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The Neoproterozoic to Mid-Devonian evolution of Scotland: a review and unresolved issues.

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r/head: Tectonic evolution of Scottish Caledonides

Abstract: The purpose of this review paper is to identify and outline some critical questions about the geology and tectonic evolution of the Scottish Caledonides in their wider Caledonian/Appalachian context. We outline what we think we know and what we perceive to be some important problems from about 1.0 Ga (Grenville Orogeny) to Middle Devonian (Acadian Orogeny). We do not attempt in-depth analyses of any terrain or tectonic topic in this review but, mainly, pose questions. Scotland is considered in the context of the Irish Caledonides and the Northern Appalachians, especially Newfoundland, so we make reference to these areas where appropriate. Each section is intended as “stand-alone”, not dependent upon prior or subsequent sections; the sequence of sections, roughly in time order, has a historical narrative thread. We have not included cross-sectional cartoons because we do not have a clear picture of plate

32 boundary zone and terrane arrangements in the Caledonides. There are too many enigmas,
33 paradoxes and unknowns to draw tectonic cross-sections with conviction.

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Introduction.

Caledonia is the Latin name given by the Romans to the land inhabited by Celtic peoples lying to the north of the outermost defenses of their province of Britannia, Hadrian's Wall from the Solway Firth to the River Tyne and briefly Antonine's Wall from the Firth of Clyde to the Firth of Forth. Suess (1906) referred to the Caledonian "pre-Devonian mountains" extending from Scotland northeast to Norway and southwest to Wales and Ireland. Given the clear involvement of Cambrian and Lower Ordovician strata in northwestern Scotland in tectonic events related to the formation of the mountains, the Caledonian orogeny has long been regarded as an early Palaeozoic event. Reviewing the historical background, and in the light of late 20th Century advances in the understanding and dating of Palaeozoic tectonic events, McKerrow *et al.* (2000) redefined the Caledonian orogeny as embracing all Cambrian, Ordovician, Silurian and Devonian tectonism associated with the development and closure "of those parts of the Iapetus Ocean that were situated between Laurentia (to the NW) and Avalonia and Baltica (to the SE and east)". Although recent work indicates that the South American portion of the Gondwanaland supercontinent may also have been involved in the Taconic tectonism along strike in Laurentia (Dalziel 2010), this definition reflects current usage.

The British Caledonides lie at the "triple junction" of three shields/platforms: the Laurentian Shield, the Baltic Shield and Avalonia; and three orogens: the Greenland/Scandinavian Caledonides, the Appalachians and the Polish Caledonides. The three orogens have partly shared and partly different histories. The Greenland/Scandinavian orogen is, dominantly, a two-sided mid-Silurian collisional system with major thrusting on both sides. The Appalachians are dominated by Ordovician (Taconic) and mid-Devonian (Acadian) orogeny, have only a minor development of Neoproterozoic rift sequences, and a sharp well-defined Cambro-Ordovician shelf edge. The Polish Caledonides are the result of ocean closure between Avalonia and Baltica during the Ordovician.

History of research on the Laurentian origin of the basement rocks of Scotland

Modern marine and satellite geophysical data clearly demonstrate that the basement rocks of northwestern Scotland were formerly adjacent to the margin of the North American continent. Accurate palaeogeographic reconstruction prior to the opening of the North Atlantic Ocean basin places the continental Rockall Bank and Scottish mainland adjacent to Greenland at the tip of a promontory between the Caledonian orogen of East Greenland and the Appalachian orogen of eastern Canada and the United States. This has been named the Scottish promontory (Dalziel and Soper 2001) and Scottish corner (Leslie *et al.* 2008).

The North American affinities of the shelly fauna in the Cambrian and Lower Ordovician platform cover of the Precambrian basement of the Northwest Highlands of Scotland were first recognized by Salter in a contribution to an article on the succession of the older rocks there by Murchison (1859), who drew attention to similarities in the preservation of these fossils and specimens from limestone of the same age in Canada. Salter remarked: “That this truly North American assemblage should be found in the extreme North of Scotland...and yet be scarcely known further south, is at least suggestive of a geographic distribution...” A half-century later, in the classic memoir on the geological structure of the north-west Highlands of Scotland (Peach *et al.* 1907), Peach was able to state “Not only are the fossils identical on both sides of the Atlantic, but the sediments in which they have been preserved present a remarkable similarity, as if the North American and Scottish rocks were deposited under similar, if not identical, physical conditions, and as part of one and the same geological and zoological province.” Subsequent studies have confirmed that the Cambro-Ordovician sequence can be correlated formation by formation to Newfoundland and NE Greenland (Cowie 1974; Smith & Rasmussen 2008; Raine & Smith 2012). The Archaean and Paleoproterozoic crystalline basement of the northwest Highlands and western isles fit well with that of the East Greenland region of Laurentia (Park 1994; Friend & Kinny 2001). The continuation of the prominent Grenville province of present-day eastern Laurentia into the western margin of Europe is still puzzling because only small occurrences of ~1.0 Ga Grenvillian rocks are known from western Ireland (Winchester and Max 1984; Daly & Flowerdew 2005) and one locality in western Scotland (Sanders *et al.* 1984; Storey 2008).

Cambrian fossils of Laurentian affinities have also been found adjacent to the Highland Boundary Fault in the youngest part of the Dalradian Supergroup that forms the Grampian Highlands, south of the Great Glen Fault. Limestones there contain both open-ocean miomerids and polymerid shelf dwellers cons-specific with taxa in the allochthonous Quebec and New York successions in the Ordovician Taconic orogen (Fletcher and Rushton 2007). Thus the Scottish Highlands represent a fragment of the Laurentian continental margin. The basement and shelf geology of Scotland records the history of this fragment while it was a part of Laurentia. This has had implications for the development of geological thought. Prior to the understanding of seafloor spreading and plate tectonics at about the time at which the *Scottish Journal of Geology* was first published, the hypothesis of continental growth, or continental accretion, was widely accepted in North America where Phanerozoic orogens surround a Precambrian core. However the presence in northwest Scotland of a fragment of this ancient core, with some of the most ancient Precambrian rocks in Europe, made this hypothesis less appealing to European geologists.

We acknowledge the many legendary geologists and their achievements at a time when roads and communication in the Scottish Caledonides were primitive. Horse, bicycle, and foot were the only form of transport before the early 20th century; topographic maps were made as the geology was being mapped. James Hutton (1726-1797), the Scottish founder of geology, introduced the concept of uniformitarianism on an ancient dynamic Earth. He recognized sedimentary strata as evidence of a great repetitive cycle of sedimentation, uplift and erosion. At Siccar Point on the Berwickshire coast of southeast Scotland, he described and evaluated the orthogonal unconformity between vertical Silurian greywackes and sub-horizontal Devonian red-beds (Old Red Sandstone). His masterpiece “Theory of the Earth” appeared in 1788 (Hutton 1788). John Playfair (1748-1819) made Hutton’s ideas more accessible in his “Illustrations of the Huttonian theory of the Earth” (1802). John MacCulloch drew the first geological map of Scotland, published in 1836, the year after his death. His map displays the main rock units of the and clearly shows a great dislocation along the later-recognized Moine Thrust Zone (MacCulloch, 1840). Other important Victorian geologists, such as De la Beche, Sedgwick, and Lyell visited and made much reference to Highland geology but did little original field work and observation there.

Early controversies

After MacCulloch, Scottish Highland geology became a focus of major controversy (Fig.1). Murchison (1859), in his pursuit for the base of the Silurian System and stratigraphical continuity, asseverated that there is a natural stratigraphic sequence from the Lewisian through the Torridonian and Durness sequence into the Moine. In 1860, the young Archibald Geikie, a acolyte of Murchison, walked along the Moine Thust Zone from Kinlochewe to Loch Broom and pronounced that there is a natural sequence from the Lewisian into the Moine (Murchison and Geikie, 1861) as averred by Murchison. This was a classic case of poor field work and a desire to please the master. The authors have all, separately, repeated Geikie's walk and marvel at how a professional geologist could fail to recognize that gneisses (Lewisian) lie above a gently-dipping contact with anchi-metamorphic sediments. However, Geikie's sycophancy worked in seeking high office and honours; he was appointed, in spite of indifferent scientific contributions in the Highlands, to the Chair of Geology at Edinburgh, Directorship of the Scottish Geological Survey, Directorship of the Geological Survey of Great Britain, and achieved FRS, and knighthood. Nicol (1861) showed that there must be a major break across what we now know as the Moine Thrust Zone. Nicol's correct intervention led to his being denigrated and abused by the Murchison/Geikie camp. Luckily, in the late 1870's, along came James Callaway, who had done superb field work in Shropshire, Anglesey, and Donegal. Mapping in the northern part of the "Assynt Bulge", he showed that Lewisian high-grade rocks are thrust, along what is now termed the Glencoul Thrust, across the imbricated low-grade Durness sequence along a platy and lenticular zone in which the rocks are heavily deformed (Callaway, 1883, 1884). Lapworth, arguably the greatest field-based geologist of all time, fresh from his work in the Dobb's Linn and other sections of the Southern Uplands, in which he defined the Ordovician System and the basic structure of the Southern Uplands, began to map the Eriboll area in the late 1870's. He demonstrated, by exquisite and meticulous, fine-scale mapping, that Moine rocks are thrust over the imbricated Durness sequence (Lapworth, 1883). Lapworth was greatly influenced by Albert Heim who had just demonstrated major overthrusting in the Swiss Alps. Lapworth's beautiful field sheets and field notebooks, recently re-discovered by Paul Smith in the Lapworth Museum in Birmingham, represent a milestone in the history of

Scottish geology. Callaway's and Lapworth's conclusions of major overthrusting in the Moine thrust zone were well-known by 1880 before they published. They were of course, anathema to Geikie, who now had the authority, as Director of the Geological Survey of Great Britain, to assemble a team of his finest geologists to, once and for all, map the Moine Thrust Zone in the Assynt region to demonstrate the correctness of the Murchison/Geikie continuous sequence view. The team included Peach, Horne, Clough, Gunn, Hinxman, and Cadell, supported by Teall as petrographer. They started mapping in 1881; within a few months, they showed, unequivocally, that Callaway and Lapworth were correct in their view that the Moine Thrust Zone exists as a major low-angle dislocation. Soon, another travesty ensued, highlighted by papers in *Nature* by Peach and Horne (1884), and Geikie (1884) announcing the discovery of the Moine Thrust and coining the term "thrust" with scant reference to Nicol, Callaway, and Lapworth. Lapworth (1885) summarized his position and coined the phrase "The Highland Controversy". Nevertheless, the superb mapping of Peach, Horne, Clough, and their Survey colleagues culminated in, perhaps, the finest publication in the field of geology, the 1907 British Geological Survey Memoir on the "Geological Structure of the North-west Highlands of Scotland" (Peach *et al.* 1907). The time line for the actors and events in this great Scottish Victorian/Edwardian geological drama is summarized in Figure 1. The Highland Controversy is analyzed in great detail in Oldroyd (1990).

In the 1950's, another unpleasant feud developed in the Northwest Highlands. Within the Moine rocks of Knoydart, Glenelg, and Morar, hornblende-gneissic rocks occur as slivers and more extensive areas beneath the Morar Division of the Moine Supergroup. W. Q. Kennedy (1955) mapped and regarded these as Lewisian basement "inliers", whereas the Imperial College school, led by John Sutton, considered them to be, following H. H. Read, 'Durcha Moine', an amphibolite-facies variant of the Moine in Sutherland. At an extraordinarily vituperative and regrettable meeting of the Geological Society of London, Kennedy's ground-breaking paper on "The structure of Morar" was ridiculed in the discussion by a succession of Imperial College speakers. Kennedy was subsequently proved right, later supported by the superb mapping of the Knoydart Peninsular by John Spring (Spring 1960), an Imperial College Ph.D student. Kennedy (e.g., 1964) turned his attention to the geology of the African continent. The Imperial College group never published a retraction or publicly acknowledged their mistake but the situation was

partly remedied by Ramsay and Spring (1962) and Poole and Spring (1974) in their papers on the Knoydart/Morar Lewisian inliers and in a sentence in the Royal Society Biographical Memoir of Kennedy (Sutton 1980). Parenthetically, in his Morar paper, Kennedy (1955), seemingly casually but correctly, recognized that the age of the main deformation of the Highlands occurred in the early Ordovician. Kennedy was, like Lapworth, a great scientist and polymath. He recognized the Great Glen Fault (Kennedy, 1946) as a major strike-slip fault, and worked and published highly-original papers on a huge range of topics mainly in Scottish and African geology.

