The Laurentian Caledonides of Scotland and Ireland

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Number of words of manuscript text: 19,227

Number of words of references: 9,265

Number of words in figure captions (16 figures): 712

No tables.

Running title: The Caledonides of Scotland and Ireland (39 characters)

Abstract

The Caledonides of Britain and Ireland are one of the most intensively studied orogenic belts in the world. This review considers all the tectonic events associated with the development and closure of the Iapetus Ocean. It first summarizes the tectonic evolution of each segment involved in the Scottish-Irish sector of the Caledonides and then reviews the temporal evolution of the Caledonian orogeny. Three main tectonic phases are recognized in the Scottish-Irish Caledonides: an Early to Middle Ordovician (475 – 465 Ma) phase termed the Grampian Orogeny, a phase of Silurian (435-425 Ma) tectonism restricted to the Northern Highland Terrane of Scotland termed the Scandian Orogeny, and an Early Devonian (395 Ma) phase, termed the Acadian Orogeny. The Grampian Orogeny was caused by the collision of the Laurentian continental margin with an oceanic arc terrane and associated supra-subduction zone ophiolites during the latest Cambrian to Early Ordovician. Following the Grampian arc-continent collision event there was a subduction polarity reversal. This facilitated continued subduction of Iapetan oceanic lithosphere and an Andean-type continental margin developed on and adjacent to the Laurentian margin in the Middle Ordovician along with a substantial thickness of accretionary prism sediments (the Southern Uplands – Longford-Down terrane). The Iapetus Ocean is believed to have disappeared by the Late Silurian based

on the faunal record and a continent – continent collision ensued. The absence of significant regional deformation and metamorphism associated with the Late Silurian collision between Avalonia and the Scottish-Irish margin of Laurentia suggests that the continental collision in this sector of the Caledonian-Appalachian orogen was 'soft' or highly oblique. The exception is the Northern Highlands Terrane of Scotland that was believed to have been situated 500 – 700 km to the north along orogenic strike. This terrane records evidence for significant Silurian regional deformation and metamorphism attributed to the collision of the Laurentian margin of East Greenland with Baltica (the Scandian Orogeny). Current controversies in the Laurentian Caledonides of Scotland and Ireland are discussed at the end of this review.

Introduction

The Caledonides of Britain and Ireland occupy a key position between the Appalachian orogen of eastern North America and the Caledonides of Scandinavia and East Greenland. They are one of the most intensively studied orogenic belts in the world, and have served as a superb natural laboratory for the development of many key geological concepts, including thrust tectonics (e.g. Peach et al., 1907), regional metamorphism (e.g. Barrow, 1893) and the origin and emplacement of granitic magmas (e.g. Read, 1957).

In this review we focus mainly on the Early Ordovician – Early Silurian evolution of the Laurentian Caledonides of Scotland and Ireland. The term 'Caledonian orogenic cycle' is employed here to include all the Cambrian, Ordovician, Silurian and Devonian tectonic events associated with the development and closure of the Iapetus Ocean, similar to the definition of McKerrow et al. (2000). These tectonic events are illustrated in Figure 1 and occurred between Laurentia (to the northwest) and Baltica and Avalonia (to the southeast and east). They encompass the evolution from the Laurentian passive margin to a series of arc–arc, arc–continent and continent–continent collisions related to the closure of the Iapetus Ocean. In Scotland and Ireland, the Caledonian orogenic cycle on the Laurentian margin comprises three main phases: an Early – Middle Ordovician (475 – 465 Ma) phase termed the Grampian Orogeny, a phase of Silurian (435-425 Ma) tectonism restricted to the Northern Highland Terrane of Scotland termed the Scandian Orogeny, and an Early Devonian (405 Ma) phase, termed the Acadian Orogeny.

The Grampian Orogeny was primarily caused by the collision of the Laurentian continental margin of Scotland and NW Ireland with an oceanic arc terrane during the latest Cambrian to Early Ordovician (Fig. 1). This arc was intra-oceanic, and was produced by the subduction of oceanic crust within the Iapetus Ocean. Following this arc-continent collision event and the associated obduction of supra-subduction zone ophiolites onto the Laurentian margin (Dewey & Shackleton, 1984), there was a subduction polarity reversal. This facilitated continued subduction of Iapetan oceanic lithosphere and an Andean-type continental margin developed on the Laurentian margin in the Middle Ordovician along with a substantial thickness of accretionary prism sediments (the Southern Uplands – Longford-Down terrane, Fig. 2).

During the Late Ordovician, Baltica and the Avalonian microcontinent progressively approached both each other (closing the Tornquist Sea) and the Laurentian margin (closing the Iapetus Ocean). The faunal record suggests that the Tornquist Sea closed in the Late Ordovician as faunas from Avalonia began to mix with Baltic faunas in the Caradoc, while by the Ashgill, British and Scandinavian faunas were similar at species level (Cocks et al., 1997). The Iapetus Ocean is believed to have disappeared by the Late Silurian based on the faunal record (e.g. Cocks and Fortey, 1982), and a continent – micro-continent collision ensued. The Northern Highlands Terrane of Scotland (Fig. 2) records evidence for significant Silurian regional deformation and metamorphism that is attributed to the collision of the Laurentian margin of East Greenland with Baltica (the Scandian Orogeny). It is thought that the Northern Highlands terrane was situated 500 – 700 km to the north along orogenic strike for it to have it participated in the Scandian Orogeny as many of the terranes generally inferred to have been positioned to the south (e.g. the Midland Valley Terrane, Fig. 2) show no evidence for this Silurian tectonic event.

The absence of significant regional deformation and metamorphism associated with the Late Silurian collision between Avalonia and the Scottish-Irish margin of Laurentia suggests that the continental collision in this sector of the Caledonian-Appalachian orogen was 'soft' or highly oblique. It is generally believed that Late Silurian / Early Devonian sinistral strike-slip movements of up to several hundred kilometres occurred along the Great Glen and Highland Boundary and Southern Upland faults (Fig. 2; Soper et al. 1992; Dewey & Strachan 2003; Cawood et al. 2012, see, however, Tanner 2008). The final stage of the Caledonian orogenic cycle in Scotland and Ireland is marked by post-orogenic clastic rocks of Middle Devonian age (or younger) resting unconformably on folded cleaved rocks that range in age from Cambrian to Early Devonian. On the Avalonian side of the Iapetus Suture this event is termed the Acadian Orogeny after Acadia, the francophone region of maritime Canada where it was originally defined. In contrast, Early Devonian deformation north of the Iapetus Suture has been ascribed to post-collisional sinistral transtension between Laurentia and Avalonia-Baltica (Dewey & Strachan 2003).

The late stages of the Caledonian orogenic cycle in Scotland and Ireland were also marked by the intrusion of large volumes of granitic magma with a predominantly calc-alkaline "I" type character. While their chemistry is clearly compatible with a subduction-related origin, much of the magmatism (which spans a time period from 430 – 380 Ma) post-dates the final closure of the Iapetus Ocean. Their genesis has been attributed by Atherton and Ghani (2002) to post-collisional slab break off.

In this review of the Laurentian Caledonides of Scotland and Ireland, we first discuss the various tectonic elements / terranes involved in the Caledonian orogeny. A summary of the temporal evolution of the Caledonian orogenic belt is then provided. The temporal evolution focusses mainly on the Grampian and Scandian orogenies and does not consider in detail late Caledonian magmatism or strike-slip faulting. Current controversies in the Laurentian Caledonides of Scotland and Ireland are then discussed at the end of this review.

Tectonic elements of the Scottish and Irish Caledonides

The various tectonic elements involved in the Caledonian orogeny in Scotland and Ireland are now discussed in turn from northwest to southeast. These tectonic elements are illustrated on Figure 2 and Figure 3 and include:

i) The Laurentian foreland (Hebridean terrane) which comprises Lewisian basement and its undeformed sedimentary cover.

ii) The Northern Highlands terrane which consists of the deformed Laurentian cover sequence of the Moine Supergroup and its probable basement represented by the "Lewisianoid" inliers of the NW Highlands.

iii) The Grampian terrane which includes the deformed Laurentian cover sequence of the Dalradian Supergroup and its basement represented by the Annagh Gneiss Complex in NW Ireland and the Rhinns Complex in SW Scotland. This terrane also locally contains Grampian syn-orogenic arc intrusives. Early Ordovician accretionary complexes (the Highland Border Complex in Scotland and the Clew Bay Complex in western Ireland) and probable para-autochthonous Laurentian crustal fragments such as the Slishwood Division crop out on the southeastern margin of the Grampian terrane (Fig. 2).

iv) The Midland Valley terrane consists of Late Cambrian – Early Ordovician suprasubduction ophiolite complexes such as Shetland to the north of mainland Scotland, Ballantrae in SW Scotland, Tyrone in NW Ireland and Clew Bay in western Ireland. It also contains fragments of the Grampian volcanic arc and its associated fore-arc basin, such as the Lough Nafooey arc and South Mayo Trough in western Ireland. Detached Laurentian crustal fragments such as the Tyrone Inlier and the Dalradian Supergroup rocks of Connemara also crop out within this composite terrane (Fig. 2). Silurian fore-arc and inter-arc successor basins were deposited on the eroded remnants of the Grampian arc and associated ophiolites.

v) The Southern Uplands – Longford-Down terrane represents a successor subduction zone system following the Grampian orogeny and comprises a thick sequence of Mid-Ordovician to Early Silurian accretionary prism rocks.

The Laurentian foreland

The Hebridean terrane of NW Scotland represents the external zone of the Laurentian Caledonides. It consists of lower-crustal, high-grade gneisses of the Archaean to Palaeoproterozoic Lewisian Gneiss Complex (Park et al. 2002; Kinny et al. 2005) that are overlain unconformably by two Precambrian sedimentary successions. The oldest of these is the c. 1200 Ma Stoer Group, a 2 km thick sequence of continental sandstones and siltstones that was deposited in a localized NNE-trending rift (Stewart 2002 and references therein). The Sleat Group of Skye may have been deposited at approximately the same time. Both sequences contain detrital zircons of Archaean to Palaeoproterozoic age that were probably derived from the nearby Lewisian Gneiss Complex, the upper part of the Sleat Group also containing some Mesoproterozoic grains for which there is no obvious exposed source in NW Scotland (Rainbird et al. 2001; Kinnaird et al. 2007).

The Stoer Group was tilted and eroded before deposition of the unconformably overlying Torridon Group. This is a 5 km thick sequence of arkosic fluviatile sandstones, derived mainly from the west (Park et al. 2002; Stewart 2002 and references therein). Detrital zircons range in age from 3.1 – 1.05 Ga with sub-populations at 1.8, 1.65 and 1.1 Ga (Rainbird et al. 2001). A maximum age for sedimentation is provided by a detrital zircon age of 1060 ± 18 Ma (Rainbird et al. 2001). Rb-Sr whole-rock regression ages of 994 ± 48 Ma and 977 ± 39 Ma obtained from siltstones are thought to correspond to the time of early diagenesis (Turnbull et al. 1996). The Torridon Group was therefore probably deposited during the final stages of the Grenville Orogeny (Rainbird et al. 2001). There are no exposed sources in the Hebridean terrane for the 1.1 Ga detrital zircons. Accordingly, the current consensus is that the Torridon Group was deposited in a foreland basin to the Grenville mountain belt, with some detritus derived from distal sources such as NE Canada (Krabbendam et al. 2008, see however Williams & Foden 2011).

The Lewisian Gneiss Complex and the Torridon Group are in turn overlain unconformably by Early Cambrian to Middle Ordovician shallow marine platform sediments that total c. 1 km in thickness (McKie 1990; Park et al. 2002). These extend from the north Scottish coast to the Isle of Skye (Fig. 4), with almost identical correlative sequences extending along the length of the Caledonide-Appalachian orogen between NE Greenland and eastern North America. These sequences are all broadly transgressive and characterized by clastic sedimentary rocks in their lower parts (the Ardvreck Group), passing upwards into carbonates (the Durness Group). The Late Arenig to Early Llanvirn age of the youngest carbonate unit in NW Scotland provides a maximum age for Caledonian orogenic activity *sensu lato*.

The Northern Highlands terrane

The Northern Highlands terrane is comprised mainly of the deformed Laurentian cover sequence of the Moine Supergroup along with local basement inliers of gneissic rocks which bear close similarities to the Lewisian Gneiss Complex. The Northern Highlands terrane is separated from the Laurentian foreland by the Scandian Moine Thrust, and from the Grampian terrane by the Great Glen Fault (Fig. 2).

Laurentian basement in the Northern Highlands terrane – the "Lewisianoid" inliers

The Moine Supergroup is structurally interleaved with infolds and tectonic slices of orthogneissic basement that has long been correlated on lithological grounds with the Archaean-Palaeoproterozoic Lewisian Gneiss Complex of the Caledonian foreland (Fig 2; Flett 1905; Peach et al. 1907; Read 1931; Tanner et al. 1970; Rathbone & Harris 1979). U-Pb SIMS zircon dating indicates Neoarchaean protolith ages in the range 2.9-2.7 Ga for basement gneisses in north Sutherland and Glenelg (Fig. 2), thus confirming the broad similarity in age with the foreland basement (Friend et al. 2008). Most inliers are dominated by tonalitic to dioritic, hornblende gneisses, with subordinate hornblendite, serpentinite and garnet-pyroxene lithologies. Metasedimentary units of marble and pelite occur in some inliers. The inliers consistently lie at the lowest structural levels in successions when the effects of thrusting and/or folding are removed. Contacts between the basement gneisses and the adjacent Moine rocks are often concordant as a result of high levels of ductile strain. However, where sedimentary structures are preserved the Moine rocks consistently face away from those basement inliers that occupy fold cores. In some cases, Moine basal conglomerates are in contact with basement gneisses and cross-bedding is preserved within a few metres of their mutual contacts (Ramsay 1958; Strachan & Holdsworth 1988; Holdsworth 1989). Accordingly, the consensus is that the inliers represent fragments of the basement upon which the Moine Supergroup sediments were deposited.

The Proterozoic history of many of the basement inliers is generally poorly constrained. The U-Pb SIMS analyses of zircons from basement inliers presented by Friend et al. (2008) yielded complex discordant patterns, probably the result of a Palaeoproterozoic metamorphic overprint, although the timing of this event cannot be determined precisely. However, a more detailed history is available for the eastern Glenelg inlier where Hf data from eclogitic mafic sheets suggest that their igneous protoliths were emplaced at c. 2.0 Ga (Brewer et al. 2003). Furthermore, Sm-Nd whole rock and mineral ages of c. 1050 Ma obtained from these eclogites imply that at least some of the basement inliers were reworked during the Grenville orogeny (Sanders et al., 1984). U-Pb zircon data suggests that upper amphibolite facies retrogression occurred at c. 995 Ma (Brewer et al., 2003).

The Strathy Complex of east Sutherland (Figs 2, 4) may represent a juvenile addition to the basement to the Moine Supergroup. It is dominated by amphibolites and banded siliceous grey gneisses, the protoliths of which were probably a series of bimodal calc-alkaline volcanic rocks (Moorhouse 1979; Moorhouse & Moorhouse 1983; Burns et al. 2004). Sm-Nd model ages of c. 1.1-1.0 Ga obtained from the amphibolites suggest a late Mesoproterozoic protolith age (Burns et al. 2004).

A Laurentian cover sequence in the Northern Highlands terrane - the Moine Supergroup

The Moine Supergroup is a metasedimentary sequence that was deposited along the eastern margin of Laurentia between c.1000 Ma, the age of the youngest detrital zircons, and before c. 870 Ma, the age of the oldest intrusive igneous rocks (Friend et al., 1997, 2003). It comprises thick, monotonous successions of psammites, semi-pelites and pelites (Holdsworth et al. 1994). Three lithostratigraphical units are recognized (from west to east): the Morar, Glenfinnan and Loch Eil groups (Holdsworth et al., 1994, Fig. 3). The Morar Group was deposited in a range of fluvial to shallow-marine environments (Glendinning 1988; Krabbendam et al. 2008) and may be laterally equivalent with parts of the Torridon Group of the Hebridean terrane (e.g. Kennedy 1951; Bonsor et al. 2012). On the mainland, the Morar and Glenfinnan groups are separated by the Sgurr Beag Thrust (Fig. 4; Tanner et al., 1970; Rathbone & Harris, 1979). A possible stratigraphic transition is preserved on the Ross of Mull (Holdsworth et al., 1987), but the terms 'Morar Group' and 'Moine Nappe' can be considered to be effectively equivalent. The Glenfinnan Group is overlain stratigraphically by the Loch Eil Group and these two units comprise the Sgurr Beag Nappe. Both sequences probably accumulated in shallow to deep-water marine environments (Strachan et al. 1988). How these units link north of the Dornoch Firth with the structurally analogous metasedimentary rocks of the Naver and Skinsdale nappes is not well understood (Kocks et al., 2006). Geochronological constraints suggest that the sub-Dalradian Badenoch Group of the Grampian Terrane (Highton et al., 1999, Fig. 3), and the Westings and Yell Sound groups of Shetland (Flinn, 1988; Cutts et al., 2009, Fig. 3) are likely to broadly correlate with the Moine Supergroup.

The tectonometamorphic evolution of the Moine Supergroup has proved much more difficult to understand than that of the younger Dalradian Supergroup east of the Great Glen Fault. While the latter is dominated by the structural and metamorphic effects of the Grampian orogenic event with little or no further modification, the Moine Supergroup displays a polyorogenic evolution. There is widespread field evidence for polyphase deformation, and complex porphyroblast growth histories imply multiple episodes of low- to upper-amphibolite facies metamorphism (e.g. MacQueen & Powell, 1977; Zeh & Millar, 2001). The timing of tectonothermal events is not defined by any intra-orogenic unconformities and is almost entirely dependent on the isotopic dating of metamorphic mineral assemblages and igneous intrusions of known structural age. A range of isotopic ages, some linked to prograde pressure-temperature histories, indicate orogenesis during the mid-Neoproterozoic ('Knoydartian' events at c. 830-725 Ma), the early Ordovician (470-460 Ma) and the Silurian (435-425 Ma) (e.g. Vance et al., 1998; Rogers et al., 1998, 2001; Kinny et al., 1999, 2003a; Cutts et al., 2010; Bird et al., 2013).

Early Ordovician (470-460 Ma) deformation and metamorphism that is correlated with the Grampian orogenic event has been demonstrated in the Sgurr Beag and Naver nappes. It may also have affected the Moine nappe, but evidence is at present ambiguous. The eastern parts of the Sgurr Beag and Naver nappes largely escaped later reworking during the Silurian, so Grampian structures in these areas are thought to be preserved in more or less their original orientation. Nonetheless, large-scale structures comparable to those recognized within the Dalradian Supergroup have yet to be identified. The dominant structures are outcrop- to kilometre-scale recumbent tight to isoclinal 'D2' folds. These commonly have curvilinear sheath geometry as a result of heterogeneous, low-angle simple shear parallel to a N-S trending mineral lineation (Holdsworth & Roberts, 1984). Microstructures and cm-scale shear zones indicate a top-to-the-north sense of shear parallel to the lineation (Strachan, unpublished data). In the eastern Sgurr Beag Nappe, the evidence that these structures are Grampian in age rests on 1) a U-Pb TIMS age of 470 ± 2 Ma obtained from titanites aligned parallel to the lineation (Rogers et al. 2001), and 2) a U-Pb SIMS zircon age of 463 ± 4 Ma obtained from a syn-kinematic pegmatite (Cutts et al., 2010). Additional evidence for Grampian metamorphism in the area derives from 1) a U-Pb LA-ICP-MS monazite age of 464 ± 3 Ma (Cutts et al., 2010) and 2) Lu-Hf and Sm-Nd mineral isochrons and garnet-whole rock ages in the range 470-460 Ma obtained from meta-basic intrusions (Bird et al., 2013). Pressure-temperature conditions for metamorphism are 7 kbar and 650°C (Cutts, et al. 2010). In the Naver Nappe, syn-D2 migmatites have yielded U-Pb SIMS zircon ages of 467 ± 10 Ma and 461 ± 13 Ma (Kinny et al., 1999). Pressure-temperature conditions for the melting are estimated at 11-12 kbar and 650-700°C, implying substantial crustal thickening (Friend et al., 2000).

Silurian (435-425 Ma) deformation and metamorphism that is correlated with the Scandian orogenic episode is widespread in the Northern Highlands Terrane of Scotland and is discussed in greater detail in the section on the Silurian collision between Baltica and Laurentia. Regional-scale, NW-directed Scandian ductile thrusting culminated in the development of the Moine Thrust Zone and was accompanied by widespread folding and fabric development under amphibolite- to greenschist-facies conditions (e.g. Strachan & Holdsworth, 1988; Holdsworth et al., 2007). A prominent mineral lineation is developed throughout the Moine nappe and the lower parts of the Sgurr Beag and Naver nappes, showing a well-defined swing from gently ESE-plunging in the west adjacent to the Moine Thrust to SSE-plunging adjacent to the Naver, Sgurr Beag and Skinsdale thrusts (Fig. 4; Phillips, 1937; Kinny et al., 2003a; Kocks et al., 2006; Law & Johnson, 2010). Microstructures indicate a general top-to-the-NW sense of shear parallel to this lineation. Subsidiary structures include the Swordly, Torrisdale and Ben Hope thrusts (Moorhouse & Moorhouse, et al. 1988; Holdsworth et al., 2001). In the vicinity of the ductile thrusts, the composite foliation that contains this lineation intensifies into broad zones of platy, high-strain blastomylonites. Tight to isoclinal folds are developed on all scales, ranging from NW-vergent to reclined, sheath fold geometries (Fig 5; Holdsworth 1989; Alsop et al. 2010, Krabbendam et al. 2011). The key evidence that demonstrates a Silurian age for these structures arises from the isotopic dating of variably-deformed and metamorphosed syn- to late-thrusting granites at different structural levels in the Sutherland nappe pile that have yielded U-Pb zircon and monazite ages of c. 435-425 Ma (Kinny et al., 2003a; Kocks et al., 2006; Alsop et al., 2010).

