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Connemara: its position and role in the Grampian Orogeny.

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Abstract

In the Irish and British Caledonides, the early Ordovician Grampian Orogeny was the result of collision between the Laurentian rifted margin and an oceanic island arc. The Connemara terrain in western Ireland differs in position and character from all other parts of the exposed Dalradian rocks of the Grampian Orogen in lying south of the collided arc and fore-arc, and in having north-verging fold nappes that developed synchronously with the intrusion of huge volumes of calc-alkaline magmas that provided the heat for regional Barrovian metamorphism. We have tested this hypothesis with a numerical model, which demonstrates its admissability. Connemara is not a terrane, displaced with respect to the remainder of the Grampian Orogen but was overridden, northwards, by the arc and its fore-arc basin (South Mayo Trough), frontal ophiolite complex (Deer Park) and accretionary complex (Killadangan). Deposition in the South Mayo Trough occurred below sea level and above the evolving Grampian Orogen, which developed on a hyper-extended rifted margin bounded to the north by the Clew Bay Line.

Key words: Connemara Arc-continent collision Barrovian

Introduction.

The early Ordovician Grampian Orogeny of the Caledonian mountain belt was pervasive across Shetland, the Highlands of Scotland, Donegal, Mayo, and Connemara (Figure 1 A). A broadly equivalent but slightly younger event, the Taconic Orogeny, occurred along the western margin of the Appalachian mountains from Newfoundland to at least Pennsylvania (Bird and Dewey, 1970). These orogenies are generally believed to have been the result of

the collision between the Laurentian continental margin and one or more island arcs with, in places, the obduction of ophiolite fore-arcs onto the continent (Nelson and Casey 1979; Dewey and Shackleton, 1984; Ryan and Dewey, 2011; Van Staal et al, 1998; Dewey and Mange, 1999; Dewey, 2003; Dewey and Casey, 2011 and 2013). The collisional suture between the arc(s) and the continental margin is the Baie Verte-Brompton Line in Newfoundland, the Clew Bay-Fairhead Line in Ireland, and the Highland Boundary Fault in Scotland (Figure 1). The Grampian Orogeny lasted only about 15 million years (475-460 Ma; Dewey, 2005), typical of many arc-rifted margin collisional orogenies such as the Miocene Bismarckian Orogen of New Guinea (Dewey and Mange, 1999), the late Miocene to recent arc-continent collision in Taiwan (Byrne et al. 2011), the early Eocene Kamchatka orogen of Russia (Konstantinovskaya 2011), and, possibly, the Palaeoproterozoic Wopmay orogen of northeast Canada (Cook 2011). However, the late Devonian to early Carboniferous collision of the Magnitogorsk arc with Laurussia in the Urals (Brown et al. 2006) and the late Cretaceous to Eocene collision of the Kohistan arc with India (Burg 2011) took 25-35 million years (Brown et al. 2011).

In spite of the basic simplicity of this model, there remain many problems in relating it in detail to the regional geology and its history and variations in the Grampian Terrain, including the following. First, the general structure of the Dalradian and Moine Supergroups, which comprise the bulk of rocks involved in the Grampian Orogeny, is not related to the collision in an obvious and simple structural way except in Connemara in western Ireland. Second, the metamorphic pattern, involving low and high-pressure and temperature facies in the Grampian terrain is difficult to relate to a simple collisional pattern. Third, the tectonic significance and basement of the Midland Valley of Scotland (Aftalion et al, 1984; Upton et al, 1976) has not been clear although it has an Ordovician arc component (Badenski et al, 2011). Fourth, the role of ophiolite obduction, so obvious in Newfoundland (Dewey and Casey, 2011, 2013), is less obvious in the Caledonides, except to some extent in Shetland (Flinn, 1958). Fifth, synchronous syn-Grampian-deformation mafic magmatism is calc-alkaline in Connemara (Yardley and Senior, 1982) and tholeiitic in Scotland (Dewey, 2005; Viete et al, 2010). Sixth, the South Mayo Trough (SMT) evolved as a fore-arc basin below or at sea level synchronously with the principal deformation and metamorphic episodes of the Grampian orogeny and its extensional unroofing in Connemara over only about fifteen million years (Dewey and Mange, 1999; Dewey, 2005). Lastly, Connemara is the only part of the Grampian Orogen south of the Ordovician arc. This has been interpreted, we suggest incorrectly, to mean that Connemara is a terrane that was detached, post-Grampian Orogeny

during mid to late Ordovician, from the main Grampian Orogen and slid in by sinistral strike-slip motion to a position south of the arc (e.g. Dewey and Shackleton, 1984; Hutton and Dewey, 1986).

