sequence recording the transition to sedimentation on the Laurentian passive continental margin (Dewey 1969). The orogenic episode affecting the orthotectonic Caledonides was termed the Grampian orogeny by Lambert & McKerrow (1976). This orogenic event is now accepted as Early Ordovician in age (e.g. Soper et al. 1999), with peak metamorphism dated at 470 Ma (Oliver et al. 2000; Friedrich et al. 1999a).

The Grampian orogeny is thought to have resulted from the Early Ordovician collision of the rifted Laurentian margin with an outboard arc terrane located to the present-day SE (e.g. Dewey & Shackleton 1984; Van Staal et al. 1998; Dewey & Mange 1999). In Scotland, the suture between the deformed Laurentian margin and the colliding arc terrane is sharply defined by the Highland Boundary Fault (Fig. 1a), which separates Dalradian Supergroup rocks from Late Palaeozoic rocks to the SE. Ophiolitic rocks of the Ordovician Highland Border Complex crop out as a series of poorly exposed fault-bound slivers.
within this fault zone (Tanner & Sutherland 2007). The continuation of the Highland Boundary Fault in Ireland is referred to as the Fair Head–Clew Bay Line and is defined by a conspicuous magnetic lineation (Max & Riddihough 1975), which runs from Fair Head in northeastern Ireland to the north shore of Clew Bay on the west coast (Fig. 1b). The major surface expression is a fault zone that in general lies about 10 km to the south of the magnetic lineament (Fig. 1b). The fault zone generally separates the Dalradian from the Irish correlative of the Highland Border Complex (the Clew Bay Complex) and an outboard volcanic arc terrane to the SE. The outboard volcanic arc terrane is represented by the Tyrone Igneous Complex in the central part of the north of Ireland, and by the Lower Ordovician Lough Nafooey Group and its associated forearc fill, the Lower to Middle Ordovician Murrisk Group of the South Mayo Trough in western Ireland (Fig. 1b). Additionally, unlike the Scottish orthotectonic Caledonides, high-grade polyphase deformed metamorphic rocks crop out to the SE (i.e. outboard) of the main belt of Dalradian outcrop (Fig. 1b).

Because of their anomalous position, the affinity and tectonic setting of these displaced terranes (Connemara, the Slishwood Division and the Tyrone Central Inlier; Fig. 1b) are of great importance to our understanding of the tectonic evolution of the Grampian orogenic belt. The allochthonous relationship of the Connemara Dalradian to the rest of the Dalradian outcrop is believed to be a result of post-Grampian sinistral strike-slip movement (Dewey & Shackleton 1984). In contrast, the mainly metasedimentary Slishwood Division displays an early metamorphic history that has not been observed in the Dalradian rocks of NW Ireland. Metabasites of the Slishwood Division record pre-Grampian eclogite-facies metamorphism and later high-pressure granulite-facies events (605–540 Ma Sm–Nd garnet ages, Sanders et al. 1987; Flowerdew & Daly 2005). Additionally, these high-grade fabrics are cut by early Grampian tonalite intrusions, which are restricted to the Slishwood Division outcrop (U–Pb SIMS zircon ages of 472 ± 6 Ma and 467 ± 6 Ma, Flowerdew et al. 2005). The Tyrone Central Inlier has long been regarded as a potential correlative of the Slishwood Division (Cole 1900; Daly 2001) because of a combination of lithological similarity and a similar tectonic position, although the Slishwood Division has also been suggested as a Dalradian correlative (Sanders 1994). However, the affinity and tectonic
setting of the high-grade metasedimentary gneisses of the Tyrone Central Inlier remains uncertain. The possibility that it represents exhumed basement of a portion of the elusive Midland Valley Terrane is now explored in detail.

Geological setting of the Tyrone Inlier

The Tyrone Inlier consists of three units. The structurally lowest unit, the Tyrone Central Inlier, consists predominantly of a series of high-grade psammitic paragneisses (Hartley 1933). These gneissose metasediments are in tectonic contact with the other two units, the Tyrone Plutonic Group and the Tyrone Volcanic Group, with the exception of the extreme southern margin of the inlier where the paragneisses are unconformably overlain by Devonian clastic sediments (Fig. 1c). The Tyrone Plutonic Group, the Tyrone Volcanic Group and the arc-related intrusive rocks that cut them (Fig. 1c) are together referred to as the Tyrone Igneous Complex (Cooper & Mitchell 2004). To the north of the inlier, greenschist- to lower amphibolite-facies Dalradian metasediments are separated from the Tyrone Volcanic Group by the Omagh Thrust (Fig. 1c).