The Grampian terrane

Much of the Grampian terrane is comprised of Dalradian Supergroup rocks that represent a deformed Laurentian cover sequence. Basement rocks in the Grampian terrane are restricted to the Annagh Gneiss Complex in NW Ireland and the Rhinns Complex in SW Scotland. This section also considers together the para-autochthonous Laurentian crustal fragments of the Slishwood Division and the Tyrone Inlier. It should be noted that the Tyrone Inlier crops out in the Midland Valley terrane and only the metasedimentary rocks are discussed here. The structurally overlying ophiolitic rocks are considered in the section on the Midland Valley terrane.

The Grampian terrane is separated from the Northern Highlands terrane by the Great Glen Fault and from the Midland Valley terrane by the Highland Boundary Fault – Fair Head-Clew Bay line. Along this fault zone crops out a series of rocks (the Highland Border Complex in Scotland and the Clew Bay Complex in western Ireland) that are believed to represent an Early Ordovician accretionary complex.

Laurentian basement in the Grampian terrane – the Annagh Gneiss Complex

The Annagh Gneiss Complex (AGC) is a Palaeoproterozoic orthogneiss terrane in western Ireland (Figs. 2, 6, 7C) that structurally underlies the Grampian Group Dalradian meta-sedimentary rocks of the northwest Mayo Inlier. The Dalradian rocks adjacent to the Annagh Gneiss Complex basement were deformed and metamorphosed under medium pressure amphibolite-facies conditions during the Grampian Orogeny, with PT estimates for staurolite–kyanite zone metamorphism close to the basement core of 8 ± 2 kbar and 620 ± 30 °C (Yardley et al. 1987). The basement gneisses reached a somewhat higher metamorphic grade with widespread migmatisation in Grenville times (van Breemen et al., 1978).

The evolution of the Annagh Gneiss Complex is described in detail in Daly (2009) and Daly (1996). Much of the AGC originated as juvenile Palaeoproterozoic crust represented by the 1753 ± 3 Ma calc-alkaline Mullet gneisses (Daly, 1996). These gneisses comprise intermediate to acid orthogneisses whose overall composition is granodioritic to granitic (Winchester and Max, 1984). Early amphibolitised basic bodies are concordant with the main gneissose foliation and may represent dykes or sills. Subsequent intrusive phases include the Late Mesoproterozoic (1271 ± 6 Ma) Cross Point gneisses which have an A-type geochemistry and Palaeoproterozoic t_{DM} ages (Daly, 1996). They probably represent anorogenic granitoids formed by melting of the pre-existing Palaeoproterozoic Mullet gneisses with the addition of a mantle-derived mafic component. The Doolough gneisses comprise a small volume of juvenile granitoids and associated basic rocks, which formed at 1177 ± 4 Ma (Daly, 1996). Grenville deformation occurred in two stages, between 1177–1015 Ma and from 995–960 Ma (Daly, 1996). These events were separated by the intrusion of the Doolough peralkaline granite at 1015 ± 4 Ma and by migmatisation and pegmatite emplacement between 995 and 980 Ma (Daly, 2009). A detailed mineral geochronology study (Daly and Flowerdew, 2005) investigated the possible presence of post-Grenville, pre-Grampian deformation in the AGC that could be attributed to late Neoproterozoic orogeny. U–Pb titanite analyses from the AGC gneisses yield a weighted mean $^{207}Pb/^{206}Pb$ age of 963 ± 8 Ma, which dates cooling after the main Grenville metamorphism. The weak discordance of the titanite data suggests that post-Grenville events had little effect on the U–Pb system in titanite.

All contacts between the Annagh Gneiss Complex and the Dalradian Supergroup are tectonic. However, the metasedimentary rocks consistently face away from the orthogneisses (Fig. 7C, Max & Long, 1985) and post-Grenville metadolerites (which are foliated but unmigmatised) cutting the AGC are similar to pre-tectonic dykes in the Dalradian (Daly, 1996). This suggests that the metasediments were stitched together with the older 'basement' prior to deformation. Sm–Nd isotopic data demonstrate that the Dalradian metasedimentary rocks were derived from a Palaeoproterozoic source similar to the Annagh Gneiss Complex (Kennedy & Menuge, 1992). K-feldspar and granitic clasts from pebbly horizons within the basal Dalradian Supergroup strata petrographically resemble lithologies within the AGC and yield U–Pb zircon ages of c. 1740 Ma and c. 980 Ma, respectively (McAteer et al., 2010a). These ages are within error of the c. 1730–1750 Ma Mullet gneisses and c. 990 Ma Grenvillian migmatitic leucosomes in the underlying AGC. U–Pb detrital zircon data suggest that that the basal Dalradian Supergroup rocks in NW Mayo are correlatives of the Grampian Group of the Dalradian Supergroup in Scotland. These data also imply the NW Mayo Grampian Group Dalradian was deposited after c. 955 Ma, with predominant input from c. 1640, c. 1500 and c. 990 Ma interpreted Laurentian sources (Labradorian, Pinwarian and Grenvillian terranes, respectively). All of these observations suggest that the Annagh Gneiss Complex represents the depositional basement to the Grampian Group Dalradian of NW Ireland (McAteer et al., 2010a).

Laurentian basement in the Grampian terrane – the Rhinns Complex

The Rhinns Complex occurs within the fault-bounded Colonsay–West Islay block which extends from the Inner Hebrides of Scotland to the island of Inishtrahull off the north coast of Ireland (Fig. 2). The Rhinns Complex is comprised of weakly deformed and metamorphosed alkaline igneous rocks, syenites and gabbros, which have geochemical signatures consistent with formation in a subduction-related magmatic arc. The protolith of the Rhinns Complex gneisses has been dated by the U-Pb zircon method at 1779 ± 3 Ma on Inishtrahull (Daly et al., 1991) and 1782 ± 5 Ma on Islay (Marcantonio et al., 1988). In both cases Sm–Nd depleted mantle model ages are only marginally older than the age of the gneissic protolith implying it represents juvenile mantle-derived crust. The largely granodioritic Colonsay orthogneisses (NE Colonsay) are older, yielding a c. 1880 Ma protolith age with c. 1800 Ma cross-cutting pegmatites (Daly et al., 2009). Metamorphic zircons from a Rhinns Complex metagabbro at Lossit Bay, Islay yielded U–Pb ages of 1725–1729 Ma (Loewy et al., 2003). This is consistent with a minimum age of 1710 Ma based on ^{40}Ar-^{39}Ar hornblende step-heating age from a discordant metagabbro 2 km northwest of Inishtrahull (Roddick and Max, 1983). To date, no evidence of deformation or metamorphism of Grenville age has been found within the Rhinns Complex.

On Colonsay and Islay (Fig. 2), the Rhinns Complex is structurally overlain by c. 5000m of low-grade Neoproterozoic clastic metasedimentary rocks, termed the Colonsay Group (e.g. Bentley, 1988). The Colonsay Group has been correlated with various Neoproterozoic successions in Scotland including the Torridonian, the Moine Supergroup and the Dalradian Supergroup, with most recent interpretations favouring a correlation with the Dalradian Supergroup (Muir et al., 1997; McAteer et al., 2010b).

The contact with the underlying Palaeoproterozoic orthogneisses is generally assumed to represent a tectonically modified unconformity (Bentley, 1988), and rare sedimentary structures suggest that the metasedimentary rocks young away from the orthogneisses (British Geological Survey, 1998). U–Pb detrital zircon ages from the Colonsay Group imply a Laurentian provenance with predominant input from a c. 1780 Ma source (Rhinns Complex) and some Grenvillian (c. 1.3–0.95 Ga), Pinwarian (c. 1.51–1.45 Ga), Labradorian (c. 1.71–1.62 Ga) and Ketilidian (c. 1.9–1.75 Ga) detritus, while U–Pb (SIMS) analyses of detrital titanite record Grenville metamorphic events in the source terranes (McAteer et al., 2010b). Felsic igneous clasts in the basal Colonsay Group (the Octofad Sandstone) resemble the underlying Rhinns Complex and yield c. 1795Ma and ca. 1400 Ma U–Pb zircon ages. The data substantiate the interpretation that the Colonsay Group rests unconformably on the Rhinns Complex, and support correlation with the Grampian Group of the Dalradian Supergroup in Scotland (McAteer et al., 2010b).

A Laurentian cover sequence in the Grampian terrane - the Dalradian Supergroup

The Dalradian Supergroup of Scotland and Ireland is a metasedimentary succession that was deposited on the eastern margin of Laurentia during the late Neoproterozoic and Early Cambrian. Existing constraints imply the base is younger than 800Ma and it extends to at least 510Ma (Smith et al., 1999; Tanner and Sutherland, 2007). It comprises a thick sequence of lithologically diverse metasediments and mafic volcanics, along with three distinct glacigenic units that are correlated with widespread Neoproterozoic glaciations (McCay et al., 2006). Lithostratigraphic correlation is hampered by the almost complete absence of stratigraphically useful fossils, complex polyphase deformation and rapid lateral facies changes. Despite these difficulties, a coherent lithostratigraphy from western Ireland to the Shetland Islands has been established (Harris et al., 1994) comprising four Groups - Grampian, Appin, Argyll and Southern Highland.

The structural history of the Scottish Dalradian has been comprehensively studied during the last century. Four main deformational episodes (D1 to D4) have been identified (e.g. Harris et al., 1976), with the structure dominated by a large, recumbent, southeastwards-vergent antiform, the D2 Tay Nappe. The core of the Tay Nappe is exposed solely in the Loch Awe Syncline of the Southwest Highlands (Stephenson & Gould, 1995). Across this steep belt there is a zone of primary facing divergence, with the structures northwest of the Loch Awe Syncline verging to the northwest and the Tay Nappe verging to the southeast (Fig. 7A). This has been interpreted as a root zone to the major nappe structures (Roberts and Treagus, 1977). In the Central Highlands, the structure is considerably more complex and the evidence for a root zone is equivocal (Rose & Harris, 2000). Most workers consider the Tay Nappe to have been developed by southeast-directed D2 shearing of upright D1 structures, with this shearing producing the grossly inverted stratigraphy in the 'Flat Belt' (e.g. Harris et al., 1976; Treagus, 1987). Mendum & Thomas (1997) consider the D1 structures to be initially recumbent and highly modified by northwest-directed D2 shearing. The Tay Nappe been folded downwards adjacent to the Highland Boundary Fault in a monoform termed the Highland Border Downbend. D4 deformation, which caused the downbend (Johnson, 1991), resulted in upright folds and an associated strong crenulation cleavage close to the Highland Boundary Fault. A comprehensive account of the structure and lithostratigraphy of the Scottish Dalradian is given in Stephenson et al. (2013) and references therein.

In Ireland, the Dalradian outcrop is fragmented into a series of inliers (NW Mayo, Donegal and the Sperrin Mountains, the Central Ox Mountains, Connemara, and NE Antrim; Fig. 2), so deformational and metamorphic events need to be correlated from inlier to inlier. All deformational and metamorphic chronologies for the Irish Dalradian presented here are local; i.e. they correspond to that inlier exclusively and no regional correlation is implied. The two Dalradian inliers in Ireland that offer the longest transects orthogonal to orogenic strike are the NW Mayo and Donegal inliers. The broad structure of the NW Mayo Inlier (Fig. 7C) is similar to that of the Southwest Highlands of Scotland. There are a series of early bedding-parallel shear zones (commonly referred to as "slides" in the literature) that are folded by later (F2) folds. There is a primary facing divergence of the F2 folds either side of a basement core, the Annagh Gneiss Complex. To the north of this 'root zone' shallowly inclined F2 folds face north; to the south, recumbent F2 folds face south (Chew, 2003). Approaching the Achill Beg Fault, the south-facing F2 antiform is rotated into a downward-facing orientation (Fig. 7B) analogous to the Highland Border Downbend. The Dalradian rocks of Donegal (Fig. 7B) show evidence of three phases of Grampian deformation. F1 folds are best seen in north Donegal where there is a primary facing divergence across the Inishowen Syncline, a structure which is similar to the Loch Awe Syncline of Scotland (Hutton and Alsop, 1996). D2 in north Donegal is associated with the development of northwest-directed thrust nappes that are separated from each other by D2 slides (Fig. 7B). Within each nappe, recumbent F2 folds face northwest (Hutton and Alsop, 1995). Further south, to the southeast of the Leennan Fault, isoclinal, recumbent F2 folds, such as the Sperrin Nappe, were transported towards the southeast (Alsop, 1996). Major recumbent F3 nappes also show a consistent vergence and sense of movement to the southeast (Alsop, 1996). During this D3 phase of southeast-directed shearing, the locally inverted Dalradian succession was thrust over elements of the colliding arc terrane along the Omagh Thrust (Fig. 7B; Alsop and Hutton, 1993).

The Dalradian outcrop in Scotland is one of the classic areas for the study of regional metamorphism. Barrow (1893) working in the SE Highlands of Scotland was the first to show that differing mineral assemblages in pelitic rocks reflect different conditions of metamorphism. It is now recognized that much of the Scottish and Irish Dalradian has experienced what is now termed Barrovian (medium-pressure) regional metamorphism. In addition to the Barrovian (medium-pressure regional metamorphism) zonal scheme, Read (1923) described the Buchan zonal scheme in the NE Scottish Highlands, which represents conditions of low-pressure, high temperature metamorphism (Harte & Hudson, 1979). Barrovian metamorphism in general postdates the regional D2 deformation (Robertson, 1994; Harte et al., 1984), and the metamorphic zones are not folded by the Tay Nappe. Instead, there is a gradual increase in metamorphic grade from greenschist facies in the southwest to middle-amphibolite facies in the northeast. Maximum P-T conditions in the central Grampian Highlands were 7-8 kbar, 500-600°C, while the presence of kyanite-bearing gneissose semipelites in the Central Highland Division (now termed the Badenoch Group) indicates P-T conditions of 7-10 kbar, 650-800°C (Phillips et al., 1999). The relationship between the Buchan and Barrovian-type metamorphism remains contentious. Some workers regard them as essentially contemporaneous (Harte & Hudson, 1979; Fettes et al., 1976), with a transition between the Buchan and Barrow series while others regard the Buchan-type metamorphism to predate the Barrovian regional metamorphism (Dempster et al., 1995). The low-pressure, high temperature regime of the Buchan metamorphism has been attributed to the heating effects of Lower Ordovician synorogenic intrusions (Harte & Hudson, 1979; Yardley and Senior, 1982), which are probably subduction-related (Yardley et al., 1982). In an alternative model for the tectonothermal development of the Buchan Block of the NE Highlands, Viete et al. (2010) proposed that emplacement of the Grampian gabbros and regional metamorphic heating occurred during Grampian syn-orogenic lithospheric-scale extension. Extension followed lithospheric thickening associated with the initiation of Grampian orogenesis and was followed in turn by renewed lithospheric thickening and the termination of extensional heating.

The metamorphic evolution of the Irish Dalradian is dominated by the development of Barrovian metamorphic assemblages, although the metamorphic grade varies significantly from place to place. In the NW Mayo Inlier, the metamorphic grade is highest closest to the basement core (the Annagh Gneiss Complex) where it locally reaches the sillimanite zone (Max et al., 1983) and post-dates the development of the main folds (locally F2 in age). The metamorphic grade decreases to the south towards Clew Bay, where the timing of porphyroblast growth took place earlier, post-dating the development of F1 folds. The metamorphic evolution of the Dalradian of the Central Ox Mountains Inlier is similar, with MP3 peak metamorphic conditions ranging from the staurolite-kyanite zone in the NW to greenschist facies in the SE. The metamorphism in Donegal reached the garnet zone over most of the inlier (Pitcher and Berger, 1972) and generally post-dates the development of F2 folds. The metamorphic grade increases approaching the Lough Derg inlier to the south, as progressively deeper structural levels are exposed through the inverted lower limb of the Ballybofey Nappe (Alsop, 1991). Here the metamorphism is in the staurolite-kyanite zone and is structurally later, post-dating the development of F3 folds. However, there are two places in the Dalradian of Ireland where Barrovian metamorphic conditions are not encountered. Adjacent to the voluminous basic and intermediate Ordovician intrusions of south Connemara, migmatitic melting of metasediments has taken place under low-pressure / high temperature conditions, analogous to the Buchan metamorphism of Scotland. This metamorphic event (which postdates the third phase of deformation in Connemara) overprints an earlier phase of regional metamorphism, which was probably in the staurolite-kyanite zone over much of the Connemara Inlier (Yardley, 1976; 1980). The second exception to the prevalence of Barrovian metamorphic conditions is encountered in the southern portion of the NW Mayo Inlier. On southern Achill Island adjacent to the Fair Head – Clew Bay Line, blueschist-facies metamorphism (indicative of high pressure, low temperature metamorphism) occurred (Fig. 6; Gray and Yardley, 1979). The MP1 blueschist-facies assemblages developed at P-T conditions of 10.5 ± 1.5 kbar and 460 ± 45 ºC contemporaneously with the Barrovian metamorphic assemblages to the north (Chew et al., 2003).

Grampian magmatism in the Dalradian is restricted to the NE Scottish Highlands and Connemara in western Ireland. Magmatic activity is comprised of syn-orogenic basic and intermediate intrusives and is interpreted as representing the roots of a volcanic arc (e.g. Yardley et al., 1982, Yardley and Senior, 1982; Tanner, 1990). In Connemara, syn-D2 to early D3 basic intrusions have yielded U-Pb zircon ages of 470.1 ± 1.4 Ma and 474.5 ± 1 Ma (Friedrich et al., 1999a). Late D3 quartz-diorite gneisses in the migmatite zone in south Connemara yield U-Pb zircon ages of 463 ± 4 Ma (Cliff et al., 1996) and 467 ± 2 Ma (Friedrich et al., 1999b). The post-tectonic Oughterard granite in Connemara has yielded a 462.5 ± 1.2 Ma U-Pb xenotime age (Fig. 6; Friedrich et al., 1999a). Basic magmatism in NE Scotland yields similar ages to the basic magmatism in Connemara. Dempster et al. (2002) and Carty et al. (2012) report ages of 470 ± 9 Ma and 471.3 ± 0.6 Ma for the post-D2, pre-D3 Insch Gabbro and the syn-D2 Portsoy Gabbro respectively. Oliver et al. (2008) report several U-Pb SIMS zircon ages for the Newer Granites of NE Scotland that cluster at c. 470 Ma. Unlike Connemara, these foliated granites are all two-mica S-types, with Nd, Sr and O isotopic systematics that suggest that they represent melted lower crustal (sedimentary) rocks that formed during peak metamorphism.

Estimates for the closure temperature of the Sm-Nd system in garnet range from c. 600°C (Mezger et al., 1992) to c. 850°C (Cohen et al., 1988). As Dalradian metamorphism rarely exceeds upper amphibolite facies, the Sm-Nd system in garnet will record garnet growth rather than cooling. Peak metamorphism in the Dalradian is constrained by Sm-Nd garnet ages of 473 – 465 Ma in the type area of Barrovian metamorphism in the Scottish Highlands (Baxter et al., 2002; Oliver et al., 2000), and by Sm-Nd garnet ages of 460 Ma in the Dalradian of NW Ireland (Flowerdew et al., 2000).

Mineral cooling ages (typically the ^{40}Ar-^{39}Ar or Rb-Sr methods applied to muscovite, biotite or hornblende) record the post-metamorphic cooling history of an orogenic belt (e.g. Cliff, 1985). Metamorphic mica cooling ages from the Scottish Dalradian such as the classic study of Dempster (1985) and Dempster et al. (1995) show a scatter in age, but most of the data range between 450-460 Ma, which is interpreted as a period of rapid cooling. The oldest Rb-Sr cooling ages of c. 568 Ma for muscovite and c. 505 Ma biotite are inconsistent with a c. 470 Ma Grampian orogeny, and their validity has been questioned (Evans & Soper, 1997). Recent geochronological studies in the Irish Dalradian (Connemara, NW Mayo and the Ox Mountains) have employed ^{40}Ar-^{39}Ar and Rb-Sr dating on a suite of metamorphic minerals (principally hornblende, biotite and muscovite). These data typically range between 470 – 455 Ma and are consistent with crystallization and subsequent cooling from the Grampian orogenic peak at c. 470 Ma (Friedrich, 1998, 1999b; Flowerdew et al., 2000; Flowerdew, 2000; Chew et al., 2003; Daly and Flowerdew, 2005).

Probable para-autochthonous Laurentian terranes - the Tyrone Central Inlier and Slishwood Division in NW Ireland

In NW Ireland, two high-grade basement paragneiss terranes, the Tyrone Central Inlier and the Slishwood Division, crop out immediately to the south of the main belt of Dalradian Supergroup rocks (Fig. 2). Their metamorphic and magmatic evolution is substantially different to that of the adjacent lower-grade Dalradian Supergroup rocks to the north, and this led to speculation that they represent exotic terranes (e.g. Max and Long, 1985; Sanders et al., 1987), although more recent research (e.g. Daly et al., 2004; Chew et al., 2008) suggests that both terranes have a Laurentian affinity. Because of their anomalous position, the affinity and tectonic setting of these displaced terranes are of great importance to our understanding of the tectonic evolution of the Grampian orogenic belt, and their geological histories are described in detail below.