We suggest that Connemara is a major key to understanding the evolution of the Grampian Orogen. Our view is that it is not a displaced terrane but part of a distal hyper-extended margin of Laurentia across which the South Mayo oceanic arc and SMT fore-arc basin was obducted. Similarly, it has been suggested that the early Notre Dame Arc of Newfoundland overthrust a hyperextended margin of the Laurentian Shelf (Van Staal et al, 2013). This concept is a critical component of our new interpretation of the evolution of Connemara and the Grampian Orogeny of Ireland and Scotland.

The Grampian Orogen

There are many summaries that describe the Grampian Orogen and its related adjacent zones (e.g. Anderton, 1982; Chew and Strachan 2014, Harris et al, 1994; MacDonald and Fettes, 2007; Stephenson and Gould, 1995; Treagus, 1987; Trewin 2002; Yardley, 1980; Dewey et al, 2015; and references therein). Therefore, it will suffice to present a very brief synopsis of the region between the Laurentian Foreland and the Iapetus Suture in Scotland and Ireland (Figure 1A) relevant to the arguments in this paper. Geographic co-ordinates are those of the present.

The Moine Series of the Northwest Highlands and the Dalradian Series of the Grampian Highlands are interpreted as sediments deposited mainly in extensional basins from about 900 Ma to early Ordovician. From about 600 Ma (Halliday et al, 1989), accelerating extension with mafic magmatism and alkaline granites led to continental rupture (Dewey et al, 2015) and, by about 540 Ma, the formation of the Laurentian margin, well-displayed in Newfoundland as a sharp rift boundary to the Laurentian continent (Bird and Dewey, 1970; Williams and Stevens, 1974) but less obviously in the Irish and British Caledonides. The pre-Laurentian margin clastic rift sequence in Newfoundland (Fleur-de-Lys) and the rest of the Northern Appalachians to New York is diminutive in width and volume in contrast to that of the Scottish and Irish Highlands (Dewey, et al, 2015). The Cambro-Ordovician continental shelf sequence is strikingly similar from Scotland to the Southern Appalachians, dominated by the Durness, St. George, and Stockbridge carbonates (Bird and Dewey, 1970). The continental shelf Pre-Cambrian basement is, variably, Grenville, Ketilidian, and Lewisian; in

Scotland and Ireland, this basement extends beneath much of the Moine and Dalradian (Brewer et al, 2003; Daly and Flowerdew, 2005; Friend et al, 2008; Kennedy and Menuge, 1992; McAteer et al, 2010a and 2010 b; Sanders et al, 1984; Winchester and Max, 1984) and, in Newfoundland, beneath the Fleur-de-Lys and Notre Dame Arc (Van Staal et al, 2013). The Ordovician Grampian Orogeny (475-460 Ma) was pervasive across the Moine and Dalradian. Deformation and metamorphic events affected the Moine during the early Proterozoic (Giletti et al, 1961).

Perhaps the greatest puzzle of the Grampian Orogeny is the facing direction, vergence, and polarity of the major recumbent folds and nappes in relation to the generally-accepted arc-continental margin collisional model. In Scotland, the Loch Awe Syncline is a “zwischengebirge” separating northwest-facing-vergence in the northwest from southeast-facing-vergence (Thomas, 1979; Treagus, 1987; Krabbendam et al, 1997) to the southeast (e.g. the Tay Nappe, which becomes downward-facing along the Highland Border, Shackleton 1958). This suggests (Tanner, 2014) that the Tay Nappe cannot be a product of northwestward fore-arc ophiolite obduction. Similarly, the dominant facing-vergence direction in North Mayo, in southern Donegal, and the Sperrin Mountains (Alsop, 1994) is to the south. In Donegal, north of the Main Donegal Granite, major folds face to the north. Only in Connemara is the facing and vergence direction of early recumbent structures, in the Twelve Bens, to the north (Figure 1C), regionally-consistent with northward overthrusting of the arc and its fore-arc.