The basement, major structure, and events.

Figure 2 is a simplified summary tectonic map of Scotland and Ireland north of the Iapetus Suture. Traditionally, the ‘basement’ rocks of Scotland have been defined as the Archaean to Palaeoproterozoic Lewisian Complex (Sutton and Watson 1951) of the northwestern coastal region and the Western Isles, unconformably overlain by late Mesoproterozoic to Neoproterozoic Torridonian strata (Park 1992). To the east, above the Moine Thrust, the meta-sedimentary Moine “Supergroup”, forming most of the Northern Highlands northwest of the Great Glen Fault, is unconformable on a gneissic basement, exposed in inliers. Some of these basement inlier rocks have yielded Neoarchaean U-Pb zircon protolith ages (Friend *et al.* 2008), confirming a Lewisian origin. Their subsequent tectono-metamorphic history before the deposition of the Moine cover is uncertain, although the basement inlier of eastern Glenelg was subjected to eclogite-facies metamorphism at about 1.0 Ga (Sanders *et al.* 1984; Brewer *et al.* 2003). A permissible model is that both Dalradian and Moine are underlain by a Neoarchean or Palaeoproterozoic basement with a Grenville 1.0 Ga overprint. This is supported/permitted by several lines of evidence. First, an unconformable contact is seen, in Co Mayo, western Ireland, between the Palaeoproterozoic Annagh Head Gneiss Complex (Winchester and Max 1984) and the Inishkea Division of the Dalradian Supergroup (McAteer *et al.* 2010a); the Annagh Head Gneiss was overprinted and intruded by granite at about 1.0 Ga (Kennedy and Menuge 1992). Second, the eastern Glenelg Lewisian basement has a “Grenville” overprint (Sanders *et al.* 1984; Brewer *et al.* 2003). Third, on the Bullard *et al.* (1965) reconstruction of the North Atlantic continents, the wide Grenville Province of Canada strikes directly towards the British Caledonides. Fourth, in the Newfoundland Appalachians, in direct strike-continuity with the Irish

Caledonides, Grenville rocks form the basement of both the Cambro-Ordovician Laurentian Shelf but also are suspected, from the isotope geochemistry of Ordovician arc systems, to lie beneath the arc(s) (Zagorevski *et al.* 2007). The Grenville Orogen consists mostly of older basement provinces transected by the Grenville Front. Perhaps the Grenville Front, after transecting the Ketilidian west of Ireland passes along the future line of the Great Glen Fault to become the ancestral Moine Thrust zone with a multiple history. However, the exact configuration of the Torridonian and Moinian basins, which has been debated since the 19th Century (e.g. Geikie 1893), remains obscure because they are separated by the Caledonian Moine thrust zone that carried the Moine over the basement rocks of the northwest foreland. Geochronometric and other geochemical studies (discussed below) have revealed that the Moine rocks were subjected to Neoproterozoic rift, intrusive and orogenic events along the margin of Laurentia prior to the opening of the Iapetus Ocean basin. Hence, they are also, at least partially, a part of the pre-Caledonian basement of Scotland, although the Neoproterozoic orogen was overprinted by Caledonian deformation and metamorphism and intruded by Caledonian granitoids. The Dalradian Supergroup, forming the Grampian Highlands to the southeast of the Great Glen Fault, rests, at least locally, on a Moine-like metasedimentary base, although the nature of the contact is unclear (Smith 1999; Leslie *et al.* 2008). The age of the base of the Dalradian is also uncertain; this succession was not affected by Neoproterozoic orogenic events. Hence, the Dalradian is not part of the Caledonian basement, and its basal strata are likely to be younger than ~750-700 Ma.

We consider the Scottish and Irish Caledonides in six zones: (i) the Northwest Foreland with a Lewisian basement inliers, (ii) the Northwest Highlands consisting of the Moine Supergroup with Lewisianoid basement inliers and a Grenville overprint, (iii) the Colonsay/Islay Zone with a Ketilidian basement, (iv) the Grampian Highlands with a probable Grenvillean basement, (v) the Midland Valley with an uncertain basement and (vi) the late Ordovician to Wenlock Southern Uplands accretionary prism. These zones are bounded by six major boundaries, the Moine Thrust Zone, the Great Glen Fault, the Highland Boundary Fault, the Southern Uplands Fault, and the Iapetus Suture Zone. We do not describe the basic detailed geology of the zones and their boundaries, which can be found in many publications such as the Geology of Scotland, (Trewin 2002). Rather, we outline the salient facts that define problems.

It is now clear that Ordovician (Grampian) deformation and metamorphism was widespread across the Highlands between the Moine Thrust and the Highland Boundary Fault. The Grampian Orogeny (Taconic Orogeny in the Appalachians) resulted from the collision of an oceanic arc(s) with the Laurentian margin (Nelson & Casey 1979; Dewey 2005), the timing and events of which, with special reference to western Ireland are summarized in Figure 3. The Wenlockian Scandian event, resulting from the Greenland/Baltica continent/continent collision, affected only the Northwest Highlands. This suggests (Dewey & Strachan 2003) that the Grampian Highlands were at least 500 km to the southwest with respect to the Northwest Highlands in the Silurian to avoid the Greenland/Baltica collision, a displacement that must have been taken up along the Great Glen Fault. The northward continuation of the Great Glen Fault probably passes through Shetland and Spitzbergen. To the south, its continuation into the Appalachians is unclear, although the dextral White Bay-Deer Lake Fault Zone is a likely candidate (Williams and Stevens 1974).

The Colonsay/Islay “Block” is enigmatic; the Dalradian Supergroup with its Ordovician Grampian deformation and metamorphism is thrust westwards across the Bowmore Sandstone along the Loch Skerrols Thrust. The Bowmore feldspathic sandstone is mostly little-deformed and of unknown age and affinity but possibly the last southwest remnant of the Moine (McAteer 2010b). To the west of the Loch Gruinart Fault, the four kilometer-thick Colonsay Group rests, with tectonic contact, upon a 1.7 Ga syenite-gneiss basement (Muir *et al.* 1994; McAteer *et al.* 2010c) probably contiguous with the Ketilidian of southern Greenland. The non-volcanic Colonsay succession consists of quartzites, feldspathic sandstones, pelites and minor carbonates mostly at greenschist-facies with a polyphase deformation sequence that varies greatly in intensity from strongly-lineated quartzites to dark phyllites. McAteer *et al.* (2010c) suggested that Colonsay Group belongs to a Grenville foreland basin, with which we concur. They also suggested that the detrital zircon population is similar to the lower Dalradian. We suggest that this correlation is unlikely: if the Colonsay Group is part of a Grenville foreland basin, the Dalradian must be at least 300 my. younger than the Colonsay Group. Many of the Colonsay Group psammites are micaceous on cleavage, whose white micas could be Ar/Ar dated; combined with high-resolution-heavy-mineral-analysis, these correlations could be tested.

The Moine and probably the Dalradian are underlain by a basement, possibly Lewisian and Ketilidian remobilized at about 1.0 Ga (Fig. 2), that was hyper-extended during the long-drawn-out late Pre-Cambrian continental rifting events that preceded the opening of Iapetus at about 550 Ma (Henderson *et al.* 2009), similar to the situation in Newfoundland (Van Staal *et al.* 2013). The basement beneath the Midland Valley is arcane with several conceivable origins including basement under-thrusting as discussed below. The Southern Uplands is a southward-thinning subduction-accretion greywacke wedge. It's northern 30 km crust was built by the rotation and vertical thickening of accreted greywacke prisms above the subducted northern Skiddaw toe of the Lake District.

The orogenies and their boundary zones

The general model (Dewey 1969, Dewey and Shackleton 1984) for the evolution of the northern Appalachians and the Scottish and Irish orthotectonic Caledonides involves the collision of the Laurentian rifted margin with an oceanic arc system and other terranes; and the obduction of fore-arc ophiolites (Dewey & Casey 2011; 2013), the Bay of Islands and Shetland Ophiolite Complexes onto the rifted margin, followed by a flip in subduction polarity (Nelson & Casey 1997) and the development of a south-facing arc and accretionary prism (Southern Uplands and South Connemara; Ryan & Dewey 2004; Dewey 2005). The supposed line or zone of arc-continent collision runs from South Achill and Clew Bay ('Clew Bay Line') in western Ireland (Chew *et al.* 2003), through Co. Tyrone, and along the Highland Boundary Fault to Shetland (Fig. 2). It is marked, discontinuously, by dismembered ophiolites, rifted margin serpentinites, fragments of accretionary prisms and blueschists (Chew 2003; Chew *et al.* 2003; Dewey & Mange 1999; Gray and Yardley 1979; Henderson and Robertson 1982; Henderson *et al.* 2009; Yardley 1980; Yardley and Senior 1982). The devil is in the details, however; the reality is much more complicated. The continental Ox Mountains and possibly the Midland Valley Terranes are of unclear provenance, although they have Laurentian affinity. The Ballantrae Ophiolite Complex was obducted onto the southern margin of the Midland Valley Terrane whereas the Shetland (Flinn 1958) and Bay of Islands complexes (Dewey & Casey 2011; 2013) were obducted onto the Grampian Terrane and Laurentian foreland respectively. The Grampian

Orogeny was accomplished during dextral transpression (Dewey 2005), the Erian and Scandian phases during sinistral transpression (Soper *et al.* 1992), the early Devonian during sinistral transtension (Dewey & Strachan, 2003) and the Acadian during north-south shortening.

We consider the gross shape of the basin(s) in which the Moine was deposited to be well-constrained. From its maximum extent in the Northwest Highlands, it narrows to the northeast and south west (Fig. 2). In Islay, if the Moine is present, it is represented only by the Bowmore Sandstone, a weakly-deformed feldspathic arenite in a zone some 10 kms wide between the Loch Skerrols Thrust, which puts the Dalradian westwards across the Bowmore Sandstone, and the Loch Gruinart Fault, west of which lie the Ketilidian-age Rhinns Complex basement and Colonsay Group cover (Muir *et al.* 1994; McAteer *et al.* 2010c). In Shetland, the obducted Unst/Fetlar Ophiolite and its underlying Dalradian sequence has a very narrow zone of Moine-like rocks, and crystalline basement to the west. Thus, in Islay and Shetland, the Moine is reduced to a narrow constricted zone between the Dalradian and northwest foreland basement. In western Ireland, the Inishkea Division of the Dalradian rests unconformably upon the Grenville Annagh Head Gneisses (Kennedy and Menuge 1992), between which the Moine is no longer present. The Moine and Torridonian are completely absent in the northern Appalachian orogen but the Torridonian may be represented in the Van Horn Sandstone Group in Trans-Pecos Texas (Davidson 1980).

Orogenic history of the Moine Supergroup

The Moine Supergroup became internationally important through the seminal studies, during the 1950's, of Gilbert Wilson and John Ramsay who unraveled the complex fold patterns that became used in many undergraduate textbooks as type examples of polyphase deformation (Wilson 1953, Ramsay 1957; 1960; 1962). At that time, because the Moine rocks were involved together with the Cambrian and Ordovician strata of the Durness succession in tectonism along the Moine thrust belt, this complex deformation (and metamorphic) history was regarded as entirely Caledonian. However, as a result of over 50 years of geochronological investigations coupled with detailed structural and metamorphic analysis, the current consensus is that Moine

rocks were affected also by Neoproterozoic orogenesis . The history of these investigations is highly instructive in showing how thinking has evolved in the interpretation of high-grade metamorphic complexes, and also how analytical techniques have evolved to the current position where significant insights into the evolution of an orogenic belt can be obtained by study of a single thin section.