The basic plutonic igneous rocks of the Tyrone Plutonic Group (Cooper & Mitchell 2004) consist of gabbros that exhibit cumulate layering overlain by a sheeted dyke complex with rare pillow lavas. The Tyrone Plutonic Group was interpreted as an ophiolite by Hutton et al. (1985), which has been intruded by a number of granitic plutons. One of these, the Craigballyharky tonalite (Fig. 1c), has yielded a 471 +2/-3 Ma U–Pb zircon age (Hutton et al. 1985). The tonalite exhibits magma mixing textures with the basic country rocks, suggesting that the tonalite was intruded into the ophiolite while the oceanic crust was still hot. Hutton et al. (1985) suggest that the magma mixing textures imply that the age of emplacement of the tonalite approximates the age of ocean floor metamorphism of the ophiolite (Hutton et al. 1985). Zircons from the Craigballyharky tonalite have also yielded a Palaeoproterozoic (c. 2 Ga) upper intercept age (Hutton et al. 1985). It is possible that this presumed detrital component is derived from the paragneisses of the Tyrone Central Inlier, which lie structurally beneath the ophiolite. Hutton et al. (1985) suggest that the presence of this inherited detrital component implies that the ophiolite was thrust over the Laurentian margin prior to tonalite intrusion at c. 471 Ma.

The predominantly extrusive rocks of the Tyrone Volcanic Group consist of basaltic pillow lavas and andesitic to rhyolitic lavas of presumed arc affinity (Cooper & Mitchell 2004 and references therein). Associated with these extrusive rocks are volcaniclastic rocks with local chert and mudstone horizons. The mudstone units associated with the volcanic series have yielded graptolite fragments originally interpreted as Llandeilo–Caradoc in age (Hartley 1936). Subsequent reinvestigation of the same locality by Hutton & Holland (1992) yielded an Arenig–Llanvirn graptolite fauna. More recently, Cooper et al. (2008) document the presence of *Isograpthus victoriae lunatus* in graptolitic mudstones from Slieve Gullion, along with a U–Pb zircon age of 473 ± 0.8 Ma for an extrusive rhyolite that sits stratigraphically below the graptolitic mudstones. *Isograpthus victoriae lunatus* is the index fossil of the *victoriae lunatus* graptolite zone, and indicates a correlation with the Australasian Castlemainian (Ca1) Stage. The U–Pb isotopic and biostratigraphical age constraints match closely with the interpolated age for the base of the Middle Ordovician (471.8 ± 0.8 Ma, Cooper & Sadler 2004).

Field relationships within the Tyrone Central Inlier

Structure and metamorphism

The Tyrone Central Inlier is composed of psammitic and semipelitic paragneisses, which are cut by various acidic intrusive rocks. Further subdivision of these gneissic rocks is hampered by a combination of poor exposure and a lack of lithological diversity. The paragneisses have experienced polyphase deformation. An early, bedding-parallel S1 foliation is folded by tight to isoclinal F1 folds (Fig. 2a). An axial-planar S2 foliation is well developed in the F2 fold hinges, but is commonly co-planar to bedding and S1 on the F2 fold limbs. Hence at many localities and in thin section, only one foliation (regarded as an S1–S2 composite foliation) may be recognized. This main fabric is typically subhorizontal, and usually dips shallowly to the NW. Locally developed small-scale, upright F2 folds affect the main fabric and are associated with the development of a S3 crenulation cleavage.

In contrast to both the Dalradian Supergroup of NW Ireland and the Slishwood Division, no metamorphosed basic rocks have been recorded within the Tyrone Central Inlier. Therefore the metamorphic grade is based entirely on assemblages observed within metasedimentary lithologies. A prograde assemblage of biotite + plagioclase + sillimanite + quartz ± muscovite ± garnet is typically observed in pelitic lithologies. Cordierite has also been observed locally (Hartley 1933). The absence of K-feldspar suggests that the second sillimanite isograd has not been reached, and hence the limited amount of prograde muscovite is probably due to it having been consumed at lower grades.