The mid-Silurian Scandian Orogeny, believed to have been the result of continental collision between the Laurentian and Baltic Shields, affected the Moine (Bird et al, 2013; Kinny et al, 2003; Strachan and Evans, 2008) but not the Dalradian; this is believed (Dewey and Strachan, 2003) to indicate that the Dalradian could not have been in the “jaws” of the Laurentia/Baltica collisional vise, and that there must have been at least 250 kms of sinistral displacement along the Great Glen Fault and its continuations.

Excluding Connemara, the Ox Mountains and other possible small areas, the southern boundary of the main Dalradian zone is the Clew Bay-Fair Head Line/Highland Boundary Fault (CB/HBF). Two distinct ultramafic associations characterize the boundary. Ophiolites, *sensu stricto*, occur as the Shetland Complex (Flinn and Oglethorpe, 2005) and as dismembered complexes in the Deer Park (Ryan et al. 1983) south of Clew Bay, Tyrone (Hutton et al. 1985), and Bute (Chew et al. 2010). These are homologous with the Bay of Islands Complex in Newfoundland and likely were parts of northwest-facing early Ordovician ophiolitic fore-arcs (Dewey and Casey, 2011; 2013). The Shetland ophiolite has

boninitic dykes (Flinn and Oglethorpe 2005) and a 484 Ma metamorphic sole (Crowley and Strachan, 2015). The synchronicity of MORB metamorphic soles at 9-10 kb and ophiolite generation below 5 kb has led to the proposition that soles were generated at the top of subducting slabs and attached to the bases of fore-arc ophiolites 10 my prior to arc-continental margin collisional obduction (Dewey and Casey, 2011; 2013). Elsewhere along the Highland Boundary Fault, and in Achill on the northern margin of Clew Bay, the dismembered ultramafics are serpentinized lherzolites commonly as megabreccias with a metasediment matrix (Kennedy, 1980; Chew, 2001). Very similar associations occur along the Highland Boundary Fault, especially at Balmaha on Loch Lomond. These are probably sub-continental mantle rocks exhumed by extension during the formation of the Laurentian rifted margin, similar to those of the Swiss Alps (Manatschal and Muntener, 2009). They are distinguished from fore-arc ophiolite complexes, mainly, by their lack of harzburgite and boninite. In South Achill, the Dalradian is affected by blueschist and high silica phengite facies metamorphism (Gray and Yardley, 1979; Chew et al., 2003), suggestive of burial to depths of 30 km, probably in a south-dipping subduction zone marked by the CB/HBF, the suture between the rifted Laurentian margin and the north-facing Lough Nafooe arc.

The Lough Nafooe Arc and its associated fore-arc basin, the South Mayo Trough (Fig 1B, are part of an oceanic arc complex that extends northeastwards to Tyrone and the Midland Valley of Scotland and southwestwards to the early Notre Dame Arc of Newfoundland, where the Baie Verte Line is the suture boundary between the arc and the Fleur-de- Lys continental margin rift sequence (Bursnall, 1973). In Tyrone, the Dalradian is thrust (Omagh Thrust) southwards onto the arc. The Ox Mountains are an enigmatic inlier of Dalradian and other Proterozoic rocks whose provenance and origin is unclear but not obviously of consequence in this paper; they may be microcontinental fragments swept up in the suture zone, analogous to the linear fragments in the Tasman Sea that will be likely swept into the future collision zone between the Vanuatu Arc and the rifted margin of Australia. The Sliswood Division in the Ox Mountains, however, is affected by and, therefore, must have lain in the Grampian Zone during the Grampian Orogeny.

The Ordovician arc in Scotland (Midland Valley) is bounded, to the south, by the Southern Uplands Fault, south of which lies the Southern Uplands, a mid-Ordovician to late Silurian accretionary prism above a north-dipping subduction zone. The Midland Valley basement contains elements of an Ordovician arc (Badenski, 2011) and Pre-Cambrian metasediment (Upton et al. 1976). The accretionary prism continues into Ireland as the Longford-Down Massif and the South Connemara Series (Ryan and Dewey, 2004). The dismembered

Ballantrae Ophiolite Complex lies beneath northward-overstepping mid-Ordovician strata at the northern margin of the Southern Uplands; its basal contact is a 478 Ma granulite/amphibolite metamorphic sole in tectonic contact with an anchi-metamorphic black shale olistostrome. Shear sense indicators show that the obduction direction was northward. The relationship between this Complex and the buried Ordovician arc is unknown. It could have been part of a back-arc basin or the fore-arc of an outboard arc thrust northward onto the Midland Valley arc.