The Tyrone Central Inlier is the structurally lowest unit within the Tyrone Inlier (Fig. 8). It consists predominantly of a series of high-grade psammitic paragneisses (Hartley 1933) in tectonic contact with the other two units of the Tyrone Inlier, an ophiolitic unit (the Tyrone Plutonic Group) and Arenig – Llanvirn arc volcanics and black shales (the

Tyrone Volcanic Group). The Tyrone Plutonic Group, the Tyrone Volcanic Group and the arc-related intrusive rocks that cut them (Fig. 8) are together referred to as the Tyrone Igneous Complex (Cooper & Mitchell 2004), and are discussed later in this article. 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. 8).

The Tyrone Central Inlier is structurally overlain by the ophiolite complex (Hutton et al., 1985). The paragneisses of the inlier have undergone polyphase deformation and metamorphism with a primary assemblage in pelitic lithologies of biotite + plagioclase + sillimanite + quartz ± garnet (i.e. sillimanite zone, below the second sillimanite isograd). Associated with this metamorphic event are abundant leucosomes. The high grade assemblages and leucosomes are cut by post-tectonic pegmatites which post-date at least two deformation fabrics. The leucosomes have yielded a weighted average ^{207}Pb / ^{206}Pb zircon age of 467 ± 12 Ma. The pegmatites have yielded 457 ± 7 Ma (465 ± 7 Ma) and 458 ± 7 (466 Ma ± 7 Ma) Rb-Sr muscovite – feldspar ages (Chew et al., 2008) with the values in parentheses denoting the Rb-Sr ages recalculated with the new ^{87}Rb decay constant of $1.3971 \times 10^{-11} a^{-1}$ of Rotenberg et al. (2012). Biotite from the main fabric in the Tyrone Central Inlier yields a ^{40}Ar-^{39}Ar age of 468 ± 1.4 Ma, while muscovite from the same pegmatites that have yielded *c.* 458 Ma (c. 465 Ma) Rb-Sr ages yields ^{40}Ar-^{39}Ar ages of 466 ± 1 Ma and 468 ± 1 Ma (Chew et al., 2008). Palaeoproterozoic Nd model ages have also been obtained from the paragneisses of the Tyrone Central Inlier. These overlap with Nd model ages obtained from both the Argyll and Southern Highland Groups (Daly and Menuge, 1989). U-Pb detrital zircon analyses from a psammitic gneiss yield age populations at 1.05 – 1.2, 1.5, 1.8, 2.7 and 3.1 Ga (Chew et al., 2008) which are ages typical of the Laurentian craton (e.g. Cawood et al., 2003). *In situ* Hf isotope analysis of zircon rims from c. 470 Ma granitoid rocks that cut the Tyrone Central Inlier paragneisses yield ε_{Hf470} values of c. -39. This isotopic signature requires an Archaean source, suggesting that rocks similar to the Lewisian Complex of Scotland occur at depth beneath the Tyrone Central Inlier (Flowerdew et al. 2009). Chew et al. (2008) suggest that the Tyrone Central Inlier is a high-grade metasedimentary terrane of Laurentian (Dalradian?) affinity which has experienced high-grade metamorphism during the Grampian Orogeny, possibly in the roots of a deforming arc. The ophiolite was juxtaposed with the Central Inlier at this time, and the two units were then intruded by a series of stitching tonalitic – granodioritic plutons at 470 - 465 Ma (Cooper et al., 2011) and accompanied by the extrusion of arc lavas. The geological history of the Tyrone Igneous Complex and the Tyrone Central Inlier is substantially different to that of the adjacent Dalradian Supergroup rocks to the northwest which have experienced greenschist-facies metamorphism and no Grampian magmatism. It is probable that the Tyrone Igneous Complex and the Tyrone Central Inlier evolved outboard of the

Laurentian margin during the Grampian Orogeny, and were finally juxtaposed with the margin when the Dalradian was thrust over the Tyrone Inlier during regional SE-directed D3 thrusting (Alsop and Hutton, 1993).

The Slishwood Division is a metasedimentary unit that crops out in the NE Ox Mountains and Lough Derg inliers and the eastern end of the Rosses Point Inlier in NW Ireland (Fig. 9). Gravity (Young, 1974) and magnetic data (Max et al., 1983a) suggest that they are all part of one basement block. The Slishwood Division has long been regarded as pre-Grampian basement (e.g. Max and Long, 1985; Sanders et al., 1987) because of its exceptionally high metamorphic grade, the complex metamorphic and structural history compared with the adjacent Dalradian Supergroup, as well as geochronological evidence. All three inliers are comprised predominantly of migmatitic psammitic gneisses with minor pelites, semipelites, calc-silicates, metabasites and serpentinites which are cut by a suite of granitic pegmatites (Flowerdew et al., 2000), while the NE Ox Mountains Inlier is also cut by several tonalite and granite bodies, possibly subduction-related, that intruded between 471 and 467 Ma (Flowerdew et al., 2005).

The Slishwood Division records pre-Grampian high-pressure granulite- and earlier eclogite-facies metamorphic events that have not been observed elsewhere in the Dalradian Supergroup rocks of Ireland (Sanders et al., 1987; Flowerdew and Daly, 2005). Sanders et al. (1987) recognised an early eclogite-facies metamorphism in the Slishwood area with metamorphic pressures estimated at 12–14 kbar. High-pressure granulite facies assemblages developed at 11 kbar and c. 860°C in response to isothermal decompression when original omphacitic clinopyroxene was replaced by sieve-textured plagioclase-augite intergrowths. Subsequently, slow isobaric cooling took place at depth with kyanite replacing sillimanite (Sanders et al., 1987). Flowerdew and Daly (2005) give pressure-temperature estimates of c. 15 kbar, 800° C for the granulite-facies assemblages in the NE Ox Mountains and Lough Derg inliers. Sm-Nd garnet – plagioclase whole-rock isochrons from the granulite-facies assemblages developed in metabasite bodies yield ages of 605 ± 37 Ma (Sanders et al., 1987) and 544 ± 52 Ma, 539 ± 11 Ma, 596 ± 68 Ma and 540 ± 50 Ma (Flowerdew and Daly, 2005). The Sm-Nd ages and pressure-temperature estimates are illustrated on Figure 9. In the Lough Derg Inlier some of the metabasite bodies preserve original gabbroic textures, one of which has yielded an igneous clinopyroxene – plagioclase whole-rock isochron of 580 ± 36 Ma (Flowerdew and Daly, 2005). This provides a maximum age for the high-grade metamorphism and suggests that gabbroic magmatism may have been related to extension associated with the opening of the Iapetus Ocean (cf. Bingen et al., 1998). U–Pb detrital zircon ages from Slishwood Division metasedimentary rocks (Daly et al., 2004) demonstrate a post-Grenvillian age for deposition of the protolith.

The Slishwood Division differs substantially from the Tyrone Central Inlier as it has experienced eclogite- and granulite-facies metamorphism prior to suturing with the Dalradian Supergroup, while it was also intruded by pre-tectonic basic sills and dykes which are notably absent in the Tyrone Central Inlier. However the subsequent Grampian (i.e. c. 475 – 465 Ma) histories of the Slishwood Division and the Tyrone Central Inlier are very similar. Both have undergone leucosome generation and subsequent intrusion of pegmatites which cut the high-grade fabrics. The high-grade fabrics in the Slishwood Division are cut by early Grampian tonalite intrusions (Fig. 9) which have yielded U-Pb SIMS zircon ages of 472 ± 6 Ma and 467 ± 6 Ma (Flowerdew et al., 2005), similar to the leucosome ages of Chew et al. (2008) from the Tyrone Central Inlier. Rb-Sr muscovite ages from the pegmatite suite in both units cluster at around c. 460 - 455 Ma (Flowerdew et al., 2000, Chew et al. 2008). Final imbrication of the Slishwood Division with the Central Ox Mountains Dalradian occurred during regional SE-directed D3 shearing (Flowerdew et al., 2000), similar to regional SE-directed thrusting of the Dalradian over the Tyrone Inlier along the D3 Omagh Thrust (Alsop and Hutton, 1993).

Early Ordovician accretionary complex sequences in the Grampian terrane

The suture between the deformed Laurentian margin (Dalradian Supergroup) and the colliding arc (Midland Valley Terrane) is sharply defined by the Highland Boundary Fault in Scotland and the Fair Head – Clew Bay Line in Ireland (Fig. 2). Along this major fault zone a series of Lower Paleozoic deep marine sedimentary rocks and isolated occurrences of mafic and ultramafic rocks crop out, termed the Highland Border Complex in Scotland and the Clew Bay Complex in western Ireland. The Highland Border and Clew Bay Complexes have figured prominently in tectonic reconstructions of the Grampian belt (e.g. Dewey and Mange, 1999), where they are usually regarded as an Early Ordovician accretionary complex.

The stratigraphical succession and age of the Highland Border Complex and its relationship to the Dalradian Supergroup have been hotly debated since the late nineteenth century, as the Highland Border Complex is poorly exposed and heavily faulted, way-up indicators are generally absent, and fossils are extremely rare. Models proposed for the Highland Border Complex can broadly be divided into two groups. According to the exotic terrane model (e.g. Curry et al., 1984), the Highland Border Complex first encountered Dalradian rocks in late Silurian–early Devonian times, after the latter had undergone polyphase Grampian (early Ordovician) deformation (Bluck & Dempster, 1991). In contrast, a recent reinterpretation of the Highland Border Complex (Tanner and Sutherland, 2007) suggests that the majority of the sequence is in stratigraphic continuity with the Dalradian Supergroup, with the exception of the fault-bounded slivers of ophiolitic rocks of the Highland Border Ophiolite (Tanner and

Sutherland, 2007). The exotic terrane model of Curry et al. (1984) was based on their four-fold stratigraphical succession for the Highland Border Complex. Assemblage 1 was regarded as the oldest unit in the complex and consists of serpentinite and associated ophiolitic rocks (gabbro and amphibolite). Assemblage 2 consists of carbonate and associated conglomerate, such as the Dounans Limestone near Aberfoyle which has yielded a Lower Arenig trilobite and brachiopod fauna (Curry et al., 1982, 1984). Assemblage 3 consists of black shale, chert and quartz wacke. Chitinozoans from the shales have yielded an age range from Upper Arenig to Upper Ashgill (Curry et al., 1984). Assemblage 4 consists of sandstone and conglomerate such as the Achray Sandstone and the Margie Series of the North Esk. Two distinct generations of chitinozoa were obtained from the Achray Sandstone at Lime Craig Quarry near Aberfoyle (Curry et al., 1984) - a reworked, blackened and flattened Llanvirn-Llandeilo fauna along with younger, undamaged Caradoc-Ashgill taxa, suggesting that the Highland Border Complex had undergone pre-Caradoc deformation and low-grade metamorphism prior to the deposition of assemblage 4. Tanner and Sutherland (2007) reinvestigated the stratigraphical succession and chitinozoan faunas of Curry et al. (1984). They found no evidence that sedimentary rocks of proven age younger than Arenig occur in the Highland Border Complex and that the 'ophiolite' lies structurally on top of the Highland Border Complex and not at the base as previously thought (Curry et al. 1984). Their model (Figs. 3, 10) is much simpler, with the Highland Border Ophiolite dividing the Complex into an older portion in continuity with the Dalradian (termed the Trossachs Group) and an upper sequence comprising the obducted ophiolite and its cover (the Garron Point Group). The Laurentian provenance of detrital zircons within the Trossachs Group reinforces its linkage with the Dalradian Supergroup (Cawood et al. 2012).

The Clew Bay Complex in western Ireland comprises a series of low-grade turbiditic metasediments which have been interpreted as representing an accretionary complex (e.g. Dewey and Mange, 1999). On Clare Island, the Clew Bay Complex comprises graphitic mudrocks, spilites, greywackes and micro-conglomerates with clasts of vein quartz, schist, gneiss, and granite. The nature of the deformation in these rocks is difficult to ascertain. Chew (2003) concluded that the Dalradian and the Clew Bay Complex on the island of Achill Beg (Fig. 6) share the same polyphase structural history across the Achill Beg Fault. This model is therefore similar to the model of Tanner and Sutherland (2007) who favour stratigraphic continuity of the Highland Border Complex with the Dalradian Supergroup. An alternative interpretation of the structure of parts of the Clew Bay Complex is given by Max (1989) who reinterpreted it to be largely tectono-sedimentary in origin (i.e. a chaotic mélange), with blocks of greywacke up to 8m across floating in a black mudstone matrix. A Middle Cambrian – Early Ordovician sponge (*Protospongia hicksi*, Rushton & Phillips, 1973) and Early - Middle Ordovician coniform euconodonts (Harper et al., 1989) have been obtained from the Clew Bay Complex. Chew et al. (2003) estimated metamorphic temperatures of 325 – 400˚C and pressures of 10 kbar for the Clew Bay Complex, which is similar to the high-pressure – low-temperature metamorphic conditions experienced by the blueschist-facies Dalradian rocks to the north while metamorphic cooling ages from ^{40}Ar-^{39}Ar ages from metamorphic muscovite cluster at c. 470 Ma (Chew et al., 2010).

Midland Valley Terrane

The Midland Valley terrane consists of Late Cambrian – Early Ordovician suprasubduction ophiolite complexes such as Shetland to the north of mainland Scotland, Ballantrae in SW Scotland, Tyrone in NW Ireland and Clew Bay in western Ireland (Figs 2, 6; note most of the Midland Valley terrane is covered by younger Middle-Ordovician to Permo-Triassic sediments that are not differentiated on Fig. 2.). It also contains fragments of the Grampian volcanic arc and its associated fore-arc basin, such as the Lough Nafooey arc and South Mayo Trough in western Ireland (Fig. 6). The eroded remnants of the Grampian orogen are overlain by Silurian successor basins.

Late Cambrian – Early Ordovician supra-subduction ophiolite complexes

The Grampian arc-continent collision event resulted in the obduction of supra-subduction zone ophiolites onto the Laurentian margin (Dewey & Shackleton, 1984). Several Late Cambrian – Early Ordovician suprasubduction ophiolite complexes are preserved on the Laurentian margin of Scotland and Ireland and can be divided into two belts. A northwestern belt occurs in close proximity to the Highland Boundary Fault – Fair Head – Clew Bay Line, and includes the ophiolitic rocks of Unst, Shetland, Bute in SW Scotland, and a series of smaller fault-bounded slivers of ophiolitic mélange comprising the Highland Border ophiolite. A southeastern belt is represented by the ophiolitic rocks of the Ballantrae Igneous Complex that is likely to have been obducted from a different suture now buried underneath younger rock units of the Southern Uplands – Longford Down Terrane (Fig. 2). Although geographically part of the northwestern belt of ophiolite complexes, the geochronological constraints on the ophiolitic rocks of the Tyrone Plutonic Group suggest it may be associated with the Ballantrae Igneous Complex (Figs. 3, 11).

The Shetland ophiolite is exposed in the northeast extension of the Grampian Terrane on the islands of Unst and Fetlar (Fig. 2). It occurs in two thrust sheets, probably part of a downfolded klippe, that overlie Dalradian metasedimentary rocks (Flinn, 1985, 2000). The most complete succession is within the lower sheet and is 7 km thick. From the base upwards it comprises a metamorphic sole, peridotite, dunite, pyroxenite and gabbro. The peridotite and the dunite are heavily serpentinized but have attracted widespread interest because of the concentration of platinum-group elements (e.g.

Prichard & Lord, 1993; O'Driscoll et al., 2012). Only the lower parts of the classic 'Penrose' ophiolite succession are definitively preserved. Minor dykes that cut the gabbro unit have been interpreted as representing the lower levels of a possible sheeted dyke complex (Flinn 1985; Prichard 1985). Geochemical analyses of the dykes indicate that they have basaltic island-arc affinities, with some high-Mg members classified as boninites (Gass et al. 1982; Moffat 1987; Spray 1988). No contiguous pillow lavas are present. A U-Pb TIMS zircon age of 492 ± 3 Ma obtained from a plagiogranite within the gabbro unit dates crystallization of the complex (Spray & Dunning, 1991). The gabbro in the lower thrust sheet is overlain unconformably by low-grade meta-siltstones with occasional metavolcanic rocks and conglomerate layers. The conglomerate layers include clasts that can be matched with distinctive lithologies in the ophiolite, including gabbro, quartz-albite porphyry and albite-granite. The sedimentary cover to the ophiolite is believed to have been derived from erosion of the ophiolite nappes as they emerged above sea-level (Flinn, 1958), but no geological relationships preclude deposition on the sea-floor *prior* to obduction. In the east of Fetlar, the lower ophiolite sheet is also overlain unconformably by the enigmatic Funzie conglomerate of Fetlar (Flinn 1956) which is dominated by quartzite clasts, the provenance of which are uncertain. K-Ar hornblende ages obtained from the metamorphic sole range between c. 479 and c. 465 Ma and are interpreted to broadly date obduction (Spray, 1988).

The Highland Border Ophiolite (Tanner and Sutherland, 2007; Tanner 2007) forms a discontinuous belt of mafic and serpentinized ultramafic rocks along the Highland Boundary Fault from Bute to Stonehaven (Fig. 10). Some of the serpentinized ultramafic rock slivers are believed to have been produced by exhumation of serpentinized sub-continental lithospheric mantle within the extending, distal portions of the Laurentian margin during the opening of the Iapetus Ocean (Chew 2001, Tanner 2007; Henderson et al., 2009) which were then incorporated into the ophiolitic mélange during the onset of collision. However at least two localities along the Highland Boundary fault zone (Scalpsie Bay on Bute and at Aberfoyle) expose a thick, locally developed 'sole' of amphibolite (Henderson and Robertson, 1982) of significantly higher metamorphic grade than the local Highland Border Complex or Dalradian Supergroup rocks. These amphibolites are believed to represent the metamorphic sole of a classic 'Penrose' ophiolite (Penrose conference participants, 1972). The peak metamorphic assemblage at Scalpsie Bay on Bute is hornblende, garnet and titanite (Henderson and Roberston, 1982). Magmatic zircons from the Bute amphibolite define a 499 ± 8 Ma U-Pb Concordia age, interpreted as dating the crystallization of its igneous protolith and therefore the formation of this part of the Highland Border Ophiolite (Chew et al., 2010). Garnet, titanite, amphibole and the whole rock define a 546 ± 42 Ma Sm-Nd isochron, while the amphibole has yielded a 537 ± 11 K-Ar age (Dempster and Bluck, 1991). More recent constraints of the age of metamorphism include a 490 ± 4 Ma ^{40}Ar-^{39}Ar hornblende age from the Bute amphibolite, and a 488 ± 1 Ma ^{40}Ar-^{39}Ar muscovite age from a metasedimentary xenolith within it, from which P-T estimates of 5.3 kbar and 580 °C relate to ophiolite obduction (Chew et al., 2010). A homogenous zircon age population from this metasedimentary xenolith intercalated within the ophiolite defines a U-Pb Concordia age of 490 ± 4 Ma. This date is interpreted to suggest a volcaniclastic origin for this rock, possibly sourced from a subduction-related magmatic arc founded on ophiolitic basement (Chew et al., 2010).

The high-grade Deer Park Complex is the correlative of the Highland Border Ophiolite in western Ireland (Fig. 6). It consists of a mélange of serpentinite, amphibolite and slivers of metasediment in tectonic (faulted) contact with the low-grade accretionary complex rocks of the Clew Bay Complex (Phillips, 1973). The amphibolites within the Deerpark Complex have a Mid Oceanic Ridge Basalt (MORB)-like trace element chemistry, but pronounced Nb anomalies and neodymium isotopic compositions that are consistent with a juvenile subduction-related origin (Chew et al., 2010). The amphibolites and serpentinites have been interpreted by Ryan et al. (1983) as representing a dismembered ophiolite. Detrital zircon U-Pb data from slivers of metasedimentary rock within the Deerpark Complex ophiolitic mélange suggest these metasediments are identical to the Dalradian Supergroup. They are interpreted as deepwater sediment on the seafloor of the Laurentian continent which was then caught up by obduction of the ophiolite (Chew et al., 2010). The "cooling" ages of metamorphic minerals in the Deerpark Complex range from c. 480 Ma (Rb-Sr and ^{40}Ar-^{39}Ar ages from metamorphic muscovite in the metasedimentary slivers) to c. 515 Ma (a ^{40}Ar-^{39}Ar hornblende age from an amphibolite) which are significantly older than the c. 470 – 455 Ma metamorphic mineral ages recorded from the Dalradian and low-grade Clew Bay Complex rocks to the north (Chew et al., 2010). The pressure – temperature conditions in the Deerpark Complex are also different to the low-temperature, high-pressure assemblages found in the Dalradian and Clew Bay Complex rocks, yielding estimates of c. 580˚C, 3.3 kbar (i.e. shallower and hotter).

The ophiolitic affinity of the high-grade metabasites and serpentinites of the Deerpark Complex and Highland Border Ophiolite means that they figure prominently in tectonic models of the Grampian Orogeny (e.g. Dewey and Mange, 1999), with the low-grade turbidites of the Clew Bay and Highland Border complexes interpreted as accretionary complexes and the Deerpark Complex and Highland Border Ophiolite representing a dismembered supra-subduction ophiolitic mélange. The metamorphic pressure-temperature estimates from the Clew Bay Complex and Deerpark Complex in western Ireland are consistent with this scenario, as the accretionary complex rocks of the Clew Bay Complex have experienced high-pressure, low temperature metamorphic conditions (c. 10 kbar, 325 – 400˚C, Chew et al., 2003) as would be expected in a subduction zone environment, while the ophiolitic rocks of the Deerpark Complex have experienced high-temperature, low-pressure metamorphic conditions typical of the metamorphic sole of an obducted ophiolite.