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Fig. 2. Field photographs from Corvanaghan Quarry [H719813] in the Tyrone Central Inlier showing (a), patchy, biotite-rich leucosome cutting a tight second-generation fold and (b), coarse muscovite-bearing pegmatite cutting earlier stictolith (fleck) leucosomes. Lens cap is 6 cm across.
Field relationships of the minor igneous intrusive rocks

The main (composite S1–S2) upper amphibolite-facies fabric in the Tyrone Central Inlier is cut by a variety of minor acidic igneous intrusive rocks. These are best seen at Corvanaghan Quarry [H719813] where the exposure is relatively fresh. Here, quartz–plagioclase leucosomes up to 10 cm wide contain biotite-rich patches up to 5 cm across that are observed to cut the S2 fabric in dark psammitic gneisses (Fig. 2a). These leucosomes are in turn cut by muscovite-bearing pegmatites (Fig. 2b). At other localities in the Central Inlier, the main high-grade fabric is cut by both quartz–K-feldspar porphyry dykes and coarse-grained quartzo-feldspathic sheets, up to 50 cm wide, which contain large (up to 10 cm long) biotite-rich patches. The quartzo-feldspathic sheets represent development of substantial leucosomes and are often cut by pegmatite veins. Their relationship with the quartz–K-feldspar porphyries is uncertain, but it is possible that these quartz–K-feldspar porphyries are coeval with the acidic hypabyssal igneous intrusions, which cut both parts of the Tyrone Plutonic Complex.

To constrain the timing and P–T conditions of peak metamorphism, the timing of subsequent igneous activity (including both leucosome generation and pegmatite development) and the later cooling history of the Tyrone Central Inlier, we have undertaken U–Pb ion microprobe dating of igneous intrusive rocks, made thermobarometric estimates on peak metamorphic assemblages, and determined 40Ar–39Ar and Rb–Sr mineral cooling ages on igneous and metamorphic phases. These data have been combined with provenance data (U–Pb laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) dating of detrital zircon combined with Sm–Nd model ages of metasedimentary rocks and lithological comparisons) to assess the affinity and tectonothermal history of the Tyrone Central Inlier, and its role within the evolution of the Grampian orogen and its possible relationship to the Midland Valley basement. For the following sections, the analytical techniques and the majority of analytical data are presented in the Supplementary Publication, available online at http://www.geolsoc.org.uk/SUP18303.

Constraining the tectonothermal evolution of the Tyrone Central Inlier

U–Pb ion microprobe dating of igneous intrusive rocks

Ion-microprobe geochronology was carried at the NordSIMS facility at the Swedish Museum of Natural History, Stockholm. Ion-microprobe U–Pb zircon geochronology offers spatial resolution of about 30 μm, enough to date different generations of growth (> 30 μm) in complex grains with multiple growth histories. A summary of the analytical method is given in the Supplementary Publication.

Three samples were analysed, two leucosomes containing biotite patches (TCI-3a [H71868128] and DC 08/01-18 [H71478336]), and a muscovite-bearing pegmatite (TCI-10 [H71378376]). Leucosome TCI-3a contains exceptionally CL-bright zircons with well-developed crystal facets. However, cathodoluminescence images reveal that the zircon is largely inherited and that overgrowths thought to have grown during leucosome intrusion were too thin to analyse. Two core analyses are concordant and yield late Mesoproterozoic ages (Table 1; Fig. 3b). The two other core analyses from this sample are slightly discordant, yielding late Mesoproterozoic and Archaean 207Pb/206Pb ages respectively (Table 1; Fig. 3b). The other leucosome sample (DC 08/01-18) also contains abundant inherited zircon, but the magmatic rims on the inherited zircon cores are more substantial (Fig. 3a). Because of the high U contents (4000–8000 ppm, Table 1), which are much higher than the 91500 standard zircon used for calibration, the data are reversely discordant (Fig. 3b; Williams 1998). However this does not affect the 207Pb/206Pb ages, which yield a weighted mean of 467 ± 12 Ma from five rim analyses, and is interpreted to date leucosome formation.

Pegmatite TCI-10 also has abundant inherited zircon with only small magmatic overgrowths (Fig. 3a). Consequently, attempts to date these rims were largely unsuccessful, with just one rim analysis (spot 11, Table 1) that was not a rim–core mixture (Fig. 3b). This analysis is concordant, yields a 206Pb/238U age of 477 ± 12 Ma and dates pegmatitic intrusion. Inherited grains yield three concordant Mesoproterozoic ages, one Palaeoproterozoic age and one near-concordant Archaean age (Fig. 3b). The inherited zircons from this sample and TCI-10 match detrital zircon age populations from the paragneisses (see below) and are therefore consistent with their derivation from the host rocks.