Dalradian rocks to the south of the CB/HBF occur in the Ox Mountains, probably as the Central Inlier beneath the Tyrone ophiolites (Chew et al, 2008), and, possibly beneath the Midland Valley. However, their main outcrop, south of the CB/HBF, is in Connemara, where a clear Dalradian stratigraphy matching Donegal and the Scottish Highlands is exposed in the Twelve Bens; they are overlain, unconformably, by Upper Llandovery strata to the north and intruded by the late Silurian Galway Granite to the south.

In Scotland, the continental shelf must have extended across at least part of the Moine because the shelf stratigraphic sequence shows no sign of an eastward facies change towards a continental edge. Part of the Banff sequence and South Highland Group must be a deeper water equivalent of the Durness shelf sequence. There is no evidence that the oceanic arc complex overthrust the Grampian Terrane north of the CB/HBF in Ireland or Scotland (Tanner, 2014) but there was substantial southward subduction of the Dalradian along the Clew Bay Suture Line as witnessed by the blueschist assemblage (Gray and Yardley, 1979) and high-Si phengite in Dalradian rocks just north of the suture. This is in contrast to Newfoundland where the Bay of Islands Ophiolite fore-arc overthrust the Laurentian margin onto the Laurentian shelf, and eclogites indicate subduction of the Fleur-de-Lys to over 30 km.

The Connemara problem

The position of Connemara to the south of the oceanic arc complex (Fig 1B) that collided with the Laurentian margin has been taken to mean that it is a terrane that was displaced from the main Dalradian zone and “shuffled”, sinistrally, to south of the collided arc (Hutton and Dewey, 1986) The principal reason for this was that it seemed difficult to believe that the thick South Mayo Trough was thrust northwards across the Dalradian of Connemara and yet remained intact and non-eroded. However, considering Connemara as a terrane displaced

201 by sinistral strike slip motion during the mid-Ordovician from west of Mayo has led to
202 kinematic difficulties and arguments about its provenance and its direction and time of travel
203 (e. g. Hutton and Dewey, 1986; McConnell et al, 2009). We suggest that these difficulties
204 and arguments can be resolved by considering Connemara to be roughly “in situ” with
205 respect to the main Dalradian zone north of the CB/HBF. A further argument in favour of this
206 interpretation is shown in Figure 2 which compares the principle tectonic zones of the
207 Ordovician Grampian and the ongoing arc-continent collision in Taiwan. Both are plotted at
208 the same projection and scale and the respective sutures are aligned. With the exception of
209 the missing or absent Grampian foreland basin, the degree of preservation of the various
210 ‘terrains’ is similar. This removes the necessity to attribute the current outcrop pattern of the
211 Grampian to later terrane displacement.

212 Many issues are resolved by considering Connemara to have been part of a hyperextended
213 margin south of the CB/HBF from Shetland to, at least, Newfoundland, including the
214 Midland Valley and Tyrone. The oceanic arc and its ophiolitic fore-arc and fore-arc basin
215 overthrust the hyperextended margin; in Newfoundland, the Bay of Islands Ophiolite
216 Complex overthrust its foreland basin on the continental shelf. We view the CB/HBF as the
217 line of rapid diminution of thickness of the Laurentian continental crust, especially well-
218 displayed as the Cambro-Ordovician shelf edge in Newfoundland. Our model for the
219 Ordovician evolution of western Ireland accounts for the synchronicity of sedimentation in the
220 South Mayo Trough and Grampian deformation and metamorphism as the South Mayo
221 Trough was thrust northwards over the Connemara Dalradian.