The Ballantrae Igneous Complex occurs towards the southern margin of the Midland Valley Terrane in SW Scotland and comprises two main rock associations (Figs 2, 11). The first is the volcano-sedimentary Balcreuchan Group (Smellie & Stone, 2001) that comprises basalt pillow lavas, agglomerates, tuffs, sandstones, black shales and cherts (Fig. 11). An early to late Arenig age is indicated by graptolite faunas. Geochemical studies have suggested a variety of different tectonic settings for these lavas including mid-ocean ridge, within-plate and island arc environments (e.g. Wilkinson & Cann, 1974; Thirlwall & Bluck, 1984; Smellie & Stone, 2001). The second association consists of serpentinized peridotite and harzburgite with minor gabbro and trondhjemite, and possible sheeted dykes (Fig. 11). Although lithological contacts are highly faulted, the overall association of rock types has led to general acceptance that they form part of a dismembered ophiolite. Isotopic ages broadly complement the faunal data. Two island-arc lavas have whole-rock Sm-Nd ages of 476± 14 Ma and 501 ± 12 Ma (Thirlwall & Bluck 1984), and a gabbro of within-plate affinity has yielded a K-Ar age of 487 ± 8 Ma (Harris et al. 1965). Olistrostromes and mélanges within the complex contain blocks of material that preserve evidence for subduction-related metamorphism. These include garnet pyroxenites metamorphosed at 10-13 kb and 900-950°C (Treloar et al. 1980) and blueschist-facies rocks. Sm-Nd isochron ages of 576 ± 32 Ma and 505 ± 11 Ma have been obtained from the garnet pyroxenites (Hamilton et al. 1984). A K-Ar age of 478 ± 8 Ma (Llanvirn) obtained from the metamorphic sole probably dates obduction (Bluck et al. 1980). The age of unconformably overlying sedimentary rocks indicates that the ophiolite was obducted and eroded by middle Llanvirn (c. 465 Ma) times.

The ophiolitic rocks of the Tyrone Plutonic Group form the southern, structurally lower portion of the Tyrone Igneous Complex (Fig. 8) and consist of a unit of gabbros and dolerites. The gabbros exhibit cumulate layering and are overlain by a sheeted dolerite dyke complex which exhibits classic one-sided chilled margins (Hutton et al., 1985). Pillow lavas are scarce within the group, and are only present as a roof-pendant within the Craigballyharky tonalite intrusion. Geochemistry has shown the sequence to be of suprasubduction affinity (Draut et al. 2009), with positive Pb, negative Nb and modest Ti anomalies (Cooper et al., 2011). Based on a magma-mixing relationship between gabbro and tonalite at Craigballyharky, Hutton et al. (1985) considered the ophiolitic rocks of the Tyrone Plutonic Group to be contemporaneous with the 472 +2/-4 Ma Craigballyharky tonalite. This U–Pb zircon age was thus taken to represent the age of the ophiolite and the timing of ophiolite obduction (Hutton et al. 1985). Cooper et al. (2011) presented a U-Pb zircon age of 479.6 ± 1.1 Ma for an olivine gabbro from the

Tyrone Plutonic Group which displays cumulate layering. Two zircon fractions gave inherited ages of c. 1015 Ma and 2100 Ma, which were attributed by Cooper et al. (2011) to possibly reflect subduction of peri-Laurentian metasediments under the Tyrone ophiolite during its formation.

The colliding volcanic arc terrane and its associated fore-arc basin

During closure of the Iapetus Ocean, subduction of Iapetus oceanic lithosphere resulted in the formation of an Early Ordovician intra-oceanic arc. In Scotland this Early Ordovician arc is inferred to lie beneath the Middle Ordovician – Permo-Triassic sedimentary cover of the Midland Valley graben between the Highland Boundary and Southern Uplands faults (Fig. 2). The basement to the Midland Valley Terrane (MVT) is known only from xenolith suites entrained within Carboniferous volcanic rocks and comprises both mafic and felsic granulite-facies metamorphic rocks along with rare granulite-facies metasedimentary xenoliths (Upton et al., 1976). The MVT basement xenoliths yield Sm-Nd model ages of 0·6-1·8 Ga (Halliday et al., 1993). Zircons from one of the rare relict metasedimentary xenoliths have yielded early Proterozoic (>2 Ga) bulk fraction U-Pb upper intercept ages, indicating the presence of old detritus in the sedimentary precursor (Halliday et al., 1984). However a younger detrital zircon population, possibly derived from an early Ordovician - middle Silurian magmatic arc, is also present ruling out a Precambrian depositional age (Badenszki et al., 2011). The timing of granulite-facies metamorphism is well constrained at 391 ± 6 Ma (Middle Devonian) by analyses of a petrographically distinct population, sometimes occurring as overgrowths on older grains (Badenszki et al., 2011).

In Ireland, Early – Middle Ordovician arc volcanics are exposed to the south of the Fair Head – Clew Bay Line (Fig. 2) in western Ireland (the Lough Nafooey arc) and in the north of Ireland (the Tyrone Volcanic Group; Figs 2, 8). The Lough Nafooey arc is exposed in a series of small, fault-bounded inliers and may form some of the basement to the Grampian fore-arc basin (the South Mayo Trough). As arc volcanism spans the Grampian arc–continent collision event, the chemistry of the arc volcanics can be used to constrain the onset of collision. The oldest (pre-collisional) arc volcanics include the lower portions of the Late Tremadoc Lough Nafooey Group and the Bohaun Volcanic Succession (Fig. 6). The age of the basaltic lavas of the Bohaun Volcanic Succession is not known, but their boninitic chemistry (Clift and Ryan, 1994) and strongly positive εNd(t) values (Fig. 12) could indicate earliest-stage formation above a young subduction zone. The light rare earth element (LREE) depletion and strongly positive εNd(t) values of the tholeiitic basalts of the basal Lough Nafooey Group (Fig. 12) and the lack of continental detritus in the oldest sediments of that group also suggest an origin far from the Laurentian margin (Ryan et al., 1980), while younger volcanic units exhibit a trend toward higher silica, higher-K compositions with increasing LREE enrichment (Ryan et al., 1980) and lower εNd(t) values (Fig. 12). Plagiogranite boulders in the basal portions of the overlying Silurian succession are unequivocally derived from the underlying Lough Nafooey Group and two clasts have yielded U–Pb SIMS zircon ages of 489.9 ± 3.1 Ma and 487.8 ± 2.3 Ma (Chew et al., 2007). Nd isotopic evidence demonstrates that the plagiogranites had assimilated some old continental crust, and therefore the arc volcanics were tapping subducting Laurentian margin sediments by 490 Ma. The Arenig Tourmakeady Volcanic Group contains andesitic and rhyolitic tuffs and volcaniclastic sediments (Graham et al., 1989). These volcanics are LREE enriched, and have strongly negative $\varepsilon N_{d(t)}$ values indicating substantial assimilation of old continental material (Fig. 12). The Tourmakeady Volcanic Group is believed to span 'hard' arc–continent collision (i.e. orogeny and regional deformation: Draut and Clift, 2001). Volcanic horizons within the the South Mayo Trough include andesitic tuffs and ignimbrites of the Rosroe Formation and ignimbritic tuffs of the Llanvirn Mweelrea Formation. These are interpreted as syn- to post-collisional arc volcanics, and are LREE-enriched, with strongly negative εNd(t) values (Fig. 12). The lowermost ignimbrite horizon within the Mweelrea Formation has yielded a U–Pb zircon age of 464.4 ± 3.9 Ma (Dewey and Mange, 1999).

The South Mayo Trough is interpreted as a fore-arc basin that developed between the accretionary complex rocks of the Clew Bay Complex and the South Mayo volcanic arc (e.g. Dewey and Mange, 1999; Fig. 6). Although many of the basal contacts are either not exposed or are faulted, the sediments in the basin were presumably deposited on the Early Ordovician arc volcanics of South Mayo. The basin fill of the South Mayo Trough (formally known as the Murrisk Group) consists of a series of predominantly deep marine volcaniclastic rocks and tuffs that shallows upwards. The South Mayo Trough is of critical importance in understanding the evolution of the Grampian Orogeny. This is because the basin was not inverted during the arc– continent collision event, but was merely buckled into a large fold, commonly known as the Mweelrea Syncline. It preserves sediment received from the deforming and unroofing orogen, and also volcanic detritus from the South Mayo arc. Whole rock geochemistry demonstrates that the lower portions of the northern limb of the South Mayo trough are derived from a source enriched in Mg, Cr, and Ni indicative of an ultramafic (ophiolitic) source region (Wrafter & Graham, 1989). This prominent ultramafic signature decreases up sequence, as does the abundance of detrital chrome spinel (Fig. 13). The drop in detrital chrome spinel abundance coincides with a sudden influx of metamorphic detritus (garnet, staurolite, sillimanite and muscovite) (Dewey & Mange, 1999). These data suggest the progressive unroofing of an ophiolite complex in the Arenig followed by the exhumation of the Grampian metamorphic belt during the middle Ordovician (Wrafter & Graham, 1989, Dewey & Mange, 1999). Detrital geochronology studies including U-Pb dating of zircons and Ar–Ar dating of white mica have revealed that the South Mayo Trough was derived from igneous and metamorphic complexes in Laurentia. U-Pb zircon ages cluster around three important periods of crustal evolution; the Lewisian (Archaean), Grenville orogeny (Mesoproterozoic) and Grampian orogeny (Ordovician) (McConnell et al. 2009; Clift et al. 2009; Mange et al. 2010).

Despite their important role in the arc–continent collision that produced the Grampian orogeny, the arc volcanics and fore-arc sediments of South Mayo are relatively undeformed. The Lough Nafooey Group, which is thought to lie underneath the 6 km of sediments that fill the South Mayo Trough, has experienced very low-grade (prehnite-pumpellyite facies) metamorphism (Ryan et al., 1980). This suggests that South Mayo did not undergo substantial tectonic burial during the Grampian Orogeny. In particular, the allochthonous position of the Connemara terrane with respect to the rest of the Laurentian margin cannot be explained by simple southwards thrusting of this terrane over the very low-grade arc and fore-arc basins of South Mayo.

The predominantly extrusive rocks of the Tyrone Volcanic Group form the upper part of the Tyrone Igneous Complex and consist of basaltic pillow lavas and andesitic to rhyolitic lavas along with banded cherts, ironstones and mudstones (Cooper & Mitchell 2004 and references therein). The mudstone units have yielded graptolite fragments of Arenig–Llanvirn age (Hutton & Holland, 1992). More recently, Cooper et al. (2008) document the presence of Isograptus victoriae lunatus in graptolitic mudstones from Slieve Gallion, along with a U–Pb zircon age of 473 ± 0.8 Ma for an extrusive rhyolite that sits stratigraphically below the graptolitic mudstones. There is evidence for at least three volcanic cycles within the Tyrone Volcanic Group, each commencing with basaltic lavas, with cycle tops characterized by the presence of laminated chert and/ or mudstone (Hutton et al. 1985; Cooper & Mitchell 2004). The basalts, andesites and rhyolites are typically LILE- and LREE-enriched with variable negative Nb anomalies (Cooper et al., 2011; Draut et al. 2009). A suite of calc-alkaline, arc-related intrusive rocks range in age from 470.3 ± 1.9 Ma to 464.3 ± 1.5 Ma and cut both the Tyrone Igneous Complex and the Tyrone Central Inlier (Cooper et al., 2011). They have geochemical affinities similar to the LILE- and LREE-enriched rhyolites and andesites of the Tyrone Volcanic Group (Cooper et al., 2011; Draut et al. 2009). Draut et al. (2009) suggested that the light REE (LREE)-enriched island-arc signatures of the volcanics and intrusive rocks of the Tyrone Igneous Complex were produced by an oceanic arc that assimilated considerable detritus from the Laurentian margin. The component of continentally derived material was observed to increase up sequence, similar to the transition from primitive intra-oceanic arc magmatism to magmatism with substantial assimilation of Laurentian material observed in the Lough Nafooey arc of western

Ireland (Draut et al., 2004). Hollis et al. (2012) suggest the Tyrone Volcanic Group represents an evolving peri-Laurentian island-arc/backarc which underwent several episodes of intra-arc rifting prior to its accretion at ca. 470 Ma to an outboard peri-Laurentian microcontinental block (the Tyrone Central Inlier). The accretion of the Tyrone arc and its associated suprasubduction-zone ophiolite was inferred to represent the final of three stages of arc-ophiolite emplacement onto the Laurentian margin recognized both in the Scottish and Irish Caledonides and the Newfoundland Appalachians.

Studies of crustal magnetization and high-level granite geochemistry in the Midland Valley and Southern Uplands – Longford Down terranes (Kimbell & Stone, 1995; Stone et al., 1997) suggest that a hidden crustal block is located beneath an allochthonous Southern Uplands Terrane. Armstrong & Owen (2001) termed this block 'Novantia' (Fig. 14) and equated it with the Annieopsquotch Accretionary Tract (ophiolite-arc terrane) of Newfoundland. They proposed that the accretion of this block in the Arenig to the southern margin of the Midland Valley Terrane was associated with obduction of the Ballantrae Igneous Complex (Fig. 14).

Silurian inter-arc sedimentation in the Midland Valley terrane

A series of geographically separate Silurian successions within the Midland Valley terrane contain evidence for contemporaneous volcanism and are inferred to have accumulated in inter-arc basins above a north-dipping subduction zone (Bluck 2002; Holland 2009 and references therein). In western Ireland, Silurian sediments rest unconformably on a range of older rocks that had been exhumed following the Grampian orogeny. The most complete succession in North Galway unconformably overlies the Dalradian of Connemara and the Ordovician sediments and volcanics of the South Mayo Trough. The 3 km thick succession is Llandovery to Wenlock in age and accumulated in a range of fluvial, shallow marine and shelf environments. In the Midland Valley terrane of Scotland, Silurian rocks are only observed to rest unconformably on older rocks in the Girvan inlier where they overlie Mid- to Late Ordovician sediments. Elsewhere, the stratigraphic bases of the local Silurian successions are unexposed. In most of the Scottish inliers, Llandovery marine turbidite sequences pass up into Wenlock fluvial sediments that include distinctive southerly-derived alluvial fan conglomerates (Bluck 1983, 1984). These include clasts of volcanic and plutonic igneous rocks, as well as a rangle of sedimentary and metasedimentary lithologies. Detrital zircons obtained from the Silurian rocks in Scotland have a very similar age distribution, irrespective of whether the samples were derived from the south or north (Phillips et al., 2009). The bimodal age distribution comprises an Arenig-Llanvirn (c. 475 Ma) component, probably derived from a mixed ophiolite-volcanic-plutonic source (presumably the Midland Valley arc and the Ballantrae-Tyrone ophiolites), and a Mesoproterozoic (c. 1 Ga) component. The latter could have been derived from the now-unexposed basement of the Midland Valley terrane.

Successor sedimentary basins: the Girvan fore-arc and the Southern Uplands–Longford Down terrane accretionary prism

The Girvan fore-arc

A succession of mainly clastic sedimentary rocks, c. 2.6 km thick, was deposited unconformably upon the Ballantrae Igneous Complex in Llanvirn-Ashgill times (Williams, 1962; Ingham, 1978; Bluck, 1983; Ince, 1984; Bluck, 2002). It is viewed as having accumulated in a fore-arc basin that developed after the accretion of the Grampian arc to the Laurentian margin and a switch in the polarity of subduction to northward-directed (Bluck, 2002 and references therein). The Girvan succession was deposited in fluvio-deltaic and marine environments and the bulk of sedimentation was controlled by displacement on normal faults with downthrow to the southeast. The succession is historically important as its rich Laurentian faunal assemblages were amongst the first to be compared with those of the Appalachians (Reed, 1935). It has assumed further importance in regional tectonic models because of provenance studies focused on the wide range of igneous and metamorphic detritus contained within major conglomerate units. These were deposited in a range of fluvial to submarine fan environments by southeast-flowing palaeocurrents. They contain basic and ultrabasic clasts, derived most probably from the Ballantrae Igneous Complex, as well as acid to intermediate igneous clasts, including hornblende-biotite granite. These clasts have a calc-alkaline chemistry and their size (some >1m in diameter) indicates a proximal source within the Midland Valley. Rb-Sr ages derived from these clasts are imprecise but consistent with more or less continuous Cambrian to Ordovician magmatism (Longman et al., 1979; Bluck, 1983). The oldest clasts could have been derived from the remnant arc that collided with the Laurentian margin during the early Ordovician, and the younger clasts likely represent the continuation of magmatic activity following a switch in subduction polarity (Bluck, 2002). Detrital garnet was derived from a number of sources, including a Barrovian metamorphic terrane which has been argued to be the uplifted and eroded Dalradian Supergroup (Hutchison & Oliver 1998).

The Southern Uplands accretionary prism

South of the Southern Uplands Fault, the Southern Uplands-Longford Down terrane comprises Ordovician and Silurian sedimentary rocks that are interpreted as an accretionary prism developed above a northwest-dipping subduction zone (Leggett et al., 1979; Leggett, 1987; Oliver et al., 2002 and references therein). The Arenig age of the oldest sedimentary rocks is consistent with initiation of subduction shortly after the Grampian orogenic event. In Scotland, the terrane comprises three fault-bounded units, the Northern, Central and Southern Belts; the Northern and Central belts probably extend laterally into Ireland. Each is divided into individual tracts a few kilometres wide and bounded by major reverse faults (Fig. 15). The sediments are all steeply dipping and strongly folded, but the overall younging direction within each tract is towards the northwest. Each fault-bounded tract is interpreted as a slice of ocean plate sedimentary cover that was detached during subduction from the down-going oceanic lithosphere and added to the leading edge of the accretionary prism (Fig. 15).

The Ordovician rocks of the Northern Belt consist of basal sequences of lava and chert (Crawford Group) and black shale (Moffat Shale Group) which were gradually buried under a southeast-prograding wedge of clastic turbidites (Leadhills Supergroup) deposited as large-scale submarine fans. The basal lavas (Arenig-Llanvirn) have diverse origins with possible MORB, within-plate and ocean island lavas and perhaps arc-related rocks all present (Oliver et al., 2002). *In situ* Caradoc volcanic rocks are mainly within-plate and ocean-island types (Phillips et al., 1995). Major conglomerate horizons derived from the northwest are dominated by clasts, some up to 1-1.5 metres in diameter, of hornblende-biotite granite (Elders, 1987). The size of the clasts implies a proximal source, thought to be the Ordovician magmatic arc that is presumed to underlie much of the nearby Midland Valley Terrane (Bluck, 1983). Dating of detrital muscovite and garnet from sandstone turbidites has yielded isotopic ages mostly in the range 480-460 Ma, consistent with derivation from the Dalradian Supergroup which was being exhumed to the northwest following the Grampian orogenic event (Kelley & Bluck, 1989; Hutchinson & Oliver, 1998).

The pattern of sedimentation established in the Northern Belt continues through the Central and Southern belts with only minor differences (Fig. 15). The Central Belt is dominated by thick successions of Silurian greywacke sandstones and minor conglomerates deposited in submarine fans. The influx of sandstones occurred diachronously southwards through the Llandovery and possibly into the Wenlock. Palaeocurrents are often southwest-directed and interpreted as axial flows along the strike of the basin (Kelling et al., 1987). High levels of ultrabasic and basic elements in some turbidites imply derivation from ophiolites. Conglomerates carry a similar clast suite to those of the Northern Belt, although the maximum clast size is 30cm and granite clasts represent a much smaller proportion of the total clast suite. The Southern Belt is composed entirely of Wenlock greywacke sandstones.

A similar structural evolution is recorded throughout the terrane. The main phase of deformation is associated with southeast-vergent thrusting/reverse faulting and folding (e.g. Leggett et al., 1979; Stone, 1995). Deformation may have initiated in partly-lithified sediments and progressed into prehnite-pumpellyite grade conditions during cleavage development. Evidence that deformation and metamorphism of the older parts of the terrane was contemporaneous with deposition of the younger parts is provided by the presence of recycled grains of prehnite and pumpellyite in turbidites. In the Northern Belt, the cleavage is axial-planar to folds. In contrast, in the Central Belt the obliquity between cleavage and fold hinges indicates a deformation regime dominated by sinistral transpression (e.g. Stringer & Treagus, 1980; Anderson, 1987; Holdsworth et al., 2002). The change from early coaxial deformation in the Northern Belt to sinistral tranpression in the central Belt may reflect a change in the angle of subduction relative to the continental margin. A final stage of deformation resulted in low-angle, northwest-directed thrusts.

The overall sedimentological and tectonic features of the Southern Uplands-Longford Down terrane compare closely with modern examples of acccretionary prisms such as the Oaxaca prism off Mexico (Leggett, 1987). An alternative interpretation, that the Northern Belt rocks were deposited in a back-arc basin, hinged critically on horizons of southeast-derived volcaniclastic detritus that were thought to have been derived from an active volcanic arc (Stone et al., 1987). Phillips et al. (2003) found no detrital zircons in these rocks that yielded U-Pb ages younger than the Neoproterozoic, and inferred a provenance from a peri-Gondwanan terrane to the south. The larger U-Pb detrital zircon dataset of Waldron et al. (2008) demonstrates the Neoproterozoic zircons are likely derived from igneous rocks associated with Iapetan rifting of the Laurentian margin with only a minor population that overlaps the Caradocian depositional age of the host sedimentary rocks. These data are difficult to reconcile with extensional continental-margin and back-arc models. With the key objection to an accretionary prism model removed they instead support an active continental-margin subduction-accretion model. Clay mineral assemblages and white mica compositions within the sedimentary rocks of the Southern Uplands-Longford Down terrane are indicative of deposition in a low heat-flow tectonic setting, consistent with an accretionary prism (Stone & Merriman, 2004).