The first evidence that the complex deformation histories of the Moine rocks might relate to more than one orogenic event came from the first Rb-Sr age-determinations of minerals and whole rocks from the Scottish Highlands by Giletti *et al.* (1961). In addition to evidence for widespread Caledonian metamorphism (420 ± 15 Ma), ages of c. 740 and c. 665 Ma were obtained for muscovite from pegmatites from Knoydart and Morar discovered by Kennedy *et al.* (1943). Giletti *et al.* (1961) concluded that: “a Pre-Cambrian event must be responsible for the formation of the pegmatites”. Rb-Sr and K-Ar mineral ages of c. 700-740 Ma obtained by Lambert and Long (1963) and Lambert (1969) from metasedimentary rocks and pegmatites in the Morar-Knoydart area and Carn Gorm (Fig. 4) confirmed this conclusion. The implicitly orogenic event resulting in these late Precambrian ages was referred to as either the Knoydartian (Bowes 1968) or Morarian (Lambert 1969). Knoydartian is now the more commonly used name.

Further complexity was introduced by Rb-Sr whole rock ages of c. 1100-1000 Ma obtained from the West Highland granitic gneiss and the Morar Pelite (Brook *et al.* 1976; 1977). These ages were thought to record peak metamorphism during the Grenville orogeny, suggesting a pre-1100 age of deposition for the Moine sediments. Further work by van Breemen *et al.* (1974; 1978) and Piasecki & van Breemen (1983) produced additional Rb-Sr and U-Pb mineral ages of c. 700-800 Ma and there was much debate as to whether the Moine rocks had been affected by separate Grenville and Knoydartian orogenic events or that the c.700-800 Ma isotopic ages were the result of incomplete resetting of older ages during the Caledonian orogeny. Early U-Pb zircon and monazite data were commonly discordant and difficult to interpret with confidence. It was only with the advent of more sophisticated dating techniques, that this debate was resolved.

The ability to analyse single grains of accessory minerals such as zircon and monazite using U-Pb isotopes has revolutionized the study of seemingly intractable metamorphic complexes. A key

target for the first modern geochronological investigation of Moine rocks was the granitic gneiss of western Ardgour, the southernmost body of the West Highland Granite Gneiss (Fig. 2). This had been interpreted by Dalziel (1966) to have resulted from more or less in situ melting of its host Moine rocks during regional, high-grade metamorphism (Barr *et al.* 1985). The U-Pb zircon age of 873 ± 7 Ma (Friend *et al.* 1997) was interpreted as dating this high-grade event because the dated grains were obtained from a migmatitic layer within the granitic gneiss. Older Proterozoic ages, mostly from 1800-1000 Ma, were obtained from 'inherited' zircon grains in the Moine sedimentary protolith of the granite gneiss. This clearly indicated a post-Grenville age of sedimentation for the Moine rocks, a conclusion substantiated by further studies of inherited/detrital zircons in Moine rocks elsewhere (Kinny *et al.* 1999; Friend *et al.* 2003; Cawood *et al.* 2004; Kirkland *et al.* 2008). The Rb-Sr whole rock ages of c. 1100-1000 Ma referred to above (Brook *et al.* 1976, 1977) were shown to be of uncertain significance.

The significance of the c. 870 Ma age for the Ardgour granitic gneiss was, however, rapidly questioned. Did it represent the age of a high-grade metamorphic (implicitly orogenic) event or the age of a pre-tectonic protolith to the gneiss? Dalziel and Johnson (1963) and Soper & Harris (1997) argued, from structural evidence, that the emplacement of the granitic protoliths of the various members of the West Highland Granite Gneiss suite occurred prior to the earliest deformation event within its host Moine rocks. This view was further developed by Millar (1999) and Dalziel and Soper (2001) who suggested an extensional origin for both the granite protolith and a suite of nearly synchronous mafic sheets cutting it and dated at 873 ± 6 Ma at Glen Doe by Millar (1999, U-Pb zircon). Recently, a reliable U-Pb date has been determined for zircon from the Sgurr Dhomhnuill augen-rich facies of the Ardgour granite gneiss north of Strontian. This rock does not have the migmatitic appearance of the gneiss elsewhere and is likely to represent the protolith with deformed feldspar phenocrysts. A U-Pb zircon age of 863 ± 7 (Cawood *et al.* in review) reinforces the interpretation that the granitic protolith of the gneiss and the mafic sheets were intruded during the same extensional event at that time.

Other U-Pb studies yielded results that substantiated the original concept of a c. 700-800 Knoydartian orogeny. U-Pb monazite data for pegmatites in Morar and the Ardnish Peninsula gave ages of 827 ± 2 and 784 ± 1 Ma respectively; structural studies suggested that they were

generated synchronously with localized high- temperature shearing and garnet-grade metamorphism (Rogers *et al.* 1998). Moreover, Sm-Nd systematics of garnets in the Moine rocks of Morar indicated that growth occurred during the interval 820-790 Ma at 650-700°C and 11-12 kbar, suggesting substantial crustal thickening (Vance *et al.* 1998).

Dalziel and Soper (2001) developed their extensional model for the origin of the West Highland Granite Gneiss and associated mafic sheets by proposing that the same interpretation could also be applied to the Precambrian pegmatites within the Moine rocks. They regarded the garnet ages and related PT work of Vance *et al.* (1998) to be of uncertain significance. Their extensional model carried the implication that orogenic deformation and metamorphism of the Moine rocks occurred entirely during the Caledonian orogeny. They suggested that the Knoydartian extension and a later phase of granitic intrusion that generated the protolith of the Carn Chuinneag-Inchbae granite and augen gneiss of the Northern Highlands at c. 600 Ma were related to the initial break-up of the Rodinian supercontinent and the incipient formation of the Iapetus Ocean basin respectively.

Resolution of the debate resulted from the realization that the only reliable way of distinguishing between shortening and extensional structures, developed in mid-crustal metamorphic regimes, is by examining the pressure-temperature evolution of isotopically-dated mineral assemblages. This approach has provided evidence for at least three Neoproterozoic orogenic events in Northern Scotland. The oldest of these is dated at c. 930 Ma and has so far only been recognized in the Westing Group metasedimentary rocks of Unst in the Shetland Islands (Cutts *et al.* 2010). PT conditions deduced for this event are c. 650°C and 8-9 kb. Detailed analysis of Glenfinnan Group (?) rocks in the Glen Urquhart area (Fig. 4), confirmed c. 825-780 Ma growth of garnet at ~650°C and 7 kb (Cutts *et al.* 2010), consistent with the results of Vance *et al.* (1998) in the Morar area. A second stage of garnet growth at Glen Urquhart occurred at $724 \pm$ Ma on a P-T path rising to 700°C and ~9.0 kb with the peak conditions associated with partial melting. This was consistent with the U-Pb age of 737 ± 5 Ma obtained from titanite (sphene) in the Lochailort area (Tanner & Evans, 2003), the two studies providing independent evidence for a distinctly younger Knoydartian event at c. 725-735 Ma.

It now appears, therefore, that the Neoproterozoic history of northern Scotland involved 1) an orogenic event at c. 930 Ma; 2) an extensional phase with granite and mafic sheet emplacement at 870-860 Ma; 3) compressional ‘Knoydartian’ orogenic phases at 825-780 Ma and ~725-735 Ma; 4) c. 590 Ma intrusion and extension related to the opening of Iapetus (i.e. Inchbae Granite gneiss). In most areas, these are only represented by the earliest folds and porphyroblasts because of extensive ductile reworking and overprinting in Ordovician and Silurian times by Caledonian orogenesis (Kinny *et al.* 1999; 2003a; 2003b; Rogers *et al.* 2001; Strachan & Evans 2008; Alsop *et al.* 2010). A major problem remains the correlation of the various phases of deformation observed in the field throughout the Moine outcrop (e.g. Ramsay 1963; Powell 1974) with these metamorphic events, particularly as there are now more metamorphic events identified than sets of fold structures in most areas (Cawood *et al.* in press). There is no known orogenic unconformity, obvious margins to these events, and no obvious way to identify this break of over 200 my between the Knoydartian and Caledonian events in the field. Regionally significant structures such as the Sgurr Beag Thrust (Fig 2) may have a Knoydartian and Caledonian history, and some major folds may be composite (Bird *et al.* 2013).

Neoproterozoic orogenic events are widespread in the southern continents and some of the orogens mark the sutures along which the Gondwanaland supercontinent was assembled in ‘Pan-African’ continent-continent collisions (Kennedy 1964). As pointed out by Dalziel and Soper (2001), they are not known in North America. However, they are found in the Laurentian Caledonides of East Greenland and Svalbard, as well as within the Laurentian-derived allochthons of Norway (Daly *et al.* 1991; Leslie *et al.* 2008; Kirkland *et al.* 2011). Metamorphic events dated at >950 Ma in East Greenland and Svalbard were thought to correspond to a northern arm of the Grenville orogeny (Park 1992; Lorenz *et al.* 2012). Explanation of significantly younger 800-700 Ma Knoydartian events in Scotland was more difficult to explain as most palaeo-continental reconstructions placed Baltica directly opposite East Greenland, and Scotland therefore occupied a position well within the Rodinia supercontinent (Dalziel & Soper 2001). One solution is that these shortening and crustal-thickening events were intra-cratonic, perhaps comparable with the Peterman orogen in central Australia (Cawood *et al.* 2004; Dewey 2005). However, more recent supercontinent reconstructions have placed Baltica significantly further south of East Greenland (Cawood & Pisarevsky 2006; Li *et al.* 2008), meaning that

Scotland would have been situated along the edge of Rodinia, close to the ‘Asgard Ocean’. Cawood *et al.* (2010) reconstructed the Neoproterozoic “Valhalla” accretionary orogen from the Moine in mainland Scotland, and broadly correlative successions in Shetland, East Greenland, Svalbard and Norway. It is notable that the reconstruction of the Valhalla orogen in the present northernmost part of Laurentia is spatially compatible with the collision of present southern Laurentia with the Kalahari craton at ~1000 Ma (Loewy *et al.* 2011; Fig. 5).

Tectonostratigraphic issues in the Northern Highlands

A long-lived controversy in Scottish geology is the extent to which the Torridonian and Moine are lateral equivalents, with differing opinions expressed by Ben Peach and his Survey colleagues (Peach *et al.* 1907). Constraints on the age of sedimentation of the two successions are relatively poor. The Torridon Group is somewhere within the Neoproterozoic by the c. 1000 Ma ages of the youngest detrital minerals and the Cambrian age of unconformably overlying sedimentary rocks. None-the-less, the most reasonable interpretation of palaeomagnetic data and isotopic data from shales thought to date diagenesis indicates probable deposition at c. 990-1000 Ma (Turnbull *et al.* 1996; Stewart 2002). The Morar Group rocks are only marginally better constrained by the youngest detrital zircon age of 980 ± 4 Ma (Peters *et al.* 2001) and the ~820 Ma age of the oldest Knoydartian metamorphic event. Slight differences in the relative proportions of different age groups of detrital zircons led Friend *et al.* (2003) and Cawood *et al.* (2007) to believe that the Torridon and Morar groups were deposited in different basins, but these could simply result from relatively few data sets. Krabbendam *et al.* (2008) argued, on general geological grounds, that the simplest solution is that the two are coeval fluvial to shallow marine successions that were deposited just after c. 1000 Ma in a foreland successor basin to a southerly Grenville orogen. This theme was pursued by Bonsor *et al.* (2012) who proposed tentative correlations between various units of the Torridon and Morar groups in northern Ross-shire. The reality or otherwise of such correlations is an important research question that could be addressed by further, much more detailed, studies of detrital mineral suites as a potential means of linkage across the Moine Thrust Zone.