40Ar–39Ar and Rb–Sr dating

Three samples were selected for 40Ar–39Ar dating. These samples include two muscovite-bearing pegmatites (samples TCI-2 [H71868128] and TCI-10 [H71378376]) and one biotite-bearing pelite (sample TCI-8 [H73178423]). Samples were irradiated at the CLICIT facility at the University of Oregon and were analysed at the 40Ar–39Ar geochronology laboratory at the University of Lund. The analytical technique is described in the Supplementary Publication, and data are presented in Table 2 and Figure 4. For the two pegmatite samples, the cores of coarse (>10 mm in diameter) muscovite crystals were analysed. Sample TCI-2 yielded a 40Ar–39Ar plateau age of 465.8 ± 1.1 Ma whereas sample TCI-10 yielded a 40Ar–39Ar plateau age of 467.8 ± 0.8 Ma (Fig. 4, Table 2). This same sample (TCI-10) yielded one concordant U–Pb zircon analysis at 477 ± 12 Ma (Fig. 3, Table 1). A 40Ar–39Ar plateau age of 468.5 ± 1.4 Ma (Fig. 4, Table 2) was obtained from biotite defining the main fabric in a garnet-bearing pelite (sample TCI-8). All three samples are characterized by consistently low Ca/K ratios (Table 2), consistent with the presence of a single K-rich phase. However, the presence of extraneous argon (Kelley 2002) in these samples cannot be ruled out. The samples contain large quantities of radiogenic 40Ar, so the data cluster close to the 39Ar/40Ar axis on an inverse isochron correlation diagram, thus yielding a poorly constrained intercept with the 36Ar/40Ar axis.

The same two muscovite-bearing pegmatite samples selected for 40Ar–39Ar dating were also dated by Rb–Sr at University College Dublin. The analytical technique is described in the Supplementary Publication and data are presented in Table 3. Both samples are characterized by high Rb/Sr ratios (20.5 and 155 respectively, Table 3). No inclusions of any other high Rb/Sr phase such as biotite were detected under the petrological microscope. They yielded virtually identical muscovite–feldspar ages and initial 87Sr/86Sr ratios (TCI-2: 457.2 ± 6.7 Ma, 87Sr/86Sr = 0.729361; TCI-10: 458.0 ± 6.8 Ma, 87Sr/86Sr = 0.72930, combined isochron with all four analyses: 457.4 ± 3.9 Ma, 87Sr/86Sr = 0.729361, Table 3), although the low Rb/Sr phase is different in the two samples (TCI-2: plagioclase; TCI-10: K-feldspar).

The discrepancy between the c. 458 Ma Rb–Sr muscovite ages from the pegmatite suite and the c. 468 Ma 40Ar–39Ar muscovite ages from the same samples is puzzling. The closure
**Table 1. U–Pb ion microprobe data from the Tyrone Central Inlier**

| Spot number | Zone     | f206% | 238U/206Pb ± α (%) | 207Pb/206Pb ± α (%) | Ages (Ma) ± α | Concentrations |
|-------------|----------|-------|--------------------|---------------------|---------------|----------------|
| TC10; pegmatite, Oughtmore [H71358376] | 1 Core   | 0.06  | 2.013              | 1.28                | 0.1907        | 2748           | 4 2600 27 |
|             |           |       |                    |                     |               | 394            | 227 264 0.575 |
|             | Mix      | 0.35  | 7.690              | 1.31                | 0.1148        | 1876           | 12 788 10 |
|             | Mix      | 0.49  | 5.722              | 1.28                | 0.1451        | 2289           | 8 1038 12 |
|             | Mix      | 0.08  | 12.497             | 1.28                | 0.0570        | 490            | 11 496 6 |
|             | Core     | 0.16  | 4.923              | 1.28                | 0.0802        | 1202           | 23 1192 14 |
|             | Core     | 0.02  | 5.647              | 1.29                | 0.0739        | 1038           | 15 1051 12 |
|             | Mix      | 0.06  | 7.105              | 1.28                | 0.0725        | 1001           | 13 849 10 |
|             | Mix      | 0.04  | 5.810              | 1.28                | 0.0723        | 993            | 25 1024 12 |
|             | Core     | 0.08  | 3.043              | 1.27                | 0.1110        | 1816           | 14 1832 20 |
|             | Mix      | 1.6   | 9.628              | 1.30                | 0.0866        | 1352           | 41 637 8 |
|             | Rim      | 0.98  | 13.015             | 1.27                | 0.0566        | 475            | 26 477 6 |

Irish National Grid references are given in square brackets after the sample number. f206 (%) is the percentage of common 206Pb, estimated from the measured 204Pb. Values in parentheses indicate that no correction has been applied owing to insignificant levels of 204Pb. All errors are at the 1σ level. Age calculations use the routines of Ludwig (2003) and follow the decay constant recommendations of Steiger & Jäger (1977).