Summary of the temporal evolution of the Grampian Orogeny: arc-continent collision along the Laurentian margin

Lambert and McKerrow (1976) recognized that the Dalradian sequences of the Scottish Highlands had undergone polyphase deformation and metamorphism during the Ordovician. This phase of orogenic activity clearly predated the post-Silurian Acadian deformation which marked the final stages of Caledonian tectonism in Britain and Ireland, and they coined the term “Grampian Orogeny” to distinguish this Ordovician tectonic event. The Grampian Orogeny is now widely regarded as having resulted from the collision of Laurentia with an oceanic arc during the Arenig (Dewey and Shackleton, 1984). It is broadly equivalent to the Taconic Orogeny of the New England Appalachians and the Humberian Orogeny of the western Newfoundland Appalachians (Dewey and Mange, 1999; van Staal et al., 1998; Dewey and Shackleton, 1984).

Closure of the Iapetus Ocean is thought to have commenced with the subduction of Iapetan crust of the Laurentian margin under a chain of primitive, continent-facing oceanic arcs during the Late Cambrian / Tremadocian (c. 500 – 480 Ma; Dewey & Mange, 1999; Van Staal et al., 1998; Fig. 16). It has been suggested that these arcs may have originally nucleated on oceanic transform faults (Karson & Dewey, 1978) during the Middle Cambrian (Dewey & Mange 1999). In SW Scotland and western Ireland the formation of oceanic crust and high-grade metamorphism associated with ophiolite obduction in the Highland Border and Deerpark (=Clew Bay) ophiolites is dated at c. 500 – 490 Ma (Chew et al., 2010) and a subduction-related magmatic arc founded on ophiolitic basement was active in both regions by ca. 490 Ma (Chew et al., 2007, 2010).

With the onset of subduction, these mafic, infant Grampian – Taconic arcs evolved into Early Ordovician intermediate arcs with associated suprasubduction ophiolites (Dewey & Mange 1999). Collision of the arc and ophiolite with the Laurentian margin is well constrained in the Baie Verte Oceanic Tract of the Notre Dame Subzone in Newfoundland. Upper Cambrian - Middle Tremadoc suprasubduction ophiolites and juvenile volcanic-plutonic complexes were obducted onto the Laurentian margin, which is thought (based on seismic reflection data) to structurally underlie the entire Notre Dame Subzone (Keen et al., 1986). The arc / ophiolite allochthon and the underlying ophiolitic mélange are cut by arc-related plutons as old as Early Arenig (Van Staal et al., 1998) and the isotope geochemistry of these tonalitic - granitic stitching plutons suggests they have ascended through continental crust (Whalen et al., 1997). Hence, if the Baie Verte Oceanic Tract does indeed structurally overlie Laurentian crust, then slab break off and a subsequent polarity reversal is implied.

In western Ireland, the detrital record of the South Mayo Trough (the Grampian fore-arc basin) implies the progressive unroofing of an ophiolite complex in the Arenig followed by the exhumation of the Grampian metamorphic belt during the middle Ordovician (Fig. 13, Wrafter & Graham, 1989, Dewey & Mange, 1999). The chemistry of the arc volcanic rocks (Lough Nafoeey arc) changes from a primitive boninitic and tholeiitic chemistry to higher silica, higher-K compositions with increasing LREE enrichment and lower εNd(t) values (Fig. 12, Clift and Ryan, 1994; Ryan et al., 1980), indicating progessive assimilation of old continental material associated with the subduction of continental margin sediments. The change in subduction polarity inferred in the Newfoundland sector of the orogen has also been suggested to have occurred in Ireland

and Scotland with the voluminous basic intrusions in the Dalradian of Connemara and NE Scotland having been interpreted as the roots of a volcanic arc (Yardley et al., 1982; Yardley & Senior, 1982), generated by subduction underneath the Laurentian margin.

Several models for the Grampian and Taconic orogens (e.g. Dewey & Mange, 1999; Van Staal et al., 1998; Dewey & Shackleton, 1984) attribute the bulk of the deformation and metamorphism to the obduction of the forearc ophiolite onto the Laurentian margin. In such models, SE-directed subduction is accompanied by obduction of a thick arc-ophiolite nappe onto the Laurentian margin which stacked the Dalradian nappe pile and accreted the arc to the margin with the collisional suture represented by the Baie Verte - Clew Bay - Highland Border Line, a diverse package of accreted material 'swept up' by the oceanic arc (Figs. 3, 14, 16; Dewey & Mange, 1999). In contrast, Tanner (this volume) proposes a model for the Grampian Orgeny in Scotland based on the regional kinematics of the polyphase-deformed Dalradian rocks, including a top-to-the-SE shear sense for D1 structures on the upper limb of the Tay nappe. The Tanner model thus infers an early stage of NW-directed subduction accompanied by obduction of an ophiolite onto the Laurentian margin. There is no difference in the timing of Barrovian metamorphism of the Dalradian Supergroup between the Scottish and Irish sectors of the orogenic belt, with abundant geochronological data demonstrating that polyphase deformation and regional metamorphism up to upper-amphibolite-facies conditions occurred over a short time period (~ 10 m.y.) during the Grampian orogeny between c. 475 and 465 Ma (Dewey, 2005). Subsequent subduction of the Iapetus Ocean under the Laurentian margin is believed to continue into the Silurian (Van Staal et al., 1998), with large amounts of material being shed off the uplifting orogen into thick accretionary prisms such as the Southern Upland and Longford - Down belts (Hutchison & Oliver, 1998).

Summary of the Silurian orogenic events resulting from the collision of Laurentia, Baltica and Avalonia and the closure of the Iapetus Ocean

Silurian collision between Baltica and Laurentia: the Scandian orogeny in the Northern Highlands Terrane

The Northern Highlands Terrane of Scotland (Figs 2, 4) records evidence for significant Silurian regional deformation and metamorphism that is attributed to the collision of the Laurentian margin of Scotland and East Greenland with Baltica (the Scandian Orogeny), resulting in widespread reworking of the Moine Supergroup. Regional-scale, NW-directed 'D2' ductile thrusting that culminated in development of the Moine Thrust Zone was accompanied by widespread folding and fabric development under amphibolite- to greenschist-facies conditions (e.g. Strachan & Holdsworth, 1988;

Holdsworth, 1989; Holdsworth et al., 2001, 2007; Kinny et al., 2003a; Kocks et al., 2006; Krabbendam et al., 2011). Field-based structural models have long-viewed the Sgurr Beag, Naver and Moine thrusts as part of the same kinematically linked system of foreland-propagating deformation (Barr et al., 1986).

Regional metamorphic grade during the Scandian event varies from low to mid-amphibolite facies in the central Moine outcrop to greenschist-facies in the vicinity of the Moine Thrust Zone (Johnson & Strachan, 2006). In north Sutherland, temperatures of >500°C are indicated by 1) a U-Pb SIMS monazite age of 431 ± 10 Ma obtained from the Naver nappe (Kinny et al., 1999); 2) kyanite, staurolite and the euhedral rims of recystallised and zoned garnets overgrowing the main Scandian schistosity (Holdsworth et al., 2001) and 3) a Scandian lineation defined by aligned hornblende needles and recrystallised feldspar augen. A partial clockwise pressure-temperature path for the Scandian event here indicates metamorphic conditions of 640-660°C and 5 kbar (Friend et al. 2000). Rb-Sr and $^{40}Ar/^{39}Ar$ mineral ages obtained in an east-west traverse across the Moine outcrop of Sutherland generally range between c. 440 Ma and c. 410 Ma (Dallmeyer et al., 2001) confirming widespread reheating during the Scandian event, even in the eastern Moines where the structural imprint is restricted.

Widespread Scandian upright folding in the central part of the Moine outcrop resulted in the formation of the Northern Highland Steep Belt (Clifford, 1957; Powell et al., 1981; Roberts & Harris, 1983). In the area south of Fannich, the Moine rocks between the 'Loch Quoich Line' and the western seaboard are generally steeply-dipping, although some areas in Knoydart and Ardnamurchan escaped the pervasive folding. A large part of the steep belt is occupied by the Glenfinnan Group. N-S to NNE-trending tight folds are developed on all scales, typically with highly curvilinear hinges and accompanied by crenulation cleavage. The stability of garnet, biotite and hornblende within crenulations suggests that deformation occurred at temperatures >500°C. There is clear evidence in the Fannich and Lochailort areas that the Sgurr Beag Thrust is folded by upright folds (Powell et al., 1981; Kelley & Powell, 1985; Krabbendam et al., 2011). The upright folds may themselves detach on the structurally underlying Moine Thrust. A U-Pb TIMS zircon age of 426 ± 3 Ma obtained from the Glen Scaddle Metagabbro which predates upright folding indicates that deformation occurred during the final stages of the Scandian event (Strachan & Evans, 2008).

The Scandian orogenic event culminated in the development of the Moine Thrust Zone which represents the western margin of the Scottish Caledonides (Figs 2, 3, 4). Within the thrust zone, Lewisian basement gneisses, and Torridonian and Cambrian-Ordovician sedimentary rocks are complexly thrust-faulted and folded (e.g. Peach et al., 1907; Elliott & Johnson, 1980; McClay & Coward, 1981). The Cambrian-Ordovician rocks record peak metamorphic temperatures of only c. 275°C in the upper anchizone

(Johnson et al., 1985), and so the thrust zone developed at much higher crustal levels than the internal ductile thrusts described above. Balanced cross-sections constructed from within the thrust zone itself, as well as the association of the Moine Thrust *sensu stricto* with a thick belt of mylonites, suggest substantial displacements (Elliott & Johnson, 1980; Butler & Coward, 1984). A total minimum displacement for the Moine Thrust Zone of c. 100 km is generally accepted. U-Pb TIMS zircon ages obtained from a range of syn- to post-thrusting intrusions in the Assynt area constrain thrusting to have occurred at c. 430 Ma (Fig. 3, Goodenough et al., 2011). This is consistent with Rb-Sr and K-Ar ages of c. 435-430 Ma obtained from recrystallised mica within mylonitic Moine rocks just above the Moine Thrust (Johnson et al., 1985; Kelley, 1988; Freeman et al., 1998).

Silurian collision between Avalonia and Laurentia

In contrast to the 'hard' Laurentia-Baltica collision detailed above, reference has already been made to the highly oblique and relatively 'soft' nature of the collision between Avalonia and Laurentia. NW-directed contractional structures such as folds, cleavage development and thrusts that developed under generally low-grade metamorphic conditions may have in part developed in conjunction with significant strike-slip displacements along the Highland Boundary and Southern Uplands faults.

The initial collision of Avalonia and Laurentia occurred after the Wenlock and it was probably at this stage that the Southern Uplands accretionary prism was overthrust onto the southern margin of the Midland Valley Terrane. A 'lost' metamorphic-igneous source for the southerly-derived Silurian conglomerates of the Midland Valley is inferred to be located at depth beneath the accretionary prism (Bluck 1984). Deep seismic reflection profiling suggests that the accretionary prism is underlain by a southward-dipping reflector which is interpreted as a north-directed thrust formed during Avalonia-Laurentia collision (Hall et al. 1984). Late, low-angle thrusts (e.g. Needham 1993) within the Northern and Central belts of the accretionary prism in Scotland probably formed at this time. The Mid-Ordovician to Silurian rocks of the Girvan inlier were deformed by NW-vergent folds and thrusts, accompanied by very low-grade metamorphism. In contrast, the Silurian rocks elsewhere in the Midland Valley terrane in Scotland were only weakly deformed, testifying to the generally 'soft' nature of the collision.

Structures developed within the Ordovician and Silurian rocks of the South Mayo Trough are consistent with the highly oblique nature of the collision indicated by palaeomagnetic studies. Widespread folding and cleavage development is known to have occurred after the Wenlock but prior to the deposition of unconformably overlying Lower Devonian strata. The upright Croagh Patrick Syncline is associated with three sets of overprinting folds and cleavages that developed during sinistral transpression (Hutton & Dewey, 1986). Metamorphic grade was sub-greenschist facies.

Current controversies in the Laurentian Caledonides of Scotland and Ireland

Despite being one of the most intensively studies orogenic belts in the world, there remain various outstanding issues in our understanding of the Laurentian Caledonides of Scotland and Ireland. These problems stem at least in part from a lack of chronological control and the difficulties in recognizing orogenic unconformities in polyphase-deformed rocks (Tanner and Bluck, 1999). Some of the outstanding issues are discussed below.

The relationship between Neoproterozoic orogenesis and the Grampian/Caledonian overprint

Geochronological studies indicate that a complex series of early to mid-Neoproterozoic orogenic events affected the Moine Supergroup and correlative units. The earliest event at c. 930 Ma is recorded in the Westing Group in Shetland (Fig. 3; Cutts et al. 2009), and a range of metamorphic events in the 840-725 Ma interval have been proposed for the Moine Supergroup and Badenoch Group (Fig. 3; Noble et al. 1996; Rogers et al. 1998; Vance et al. 1998; Highton et al. 1999; Tanner & Evans 2003; Cutts et al. 2010). These successions were probably located near to the periphery of Rodinia during the Neoproterozoic (Li et al. 2008) and it seems likely that these metamorphic events resulted from accretionary processes (Cawood et al. 2010; Kirkland et al. 2011).

The relative intensities of Neoproterozoic versus Lower Palaeozoic orogenic events has been much debated at different localities. The early (D_1) nappe-scale folds within the Morar Group between Morar and Glenelg (Ramsay, 1958; Powell, 1974) seem likely to be Neoproterozoic in age, although this is the only area where such structures have been yet identified. Tanner & Evans (2003) further argued that the Sgurr Beag Thrust between Lochailort and Kinlochourn is Neoproterozoic in age, although it is regarded as essentially a Caledonian structure in the Fannich area to the north (Kelley & Powell 1985; Krabbendam et al. 2011). East of Fannich, intrusion of the Carn Chuinneag Granite at 594 Ma (Oliver et al. 2008) was thought to have post-dated D_1 deformation and metamorphism (Wilson & Shepherd 1979), although this was challenged by Soper & Dalziel (1997) who concluded that intrusion occurred pre-D_1. Further geochronological and structural studies are necessary in all these areas. In general, it seems to be the case that ductile reworking during the Caledonian orogeny effected considerable modification of Neoproterozoic structures and metamorphic assemblages in most if not all areas. The Neoproterozoic events are now represented by the oldest (and often composite) foliations, isoclinal folds and porphyroblasts with few examples of tectonic windows of low Caledonian strain.

The duration of Dalradian Supergroup sedimentation and the presence and significance of intra-Dalradian unconformities

The stratigraphically lowest part of the Dalradian Supergroup that is constrained by reliable geochronological data is the c. 600 Ma (U-Pb zircon; Halliday et al., 1989; Dempster et al. 2002) Tayvallich Volcanic Group which marks the top of the Argyll Group. Much debate has centred around the duration of sedimentation represented by the underlying Argyll, Appin and (basal) Grampian groups. The Badenoch Group that forms part of the basement to the Dalradian Supergroup in Scotland was affected by high-grade metamorphism at c. 840 Ma (Highton et al., 1999) and this must represent a lower limit for Dalradian sedimentation. However, whether the Dalradian basin was initiated at, say, c. 800 Ma, or substantially later, remains controversial. Debate centres around two issues. The first concerns the field relations of deformed pegmatites in the Grampian Highlands that have yielded U-Pb monazite ages of c. 800 Ma (Noble et al., 1996). One view holds that these pegmatites intrude the basal Grampian Group (Piasecki & van Breemen 1983), in which case Dalradian sedimentation must have commenced prior to 800 Ma (Noble et al., 1996). The alternative view is that these pegmatites only intrude the Badenoch Group (Smith et al., 1999), in which case they place no constraint on the age of the Grampian Group. The second issue concerns the age of the Port Askaig Tillite at the base of the Argyll Group. The general consensus has been that this correlates with the global c. 720 Ma Sturtian glacial event (Prave et al., 2009). However, a rather younger age is implied by the data of Rooney et al. (2011) who have presented a Re-Os age of 660 ± 10 Ma for deposition of the Ballachulish Slate in the middle of the underlying Appin Group. They correlate the Port Askaig Tillite with the ~650 Ma end-Sturtian glacial events in Australia, and thus Dalradian sedimentation may have been initiated as late as 700 Ma.

Irrespective of whether or not Dalradian sedimentation was initiated at >800 Ma or 700 Ma, a related issue concerns the continuity or otherwise of the succession. The general consensus has been that it is broadly continuous and has only been affected by one orogenic event (the Caledonian *sensu lato*). However, Hutton & Alsop (2004) proposed that the Dalradian succession contains a fundamental orogenic unconformity located within the Argyll Group. They infer that the intra-Argyll Group Stralinchy Conglomerate in Donegal, NW Ireland, contains clasts that closely resemble the local Dalradian rocks and that these clasts include pre-incorporation deformation fabrics formed at low-mid greenschist facies grade. Hutton & Alsop (2004) attributed these fabrics to a Neoproterozoic orogenic event that affected the lower part of the Dalradian succession. If Dalradian sedimentation commenced at c. 800 Ma, then such an event might, for example, correlate with the youngest of the Knoydartian events identified within the Moine Supergroup at c. 735-725 Ma (Tanner & Evans, 2003; Cutts et al., 2010).

Reinterpretation of the Stralinchy Conglomerate as a glacial tillite by McCay et al. (2006) does not change the nature of the debate if the clasts were derived from the local Dalradian. This was disputed by Tanner (2005) who argued that the clasts are more likely to be extrabasinal, and also that there was no evidence of an orogenic unconformity at the equivalent lithostratigraphic level within the Scottish Dalradian succession.

When did Iapetus open in this segment of the Caledonian – Appalachian belt?

There is abundant evidence that the final rifting event to affect Laurentia initiated during the late Neoproterozoic. Such evidence includes the stratigraphic rift-to-drift transition in Laurentian margin sequences at the Precambrian-Cambrian boundary (e.g. Bond et al., 1984, Williams & Hiscott, 1987), and the voluminous rift-related magmatism along the Laurentian margin which lasted from ~ 620 Ma to 550 Ma (e.g. Kamo et al., 1989; Bingen et al. 1998; Cawood et al., 2001, Kinny et al., 2003b). However the precise timing of break-up is more difficult to assess, mainly because of the poor available constraints on the timing of the rift-drift transition along many sectors of the Laurentian margin. Van Staal et al. (in review) consider that although the sense of diachoneity is poorly constrained, available data suggest that rifting progressed from northeast to southwest in present coordinates, being the oldest in Baltica (Bingen et al., 1998; Svenningsen, 2001) and becoming younger in Scotland (e.g. Leslie et al., 2008) and the Appalachians (van Staal et al., 1998; Cawood et al., 2001).

The timing of rifting is probably best constrained on the Appalachian margin. Here the last major magmatic pulse between 615 and 570 Ma is generally thought to be related to the opening of the Iapetus Ocean (Kamo et al., 1989; Cawood et al., 2001), consistent with paleomagnetic evidence that suggests that eastern Laurentia had separated from its conjugate margin(s) during the Late Ediacaran (McCausland et al., 2007). However, thermal subsidence analysis suggests the rift-drift event appears to have taken place during the late Early Cambrian, at least 30-40 my later, along the length of the Appalachian margin (Bond et al., 1984; Williams and Hiscott, 1987; Cawood et al., 2001; Waldron and van Staal, 2001), which is supported by a small, latest Ediacaran rift-related pulse of predominantly MORB magmatism between 565 and 550 Ma along the Appalachian Humber margin (Cawood et al., 2001, Hodych and Cox, 2007). To explain this apparent paradox, Cawood et al. (2001) and Waldron and van Staal (2001) invoked a multistage rift history that involved an initial separation of Laurentia from the west Gondwana cratons at ca. 570 Ma, followed by rifting of a further block or blocks from Laurentia (e.g. the Dashwoods ribbon microcontinent) at ca. 540–535 Ma into an already open Iapetus Ocean to establish the main passive-margin sequence in eastern Laurentia.

On the Scottish-Irish sector of the Laurentian margin, basic volcanic activity in the Dalradian Supergroup occurred throughout the Argyll Group and the lower part of the Southern Highland Group, reaching its greatest development in the Easdale and Tayvallich subgroups of the Argyll Group (Fettes et al., 2011). Absolute age constraints on the timing of volcanic activity are poor, with the only reliable geochronology being the U-Pb zircon dates of 595±4 Ma on a keratophyre intrusion (Halliday et al., 1989) and of 601±4 Ma on a felsic tuff (Dempster et al., 2002) from within the Tayvallich Volcanic Formation of the upper Argyll Group. Fettes et al. (2011) provided age estimates on the age of volcanic activity within the Dalradian Supergroup based on lithostratigraphic and chemostratigraphic correlation arguments that are summarised as follows. The first, minor, volcanic episode occurred at the base of the Argyll Group (Islay Subgroup) in NE Scotland (Stephenson and Gould, 1995; Chew et al., 2010). The age is uncertain, with a maximum age of 720 Ma and a minimum age of 640 Ma depending on whether the main Dalradian glacial horizon (the Port Askaig Tillite and its correlative horizons) is equivalent to the Sturtian or Marinoan global glacial. This phase of volcanism was followed by a period of relative quiescence. The major phase of activity occurred during Easdale Subgroup times (at around ~630 to 620 Ma) associated with increased crustal extension. The final phase took place during Tayvallich Subgroup – basal Southern Highland Group times (between ~610 and 590 Ma), with all activity finished by ~570 Ma. An extensive suite of rift-related silicic intrusions, the Vuirich suite (along with temporal equivalents in the Northern Highlands Terrane such as the Carn Chuinneag granite), is believed to have been emplaced at ~590 Ma (Fig. 3; Rogers et al., 1989) suggesting a major episode of bimodal magmatism at that time (Macdonald & Fettes, 2006).