The age of deposition of the Morar Group and whether or not it correlates with the Torridon Group has further ramifications for the status of the Moine rocks as a 'Supergroup'. The tripartite division of the Moine rocks into Morar, Glenfinnan and Loch Eil 'divisions' (Johnstone *et al.* 1969; Johnstone 1975) was superseded by the proposal that these divisions have the status of groups; from that arose the concept of a Moine Supergroup (Roberts *et al.* 1987; Holdsworth *et al.* 1994). For this to be valid, the boundaries between constituent groups have to be stratigraphic. Although the Morar-Glenfinnan contact is defined by the Sgurr Beag Thrust on the mainland, this does not appear to be the case on the Ross of Mull where it was interpreted as stratigraphic (Holdsworth *et al.* 1987). The Glenfinnan-Loch Eil contact was similarly shown to be stratigraphic elsewhere (Dalziel 1966; Roberts and Harris 1983). However, recent U-Pb dating of detrital zircons from the Glenfinnan Group at Glen Urquhart has important implications. The youngest zircon ages are 908 ± 8 Ma and 917 ± 13 Ma, which represent a lower age limit for sedimentation (Cutts *et al.* 2010). This dataset poses the question: is the Morar Group also younger than 920-900 Ma? Cawood *et al.* (2010) identified two major cycles of sedimentation and orogenic activity within the Neoproterozoic rocks of the North Atlantic borderlands. The older successions were affected by 'Renlandian' orogenic activity at 930-920 Ma, and this was followed by a further cycle of sedimentation in post-900 Ma successor basins that were later affected by Knoydartian events 820 Ma onwards. The Glenfinnan and Loch Eil Groups fall within the latter category. The central question is whether the Morar Group is part of the same package and not, therefore, correlative with the Torridon Group, or is it distinctly older than the Glenfinnan-Loch Eil succession? If the latter, the Morar-Glenfinnan contact on the Ross of Mull may hide a cryptic sedimentary break. Does this also correspond to an orogenic unconformity between Morar Group rocks affected by 930-920 Ma tectonic activity and a younger Glenfinnan Group?

Northwest Foreland and Moine Thrust Zone: comparisons with the Appalachians

The Eriboll through Durness sequence of the Northwest Foreland is part of a Cambro-Ordovician continental shelf along the margin of Laurentia from Alabama to northeast Greenland (Dewey 1969). It is also found in the Cuayania terrane in northwestern Argentina that originated in the Ouachita embayment south of Alabama (Dalziel & Soper 2001) (Fig. 5). The

Assynt Culmination beneath the Moine Thrust is the finest repository of superbly-exposed orogenic thrust margins in the world and has been superbly mapped by generations of geologists (e.g. Coward 1985; British Geological Survey 2007). West of the Moine Thrust is the Lewisian crystalline basement, recording Neoarchean (3000 - 2700 Ma) to Palaeoproterozoic (2000 - 1670 Ma) igneous, metamorphic and tectonic events (Park *et al.* 2002; Friend & Kinny 2001; Goodenough *et al.* 2013). East of the Moine Thrust, basement to the Moine may be Lewisian remobilized at about 1.0 Ga during the Grenville Orogeny, whose foreland basin may be the Colonsay succession of Islay and Colonsay (McAteer *et al.* 2010c). We speculate that the Moine Thrust Zone has had a long history as the Grenville Front, a Moine basin-bounding extensional zone, possibly the Knoydartian, the boundary of Grampian deformation (hence termination of Durness carbonate deposition in the early Ordovician), and the Scandian orogenic front in the mid-Silurian.

In the Appalachians, especially in New England and Newfoundland, the shelf edge to the Iapetus Ocean is delineated precisely and sharply by an abrupt Cambro-Ordovician facies change from shallow marine strata to continental slope and rise clastic sediments (Williams and Stevens 1974), although the continental rise was a hyper-extended margin with Grenville basement (Van Staal *et al.* 2013). This margin was destroyed and its rift-phase Fleur-de-Lys sediments were deformed and metamorphosed to, locally, eclogite facies by the obduction of the Bay of Islands Ophiolite Complex, the fore-arc to the Lushs Bight Arc. Beneath the Ophiolite Complex, a turbidite (Goose Tickle) foreland basin was generated during the Taconic (Grampian) orogeny in early to mid-Ordovician times (Williams and Hiscott 1987). The westward movement of and loading by Bay of Islands Ophiolite Complex generated a peripheral bulge disconformity beneath the Table Head base of the Goose Tickle foreland basin (Bird & Dewey 1970). This clear sharp, rifted, continental margin destroyed by arc-continent collision is not evident in northwest Scotland in the Moine Thrust Zone. Here, early Llanvirnian cessation of carbonate deposition in the Durine Formation of the Durness Group led Kennedy (1955) to the prescient conclusion that major orogeny began in the Highlands in early Ordovician times. The equivalent of the Goose Tickle foreland basin and ophiolite obduction is absent or, at least, has not been preserved in the Scottish Highlands. We speculate that Grampian ophiolite obduction and the consequent foreland basin did not develop in Scotland because of the very wide Proterozoic rift

complexes that confined Grampian ophiolite obduction to a very narrow zone along the Clew Bay/Fair Head/Highland Boundary Fault Zone (e.g. Tanner 2007). Major ophiolite obduction across the Highlands, as envisaged by Dewey and Shackleton (1984) is difficult to demonstrate and an arc-continent bulldozing mechanism might be sought for the Grampian Orogeny in Scotland and Ireland.

The final displacement along the Moine Thrust Zone (Elliot and Johnson 1980) is of Silurian (c. 430 Ma) age as demonstrated by the precise U-Pb zircon dating of broadly syntectonic igneous suites in the Assynt area (Goodenough *et al.* 2011) and their structural relationships (Searle *et al.* 2010). Whether there are sets of structures that relate to earlier displacements (e.g. Grampian, and/or Mayoian, see below) will be uncertain until the precise extent and margins of Knoydartian, Grampian, and Scandian structures in the Moine is known and further radiometric dating of fabrics along the Moine, Glencoul, Benmore, and other thrusts, are undertaken. However, as Kennedy (1955) pointed out, the youngest strata to have been involved in the Moine Thrust Zone are the early Ordovician (Llanvirn) Durine Member of the Durness Limestone, which strongly suggests that the Grampian Orogeny terminated deposition on the shelf. The oxidized Torridonian and anchi-metamorphic Cambro-Ordovician sequence indicates very low temperatures below the Moine Thrust (e.g. Johnson *et al.* 1985) and suggest that the Moine Nappe was thin west of the Sole Thrust and, therefore, with little more than 77 km displacement (calculated from the Assynt Sheet, British Geological Survey 2007). Nevertheless, loading by the Moine Nappe would surely have generated foreland basins unless the *Lithosphere* were thinned and weakened for which there is no obvious evidence such as major magmatic outbreaks. The powerful basement thrusting and imbrication in the Assynt Culmination does not indicate, we suggest, a weak crust and thinner *Lithosphere* but the thrust detachment of the tops of post Torridonian/pre-Eriboll normal fault blocks (Soper and England 1995). The Lewisian basement had been last affected by the late-Laxfordian event at c. 1650 Ma (Friend & Kinny 2001) and, therefore, would have had substantial flexural strength. Hence, any foreland basin would have been small amplitude/long wavelength and easily removed (eg. Larson *et al.* 1999). The Cambro-Ordovician shelf sequence shows no sign of sudden thinning and/or facies change eastwards; its eastern limit is unknown. It did not cover the Dalradian because the coeval early Ordovician McDuff Slates and the middle Cambrian Leny Limestone are in deeper water facies.

Therefore, although the basic plate tectonic model for the Cambro-Ordovician evolution of the Caledonides and Northern Appalachians is that of an oceanic island arc complex colliding with the Laurentian margin (Nelson & Casey 1979), there are substantial differences. In the Appalachians, the arc collided with a very sharp rifted margin with the obduction of fore-arc ophiolites across narrow poorly-developed rift complexes onto the Laurentian foreland and loading of the margin to develop foreland basins (Dewey & Casey 2013). In the Scottish and Irish Caledonides, the arc collided with a much wider, more diffuse, and longer-lived rifted margin with less or no ophiolite obduction, and bull-dozing by the arc, perhaps similar to Taiwan.

The Dalradian, Grampian, Highland Boundary Fault, and Midland Valley

The Dalradian Supergroup lies in a block bounded by the Great Glen and Highland Boundary Faults (Fig.2), and moved by at least 500 km into its position relative to the Moine between 428 and 385 Ma at a minimum average rate of about 11.6 mm/a (Dewey & Strachan 2003). That the Dalradian “belongs” to the Laurentian margin of Iapetus is shown by its North American fauna (Fletcher and Rushton 2007; Stubblefield 1956), its broad stratigraphic similarity with late Neoproterozoic sequences in East Greenland and Newfoundland and its Laurentian sources as seen in detrital zircon populations (Cawood *et al.* 2003).

The stratigraphy of the Dalradian is very well-defined (Anderton 1982; Harris *et al.* 1994; Strachan *et al.* 2002; Stephenson & Gould 1995) with the Port Askaig Tillite sequence (Marinoan glaciation, c. 635 Ma) a key time-rock marker (e.g. Brasier & Shields 2000). The Dalradian is mostly shallow marine and deposited in extensional basins but the highest, South Highland Group strata are mostly deep-water greywackes and pelites, a large part of which must be Cambrian-lower Ordovician (Molyneux 1998; Tanner 2011). This latter sequence begins with the Tayvallich Formation mafic volcanics at c. 600 Ma (Halliday *et al.* 1989) roughly equivalent to the Lighthouse Cove Basalts of Newfoundland (Williams & Hiscott 1987), a sequence representing accelerated *Lithospheric* thinning heralding the opening of Iapetus between

Laurentia and the Andean margin of South America. The bulk of the deformation and metamorphism of the Dalradian Supergroup is early to mid-Ordovician (Grampian; Dewey & Mange 1999).

The structure, although well-documented (Thomas 1979; Treagus 1987), is less understood. The dominant structure is the southeast-facing, and probably southeast-verging, Tay Nappe with its downward –facing nose along the Highland Border (Shackleton 1958; Krabbendam *et al.* 1997; Tanner 2013), and the Loch Awe Syncline to the northwest. In Connemara, major D2/D3 fold nappes face northwards consistent with models that involve collision of an oceanic arc with and overthrusting onto the Laurentian margin (Dewey 2005). However to the north of Clew Bay, the nappes of North Mayo face to the southeast (Chew 2003). The Tay Nappe is enigmatic in that it faces to the southeast. Four possible reasons are: 1. That the nappe was gravitationally-driven by spreading and/or sliding from a Loch Awe *zwischengebirge* high, 2. That the Tay Nappe is a retrocharriage backfold of the top limb of a north-verging D1 nappe, 3. That the Midland Valley Terrane underthrust the Grampian Highlands directly beneath and caused the Tay Nappe, 4. That the Tay Nappe was a large south-verging fold above a north-dipping subduction zone, or 5. That the Midland Valley Terrane formed a wedge that separated the Dalradian from its basement, thus, simultaneously, generating the Tay Nappe and a basement to the Midland Valley. This wedge model is similar to the crustal delamination model Waschbusch *et al.* (1998) for the South Island of New Zealand; a Tasman wedge is driving eastwards along the Moho of the South Island separating the crust, which passes through a monocline to form the Southern Alps, and the mantle, which is subducting beneath the Tasman Sea.

Two key points emerge; first, that simple plate tectonic cross-sectional solutions cannot be applied along the length of the Caledonian/Appalachian Belt or any mountain range and, second, that the existence of a basement or presumed basement must not be taken to mean that the basement was, necessarily, the foundation for the development of rock systems above. However, it is possible that the Midland Valley has an “autochthonous” basement; if so, the Midland Valley may have been a micro-continent with a small ocean between it and the Dalradian margin that closed along the Highland Boundary Fault Zone; a problem with this interpretation is that there is no evidence of subduction-related magmatism in the Midland Valley or in the Highlands

prior to the mid-Silurian. Clearly, oceanic *Lithosphere* must have existed along the Highland Boundary Fault Zone because the Zone contains Ordovician ophiolites (Bute, Shetland), which have a fore-arc affinity. Sheared serpentinitized lherzolites with sheeted carbonates and gabbro slices probably represent sub-continental mantle beneath an extensional detachment along the original margin of Iapetus. These sub-continental mantle rocks are known also in western Ireland along the Clew Bay suture zone (Chew 2001; Kennedy 1980) and in the Baie Verte Suture Zone in Newfoundland (Bursnall 1973; Van Staal *et al.* 2013) where they mark the Laurentian margin of Iapetus against which an oceanic arc collided during the early Ordovician (Nelson & Casey 1979). These lherzolitic associations are common in the Swiss Alps (Malenco/Platta Nappe) and in the Sestri-Voltaggio zone of the Ligurides of Italy where they represent sub-continental mantle tectonically denuded at a magma-poor rifted margin during Jurassic extension to generate para-oceans (Manatschal & Muntener 2009). How then to evaluate the tectonic role of the Highland Boundary Fault? The presence of rifted (early Cambrian) margin sub-continental mantle rocks (Henderson *et al.* 2009) and earliest Ordovician fore-arc ophiolites indicates that an arc collided with a rifted margin. By analogy with western Ireland and Newfoundland, the arc faced and collided with the Laurentian margin during the early Ordovician (Dewey 2005) but, unlike Newfoundland, its fore-arc ophiolites did not obduct very far, if at all, onto the rifted margin. Rather, we suggest, the arc bulldozed the Laurentian margin to cause the Grampian Orogeny, a very short-lived event followed by subduction polarity flip to initiate a trench on the south side of the South Connemara/Southern Uplands accretionary prism (Ryan & Dewey 2004). Although the Midland Valley and the South Mayo Trough appear to be parts of the same terrane (Fig. 2), there are clear and significant differences. The South Mayo Trough was the fore-arc of an oceanic island arc until about 477 Ma in the early Arenig when the arc magmas became contaminated by the subduction of Laurentian margin sediments to generate a silicic arc immediately prior to collision (Draut & Clift 2001). The obduction of the hot arc onto the Laurentian margin is believed to have generated the north-verging nappes and account for the Barrovian metamorphism of the Dalradian rocks of Connemara. In contrast, the Midland Valley may have, in part, a Pre-Cambrian basement (Aftalion *et al.* 1984; Upton, *et al.* 1976) and there is no clear evidence for an Ordovician arc. However, Badenszki *et al.* (2011) have shown, from Carboniferous diatreme xenoliths, that zircons may have been derived from an Ordovician/Silurian arc. The tectonic provenance and significance of the Midland Valley