The **P–T** estimates of peak metamorphic assemblages

The **P–T** conditions of metamorphism of the Tyrone Central Inlier have been constrained by three separate approaches: (1) ‘conventional’ geothermobarometry, using experimentally determined equilibria of mineral reactions in **P–T** space; (2) a refinement of the above technique, which involves seeking additional reactions that are not experimentally determined in conjunction with an internally consistent thermodynamic dataset (e.g. Powell & Holland 1988) and using computer software (such as the average **P–T** function of THERMOCALC (Powell & Holland 1988)) to find the optimum **P–T** in such over-determined systems; (3) construction of phase diagrams that summarize the entire pressure–temperature–composition information of metamorphic rocks in an appropriate model system for a specified bulk composition (i.e. a **P–T** pseudosection, e.g. Powell et al. 1998; Will 1998).

Sample TC1-8 was selected for electron microprobe analysis at the University of Lausanne. A description of the analytical technique and data tables with representative mineral analyses and results of the THERMOCALC average **P–T** calculations are given in the Supplementary Publication, and **P–T** estimates are illustrated in Figure 5. Sample TC1-8 contains an assemblage of biotite + plagioclase + sillimanite + quartz + garnet + muscovite. Small, biotite-bearing quartzo-feldspathic patches are locally developed and may represent minor melt development that was frozen in situ. The garnet is often heavily resorbed, and compositional zoning profiles demonstrate that the core is enriched in almandine, grossular and pyrope and depleted in spessartine relative to the rim (Table 1; Supplementary Publication).

Conventional thermobarometric estimates utilize the garnet–biotite thermometer of Ferry & Spear (1978) and the garnet–aluminium silicate–silica–plagioclase (GASP) barometer of Kozlowski & Newton (1988). The intersection between the two equilibria occurs at c. 680 °C, 7.5 kbar (Fig. 5), very close to the centre of the THERMOCALC average **P–T** ellipse (670 ± 113 °C, 6.8 ± 1.7 kbar, ellipse in Fig. 5; Table 2 in the Supplementary Publication). To further constrain the **P–T** conditions we have utilized the MnNCKFMASH pseudosection of Johnson & Brown (2004), which used an average metapelitic composition taken from the literature (n = 554 analyses) that closely approximates the bulk whole-rock composition of our sample (TCI-8 wt% oxide: SiO₂ 59.02%, TiO₂ 1.24%, Al₂O₃ 18.94%, FeO 9.66%, MnO 0.32%, MgO 2.75%, CaO 0.94%, Na₂O 1.44%, K₂O 3.43%, P₂O₅ 0.26%). The small difference in composition between TCI-8 and the composition utilized by Johnson & Brown (2004) may affect the absolute position in **P–T** space of mineral assemblage boundaries and the relative abundance of...
phases, but it is likely that the overall topology of the pseudosection is correct. $P$–$T$ estimates are thus further constrained by the complete absence of kyanite, staurolite and K-feldspar from the Tyrone Central Inlier. The intersection of the average $P$–$T$ error ellipse with the predicted stability of observed phases derived from the $P$–$T$ pseudosection is marked by the highlighted polygon within the $P$–$T$ ellipse in Figure 5. Combined, these data imply $P$–$T$ conditions of $c.$ 690/6 308 C, 7/6 1.7 kbar for the peak metamorphic assemblage, but we have utilized the more conservative error from the THERMOCALC average $P$–$T$ ellipse (670/6 1138 C, 6.8/6 1.7 kbar).

Provenance and affinity of the Tyrone Central Inlier

$U$–$Pb$ LA-MC-ICP-MS dating of detrital zircon

$U$–$Pb$ LA-MC-ICP-MS analyses of detrital zircons were undertaken from a psammitic gneiss from Corvanaghan Quarry (sample JTP-210 [H7180 8135]). The sample was analysed using a Nu-Plasma HR multicollector ICP-MS system with a New Wave Research solid-state Nd:YAG laser ablation system with a 193 nm wavelength (UP193SS) at the NERC Isotope Geosciences Laboratory in Keyworth, Nottingham. (Supplementary Publication, Fig. 6).