Associated with the Easdale Subgroup volcanism is a stratigraphic horizon with abundant serpentinite olistoliths embedded in a graphitic pelite matrix (Kennedy, 1980). The serpentinite bodies are also associated with deep-marine psammitic wackes and graphitic pelites. A discontinuous horizon of serpentinite bodies has also been documented in Easdale Subgroup rocks of central and NE Scotland (Garson & Plant, 1973). These serpentinite bodies in Ireland and Scotland have been interpreted as protrusions of serpentinized mantle onto the seafloor that were generated in Easdale Subgroup times during a phase of major crustal extension leading to the formation of an ocean-continent transition zone (Chew, 2001). Easdale Subgroup volcanism has been suggested above to have occurred at around ~630 to 620 Ma (Fettes et al., 2011), and therefore the onset of hyperextension and break-up is inferred to have started at this time. This is substantially older than the timing of hyperextension and break-up on the Appalachian Humber margin. The Birchy Complex of Newfoundland is regarded to represent a fossil ocean-continent transition zone (van Staal et al., in press), and although it closely resembles and has been correlated with the Easdale Subgroup in western Ireland (Winchester et al., 1992), it is substantially younger at c. 558 Ma (van Staal et al., in press).

The supra-subduction ophiolite vs sub-continental lithospheric mantle debate in the Highland Border

The recent reinterpretation of the Highland Border Complex (Tanner and Sutherland, 2007) suggests that the majority of the sequence is in stratigraphic continuity with the Dalradian Supergroup, with the exception of a series of poorly exposed fault-bound slivers of ophiolitic rocks within the fault zone, known as the Highland Border Ophiolite (Tanner and Sutherland, 2007). The affinity of this suite of ophiolitic rocks has also been called into question by Tanner, who suggests that they represent exhumed serpentinised sub-continental lithospheric mantle, similar to the Ligurian-type ophiolites of northern Italy.

The principal findings of Highland Workshop 2008 field excursion to the Highland Border that addressed these issues have been synthesized by Leslie (2009) and Henderson et al. (2009) and are summarized here. Fragmental ophicarbonate-rock is widespread from Aberfoyle to Bute along the Highland Boundary Fault (Fig. 10) and exhibits a striking resemblance to material recovered from modern Iberia-type ocean-continent transitions. Additionally the more tectonised examples of HBO serpentinites and ophicarbonate-rocks are also remarkably similar to examples from Ligurian-type ophiolites. The field observations broadly support a model in which the sheared and fragmental ophicarbonate-rocks and associated sediments of the HBO originated in a stretching ocean-continent transition setting, now preserved as a fragment of Ligurian-type ophiolite on the southeastern margin of the Grampian orogenic belt. The discontinuous horizon of serpentinite bodies in the Easdale Subgroup rocks of the Dalradian Supergroup of Ireland and Scotland described by Chew (2001) are likely intimately associated with the HBO, with both units representing small slices of exhumed serpentinised sub-continental mantle that originally lay beneath an extending Dalradian basin during the opening of the Iapetus Ocean.

However, not all exposures of mafic and ultramafic rocks within the HBO represent exhumed serpentinised sub-continental lithospheric mantle. For example, the geochronology and P-T work presented by Chew et al. (2010) demonstrate that the Bute Amphibolite (Fig. 10) represents a fragment of a Grampian supra-subduction zone ophiolite that was obducted at c. 490 Ma. A similar scenario is present on the Baie Verte peninsula in Newfoundland, where the Birchy Complex of Newfoundland that represents a c. 558 Ma ocean-continent transition zone (van Staal et al., in review) is in tectonic contact (along the Baie Verte – Brompton line) with the 490 Ma supra-subduction zone Taconic ophiolites of the Baie Verte Oceanic Tract. The fragmentary and challenging nature of the geological record within the Highland Boundary fault zone means that the tectonic affinity of many slivers of mafic and ultramafic rock within the HBO will remain unknown.

The cause of the rapid, synchronous 475 – 470 Ma Grampian orogenic peak

A short, synchronous Grampian orogenic episode is inconsistent with models of conductive heat transfer in thickened crust (e.g. Dewey, 2005; Baxter et al., 2002), and these authors suggest that the ca. 470 Ma Grampian metamorphic peak may have resulted from advective heat transfer from voluminous syn-orogenic intrusive rocks in the Dalradian block, similar to the original suggestion of Barrow (1893). This hypothesis is supported by thermal modeling of Sr diffusion profiles in apatite from the Barrovian zones of NE Scotland which demonstrates that the thermal peak was brief and lasted only a few hundred thousand years, which is one or two orders of magnitude shorter than the timescales predicted by conductive relaxation of over-thickened crust (Ague and Baxter, 2007). However, although this model may be appropriate for much of NE Scotland and Connemara, most of the Dalradian block is devoid of syn-orogenic intrusive rocks, and a ca. 470 Ma orogenic peak is still detected in such rocks by geochronological studies in NW Ireland (e.g. Flowerdew et al., 2000). Vorhies & Ague (2011) constrained the P–T evolution of the Barrovian metamorphic zones in the Grampian Terrane in Scotland along orogenic strike using a combination of thermobarometry and pseudosection analysis. They attributed regional metamorphism to be associated with the thermal relaxation of tectonically overthickened crust, but that the NE part of the Grampian terrane required additional advective heat input driven by a brief (of the order of 1 Ma or less) thermal pulse to achieve peak thermal conditions. This heat was probably supplied by synorogenic magmas (e.g. Newer Gabbros) and the associated elevated crustal heat flow. Chew et al. (2010) invoked a phase of collisional thickening beginning at c. 490 Ma based on geochronological constraints from Grampian ophiolites on the timing of obduction. As there is limited evidence for obduction of a thick slab of oceanic lithosphere, Chew et al. (2010) inferred that the deformed Laurentian margin structural pile comprised mainly Dalradian nappes. However the cause of the rapid, synchronous Grampian orogenic peak remains enigmatic.

Is there evidence for a Late Ordovician accretionary event in Scotland and Ireland?

The existing two stage Grampian-Scandian tectonic model for the Caledonides in the British Isles is likely to be overly simplistic. More protracted accretionary histories have been developed for other parts of the Laurentian margin such as Newfoundland and the Laurentian-derived Uppermost Allochthon in Norway. In addition to early Ordovician tectonism broadly equivalent to the Grampian event in Scotland and Ireland, these other areas also contain evidence for accretionary events at c. 450 Ma. In Newfoundland this is represented by the 'Taconic II' collision of arcs and the Laurentian margin (van Staal et al., 2009), and in the Uppermost Allochthon of Norway by eclogite-facies metamorphism (Roberts, 2003; Corfu et al., 2002). Mention has been made above of the probable existence of a hidden crustal block located beneath an allochthonous Southern Uplands – Longford Down Terrane (Kimbell & Stone, 1995; Stone et al., 1997). Armstrong & Owen (2001) proposed that this is composed of two seperately accreted terranes: 'Novantia' that was accreted during the Arenig, and an outboard terrane that was accreted in the late Caradoc-Ashgill. The time of accretion corresponds to a brief hiatus in the Late Ordovician sedimentary record of the Southern Uplands accretionary prism (equivalent to one graptolite zone in Scotland with a longer break in Ireland; Barnes et al., 1995). Armstrong & Owen (2001) equated this outboard terrane with the Popelogan – Victoria Arc – Grangegeeth Terrane of Newfoundland – Ireland (Fig. 14; van Staal et al. 1998 and references therein).

To date, there has been little consideration of the potential record of Late Ordovician accretion within the 'Orthotectonic' Caledonides north of the Highland Boundary Fault. However, we note that it is broadly coincident with formation of the downward-facing Highland Downbend in western Ireland (Fig 7C; dated at c. 448 Ma, Chew et al., 2003). Furthermore, regional upright 'D3' folding of Dalradian rocks in the Central Highlands of Scotland was synchronous with the intrusion of the Glen Kyllachy granite (van Breemen & Piasecki, 1983) that has recently yielded a U-Pb zircon age of 451 ± 4 Ma (Oliver et al., 2008). Shortening was only of the order of c. 5-10% and associated with crenulation of pre-existing schistosities at greenschist-facies temperatures (Phillips et al., 1999).

In the Northern Highlands Terrane, Bird et al. (2013) have identified evidence for c. 450 Ma garnet-grade metamorphism and accompanying deformation in the western Moine Supergroup (Morar Group). Various pegmatites in the Glenfinnan Group that have yielded Rb-Sr ages of c. 445-450 Ma (van Breemen et al., 1974) may have been associated with this tectonic event, as well as the Glen Dessary syenite (448 ± 3 Ma; Goodenough et al., 2011). Bird et al. (2013) explain this tectonic event by invoking collision of an arc or a microcontinental fragment with the segment of the Laurentian margin that contained the Northern Highland Terrane (far removed at that time from the Grampian Terrane).

The Caledonides of Britain and Ireland have proven to be a superb natural laboratory for the development of many key geological concepts. The abundance of detailed regional field mapping undertaken during the 20th century has been more recently augmented by a substantial geochemical, petrological and high-precision geochronological database along with targeted field mapping studies. Certain questions are likely to remain difficult to resolve, such as obtaining absolute age constraints on key horizons within the non-fossiliferous Neoproterzoic successions which are typically devoid of volcanic horizons amenable to producing high-precision magmatic crystallization ages. However, with the ever increasing sophistication of geochronological and petrological techniques, key research questions such as the cause of the rapid Grampian regional metamorphic peak and also the relationship between Neoproterzoic orogenesis and the Caledonian overprint (a common feature of the northeast Laurentian margin in the North Atlantic, Cawood et al., 2010) may ultimately prove possible to disentangle.

Acknowledgements

DC would like to thank Stephen Daly, John Dewey, Michael Flowerdew, John Graham, Ben Kennedy, Barry Long, Geoff Tanner and Ken Chew for many stimulating discussions about Caledonide geology. Cees van Staal, an anonymous reviewer and volume editor Deta Gasser are thanked for comments and suggestions that significantly improved this manuscript.

Figure captions

Figure 1. Schematic tectonic evolution of the Caledonian orogenic cycle (the closure of the Iapetus Ocean), showing major orogenic events (e.g. the Grampian, Scandian and Acadian). Volcanic arcs are shown in green; trenches are shown in blue and indicate the polarity of subduction; collisional orogens are shown in red.

a) south-directed subduction creates a volcanic arc within the Iapetus Ocean outboard of Laurentia. b) This arc collides with Laurentia causing the Grampian Orogeny, and north-directed subduction under Laurentia begins, contemporaneous with south-directed subduction beneath Avalonia. c) The Iapetus Ocean has nearly closed. The "head-on" collision of Baltica and Laurentia causes the Scandian Orogeny, while the highly-oblique collision between Laurentia and Avalonia causes the Acadian Orogeny.

Figure 2. Geological map of the Caledonides of NW Ireland and Scotland. Inset shows a simplified geological map of Shetland and its relationship to the British and Irish Caledonides.

Figure 3. Tectonostratigraphic scheme for the Laurentian Caledonides of Scotland and Ireland. Time is represented on the y-axis (note the change of scale at 600 Ma) and

distance from the Laurentian foreland is represented along the x-axis. Colours of the different units where possible follow those used in Figure 2.

Figure 4. Geological map of the Laurentian foreland and the Northern Highlands terrane after Strachan et al. (2010) with Caledonian thrusts and L_2 mineral lineations within the Moine rocks of Ross-shire and Sutherland after Law et al. (2010). Lineations are dominantly of Scandian and Grampian age west and east of the Naver/Swordly thrusts repectively. Abbreviations as follows from north to south: LE, Loch Erribol; SC, Strathy Complex; TT, Torrisdale Thrust; ST, Sole Thrust; MT, Moine Thrust; BHT, Ben Hope Thrust; SWT, Swordly Thrust; SKT, Skinsdale Thrust; AT, Achness Thrust; LB, Loch Borrolan; NT, Naver Thrust; CCG, Carn Chuinneag Granite; SBT, Sgurr Beag Thrust; G, Glenelg; FAGG, Fort Augustus Granite Gniess; AGG, Ardgour Granite Gneiss. The Naver and Skinsdale nappes lie above the Naver and Skinsdale thrusts respectively.

Figure 5. Cross-sections across the Morar Group in Sutherland (after Alsop et al., 2010) and the Fannich area (after Krabbendam et al., 2011).

Figure 6. Geological map of the pre-Devonian rocks of western Ireland after Chew et al. (2007).

Figure 7. Schematic structural sections though (a) the Grampian Belt in Scotland, (b) NW Mayo and (c) Donegal. Adapted from Strachan (2000) and Chew (2003). The profile traces are shown on Figs 2, 4 and 5.

Figure 8. Geological map of the Tyrone Igneous Complex and the Tyrone Central Inlier (Hutton et al., 1985).

Figure 9. Geological map of the Slishwood Division after Flowerdew and Daly (2005). Pressure – temperature estimates and Sm-Nd garnet ages for the pre-Grampian granulite facies event in the Slishwood Division from Flowerdew and Daly (2005) and Sanders et al. (1987) are also illustrated.

Figure 10. Geology and the revised stratigraphic model of the Highland Border region after Tanner and Sutherland (2007).

Figure 11. Simplified map of the Ballantrae complex. Modified from Sawaki et al. (2010) after Smellie and Stone (2001) and Kimbell and Stone (1995).

Figure 12. Temporal evolution of some geochemical parameters of the South Mayo volcanic arc and its proposed link with orogenic evolution (Draut et al., 2004).

Figure 13. Temporal evolution of detrital heavy mineral assemblages of sandstones from the northern limb of the South Mayo Trough. The percentage of each component (e.g. chrome spinel or metamorphic detritus) is illustrated in the histogram. Also shown

is the whole rock geochemistry (Wrafter and Graham, 1989) and a U-Pb zircon age from an ignimbrite (Dewey and Mange, 1999).

Figure 14. Simplified tectonic reconstruction illustrating the relative position of terranes up to and during the Grampian Orogeny (after Armstrong and Owen, 2001). NH = Northern Highland Terrane; GT = Grampian Terrane; LN-MV = Lough Nafooey – Midland Valley Arc; Nov. = Novantia; PVA = Popelogan – Victoria Arc – Grangegeeth Terrane.

Figure 15. The accretionary prism model for the formation of the Longford-Down – Southern Uplands Terrane during Late Ordovician to Early Silurian times after Anderson (2004).

Figure 16. (a) Schematic model of the tectonic evolution of the Laurentian margin in Scotland and Ireland at (a) 490 Ma and (b) 480 Ma. HBC = Highland Border Complex, CBC = Clew Bay Complex, HBF = Highland Boundary Fault, FHCBL = Fair Head – Clew Bay Line, modified after Chew et al. (2010).

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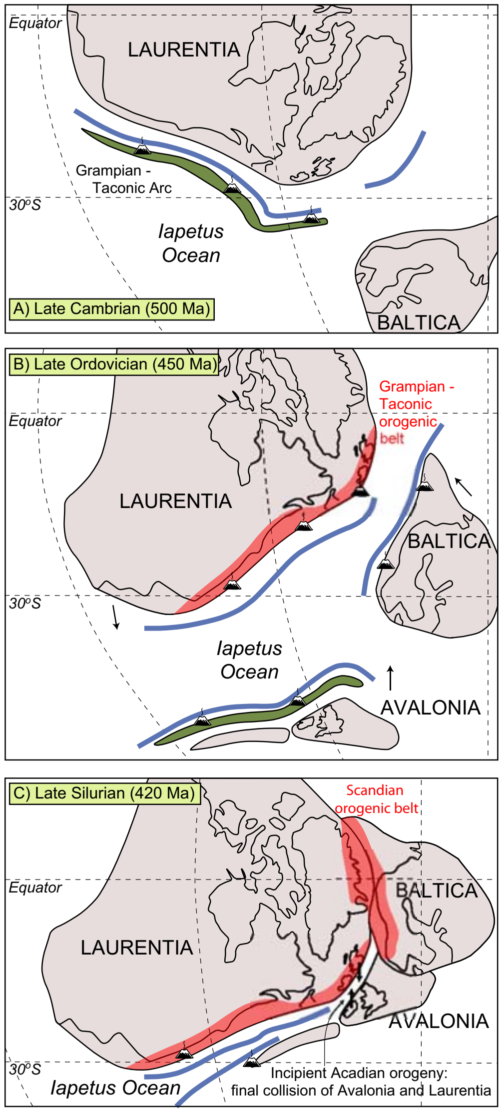
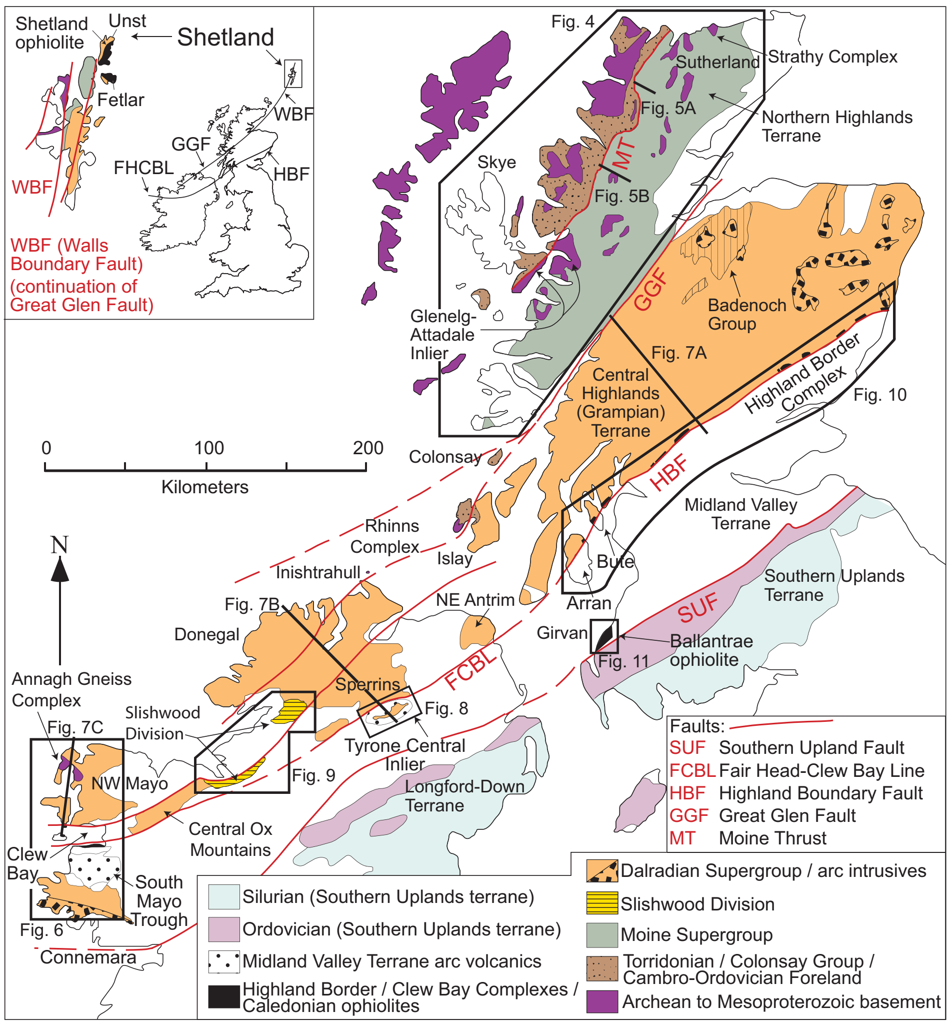
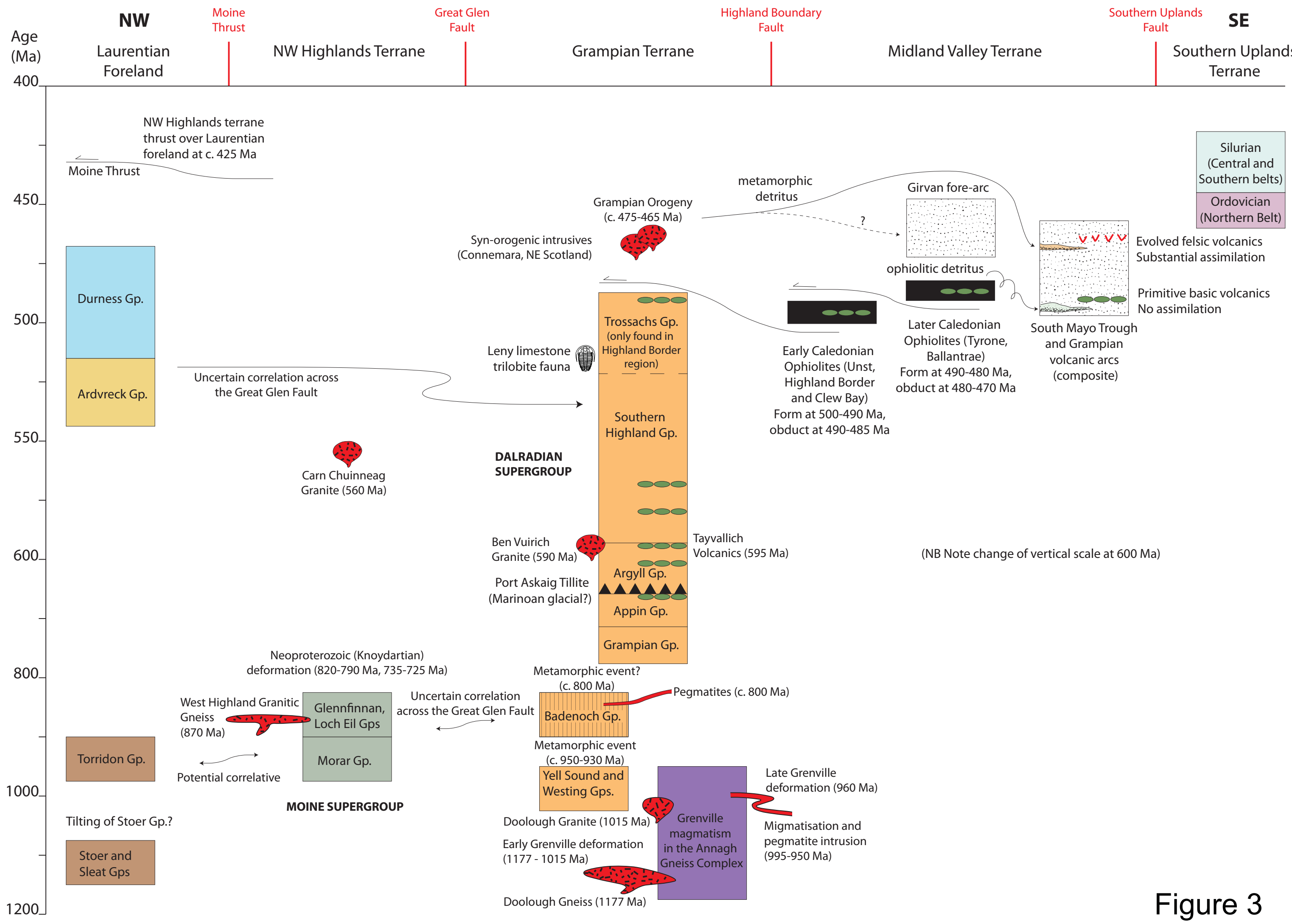