Terrane is obscure; it may be an Ordovician arc with continental basement fragments or it may be, partially, the equivalent of the Ox Mountains Terrane in Ireland. The Ballantrae Ophiolite Complex is on the southern margin of the Midland Valley and, although it has a subduction metamorphic sole, subjacent rocks are not seen (e.g. Stone 2014a). The Midland Valley Silurian shallow marine to fluviatile sediments can be interpreted as a fore-arc basin north of the Southern Uplands accretionary prism. In the South Mayo Trough, the Silurian fore-arc basin contains andesitic detritus and a diorite sill, establishing its arc credentials above a north-dipping subduction zone (Dewey 2005).

In Banffshire, the greenschist/epidote amphibolite Upper Dalradian succession sits in a broad synclinorium, bounded to the west by a major extensional detachment zone (top down to the east) from Portsoy in the north to at least the southwest margin of the Morven-Cabrach Gabbro (Viète *et al.* 2010). The low-grade hanging wall contains the classic mafic/ultramafic intrusions of Inch, Haddo House, and Huntly, above the subjacent higher-grade footwall to the west. The mafic/ultramafic intrusions are tholeiitic, in contrast to the calc-alkaline mafic/ultramafic intrusions of Connemara but both were intruded during the Grampian deformation sequence. To the southeast of the Banff Syncline all major structures, including the Tay Nappe and the Banff hanging wall of the Portsoy Detachment, verge to the southeast. We do not understand the origin of this dominant southeast vergence beyond that it involves a massive southeastward translation of the upper part of the Grampian structural pile (Krabbendam *et al.* 1997; Tanner 2013).

In Connemara, a strong case can be made for relating the Barrovian metamorphism to the northward obduction of a hot oceanic arc across the Laurentian margin with the injection of calc-alkaline mafic/ultramafic magmas from the arc into the evolving, north-verging D2/D3 nappes (Wellings 1998). It is difficult to ascribe the Barrovian metamorphism of Scotland to such a mechanism because the major folds face to the south-east, across the classic Barrovian zones.

The Highland Boundary Fault Zone drops Devonian strata against the Highland Border downward-facing down-bend. Its straightness has led to the notion that it must be a large-displacement strike-slip fault. However, Tanner (2011) has adduced cogent evidence that

sinistral post-Silurian strike-slip cannot be large (tens of kilometres) and must be Ordovician perhaps of the same age as the sinistral motion that emplaced the Connemara Terrane to the South of the South Mayo Trough.

Mayoian.

The Mayoian phase of shortening somewhere between 460 Ma and 443 Ma is an enigmatic feature of the Scottish and Irish Caledonides (Fig.3) and the western Appalachians of Newfoundland (the Salinic). Steve Temperly has, on many informal occasions and discussions at meetings, drawn attention to this orogenic phase and its regional importance. We call it Mayoian from its clear and strong expression in the South Mayo Trough, where Llandoveryian strata rest unconformably upon early Ordovician rocks on the northern and southern sides of the Trough, cutting out several thousands of metres of Ordovician strata that are preserved within the Trough (Dewey 1963). The pre-Late Llandovery detachment and docking of the Connemara Dalradian Terrane may be Mayoian (Dewey 2005). The Mayoian is also expressed by shortening structures in the Moine (Bird *et al.* 2013) and Dalradian (Chew & Strachan 2013). The Highland Border downbend (Shackleton, 1958) may be Mayoian. We do not understand the origin of this shortening but speculate that it may have been the result of subduction slab flattening, like the current Pampean Ranges of Argentina and the Laramide Orogeny in the western United States. The Mayoian affects both Moine and Dalradian Terranes; it is arc-related because the Moine and Dalradian were not juxtaposed until after the Scandian collision.

Southern Uplands

The Ordovician and Silurian rocks of the Southern Uplands (Fig.6) constitute one of the World's finest examples of an extinct subduction-accretion wedge (Dewey 1971; Leggett *et al.* 1979; Stone 1995; 2014b). The Midland Valley Terrane, to the north, is a fragment of, possibly, Neo-Proterozoic *Lithosphere* and/or Ordovician arc that was overthrust northwards by the Ballantrae Ophiolite Complex in the early Llanvirn. The Ballantrae Complex was covered by a shallow marine Caradoc sequence, which shows that it could not have been the source of the Portpatrick blue-schist detritus (Kelling 1961). Ordovician rocks between the Southern Upland Fault and the

Glen App Fault represent the zone of subduction polarity flip, to northward subduction from South Connemara to Scotland that was the harbinger of the South Connemara, Southern Uplands and Longford-Down accretionary prism (Ryan & Dewey 2004). That the Southern Uplands are an accretionary prism is demonstrated by the southward-younging diachroneity of both the onset and cessation of turbidite (trench facies) sedimentation (Fig. 6 and Stone 2014b). Between the Glen App Fault and the Carghidown sequence, the turbidite facies succeeds the Moffat Shale (oceanic facies). From the Carghidown sequence to the Iapetus Suture, the turbidite facies has no exposed Moffat Shale substrate. We take this to mean that, at the Kirkmaiden sequence, (M. crispus zone), the subduction interface switched from the shale/basalt contact to the base of the greywackes, possibly induced by the thinned northern edge of the Lake District Terrane beginning to underthrust the Southern Uplands accretionary prism. Tight collision between the Southern Upland accretionary prism and the Lake District was in M. lundgreni times (c. 424 Ma) when the first debris of Southern Upland origin arrived in the Lake District (Soper & Woodcock 2003). The gentle northward dip of the base of the accretionary prism above the subducted northern margin of the Lake district can be seen on the WINCH seismic reflection profile (Hall *et al.* 1984).

Subduction-accretion began in N. gracilis times at about 456 Ma and progressed southwards until M. lundgreni times at about 424 Ma (Fig. 6) when the Southern Uplands collided with the Lake District to cause the Erian phase of deformation. Southward progression of subduction-accretion of about 5.14 mm/a is expressed perfectly with the onset and cessation of turbidite deposition in greywacke packages of about 1.2 my (roughly the same length as a graptolite zone) above oceanic dark shales, (Fig. 6).

The extent of end-Silurian Erian deformation in relation to southward-younging subduction-accretion deformation in the Southern Uplands is not yet clear (Stone *et al.* 1997). In the Ordovician-Silurian South Mayo Trough in western Ireland, Erian sinistral transpression (Soper *et al.* 1992) is recorded in a very complex sequence of anchimetamorphic to greenschist –facies structures, and was the result of very oblique (less than 20°) closure of the Iapetus suture close to the Silurian/Devonian boundary. The regional clockwise-oblique cleavage of the Southern Uplands (Stringer and Treagus 1980) suggests, at least partly, Erian sinistral transpression.

Detrital heavy minerals in the Southern Uplands (Kelling 1961; Mange *et al.* 2005) record the Caradoc to Wenlock (c. 458 – 423 Ma) erosion of an obducted ophiolite complex and the Dalradian metamorphic complex. That the Southern Uplands are a subduction-accretion prism and not a collisional foreland basin is indicated by the black shales of zones 2 to 8 (e.g. Moffat Shale) and their subjacent mafic volcanics in the Leadhills Group (Fig. 6; Stone 2014b). A difficult problem has been the source of sediments of the Southern Uplands. Kelling (1961) was the first to characterize the detrital heavy mineral assemblages across the Rhinns of Galloway. Mange *et al.* (2005) conducted a comprehensive survey of heavy minerals assemblages across the Southern Uplands; Grampian metamorphic and Laurentian detritus is dominant throughout with ophiolitic, glaucophane and lawsonite detritus in the Portpatrick Formation. Clearly, the Grampian metamorphic complex, the Laurentian basement, and an obducted ophiolite complex were sourcing the subduction-accretion prism but the source of the higher pressure blueschist minerals is not clear. The low-grade assemblage of the Ballantrae Ophiolite Complex is an unlikely source for the lawsonite. Alternatively, lawsonite is recorded in the Cadomian blueschist complex of Anglesey. Stone and Evans (2001) have recorded Cadomian-age zircons in the Southern Uplands but Waldron *et al.* (2008; 2014) have shown that the zircons were sourced, probably, from igneous sources associated with rifting of the Laurentian margin, not from Avalonia.

Newer granites

The Siluro-Devonian granite suite (the Newer Granites, Fig. 7) is the last major “cratonizing” event in Scotland. Late Pre-Cambrian/early Cambrian granites such as the Ben Vurich and the alkaline Inchbae-Carn Chuinneag bodies are probably related to continental stretching immediately before the opening of Iapetus and will not be considered here. Caledonian plutonic activity in Britain and Ireland occurred during two main episodes, the 470-460 Ma Grampian Orogenic event and the 447-383 Ma granitoids that were emplaced during and after the final closure of the Iapetus Ocean. Read (1961) named these two intrusive suites the “Older Granites” and “Newer” Granites. The Newer Granites of the British and Irish Caledonides (Fig. 7) have the appearance of a bottle of red ink splashed across the map; they intrude almost all zones of the

orthotectonic and paratectonic Caledonides (Dewey 1969) with a wide variety of I- and S- types (Chappell & White 1974; 2001). A quick reminder: I-type granites have a meta-igneous source, are generally higher-temperature, higher-Na₂O, oxidized (magnetite-bearing; Ishihara 1977)), and hornblende-bearing, commonly with mafic enclaves and co-mingling relationships, whereas S-types are partial melts of meta-sediments, reduced (ilmenite-bearing; Ishihara 1977)), higher-K₂O and alumina, and garnet and/or cordierite-bearing, commonly with meta-sediment enclaves.

The Newer Granites have been studied intensively over many decades and much classic and pioneering work has been done, such as on the Donegal batholith (Pitcher & Berger 1972; Hutton 1982; Stevenson 2008; Stevenson *et al.* 2008). Despite this, there remain many unresolved issues. Some are typical of granites irrespective of age or setting such as the perennial protolith debate about crustal and mantle sources and the relative proportions and significance of contribution from different reservoirs (Chappell 1996); this debate feeds into the origin and development of the continental crust, whether by recycling of existing crust by partial melting or by addition of new crustal material with a significant mantle component. This (Chappell & White 1974; 2001) is largely a geochemical and isotopic discussion, ubiquitous to granites worldwide, and the reader is referred to Stephens and Halliday (1984), Atherton and Ghani (2002), Fowler *et al.* (2001, 2008), and Neilson *et al.* (2009).

The fundamental problem of Caledonian granites is that they were generated and emplaced over a long time, and emplaced into extremely heterolithic crust across an orogen that was involved in multiple amalgamation and accretion events during the complex collisions of Baltica, Laurentia and Avalonia as the Iapetus Ocean closed, and in subsequent post-closure tectonics. No single tectonic model for magma genesis explains the genesis and evolution of the Newer Granites. However, using an array of relevant multidisciplinary techniques, major advances have been made recently. The plutons were emplaced over 67 My (447 Ma to 380 Ma) during the Scandian Orogeny, the docking of Laurentia and Avalonia, late Caledonian sinistral transcurrent lock-up (Hutton and Reavy 1992) and the Acadian Orogeny (Woodcock *et al.* 2007). They are present in all terranes north of the Iapetus. We first outline the petrological aspects of the intrusions and suites in different terranes, assess gross similarities, and highlight major unresolved problems.