Sample JTP-210 exhibits prominent $U$–$Pb$ age peaks at $c.$ 1050 Ma, 1200 Ma and 1500 Ma, with more restricted peaks at $c.$ 1800 Ma, 2500–2700 Ma and 3100 Ma (Fig. 6). Comparing this population distribution with published data from East Laurentia (e.g. Cawood et al. 2007) suggests that the Tyrone Central Inlier is of Laurentian affinity and is thus not exotic to the Laurentian margin. Comparing the Tyrone Central Inlier data with published detrital zircon ages from metasediments from this sector of the Laurentian margin (e.g. the Moine and Dalradian Supergroups) reveals that all these sequences exhibit prominent peaks in the 1000–1800 Ma age range (Cawood et al. 2007). It is the presence or absence of older (e.g. Archaean) detrital grains that is one of the most useful discriminators between these sequences. Although based on a small dataset ($n = 33$), the Tyrone Central Inlier exhibits strong similarities to the Argyll and Southern Highland Groups of the Dalradian, which are characterized by a significant population between 2.5 and 2.7 Ga (Cawood et al. 2003, 2007). This old population is missing from the Grampian Group of the Dalradian (Cawood et al. 2003, 2007; Banks et al. 2007), the Moine Supergroup (Friend et al. 2003; Cawood et al. 2004, 2007) and the Slidwood Division (Flowerdew et al. 2005, and unpublished data). The youngest detrital zircon, Z34_2, has a concordia age of 999 ± 23 Ma, which shows that deposition of the Tyrone Central Inlier metasediments took place after this time.
Sm–Nd model ages ($T_{DM}$)

Several studies have documented that the Sm–Nd isotopic signature of sedimentary rocks is usually unfractionated between the source area and the clastic sediment derived from it (e.g. Goldstein & Jacobsen 1988; Nelson & DePaolo 1988; McLennan et al. 1989; Mearns et al. 1989). The sediment produced may be of mixed provenance, and as such the Sm–Nd isotopic signature of a whole-rock sample is a weighted average of the Sm–Nd isotopic signature of its various protoliths.

Five psammitic samples and one pelitic sample from the Tyrone Central Inlier were analysed at University College Dublin.
Analytical details are in the Supplementary Publication, and data are presented in Table 4. The 147Sm/144Nd ratios (0.099–0.1192, Table 4) of all six samples fall within the normal range for clastic sediments (Mearns et al. 1989). Depleted mantle model ages (TDM) ages range from 1.65 to 2.41 Ga (mean $\bar{\text{TDM}} = 2.08$ Ga, $n = 6$, Table 4). Comparing the Tyrone Central Inlier with Sm–Nd data from other metasedimentary rocks on the Laurentian margin and from the Midland Valley Terrane reveals similarities to Sm–Nd data from the Argyll and Southern Highland Groups of the Dalradian, consistent with the detrital zircon analysis from sample JTP-210. TDM model ages for the Argyll Group range from 1.65 to 2.39 Ga (mean $\bar{\text{TDM}} = 1.99$ Ga, $n = 5$, Daly & Menuge 1989; Flowerdew et al. 2000), and TDM model ages for the Southern Highland Group are virtually identical and range from 1.79 to 2.36 Ga (mean $\bar{\text{TDM}} = 2.03$, $n = 5$, Daly & Menuge 1989). In contrast, TDM model ages from the Grampian and Appin Groups of the Dalradian are significantly younger, ranging from 1.64 to 1.7 Ga (mean = 1.67 Ga, $n = 3$) and from 1.73 to 2.02 Ga (mean = 1.91 Ga, $n = 3$), respectively (Daly & Menuge 1989). TDM model ages from the Slishwood Division metasedimentary rocks (Fig. 1b) are also younger (one analysis at 1.59 Ga, Flowerdew & Daly 2005; three analyses ranging from 1.54 to 1.58 Ga, Table 4).

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### Table 3. Rb–Sr muscovite–feldspar mineral ages from the Tyrone Central Inlier

| Sample  | Type     | Grid reference | Locality   | Rb (ppm) | Sr (ppm) | $^{87}\text{Rb}^{86}\text{Sr}$ | $^{87}\text{Sr}^{86}\text{Sr}$ | $\pm 2\sigma$ | Age (Ma) |
|---------|----------|----------------|------------|----------|----------|-------------------------------|-------------------------------|--------------|----------|
| TCI-2   | Muscovite| H71868128      | Corvanaghan| 262.5    | 12.78    | 1.132580                      | 0.000080                      | 457.2 ± 6.7  |
| TCI-2   | Plagioclase| H71868128     | Corvanaghan| 9.432    | 348.8    | 0.729872                      | 0.000048                      | 458.0 ± 6.8  |
| TCI-10  | Muscovite| H71378376      | Oughtmore  | 667.0    | 4.328    | 4.804780                      | 0.000180                      | 1813         |
| TCI-10  | K-feldspar| H71378376     | Oughtmore  | 252.7    | 182.9    | 0.755512                      | 0.000080                      | 1651         |

All four analyses combined yield an isochron of 457.4 ± 3.9 Ma with initial $^{87}\text{Sr}^{86}\text{Sr} = 0.729361$ (MSWD = 0.025).