Equator
LAURENTIA
Grampian -
Taconic Arc
30°S
Iapetus
Ocean
BALTICA
A) Late Cambrian (500 Ma)
B) Late Ordovician (450 Ma)
Grampian -
Taconic
orogenic
belt
Equator
LAURENTIA
BALTICA
30°S
Iapetus
Ocean
AVALONIA
C) Late Silurian (420 Ma)
Scandian
orogenic belt
Equator
BALTICA
LAURENTIA
AVALONIA
30°S
Iapetus Ocean
Incipient Acadian orogeny:
final collision of Avalonia and Laurentia

Figure 1



Shetland ophiolite
Unst
Shetland
Fetlar
WBF
GGF
FHCBL
HBF
WBF (Walls Boundary Fault) (continuation of Great Glen Fault)
Fig. 4
Sutherland
Strathy Complex
Fig. 5A
Northern Highlands Terrane
Skye
MT
Fig. 5B
GGF
Badenoch Group
Glenelg-Attadale Inlier
Fig. 7A
Central Highlands (Grampian) Terrane
Highland Border Complex
Fig. 10
0
100
200
Kilometers
Colonsay
HBF
Midland Valley Terrane
Rhinns Complex
Islay
Bute
Southern Uplands Terrane
N
Inishtrahull
Arran
Fig. 7B
NE Antrim
SUF
Donegal
Girvan
Ballantrae ophiolite
Fig. 11
Sperrins
FCBL
Annagh Gneiss Complex
Slishwood Division
Fig. 8
Fig. 7C
Tyrone Central Inlier
NW Mayo
Fig. 9
Longford-Down Terrane
Central Ox Mountains
Clew Bay
South Mayo Trough
Fig. 6
Connemara
Faults:
SUF Southern Upland Fault
FCBL Fair Head-Clew Bay Line
HBF Highland Boundary Fault
GGF Great Glen Fault
MT Moine Thrust
Silurian (Southern Uplands terrane)
Ordovician (Southern Uplands terrane)
Midland Valley Terrane arc volcanics
Highland Border / Clew Bay Complexes / Caledonian ophiolites
Dalradian Supergroup / arc intrusives
Slishwood Division
Moine Supergroup
Torridonian / Colonsay Group / Cambro-Ordovician Foreland
Archean to Mesoproterozoic basement

Figure 2



NW
SE
Age (Ma)
Moine Thrust
Great Glen Fault
Highland Boundary Fault
Southern Uplands Fault
Laurentian Foreland
NW Highlands Terrane
Grampian Terrane
Midland Valley Terrane
Southern Uplands Terrane
400
450
500
550
600
800
1000
1200
NW Highlands terrane thrust over Laurentian foreland at c. 425 Ma
Moine Thrust
Silurian (Central and Southern belts)
Ordovician (Northern Belt)
metamorphic detritus
Girvan fore-arc
Grampian Orogeny (c. 475-465 Ma)
?
Syn-orogenic intrusives (Connemara, NE Scotland)
Evolved felsic volcanics Substantial assimilation
ophiolitic detritus
Primitive basic volcanics No assimilation
Durness Gp.
Trossachs Gp. (only found in Highland Border region)
Later Caledonian Ophiolites (Tyrone, Ballantrae) Form at 490-480 Ma, obduct at 480-470 Ma
South Mayo Trough and Grampian volcanic arcs (composite)
Leny limestone trilobite fauna
Early Caledonian Ophiolites (Unst, Highland Border and Clew Bay) Form at 500-490 Ma, obduct at 490-485 Ma
Uncertain correlation across the Great Glen Fault
Ardvreck Gp.
Southern Highland Gp.
DALRADIAN SUPERGROUP
Carn Chuinneag Granite (560 Ma)
Ben Vuirich Granite (590 Ma)
Tayvallich Volcanics (595 Ma)
(NB Note change of vertical scale at 600 Ma)
Argyll Gp.
Port Askaig Tillite (Marinoan glacial?)
Appin Gp.
Grampian Gp.
Neoproterozoic (Knoydartian) deformation (820-790 Ma, 735-725 Ma)
Metamorphic event? (c. 800 Ma)
Pegmatites (c. 800 Ma)
West Highland Granitic Gneiss (870 Ma)
Glennfinnan, Loch Eil Gps
Uncertain correlation across the Great Glen Fault
Badenoch Gp.
Torridon Gp.
Morar Gp.
Metamorphic event (c. 950-930 Ma)
Potential correlative
Yell Sound and Westing Gps.
Late Grenville deformation (960 Ma)
MOINE SUPERGROUP
Tilting of Stoer Gp.?
Doolough Granite (1015 Ma)
Grenville magmatism in the Annagh Gneiss Complex
Migmatisation and pegmatite intrusion (995-950 Ma)
Early Grenville deformation (1177 - 1015 Ma)
Stoer and Sleat Gps
Doolough Gneiss (1177 Ma)

Figure 3

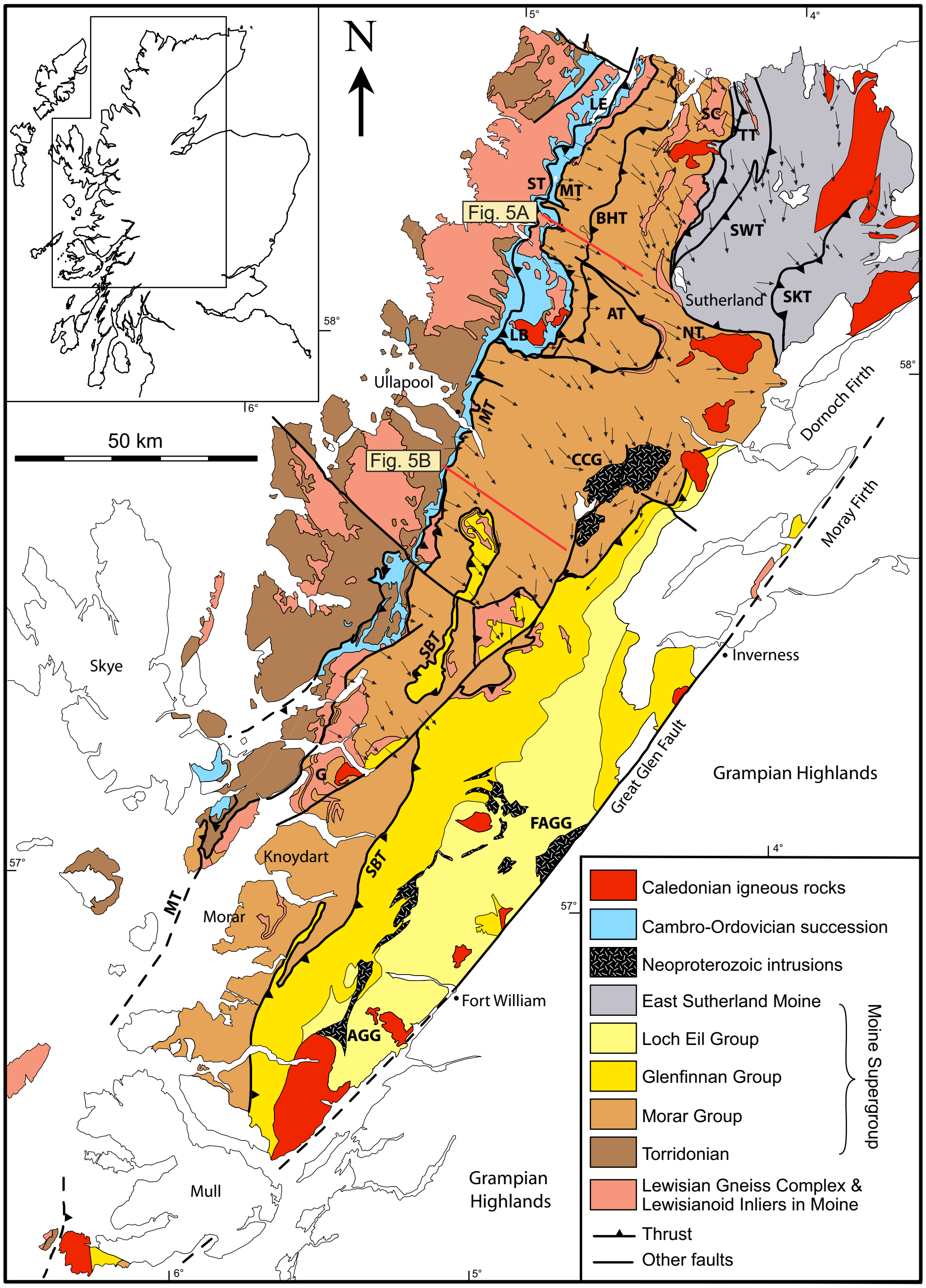

N
50 km
Fig. 5A
Fig. 5B
LE
SC
TT
ST
MT
BHT
SWT
Sutherland
SKT
AT
NT
LB
Ullapool
CCG
Dornoch Firth
Moray Firth
SBT
Skye
Inverness
Grampian Highlands
Great Glen Fault
G
FAGG
Knoydart
Morar
Fort William
AGG
Mull
Grampian Highlands
Caledonian igneous rocks
Cambro-Ordovician succession
Neoproterozoic intrusions
East Sutherland Moine
Loch Eil Group
Glenfinnan Group
Morar Group
Torridonian
Moine Supergroup
Lewisian Gneiss Complex &
Lewisianoid Inliers in Moine
Thrust
Other faults
5°
4°
6°
57°
58°

Figure 4

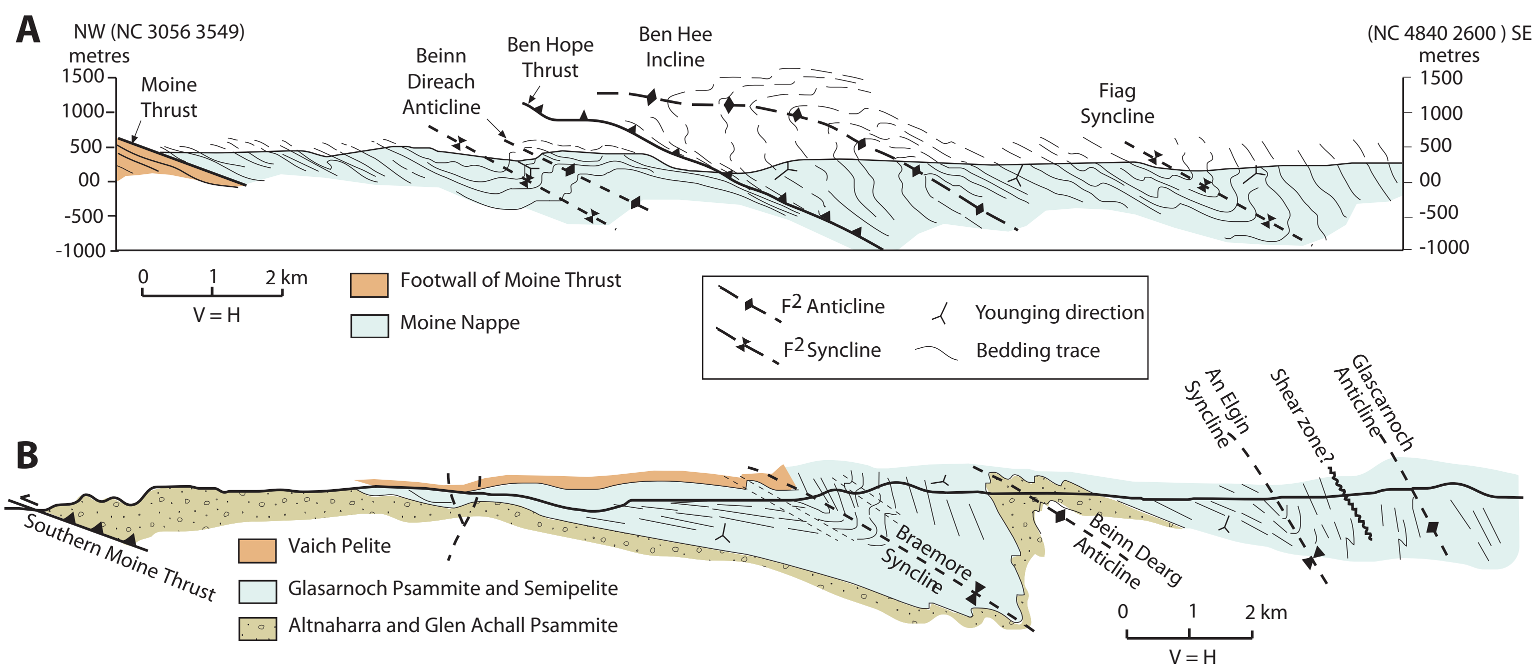
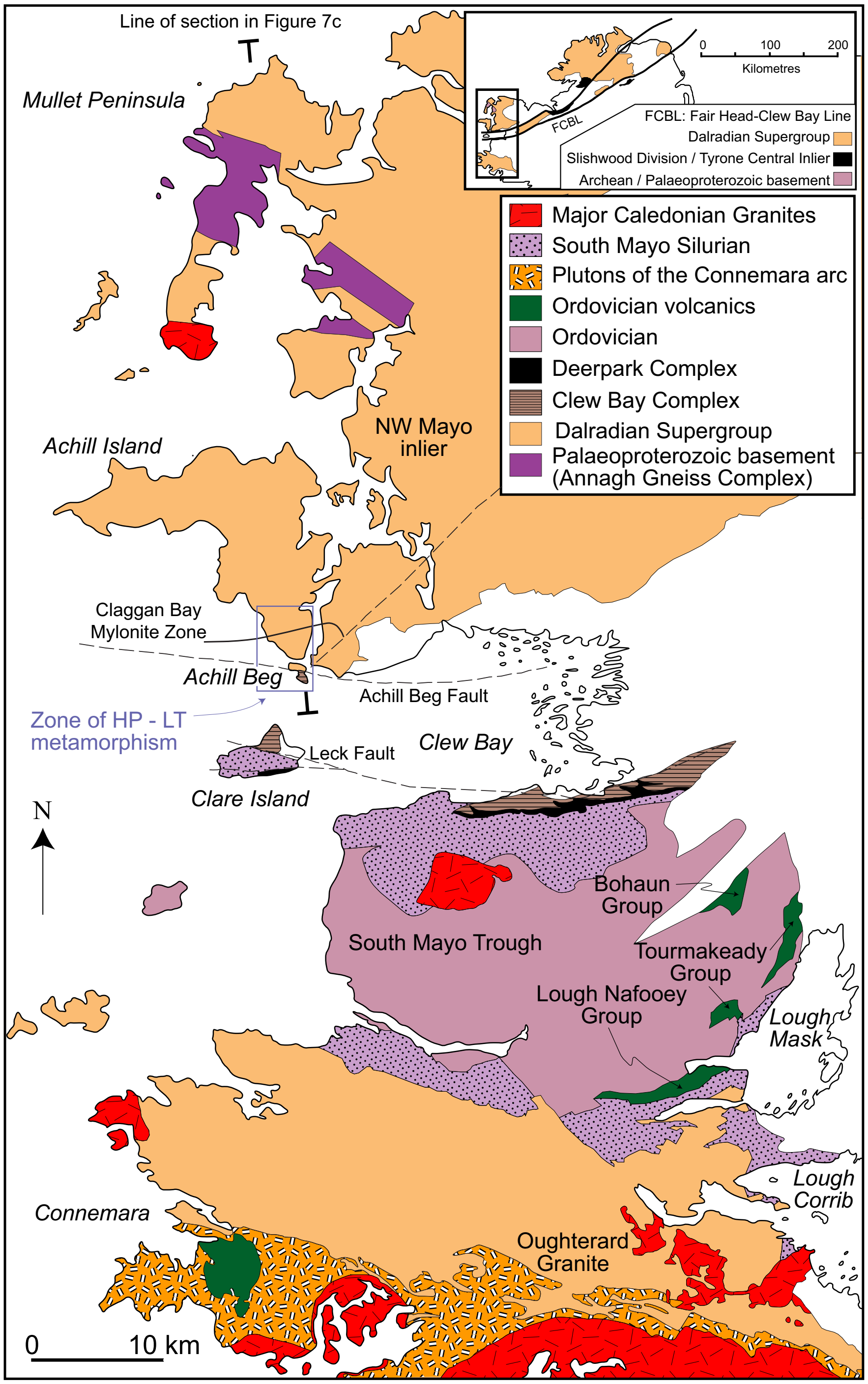
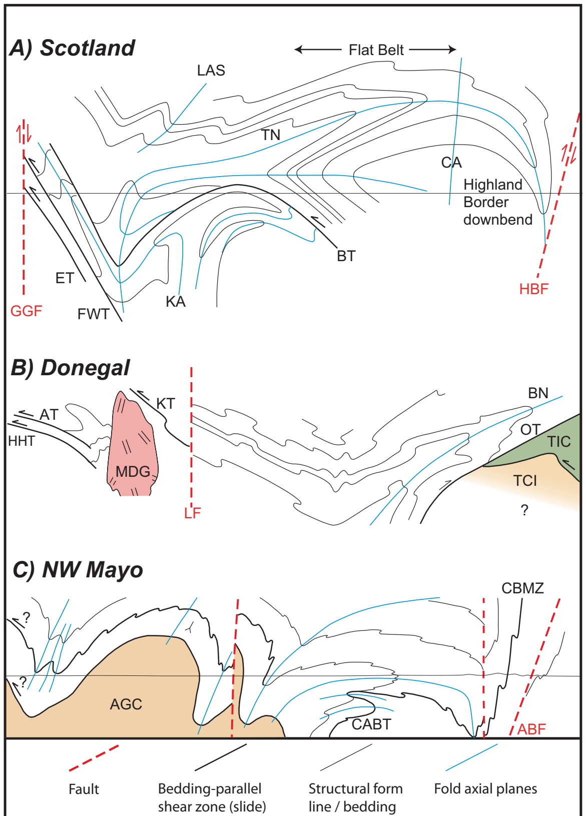

A
NW (NC 3056 3549)
metres
1500
1000
500
00
-500
-1000
Moine Thrust
Beinn Direach Anticline
Ben Hope Thrust
Ben Hee Incline
Fiag Syncline
(NC 4840 2600) SE
metres
0
1
2 km
V = H
Footwall of Moine Thrust
Moine Nappe
F2 Anticline
F2 Syncline
Younging direction
Bedding trace
B
Southern Moine Thrust
Vaich Pelite
Glasarnoch Psammite and Semipelite
Altnaharra and Glen Achall Psammite
Braemore Syncline
Beinn Dearg Anticline
An Elgin Syncline
Shear zone?
Glascarnoch Anticline

Figure 5



Line of section in Figure 7c
Mullet Peninsula
0 100 200
Kilometres
FCBL
FCBL: Fair Head-Clew Bay Line
Dalradian Supergroup
Slishwood Division / Tyrone Central Inlier
Archean / Palaeoproterozoic basement
Major Caledonian Granites
South Mayo Silurian
Plutons of the Connemara arc
Ordovician volcanics
Ordovician
Deerpark Complex
Clew Bay Complex
Dalradian Supergroup
Palaeoproterozoic basement
(Annagh Gneiss Complex)
NW Mayo
inlier
Achill Island
Claggan Bay
Mylonite Zone
Achill Beg
Achill Beg Fault
Zone of HP - LT
metamorphism
Leck Fault
Clew Bay
Clare Island
N
Bohaun
Group
South Mayo Trough
Tourmakeady
Group
Lough Nafooey
Group
Lough
Mask
Lough
Corrib
Connemara
Oughterard
Granite
0
10 km