The vast majority of the Newer Granites in Scotland and NW-Ireland are I-type (*sensu lato*), taken, here, to indicate crustal melting with a possible, small, mantle contribution. This differs from the original definition (Chappell & White 1974), which underplayed or ignored mantle involvement. Such intrusions typically show a broad range of lithologies from diorite/quartz diorite through granodiorite to granite. They are, commonly, composite with internal contacts (Cruden *et al.* 1999); if these contacts are absent, they are normally-zoned, generally more primitive/mafic at the margins or, less commonly, reversely-zoned. Coeval mafic enclaves are very common especially in the diorite/granodioritic components. Associated appinite suites range in composition from ultramafic to intermediate, have euhedral hornblende, are commonly very coarse grained/pegmatitic. and commonly occur in diatremic pipe-like forms. They are taken, generally, to represent evidence of an enriched mantle origin and are intimately linked to granitoid genesis. Some workers have argued that these magmas are involved in crustal underplating and/or crustal melting (Stephens & Halliday 1984) or argued that fractionation of such compositions was a significant process in granite generation (Fowler *et al.* 2008). In the Grampian Terrane, intrusions such as Ballachulish, Etive, Rannoch Moor, Strath Ossian, Foyers and Ross of Mull, Strontian, Cluanie, Rogart, Helmsdale and Strath Halladale in the eastern Northern Highlands are I-type.

There are significant regional departures, such as the trend to more syenitic and alkaline compositions towards the north-west in the North-west Highlands (Fowler *et al.* 2008; Goodenough *et al.* 2011). Ratagain is transitional between the normal I-types and the more alkaline types. Glen Dessarry is syenitic and the complexes in the far NW are extremely alkaline; Loch Ailsh and Loch Loyal are quartz-bearing syenites whereas Loch Borralan is the only nepheline syenite in the UK (Parsons 1979).

In southern Scotland, several intrusions in the Southern Uplands (Cairnsmore of Fleet and Criffell) are S-type and several of the plutons in Aberdeenshire (Cairngorm and Peterhead) are more A-type in character. The suite concept (White & Chappell 1983; Chappell 1996), based on their petrography and composition, may reflect the involvement of different protoliths.

Stephens & Halliday (1984) first distinguished the Argyll, South of Scotland and Cairngorm Suites (Fig. 7) south of the Great Glen; the first two suites are, dominantly, I-type. Hornblende is

characteristic of diorites in the Argyll Suite, and associated appinites are abundant. Geochemically, this suite is typified by very high abundances of Sr and Ba and low abundances of Nb, Th and Rb. This Sr and Ba enrichment was attributed to enriched mantle fluids that initiated lower crustal melting to generate I-type magmas, although Fowler *et al.* (2008) proposed that similar characteristics in intrusions NW of the Great Glen could be the result of small volume-assimilation products of mantle-derived appinitic magmas. The South of Scotland suite (Stephens & Halliday 1984) includes Garabal Hill, Comrie and Arrochar in the southern Highlands, Glen Tilt and Glen Doll in the north-east Highlands and other bodies in the Midland Valley and Southern Uplands. Although generally I-type, this suite has pyroxene-rich diorites and low Ba and Sr contents. Cairnsmore of Fleet and Criffell have S-type characteristics. The Cairngorm suite consists of red-biotite granites some of which have A-type affinities; in contrast to the other suites, they have high trace element abundances of Nb, Rb and Th and low abundances of Ba and Sr. In Ireland, the Donegal granites, which were emplaced into the along-strike equivalent of the Grampian Terrane, are also broadly I-type with abundant appinites; therefore, it is possible that they could be assigned to the Argyll suite. However, the Newry Complex, which lies within the Longford-Down Massif, is I-type but is along strike from S-type plutons in the Southern Uplands.

Stone *et al.* (1997) noted a distinction based on geochemical and isotopic characteristics between granites north and south of the Moniaive Shear Zone, and the associated Orlock Bridge Fault, suggesting that this reflects a compositional break in the crust at this structure. North of the Orlock Bridge Fault, intrusions are older (c. 410 Ma) whereas intrusions to the south are, typically, younger (c. 395 Ma). They highlighted the Pb isotope similarities between granitoids of the Lake District and those south of the Orlock Bridge Fault, previously noted by Harmon & Halliday (1980) and Thirlwall *et al.* (1989), expanding their synthesis into an Avalonian terrane. I-type granites to the north and S-types to the south of the Orlock Bridge Fault with chronological and geochemical differences suggest different petrogenetic mechanisms for each group (see Atherton & Ghani 2002; Brown *et al.* 2008; Neilson *et al.* 2009; Stone *et al.* 1997).

From this distinction, and following Brown *et al.* (2008), we define the Northern Granites, which are those granites believed to be of Caledonian origin north of the Orlock Bridge Fault (this grouping includes the three suites already recognized by Stephens & Halliday (1984)) and the

897 Trans-Suture Suite which includes those granitoids that are late Caledonian and sited south of the
 898 Orlock Bridge Fault. However some Irish Granites, for reasons discussed below, do not fit easily
 899 into either of these categories and they are grouped here as Unassigned Irish Granites.

900 Within the Northern Granites, consideration must be given to the tectonic history of the
 901 individual terrane. In the broadest terms, any granitoids that occur within the Northern Highlands
 902 Terrane, and are between 467-425 Ma, are likely to be related to northward subduction and
 903 Scandian collision between Laurentia and Baltica. All Newer Caledonian granites south of the
 904 Great Glen Fault and north of the Orlock Bridge Fault are likely to be associated with the
 905 accretionary processes involving Laurentia and Avalonia. Early models proposed that continued
 906 subduction of the Iapetus Ocean crust beneath the Laurentian margin drove calc-alkaline
 907 magmatism north of the Orlock Bridge Fault (Soper 1986). A suite of appinite and lamprophyre
 908 dykes was synchronous with these granites (Rogers & Dunning 1991; Atherton & Ghani 2002;
 909 Fowler *et al.* 2001; Macdonald & Fettes 2007; Pitcher & Berger 1972). From the association of
 910 these minor intrusions with I-type granites, several authors suggested that magmatism was
 911 caused by crustal melting initiated by hydrous mantle-derived magmas, driven by active
 912 subduction of the Iapetus Ocean under the Laurentian Margin (Dewey 1971; Soper 1986;
 913 Thirlwall 1988). Oliver *et al.* (2008) envisaged continental margin subduction analogous to the
 914 Andean margin (Pitcher *et al.* 1982).

915 However, much of this magmatism cannot be related to active subduction because most granites
 916 were emplaced well after subduction had ceased and collision had occurred (Pitcher 1982;
 917 Neilson *et al.* 2009). Pitcher (1982) termed them “Caledonian I-types” to distinguish the Argyll
 918 and Donegal granites from the Andean I-types.

919 Atherton & Ghani (2002) proposed that collisional/post-collisional slab break-off could have
 920 would have allowed the asthenosphere, at about 1,330°C, to rise, impinge on, and melt the base
 921 of the *Lithospheric* mantle to produce a lamprophyric under-plate with associated dykes and
 922 appinite intrusion; high temperatures at the base of the *Lithosphere* may have melted this
 923 underplate to produce the granites. This predicts a short peak in magmatism that would have
 924 significantly postdated active subduction. This model is somewhat confusing because their
 925 diagrams clearly relate to the Scandian convergence whereas many of the granites are in the

926 Grampian Terrane and Donegal, which were then hundreds of kilometres south of the region that
 927 experienced Scandian collision.

928 In the Northern Highlands, a problem is the petrogenesis of alkaline magmas within what was
 929 first a subduction and then a collisional setting. Goodenough *et al.* (2011) have dated the
 930 duration of the Scandian event; much of the magmatism is later than active subduction. The Glen
 931 Dessarry Pluton (447 ± 2.9 Ma) pre-dates the formation of the early Scandian steep belt, and,
 932 therefore, sets a lower limit to Scandian deformation. The late suite of the Loch Borralan Pluton
 933 (429.2 ± 0.5 Ma) is roughly synchronous with (Searle *et al.* 2010) to just after Moine thrusting
 934 (Goodenough *et al.* 2011) Scandian thrusting. Scandian shortening had, therefore, ceased by c.
 935 430 Ma; the pulse of appinites and granites at 425 Ma (Fowler *et al.* 2008) could be explained by
 936 post-Scandian slab break off; at this time, orogen-parallel strike-slip motion began (Dewey &
 937 Strachan 2003).

938 In the Grampian Terrane, there is no evidence of subduction-related magmatism; the terrane
 939 would have been several hundred kilometres north of the active trench. Neilson *et al.* (2009)
 940 argued that the subduction of Avalonia beneath Laurentia would have been resisted by c. 430 Ma
 941 and the supply of hydrated oceanic *Lithosphere* within a subduction system would have ceased.
 942 New dating of granitoids, dykes and volcanics in south-west Argyllshire show that magmatism
 943 continued for at least 25 Ma after subduction had ceased and was not defined by a single short
 944 pulse as predicted by Atherton & Ghani (2002). Neilson *et al.* (2009) envisage slab break-off and
 945 the rise of hot asthenosphere to the base of the *Lithosphere* to melt and form appinitic and
 946 lamprophyric magmas. Because of the large volume of intermediate and felsic magmas
 947 generated, Neilson *et al.* (2009) favour continual underplating and melting of mafic crust
 948 representing substantial crustal recycling. They propose that this asthenospheric heat was
 949 sufficient to drive magmatism for the subsequent c. 22 My.

950 In Ireland, no granites are attributed to Scandian orogenic processes. The age, tectonic setting
 951 and geochemistry of the Donegal Granites (Stevenson *et al.* 2008) are consistent with the slab
 952 break-off model of Atherton & Ghani (2002) and Neilson *et al.* (2009). They are therefore
 953 assigned to the Northern Granites.

954 The Trans-Suture Suite of (Brown *et al.* 2008) includes all granitoids south of the Orlock Bridge
 955 Fault. The Trans-Suture Suite is S-type; most plutons contain two mica granites; ages range
 956 between c. 400-390 Ma. It includes the classic S-type Leinster Granite and the Isle of Man
 957 granites. The Leinster Granite, the largest granitoid in the British Isles, clearly lies south of the
 958 Orlock Bridge Fault. Because it is S-type and dated at 405 $\pm$ 2 Ma (O'Connor *et al.* 1989), it is
 959 assigned to the Trans-Suture suite. Detailed petrographic work has shown multiple mixing events
 960 of batches of felsic compositions (Grogan & Reavy 2002).

961 The Newry Igneous Complex (Fig.7), however, exhibits strong I-type affinities and ages of c.
 962 420-410 Ma (Meighan *et al.* 2003). Although it lies south of the Orlock Bridge Fault, its age and
 963 characteristics are more consistent with the Northern granitoids; it is therefore anomalous in the
 964 context of the model proposed by Brown *et al.* (2008) and is grouped with other Unassigned
 965 Granites.

966 Whereas all these trans-suture intrusions (excluding Newry) share some S-type affinities, Brown
 967 *et al.* (2008) suggest that they are not S-type *sensu stricto* but that they tend towards this end
 968 member compared with granites further north. In many cases, they are zoned with S-type
 969 interiors and I-type outer margins and contain mafic enclaves throughout (e.g, the Criffell pluton
 970 (Stephens 1992; Stephens & Halliday 1984)). The Trans-Suture Suite was emplaced on both
 971 sides of the Iapetus Suture, was coincident with Acadian orogenic deformation in Britain and
 972 Ireland, and post-dates an episode of transtension that followed the Caledonian Orogeny between
 973 410-400 Ma (Dewey & Strachan 2003). These granitoids are closely associated with a
 974 prominent porphyritic lamprophyre dyke swarm that extends from the Central Belt of the
 975 Southern Uplands into eastern Ireland (Rock *et al.* 1986; Vaughan 1996).