### Table 4. Sm–Nd isotopic data for whole-rock samples from the Tyrone Central Inlier

| Sample       | Type    | Grid reference | Locality   | Sm (ppm) | Nd (ppm) | $^{147}\text{Sm}^{144}\text{Nd}$ | $^{143}\text{Nd}^{144}\text{Nd}$ | $\pm 2\sigma$ | TDM (Ma) |
|--------------|---------|----------------|------------|----------|----------|-------------------------------|-------------------------------|--------------|----------|
| DC 08/01-13  | Psmamite| H71508351      | Oughtmore  | 2.90     | 17.1     | 0.1023                        | 0.511279                      | 0.000022     | 2405     |
| DC 08/01-20  | Psmamite| H71686128      | Corvanaghan| 5.59     | 28.3     | 0.1192                        | 0.511910                      | 0.000016     | 1813     |
| DC 09/02-1   | Psmamite| H71768242      | Beltonanean| 3.58     | 20.7     | 0.1044                        | 0.511437                      | 0.000020     | 2228     |
| DC 09/02-2   | Psmamite| H72458342      | Beltonanean| 3.14     | 18.2     | 0.1042                        | 0.511319                      | 0.000012     | 2390     |
| TCI-1c       | Psmamite| H71686128      | Corvanaghan| 14.0     | 80.1     | 0.1059                        | 0.511617                      | 0.000008     | 2003     |
| TCI-8        | Pelite  | H73178423      | Friars Rock| 8.33     | 50.9     | 0.0990                        | 0.511791                      | 0.000018     | 1651     |

### Fig. 5. MnNCKFMASH $P$–$T$ pseudosection for an average subaluminous metapelite showing calculated stable parageneses taken from Johnson & Brown (2004). The depth of shading reflects increased variance. $P$–$T$ estimates from this study employing conventional geothermobarometers (lines) and THERMOCALC average $P$–$T$ estimates (ellipse) overlie the pseudosection. Grt-Bt denotes the garnet–biotite thermometer of Ferry & Spear (1978); GASP denotes the garnet–aluminate silicate–ilica–plagioclase (GASP) barometer of Koziol & Newton (1988). Mineral abbreviations follow Kretz (1983).

### Fig. 6. U–Pb zircon probability density distribution diagram for a psammitic gneiss (sample JTP-210) from Corvanaghan Quarry [H71808135].
mean = 1.55 Ga, Sanders et al. 1987). $T_{DM}$ model ages for the felsic, predominantly metasedimentary, lower crustal xenoliths from the Midland Valley Terrane in Scotland have a mean $T_{DM}$ age of 1.34 Ga (Halliday et al. 1993).

Discussion and conclusions

The detrital zircon data suggest a Laurentian affinity for the Tyrone Central Inlier, with both the detrital zircon U–Pb and whole-rock Sm–Nd model age data favouring a Late Dalradian affinity for these rocks. In particular, they rule out a correlation with the Midland Valley Terrane basement and the Slishwood Division (a high-grade metasedimentary terrane located 50 km to the west; Fig. 1b), which was juxtaposed with unequivocal Dalradian rocks during the Grampian orogeny (Flowerdew et al. 2000). The Tyrone Central Inlier also differs from the Slishwood Division in that the latter experienced eclogite- and granulite-facies metamorphism prior to suturing with the Dalradian units (Sanders et al. 1987; Flowerdew & Daly 2005). Also, the Slishwood Division was intruded by pre-tectonic basic sills and dykes, which are notably absent in the Tyrone Central Inlier.

However, the Grampian orogenic (i.e. c. 475–465 Ma) histories of the Tyrone Central Inlier and Slishwood Division are very similar. Both have undergone leucosome generation and subsequent intrusion of pegmatites that cut the high-grade fabrics. Leucosome development in the Tyrone Central Inlier is constrained by a $^{207}$Pb/$^{206}$Pb zircon age of 467 ± 12 Ma. Rb–Sr muscovite ages from the pegmatite suite in both inliers cluster at around c. 460–455 Ma (this study, Flowerdew et al. 2000). However, $^{40}$Ar–$^{39}$Ar dating of coarse magmatic muscovite and U–Pb dating of magmatic zircon from the pegmatite suite in the Tyrone Central Inlier in this study implies that a c. 470 Ma intrusion age is more likely. Both the Tyrone Central Inlier and Slishwood Division are intruded by c. 470 Ma arc-related plutons (Cooper & Mitchell 2004; Flowerdew et al. 2005). $P$–$T$ conditions of peak metamorphism in both inliers are extreme relative to those for the Dalradian rocks to the NW. The $P$–$T$ conditions of granulite-facies metamorphism in the Slishwood Division are c. 15 kbar, 800 °C (Flowerdew & Daly 2005), whereas $P$–$T$ estimates for upper amphibolite-facies metamorphism in the Tyrone Central Inlier are c. 6.8 kbar, 670 °C (this study). In contrast, the Dalradian rocks of the Sperrin Mountains immediately to the NW of the Tyrone Central Inlier are of substantially lower grade (greenschist to lower amphibolite facies; Long 1997). These Dalradian rocks have not yielded any evidence of Grampian arc-related magmatism. Final imbrication of the