Figure 6

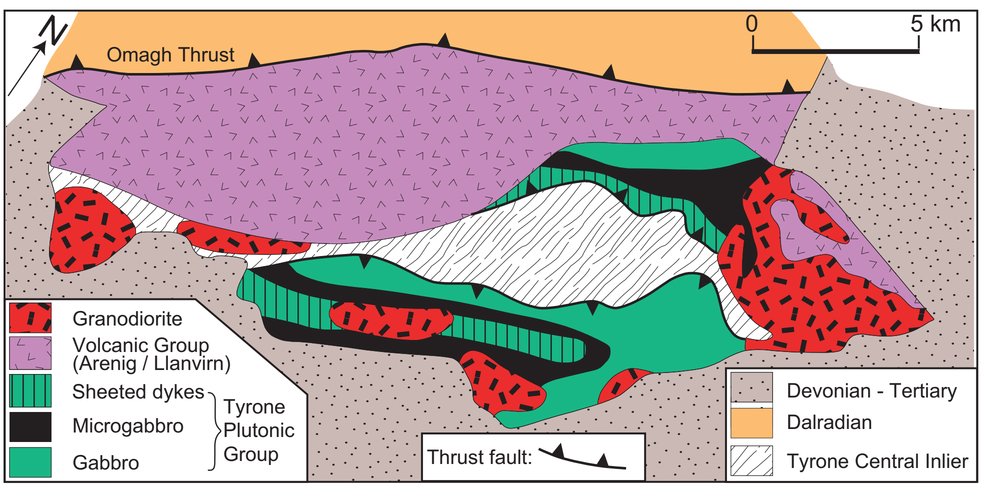


Scotland. BT: Boundary Thrust CA: Cowal Antiform ET: Eilrig Thrust FWT: Fort William Thrust HBF: Highland Boundary Fault GGF: Great Glen Fault LAS: Loch Awe Synform KA: Kinlochleven Anticline TN: Tay Nappe

Donegal. AT: Ardsbeg Thrust BN: Ballybofey Nappe HHT: Horn Head Thrust KT: Knockateen Thrust LF: Leenan Fault MDG: Main Donegal Granite OT: Omagh Thrust TIC: Tyrone Igneous Complex TCI: Tyrone Central Inlier

NW Mayo. ABF: Achill Beg Fault AGC: Annagh Gneiss Complex CABT: Central Achill Boundary Thrust CBMZ: Claggan Bay Mylonite Zone

Figure 7



N
Omagh Thrust
0
5 km
Granodiorite
Volcanic Group
(Arenig / Llanvirn)
Sheeted dykes
Microgabbro
Gabbro
Tyrone
Plutonic
Group
Thrust fault:
Devonian - Tertiary
Dalradian
Tyrone Central Inlier

Figure 8

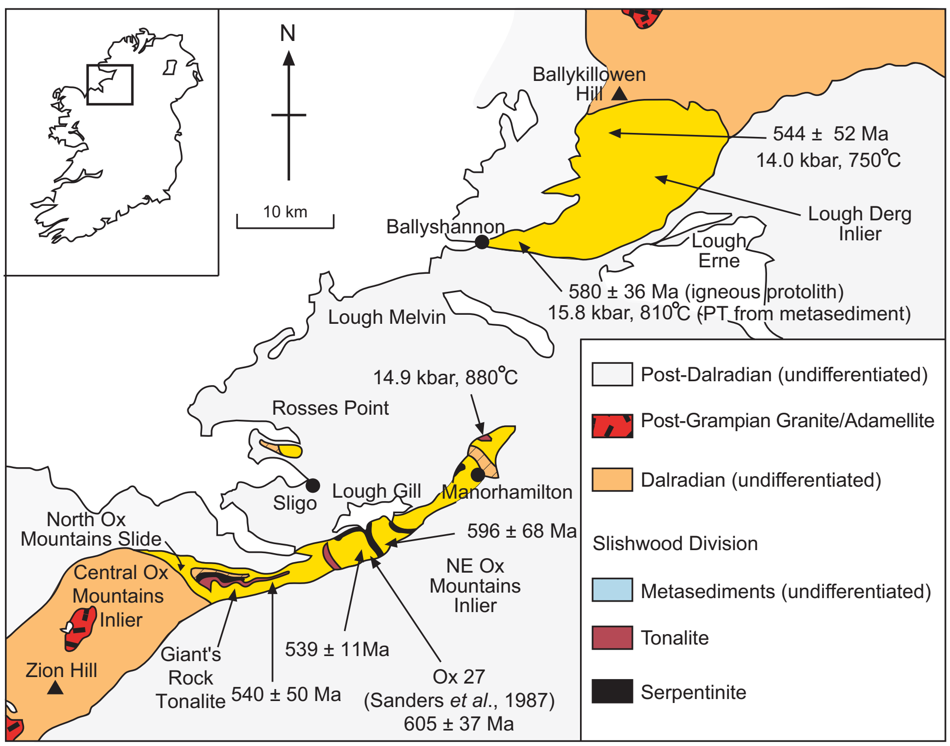

N
10 km
Ballykillowen Hill
544 ± 52 Ma
14.0 kbar, 750°C
Lough Derg Inlier
Ballyshannon
Lough Erne
580 ± 36 Ma (igneous protolith)
15.8 kbar, 810°C (PT from metasediment)
Lough Melvin
14.9 kbar, 880°C
Rosses Point
Sligo
Lough Gill
Manorhamilton
596 ± 68 Ma
North Ox Mountains Slide
Central Ox Mountains Inlier
NE Ox Mountains Inlier
Zion Hill
Giant's Rock Tonalite
540 ± 50 Ma
539 ± 11Ma
Ox 27 (Sanders et al., 1987) 605 ± 37 Ma
Post-Dalradian (undifferentiated)
Post-Grampian Granite/Adamellite
Dalradian (undifferentiated)
Slishwood Division
Metasediments (undifferentiated)
Tonalite
Serpentinite

Figure 9

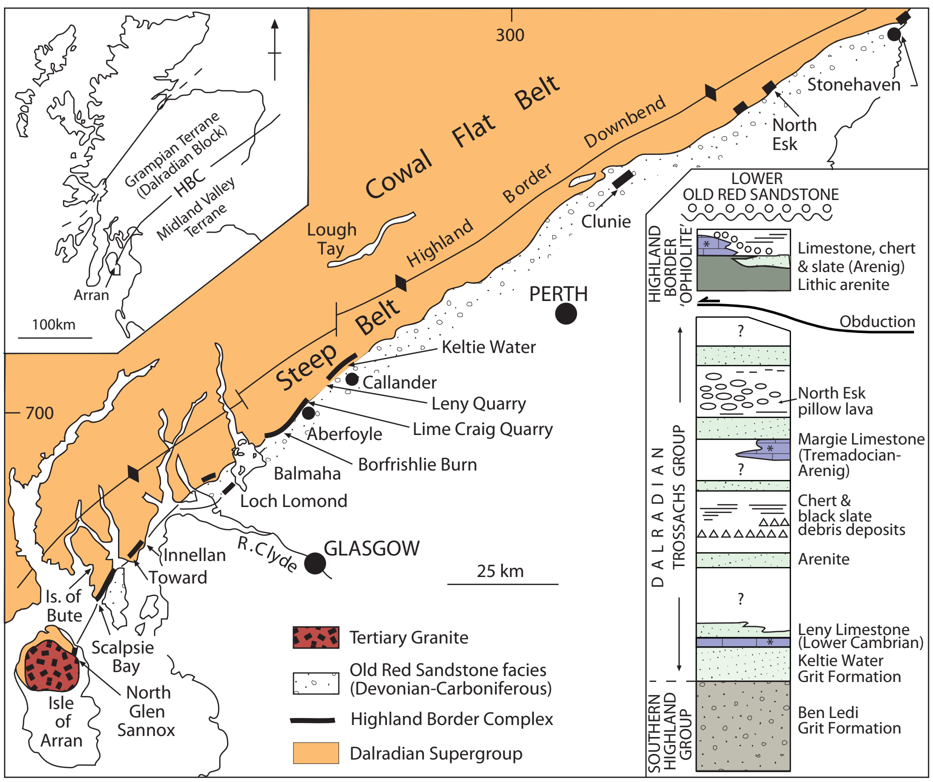

300
Cowal Flat Belt
Highland Border Downbend
Steep Belt
Lough Tay
Stonehaven
North Esk
Clunie
PERTH
Keltie Water
Callander
Leny Quarry
Lime Craig Quarry
Aberfoyle
Borfrishlie Burn
Balmaha
Loch Lomond
R.Clyde
GLASGOW
Innellan
Toward
Is. of Bute
Scalpsie Bay
North Glen Sannox
Isle of Arran
700
25 km
Grampian Terrane (Dalradian Block)
HBC
Midland Valley Terrane
Arran
100km
Tertiary Granite
Old Red Sandstone facies (Devonian-Carboniferous)
Highland Border Complex
Dalradian Supergroup
LOWER OLD RED SANDSTONE
HIGHLAND BORDER 'OPHIOLITE'
Limestone, chert & slate (Arenig)
Lithic arenite
Obduction
DALRADIAN TROSSACHS GROUP
North Esk pillow lava
Margie Limestone (Tremadocian-Arenig)
Chert & black slate debris deposits
Arenite
Leny Limestone (Lower Cambrian)
Keltie Water Grit Formation
SOUTHERN HIGHLAND GROUP
Ben Ledi Grit Formation

Figure 10

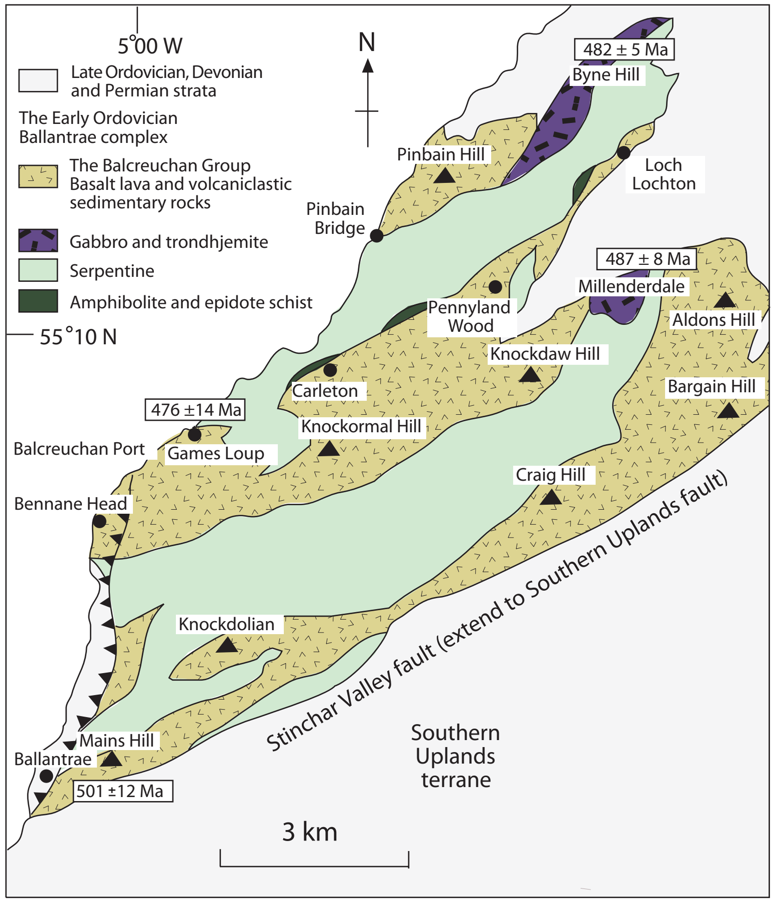
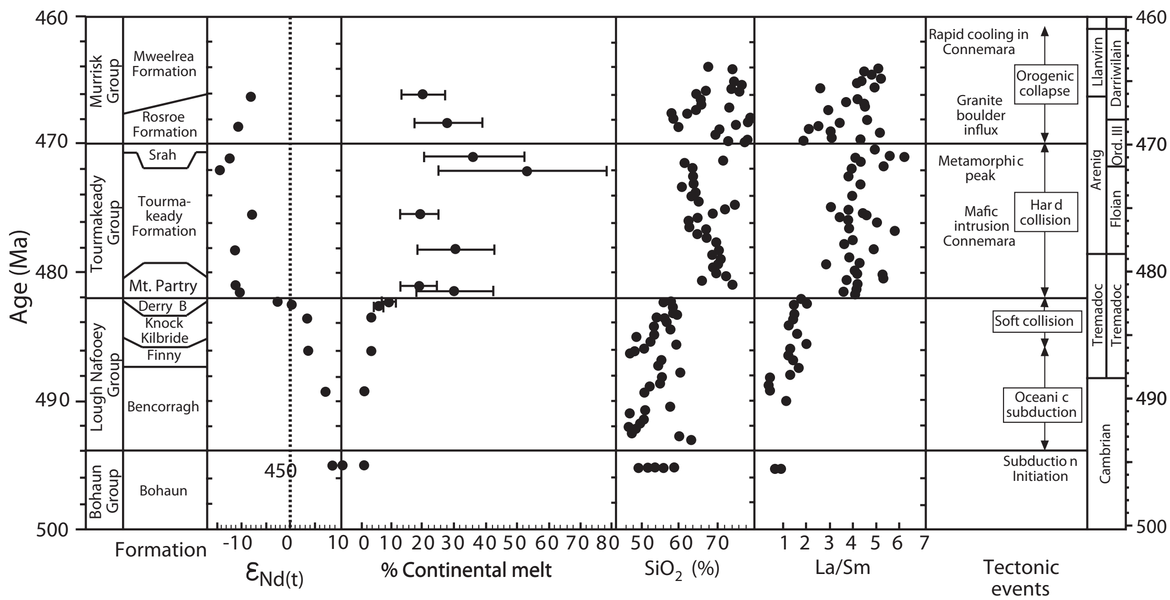

5°00 W
N
Late Ordovician, Devonian and Permian strata
The Early Ordovician Ballantrae complex
The Balcreuchan Group Basalt lava and volcaniclastic sedimentary rocks
Gabbro and trondhjemite
Serpentine
Amphibolite and epidote schist
55°10 N
482 ± 5 Ma
Byne Hill
Pinbain Hill
Loch Lochton
Pinbain Bridge
487 ± 8 Ma
Millenderdale
Pennyland Wood
Aldons Hill
Knockdaw Hill
Carleton
Bargain Hill
476 ±14 Ma
Knockormal Hill
Balcreuchan Port
Games Loup
Craig Hill
Bennane Head
Stinchar Valley fault (extend to Southern Uplands fault)
Knockdolian
Southern Uplands terrane
Mains Hill
Ballantrae
501 ±12 Ma
3 km

Figure 11



Age (Ma)
Murrisk Group
Mweelrea Formation
Rosroe Formation
Tourmakeady Group
Srah
Tourma-keady Formation
Mt. Partry
Lough Nafooey Group
Derry B
Knock
Kilbride
Finny
Bencorragh
Bohaun Group
Bohaun
450
Formation
$\varepsilon_{Nd(t)}$
% Continental melt
SiO_2 (%)
La/Sm
Rapid cooling in Connemara
Orogenic collapse
Granite boulder influx
Metamorphic peak
Mafic intrusion Connemara
Hard collision
Soft collision
Oceanic subduction
Subduction Initiation
Tectonic events
Llanvirn
Darriwilain
Arenig
Ord. III
Floian
Tremadoc
Tremadoc
Cambrian

Figure 12

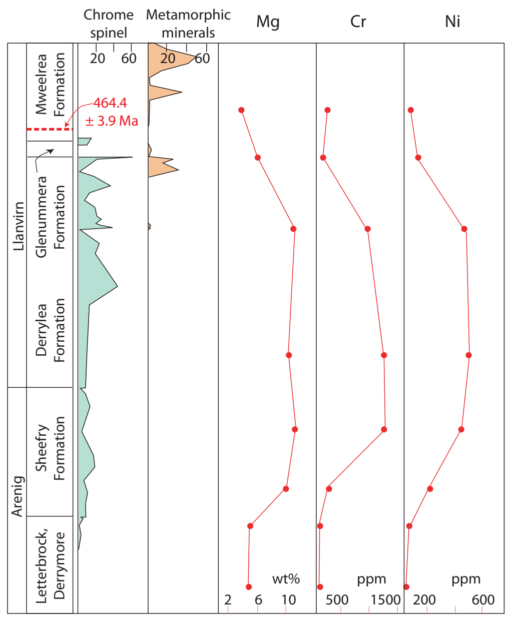

Chrome spinel
Metamorphic minerals
Mg
Cr
Ni
20
60
20
60
Llanvirn
Arenig
Mweelrea Formation
464.4
± 3.9 Ma
Glenummera Formation
Derrylea Formation
Sheefry Formation
Letterbrock, Derrymore
wt%
ppm
ppm
2
6
10
500
1500
200
600

Figure 13

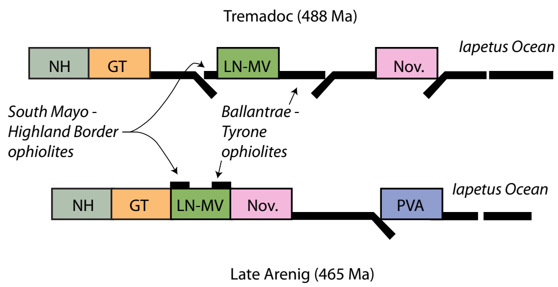
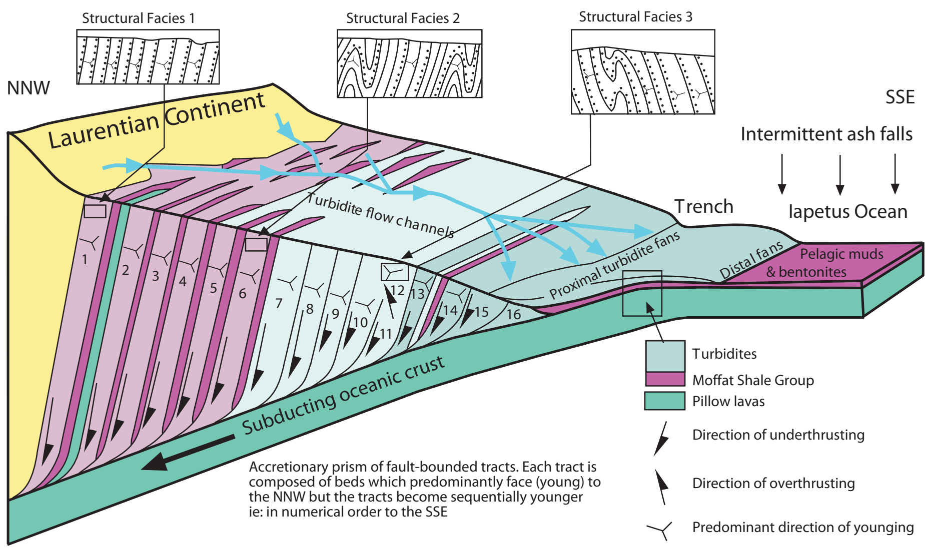

Tremadoc (488 Ma)
NH
GT
LN-MV
Nov.
Iapetus Ocean
South Mayo - Highland Border ophiolites
Ballantrae - Tyrone ophiolites
NH
GT
LN-MV
Nov.
PVA
Iapetus Ocean
Late Arenig (465 Ma)

Figure 14



Structural Facies 1
Structural Facies 2
Structural Facies 3
NNW
SSE
Laurentian Continent
Intermittent ash falls
Trench
Iapetus Ocean
Turbidite flow channels
Proximal turbidite fans
Distal fans
Pelagic muds
& bentonites
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Subducting oceanic crust
Turbidites
Moffat Shale Group
Pillow lavas
Direction of underthrusting
Direction of overthrusting
Predominant direction of younging
Accretionary prism of fault-bounded tracts. Each tract is composed of beds which predominantly face (young) to the NNW but the tracts become sequentially younger ie: in numerical order to the SSE

Figure 15

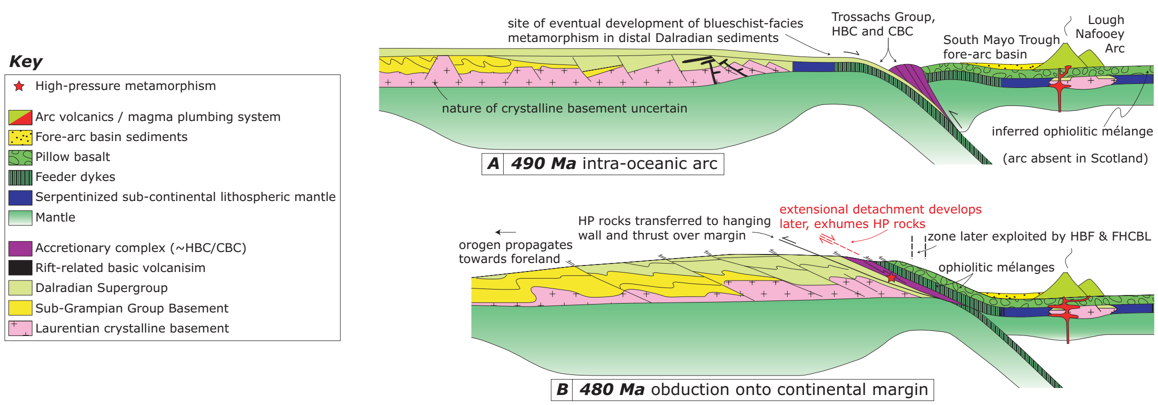

Key
High-pressure metamorphism
Arc volcanics / magma plumbing system
Fore-arc basin sediments
Pillow basalt
Feeder dykes
Serpentinized sub-continental lithospheric mantle
Mantle
Accretionary complex (~HBC/CBC)
Rift-related basic volcanisim
Dalradian Supergroup
Sub-Grampian Group Basement
Laurentian crystalline basement
site of eventual development of blueschist-facies
metamorphism in distal Dalradian sediments
Trossachs Group,
HBC and CBC
South Mayo Trough
fore-arc basin
Lough
Nafooey
Arc
nature of crystalline basement uncertain
inferred ophiolitic mélange
(arc absent in Scotland)
A 490 Ma intra-oceanic arc
HP rocks transferred to hanging
wall and thrust over margin
extensional detachment develops
later, exhumes HP rocks
zone later exploited by HBF & FHCBL
orogen propagates
towards foreland
ophiolitic mélanges
B 480 Ma obduction onto continental margin

Figure 16