976 Several models have been proposed for the Trans-Suture Suite; the key points include the clearly
 977 younger age of these intrusions (c. 20-30 My after final Laurentian-Avalonian convergence),
 978 their occurrence north and south of the Iapetus Suture, and their S-type chemistry, which reduces
 979 the feasibility of models applicable to the Northern Suite (see Brown 1991; Soper 1986; Atherton
 980 & Ghani 2002). Magmatism driven by subduction of Iapetan and Avalonian *Lithosphere* or slab
 981 break-off are not feasible because of the occurrence of granitoids south of the Iapetan Suture

Zone. Orogenic crustal thickening, and/or decompression leading to melt generation are also highly unlikely because magmatism continued for up to 40 My after these processes terminated.

Brown *et al.* (2008) proposed that the extensive suite of lamprophyre dykes, generated during the 410-400 Ma period of transtension, advected heat through the *Lithosphere* thus driving melting of the crust. The granitoids were of hybrid origin with overall S-type affinity but also containing relatively primitive mafic components (e.g. Criffell). Mafic magmas charged with volatiles, derived from partial melting of metasomatized sub-continental *Lithospheric* mantle, were emplaced during Devonian transtension (Dewey & Strachan 2003) and decompression, promoting anatexis and upward propagation of melt. Brown *et al.* (2008) concluded that continued migration of lamprophyric melt through the crust was responsible for crustal melt generation during 410-400 Ma transtension and that emplacement of this magma in the mid to shallow crust was achieved later during the Acadian Orogeny. A problem with this model is that no magmatism was recorded in the Trans-Suture Suite during the period of transtension, which was suggested as being responsible for magma genesis. One might expect a continuation of plutonic activity throughout and shortly after the controlling tectonic event. Furthermore, the model does not consider the role of the Rheic oceanic crust, which was being subducted beneath the accreted Avalonian-Laurentian continent during genesis and emplacement of these granitoids (McCarthy 2013). Acadian deformation is recognised as early as 400 Ma (Sherlock *et al.* 2003; Woodcock *et al.* 2007); presumably subduction of Rheic Ocean *Lithosphere* was active at this time and earlier.

Several Irish granites belong neither to the Northern Granites or the Trans-Suture Suite. The Newry Granite problems have already been highlighted. The Siluro-Devonian Galway Granites are north of the OBF; the largest intrusion, the Main Batholith, straddles the Skird Rocks Fault (SRF) (either an extension of the Southern Uplands Fault (Feely *et al.* 2006; Leake 2006) or a southern splay of the Highland Boundary Fault (Ryan *et al.* 1995). The Galway Granites mostly meet the criteria for belonging to the Northern Granites. They are all I-type (Feely *et al.* 2006), located north of the OBF, and most were emplaced between 425-405 Ma (Selby *et al.* 2004; Feely *et al.* 2007). They are, geochemically, similar to the Argyll Suite (Crowley 1997). The largest volumes of magma in Galway were emplaced between 402-397 Ma, the latest (Costelloe-

Murvey) is 380.1 ± 5.5 Ma (Feely *et al.* 2007; 2010). Therefore, the younger intrusions are temporally related to the Trans-Suture Suite but are tectonically out of place north of the OBF. The older intrusions (425-405 Ma) are consistent with models proposed for the Northern Granites but share a spatial and geochemical association with the younger intrusions and are unlikely to be petrogenetically distinct.

The most perplexing issue of the Galway granites is the broad spectrum of crystallisation ages in the batholith and surrounding plutons. The earliest date is in the Omev Pluton, which has a secondary molybenite age of 422.5 ± 1.7 Ma (Feely *et al.* 2007), implying that the granite predates this. The youngest crystallisation age is in a sample collected from the Main Batholith and yields a U-Pb zircon age of 383.3 ± 1.1 Ma (data reviewed in Feely *et al.* (2010)). Therefore, magmatism extended for a minimum of c. 40 My, was initiated prior to regional sinistral strike-slip, continued through regional sinistral transcurrent movements and Acadian orogenesis and persisted, then for a further c. 7 My. This broad spectrum of ages does not fit any existing model for regional-scale petrogenesis. It is difficult to envisage how slab break-off could generate large volumes of melt for over c. 37 My in Connemara and not continue to feed other batholiths across Britain and Ireland after 400-390 Ma. Neither the model of Brown *et al.* (2008), nor that of possible subduction-driven magmatism (Rheic Ocean) proposed by McCarthy (2013), can account for the petrogenesis of the earlier constituents of the Galway Granite because transtension/subduction began at least 12 My after the first pluton became emplaced.

A consensus is now emerging: north of the Great Glen Fault, intrusions that are older than 430 Ma can be attributed to subduction and thickening during the Scandian Orogeny (Dewey 1971; van Breemen & Bluck 1981). For other granitoids north of the Orlock Bridge Fault, a slab break-off model of some type can account for the surge in plutonic activity at c. 420-400 Ma (Atherton & Ghani 2002; Neilson *et al.* 2009). South of the Orlock Bridge Fault, intrusions have a different origin resulting in granitoids with ages ≤ 400 Ma and S-types with I-type components. Whether Devonian transtension was the sole tectonic control or whether subduction and dehydration of the Rheic oceanic crust (McCarthy 2013) had a role in prolonging magmatism is unresolved. The composition of the Newry Complex is anomalous for its location and the petrogenetic story of the Galway batholith is still unclear.

Old Red Sandstone (Devonian) tectonics and sedimentation and the role of the Acadian orogeny

Much debate over the last twenty-five years has centred around the extent and regional tectonic significance of Devonian deformation in Scotland (Norton *et al.* 1997), and how this might relate, if at all, to broadly coeval Acadian events south of the Iapetus Suture (Rogers *et al.* 1989; Dewey & Strachan 2003; Mendum & Noble 2010). Old Red Sandstone (Devonian) continental rocks of the Orcadian basin unconformably overlie deeply-eroded Moine and Dalradian metamorphic complexes around the Moray Firth, and on Orkney and Shetland (Trewin & Thirlwall 2002, and references therein). In many parts of the mainland basin, the Old Red Sandstone rocks are undeformed, apart from local tilting, and there is more or less complete stratigraphic continuity from the Emsian to Fammenian. Local unconformities have been attributed to extensional faulting (Rogers *et al.* 1989) or an increase in extension-related subsidence. In contrast, Lower Old Red Sandstone deposits NW of the Moray Firth in Caithness were folded twice before deposition of unconformably overlying Middle Old Red Sandstone successions (Dewey & Strachan 2003), and there is significant folding of the Middle Old Red Sandstone deposits of western Shetland (Mykura 1991; Seranne 1992).

South of the Highland Boundary Fault, early Devonian strata of the Midland Valley are disposed in pre-late Devonian folds (e.g. Strathmore Syncline). These folds have been attributed to the Acadian orogenic event (Friend *et al.* 2000) that formed the slate belts of England and Wales during the late Emsian (Woodcock *et al.* 2007). Early Devonian strata just to the north and south of the Midland Valley are undeformed; therefore, it might be supposed that deformation of the Midland Valley succession resulted from localised sinistral reactivation of the Highland Boundary and Southern Upland faults during Acadian convergence. The same explanation could be invoked to explain the localized folding of Old Red Sandstone rocks north-west of the Moray Firth and in Shetland, both areas located close to the Great Glen-Walls Boundary fault system, although deformation in Shetland is significantly younger than any documented Acadian events in England and Wales.

An alternative view stems from recognition that folding need not necessarily signify crustal shortening; large-scale folding can occur during transtension (Dewey 2002). Krabbendam and Dewey (1998) demonstrated that widespread folding accompanied transtensional exhumation of coesite eclogites of the Western Gneiss Region in south-west Norway between c. 420 and 390 Ma. Dewey and Strachan (2003) extended the concept across the wider North Atlantic region, proposing that sinistrally-transpressive Scandian collision was followed by a period of sinistral transtension that extended from the late Silurian into Middle Devonian times, creating the Old Red Sandstone basins and deforming their sedimentary fill. Critical to this model is the interpretation that many of the folds that deform the Old Red Sandstone successions in areas such as Shetland, Caithness and East Greenland are essentially syn-depositional (Seranne 1992). This interpretation separates the formation and deformation of the Scottish Old Red Sandstone successions from the broadly coeval Acadian orogeny that led to the formation of the slate belts of Wales and the Lake District (Woodcock *et al.* 2007,). This is reinforced by the realization that a substantial succession of now-eroded Old Red Sandstone rocks must have been deposited over northern England, most likely also in transtensional basins, prior to the Acadian orogeny (Soper & Woodcock 2003). Regional transtension across northern England and southern Scotland was also invoked as a mechanism for generating the Trans-Suture Granites (see however, comments above).

Summary and models

Increasing knowledge of the Scottish Highlands, especially fine-scale geochronology linked convincingly to fabrics and structures, is leading to a deeper understanding of the complexity of their geological history between 1Ga and 400 Ma. Further advances will depend upon new very fine-scale mapping, geochronology, structural analysis, petrology, sedimentology, geochemistry, and high-resolution-heavy-mineral analysis. In developing tectonic models, one is faced with the pixel-size problem, that of linking small-scale complexity with large-scale simplicity (Dewey 1975; Dewey & Casey 2013). The whole of Scotland could fit within a very small portion of a plate boundary complex (Dewey 1982). Also, we are beset with the inversion problem; it is relatively easy to build numerical and kinematic forward models that make precise predictions about tectonic evolution but very difficult to impossible to build convincing tectonic models

from data, however much and in what detailed it is acquired. Also, an orogen can be “over-terrained” (Sengor & Dewey 1990). The terrane concept (Coney *et al.* 1980) has been useful in the “outboard” parts of circum-Pacific accretionary orogens where terranes have been displaced, relative to adjacent terranes by, perhaps, thousands of kilometres but has led to an overzealous search for differences rather than similarities, and cryptic and hallucinosutures and transform boundaries in many orogens that show substantial along-strike continuity of zones. For example, we suggest, for strong geological reasons, that the Great Glen Fault must have at least 500 km of sinistral displacement. Conversely, the Highland Boundary Fault, because of its prominence and linearity, has been suggested to be a major sinistral transform roughly coincident with the principal Grampian major arc-continent suture; Tanner (2011) has argued, cogently, that the geology of the Highland Boundary Fault Zone does not permit this interpretation. Major ‘terraining’ (terrane shuffling) is characteristic of orogens at continental margin, such as the Cordilleran system and collisional orogens where there is substantial strike-slip motion (Van Staal *et al.* 1998). Also, the term “terrane tectonics” is inappropriate (Sengor & Dewey (1990); terraining is a product of processes inherent in plate kinematics, not another kind of tectonic process. Consequently, it is generally unwise to draw palaeo-tectonic sections across orogens because components of those sections may have been hundreds or thousands of kilometers from each other at the time for which the section is drawn.. However, in spite of all these potential pitfalls, we summarize what we perceive to be plausible models for the post-Grenville evolution of the Appalachian/Caledonian Laurentian margin as follows. From about 900 Ma to 600 Ma, slow intra-continental rifting in a multi-basin complex led to the deposition of the Moine assemblage and most of the Dalradian. The edge of the rifted zone in Scotland was probably the Grenville Front, later to become the Moine Thrust Zone. Within the Moine Supergroup, early rifting and magmatism was followed by Knoydartian shortening. The shortening seems to have no clear boundaries, no unconformities, and no molasse. The event may have been diffuse, far-field, intracontinental shortening (Dewey 2005) like the huge Carboniferous Peterman event of the Amadeus Basin in central Australia, the Antler event in Colorado, and the many examples of basin inversion, or it was part of a “Valhalla” continental margin accretionary event (Cawood *et al.* 2010). The latter interpretation, with Scotland and the Rockall Bank located between Baltica and Greenland at 1.0 Ga, is compatible with the interpretation of Loewy *et al.* (2011) that Coats Land, Antarctica, at the head of the Weddell Sea, was a small fragment of southern Laurentia

(present coordinates) and attached to the Kalahari craton of Africa at that time across a Grenvillian suture (Fig.3). This is also compatible with the so-called ‘SAMBA’ connection between the Sveconorwegian province of Baltica and the Sunsas orogen of Amazonia as proposed by Johansson (2014).