222

223 **Irish Caledonides from Clew Bay to Galway Bay**

224

225 The basic geology of the region with a north-south section is shown in Figure 1 and its major
226 events are summarized in Figure 3. The Grampian geology of Connemara differs from that
227 north of the CB/HBF; only the Dalradian stratigraphy is fundamentally the same. North of the
228 Clifden Steep Belt, in the Twelve Bens Zone, the classic Dalradian stratigraphy is disposed in
229 major D2/D3 recumbent folds that verge northwards. D1 is represented by an early
230 penetrative fabric with which no known folds are associated. The Connemara Antiform folds
231 the D2/D3 folds and plunges gently to the east. Metamorphic grade in the Twelve Bens Zone
232 is mainly sillimanite-garnet-amphibolite but reaches kyanite in the west. North of the north-

dipping and throwing Renvyle/Bofin Slide, metamorphic grade drops to andalusite; calc-alkaline gabbro to ultramafic bodies (Dawros, Currywongaun, Doughruagh) were intruded mainly during D3 (Wellings, 1998). An aluminosilicate triple point, at about 500°C/5 kb/15 km, lies somewhere in west Connemara south of Ballynakill Bay. In the Clifden Steep Belt, D2/D3 folds are tightened and steepened and intruded by the Cashel-Lough Wheelaun calc-alkaline mafic/ultramafic bodies (Leake, 1989). To the south of the Clifden Steep Belt, Dalradian metasediments are pervasively migmatized and injected by quartz-diorites with abundant sillimanite and cordierite. Calc-alkaline mafic-ultramafic complexes occupy about sixty percent of the area with both large intrusive bodies such as Errisbeg (Morton, 1964) and regional agmatites. It is likely that the Renvyle/Bofin Slide was the base of a D2/D3 nappe that carried andalusite-facies rocks with the D2/D3 Dawros/Currywongaun/Doughruagh mafic/ultramafic intrusions (Wellings, 1998) northwards over the Twelve Bens Zone; the Slide, subsequently, became a north-dropping extensional detachment.

Regional kyanite/sillimanite/andalusite/garnet/staurolite metamorphism occurred during D2 and was accompanied by northward-diminishing calc-alkaline magmatism, which intensified with regional migmatization, melting, sillimanite, cordierite, and quartz diorites during D3. This lasted only about 5 m.yr. (c. 475-470Ma (Friedrich et al. 1999a and b) and suggests a causal relationship between the 1200°C mafic/ultramafic magmatism, melting, sillimanite and metamorphism. In turn, we suggest that the calc-alkaline magmas were derived by partial melting of the shallow asthenosphere of the overthrusting hot arc with advected heat rapidly generating the metamorphism. This is in contrast to the roughly synchronous (post D2, pre-D3) tholeiitic magmatism of Scotland, which has been attributed to regional extension (Viète et al, 2010). The ultramafic/mafic complexes may have been in a high level nappe above the Renvyle/Bofin Slide (Fig. 1B and an unidentified slide in the Clifden Steep Belt. Structural data suggest that the Grampian event has a significant dextral component (Harris, 1995; Dewey, 2005)

Blueschists in south Achill (Gray and Yardley, 1979) and high-Si phengite schists north of Clew Bay indicate that a strip of Dalradian rocks enjoyed HP/LT Grampian metamorphism to 10.5 + 1.5 kbar and 460 +/- 45 °C at ~460 Ma (Chew et al., 2003), probably in the Clew Bay Suture subduction zone, similar, in tectonic position, to the Fleur-de-Lys eclogites west of the Baie Verte Suture in Newfoundland (Church, 1969; De Wit and Strong, 1975). The timing and mechanism of exhumation of these HP rocks, whether by eduction and, or channel flow, is unclear. Cleavages associated with nappe formation on either side of the Achill Beg Fault, which separates these two complexes, are of similar age, 460 Ma (Chew 2003)

suggesting that the exhumation may have taken place at this time.