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**Fig. 7.** Schematic reconstruction of the Late Neoproterozoic–Early Palaeozoic tectonic evolution of the Tyrone Central Inlier. TCI, Tyrone Central Inlier; TPG, Tyrone Plutonic Group; TVG, Tyrone Volcanic Group; OT, Omagh Thrust; CBC, Clew Bay Complex; LD, Longford–Down terrane; LNA, Lough Nafooey Arc.
Tyrone Central Inlier with the Dalradian rocks was achieved during regional SE-directed thrusting of the Dalradian units over the Tyrone Central Inlier and Tyrone Igneous Complex along the D3 Omagh Thrust (Alsop & Hutton 1993). The Shlishwood Division was also imbricated with Dalradian rocks during SE-directed D3 shearing (Flowerdew et al. 2000).

It is suggested that the Tyrone Central Inlier represents an isolated (and perhaps completely detached) segment of the Laurentian passive margin, which was incorporated into an outboard volcanic arc terrane prior to accretion onto the Laurentian margin during Grampian orogenesis. The question remains as to how this microcontinental block was generated on the Laurentian margin.

Small, tectonically isolated fragments of continental crust (microcontinents) are commonly accreted to orogenic belts. Possible mechanisms for the formation of microcontinents include strike-slip translation; for example, Baja California has been translated by hundreds of kilometres along the Gulf of California (Larson et al. 1968). Another possible mechanism for microcontinent formation is re-riifting of a continental margin, which has the effect of isolating a passive margin segment within a tract of oceanic crust (Vink et al. 1984; Müller et al. 2001). In both of these scenarios, the resultant microcontinental blocks are likely to be preserved in any future accretion event because of their buoyancy. We favour the second scenario for the outboard location of Tyrone Central Inlier relative to the Laurentian margin. A similar tectonic model was envisaged for isolation of the Dashwoods block from the Humber zone during opening of Iapetus on the Newfoundland segment of the Laurentian margin (Cawood et al. 2001; Waldron & van Staal 2001).

The Tyrone Central Inlier is envisaged as a Laurentian microcontinental block produced during opening of the Iapetus Ocean at c. 570 Ma (Fig. 7a). The Iapetus Ocean started to close during the Late Cambrian–Early Ordovician and an intra-oceanic arc, such as the Lough Nafooey Arc in western Ireland, was initiated during the Early Tremadoc (Dewey & Mange 1999). This arc had encountered the Laurentian margin by c. 490 Ma (Crawford et al. 2007). An along-strike equivalent to the Lough Nafooey Arc is inferred for the Tyrone segment of the Laurentian margin (Fig. 7b). Continued closure of the Iapetus Ocean caused obduction of suprasubduction-zone ophiolites such as the High-land Border and Shetland ophiolites and the Deer Park Complex in western Ireland (Dewey & Mange 1999), and the thrusting of the ophiolitic rocks of the Tyrone Igneous Complex over the Tyrone Central Inlier (Fig. 7c; Hutton et al. 1985). At this time, the Tyrone Central Inlier high-grade metamorphism is envisaged to have commenced. A reversal in subduction polarity is inferred at around 470 Ma in western Ireland (Dewey & Mange 1999); a similar situation is envisaged here to produce a continental arc in the Tyrone Central Inlier (Fig. 7d), with continued high-grade metamorphism and deformation (including leucosome and pegmatite development) in the roots of this deforming arc. The Tyrone Central Inlier–Tyrone Plutonic Group were then intruded by a series of stretching tectonics–granodioritic plutons at 470–465 Ma (Cooper & Mitchell 2004) and accompanied by the extrusion of arc lavas (Fig. 7d). Final juxtaposition of the inlier with the Laurentian margin occurred during regional SE-directed D3 thrusting of the Dalradian units over the Tyrone Central inlier along the Omagh Thrust (Fig. 7e) (Alsop & Hutton 1993).

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