From about 600 to 540 Ma, bimodal mafic (e.g. Lighthouse Cove Basalts, Tayvallich Volcanics) and silicic (e.g. Ben Vuirich and Carn Chuinneag granites) magmatism broke out along the Moine/Dalradian rifted belt. This was probably the result of accelerated rift-thinning of the *Lithosphere*, which led, in the latest Precambrian, to continental splitting and the origin of Iapetus and its rifted Laurentian margin from Alabama to northern Greenland. The edge of Iapetus probably coincided, roughly with the Baie Verte-Brompton-Clew Bay-Fair Head-Highland Boundary Fault Line, where two distinct ultramafic associations occur. First, serpentized Iherzolitic mélanges, pillow lavas, gabbro slices and dark grey phyllites (e.g. South Achill, Chew 2001, 2003; Henderson *et al.* 2009) are probably the result of early Cambrian extensional detachments bringing up sub-continental mantle at a magma-poor rifted margin, with small partial melts, onto the sea floor. Second, the ophiolite suites (e.g. Shetland, Bute), are the remains of early Ordovician fore-arcs in the collision zone (Dewey & Casey 2013). In the early Cambrian, subsidence of the NW Foreland shelf led to the establishment of the Eriboll to Durness continental shelf with notable, along-strike, detailed stratigraphical continuity along the length of the Appalachian-Caledonian Orogen.

In the very broadest terms, the Grampian event (Fig. 3) that deformed the Dalradian and the Moine was the result of the short-lived collision of an oceanic arc(s) complex with the rifted Laurentian margin along the Baie Verte-Brompton-Clew Bay-Fair Head-Highland Boundary Fault Line (Van Staal *et al.* 1998). The contrast between the Highlands and Newfoundland is instructive. In Newfoundland, the fore-arc ophiolite was obducted onto the foreland to create a foreland basin upon which the Bay of Islands ophiolite complex is superbly preserved, and the Fleur-de-Lys is but a small remnant of the Moine/Dalradian. In contrast, in the Highlands, the Moine and Dalradian Supergroups occupy a huge volume and area, there is no Grampian foreland basin preserved, and ophiolites are preserved only in the suture zone and in Shetland as an ophiolite complex apparently banked against the Laurentian rifted margin. Perhaps the large

volume of rifted margin sediments prevented the extensive obduction of ophiolites across the Scottish margin and they were bull-dozed rather than deformed beneath an obducted ophiolite. Connemara is the only segment of the British and Irish Caledonides in which a convincing case can be made for the formation of north-verging Dalradian nappes beneath an obducting arc/ophiolite sheet.

The Dalradian contains Laurentian faunas in the Leny Limestone and has Laurentian-derived clastic zircons. Furthermore, the arc that collided with the Laurentian margin contains Laurentian Ordovician faunas. These data prevent the Dalradian and its colliding arc from having an exotic origin; both must have been close to the Laurentian margin. Also, the arc complex had a huge strike length from Shetland at least to New York. It could not have moved through a narrow oceanic gap in the opposing Iapetan margin, as did the Caribbean arc move through a gap between North and South America.

The Scandian Orogeny affected only the Moine, in which it generated the latest phase of massive thrust slip in the Moine Thrust Zone and large-scale penetrative strain. How much of the imbricate and basement-involved thrusting in the Moine Thrust Zone is Scandian and/or Grampian is unclear and is a major problem that will be solved by direct dating of thrust surfaces. The Scandian Orogeny was generated by the mid-Silurian collision of Laurentia with Baltica. The absence of any evidence of the Scandian Orogeny over most of the Dalradian terrain suggests that the Dalradian was not in the jaws of the collisional vise, which, in turn, suggests that late Silurian/Devonian sinistral motion of at least 500 km along the Great Glen moved the Dalradian into its present position with respect to the Moine.

Any single orogenic tectonic model, such as a westward-extruding wedge above the Moine Thrust and below the Banff Extensional Detachment, that purports to provide an explanation for the Grampian and Scandian as a single continuous, diachronous 45 my event, as in the Himalayas, cannot be viable. It is now clear that the short-lived Grampian event affected both the Moine and Dalradian, whereas the Scandian event is confined to the Moine (Fig 5); there was no simple westward-progression of deformation across the Highlands. Also, the Dalradian was not outboard of the Moine until after the Scandian collision. Similarly, orogenic lower crustal flow

models are inappropriate for the Grampian and Scandian Orogenies; the rocks are mostly metasediments with a coherent stratigraphy in greenschist to garnet-amphibolite facies of the middle and upper crust.

We have merely scratched the surface of the myriad of problems that remain about our understanding of Caledonide geology, many of which depend upon a new generation of meticulous field mapping and outcrop observation. As Kevin Burke has remarked on many occasions, “little can be understood in geology without a detailed map”. There are too few people with the skills and knowledge to design integrated research programmes that involve making maps and observations in the field where the truth resides. All modeling is important in giving us ideas and constraining kinematic models but it is facile solely to sit in front of a computer and compose drivel. There are now Professors of Geology who have never made a map, used a petrographic microscope, or studied rocks, minerals or fossils. We have composed this paper in an assertive style, and hope that it will inspire new generations of geologists to discover the joys and fulfillment of mapping and field observation and the analysis and synthesis of regional geology. There is much to be done.

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- 1907
- 1908
- 1909 **Figure captions.**
- 1910
- 1911 1. Highland Controversy time-line; illustrates the relationship between the ‘actors’ in one of
 1912 the greatest controversies in Scottish geology, the recognition of the Moine Thrust. James Nicol

first recognized the dislocation along the Moine Thrust Zone. For twenty years, Nicol was vilified as the lone proponent of a Moine Dislocation” until Callaway and Lapworth showed, by meticulous mapping, that the Moine rocks are thrust upon the foreland, confirmed , a few years later, by Peach and Horne and their colleagues.

2. A Simplified Tectonic Map of Scotland and Ireland north of the Iapetus Suture (simplified from British Geological Survey (1996). B. Restoration to the late Silurian by removing 500 kilometers of sinistral displacement on the Great Glen Fault, the principal evidence for which is the absence of Scandian deformation in the Dalradian. BA-Ballantrae, BU-Bute, CBS-Clew Bay Suture, CIT-Colonsay-Islay Terrane, CT-Connemara Terrane, DP-Deer Park, HBF-Highland Boundary Fault, GGF-Great Glen Fault, IS-Iapetus Suture, LDT-Longford/Down Terrane, LST-Loch Skerrols Thrust, MVT-Midland Valley Terrane, OBF-Orlock Bridge Fault, OMT-Ox Mountains Terrane, PPT-PortPatrick Terrane, SCT-South Connemara Terrane, SH-Shetland, SMT-South Mayo Terrane, SUF-Southern Uplands Fault, SUT-Southern Uplands Terrane, TY-Tyrone. Ornament: oblique fine lines-early Ordovician (Grampian) deformation, horizontal fine lines-mid-Silurian (Scandian) deformation, heavy vertical lines, end- Silurian (Erian) deformation, fine vertical lines-Ordovician/Silurian subduction-accretion deformation.

3. Knoydartian, Grampian, Mayoian, Scandian, Erian, and Acadian events and their associated facies and structures.

4. Simplified geological map of the Moine Supergroup and northwestern Caledonian foreland of the Northern Highlands of Scotland (modified from Strachan *et al.* 2010); inset shows location on a smaller scale. Abbreviations as follows, from north to south: LE, Loch Eriboll; T, Tongue; MT, Moine Thrust; SKT, Skinsdale Thrust; NT, Naver Thrust; ST, Swordly Thrust; LB, Loch Borolan; D, Dura; OB, Oykeall Bridge; CCG, Carn Chuinneag Granite; F, Fannich; IBG, Inchbae Augen Gneiss; CG, Carn Gorm; SC, Scardroy; SBT, Sgurr Beag Thrust; LM, Loch Monar; GU, Glen Urquhart; Dr, Druimnadrochit; Av, Avernish; G, Glenelg; GD, Glen Doe Granitic Gneiss; FAGG, Fort Augustus Granitic Gneiss; K, Kinlochour; LA, Loch Arkaig

1944 Granitic Gneiss; WHGG, West Highland Granitic Gneiss; SB, Sgurr Beag; L, Lochailort; LE,
 1945 Loch Eilt; GF, Glenfinnan; Ar, Ardnish; LEL, Loch Eil; GSM, Glen Scaddle Metagabbro; SD,
 1946 Sgurr Dhomhnuill Augen Gneiss; AGG, Ardgour Granitic Gneiss; AD, Ardnamurchan; LS, Loch
 1947 Sunart; SM, Sound of Mull; RM, Ross of Mull.

1948
 1949

1950 5. Part of the Rodinian supercontinent at 1.0 Ga in present day Laurentian coordinates with
 1951 Baltica positioned as in Cawood *et al.* (2010) and with Kalahari and part of Antarctica as in
 1952 Loewy *et al.* (2011). Major cratons: LAU-Laurentia; BAL - Baltica; AM - Amazonia; K -
 1953 Kalahari. Smaller features (clockwise from top); GRN - Greenland; VO - Valhalla orogen; BI -
 1954 fragments of the British Isles (see inset); SR-southern Rockall Bank; N - Newfoundland (Long
 1955 Range Peninsula); AQ - Arequipa massif; SO Sunsas orogen; AF - Antofalla massif; O -
 1956 Oaxaca terrane; WP - western Pampeanas; CU - Cuyania terrane (greater Argentine Pre-
 1957 Cordillera); NN - Namaqua-Natal orogen; G - Grunehogna terrane (Dronning Maud Land,
 1958 Antarctica); M - Maud orogen (Heimefrontfjella, Antarctica); C - Coats Land, Antarctica. Inset:
 1959 enlargement of area between Greenland and Baltica. NWF - Northwest Foreland (Laurentian);
 1960 NH Northern Highlands (? Grenvillian, see text); GH - Grampian Highlands (? Grenvillian, see
 1961 text); WI - western Ireland (Grenvillian, see text); MV - Midland Valley (? Grenvillian, see
 1962 text). Speckled ornament-Grenvillian (GR) of Laurentia and presumed 1.0 Ga equivalents (see
 1963 text)

1964

1965 6. Stratigraphy of Southern Uplands (from Mange, *et al.* 2005) showing the diachronous
 1966 southward progression of the beginning and end of greywacke turbidites.

1967
 1968

1969 7. Caledonian Newer Granites of Scotland and Ireland

1970

- extensional collapse
- transtension
- transpression
- strike-slip
- nappes
- steep cleavage
- retro-charriage
- thrusting
- collision
- unconformity
- open folding
- non-marine "red beds"
- shallow marine clastics
- argillites/turbidites
- shallow carbonate
- greenschist
- Barrovian
- blueschists
- "granites"
- mafic / ultramafic intrusion
- calc-alkaline volcanic
- ophiolite obduction
- ophiolites
- Croagh Patrick
- Lettergesh

1. Ben Loyal. 2. Strath Halladle. 3. Loch Barralan.
4. Loch Ailsh. 5. Helmsdale. 6. Rogart. 7. Carn
Chuinneag. 8. Fearn. 9. Migdale. 10. Ratagain. 11.
Cluanie. 12. Glendessary. 13. Strontian. 14. Ross
of Mull. 15. Abriachan. 16. Moy. 17. Ardclach. 18.
Foyers. 19. Allt Crom. 20. Corrieyairack. 21. Nevis.
22. Strath Ossian. 23. Moor of Rannoch. 24.
Ballachulish. 25. Etive. 26. Loch Melford. 27.
Strichen. 28. Grantown. 29. Ben Rinnes. 30.
Ardlethen. 31. Peterhead. 32. Monadliath. 33.
Cairngorm. 34. Lochnager. 35. Aberdeen granites
including Skeen and Hill of Fare. 36. Bennachie.
37. Glen Tilt. 28. Mt. Battoch. 39. Comrie. 40.
Garabal Hill. 41. Arrochar. 42. Distinkhorn. 43.
Spango Water. 44. Cairnsmore of Cairspairn. 45.
Loch Doon. 46. Cairnsmore Fleet. 47. Criffel
Dalbeattie. 48. Rosses, trawenagh Bay & Torr.
49. Fanad. 50. Ardara. 51. Main Donegal. 52.
Barnesmore. 53. Ox Mountains. 54. Newry. 55.
Corvock. 56. Omey. 57. Roundstone 58. Galway
59. Carna. 60. Leinster.