The HP rocks are bounded to the south by the anchi-metamorphic Ballytoohy Series and Killadangan Complex (Fig. 3), probably parts of a subduction-accretion complex at the leading edge of the South Mayo oceanic arc, immediately north of dismembered ophiolites of the Deer Park Complex (Ryan et al. 1983), a probable backstop to the Killadangan Complex (Dewey and Ryan, 1990). The oceanic volcanic arc is represented some 20 km to the south by the Lough Nafooe Group (Ryan et al, 1980) consisting of pillow basalts and epiclastic andesites, succeeded by the Glensaul Group of silicic extrusive and hypabyssal volcanics believed to be derived by the melting of subducted continental margin sediments indicating the imminent collision of the arc with the continental margin (Draut and Clift, 2001). This mafic to silicic transition seems to be characteristic of the collision of oceanic arcs with continental margins. The volcanic arc is succeeded by the lower Rosroe Group, fan deltas with boulder conglomerates containing volcanic detritus, and blocks of fossiliferous limestone clearly from the upper part of the Glensaul arc. The upper Rosroe contains tonalities indicating greater uplift and erosion of the arc at about 467 Ma (Clift et al. 2009), which we ascribe to the latest stages of the arc/margin collision. Tonalite boulders in basal Silurian strata on the Kilbride Peninsula contain tonalite boulders dated at 488 Ma (Chew et. 2007), which they ascribe to the late stages of the Lough Nafooe arc. Andesite tuffs in the Lower Rosroe indicate that volcanism was still occurring during the collision.

To the north and correlative with the Lough Nafooe to lower Rosroe sequence is a very thick (9 km) succession (Fig. 3) of conglomerates (Letterbrock), slates (Derrymore), and turbidites (Sheeffry and lower Derrylea deposited in a fore-arc basin, the South Mayo Trough, (Dewey and Ryan, 1990). The Sheeffry and lower Derrylea was sourced from the arc to the south and from the Laurentian continent showing that the arc, its fore-arc basin, backstop, and accretionary prism had already collided with the Laurentian continent. This is consistent with the isotopic dating of the Grampian deformation and metamorphism of Connemara from about 475 to 468 Ma (Friedrich et al., 1999a and 1999 b). Sedimentary petrography (Dewey, 1963; Dewey and Mange, 1999) and geochemistry (Wrafter and Graham, 1989) of the Derrymore to lower Derrylea shows that an ophiolite sheet, of which the Deer Park Complex is a remnant, was eroded down to mantle ultramafic rocks during this period. The eroding ophiolite sheet must have lain between the Deer Park Complex and the South Mayo Trough and was probably shortened and largely cut out by a major pre-Silurian, probably Mayoian (Fig. 3), thrust. The Deer Park ophiolite (484 Ma, Chew et al, 2010) is of roughly the same age (Tremadocian/earliest Arenigian) as the Bay of Islands Ophiolite

Complex in Newfoundland and the Tyrone, Ballantrae, and Shetland ophiolites.

Of great significance and a critical part of our model of the evolution of Connemara is the synchronicity of the Grampian deformation and metamorphic sequence of Connemara with the Glensaul silicic volcanics and the Sheeffry Formation (Fig.3). Not only are the fore-arc basin sediments of the South Mayo Trough preserved but were below sea-level throughout the main phases of the Grampian Orogeny yet did not receive Grampian metamorphic detritus until the deposition of the Upper Derrylea (Dewey, 2005; Ryan 2008). Only during the Rosroe was the arc eroded to the depth of tonalite bodies. Also, there is no evidence that any part of the Grampian orogeny was above sea level until the upper Rosroe and upper Derrylea when Grampian detrital garnet, staurolite, and white mica flooded into the South Mayo Trough (Dewey and Mange, 1999) and define the base of the upper Derrylea. The very sudden appearance of Grampian detritus with staurolite and garnet suggests that erosion was not the main denudation mechanism but rather that extensional denudation was the principal way in which Grampian metamorphic rocks were exhumed. The Gowlaun and Renvyle/Bofin Slides are the principal candidates for extensional detachments but the Clew Bay and other slides Slide, also, may have been active. In Scotland, the south-east-dipping Portsoy extensional slide may have developed at this time. The Gowlaun and Renvyle/Bofin Slides incorporated ultramafic blocks now totally serpentized; it is not clear whether they were derived from the syn-D3 mafic-ultramafic intrusive complexes or the 484 ophiolite. Extensional detachment unroofing and exhumation of the Grampian orogeny in Connemara may have been related to subduction “polarity flip” from north to south-facing as a result of collisional blocking by the CB/HBF “rampart” and extension of the Orogen towards the new subduction zone free face. An extensional phase in the South Mayo Trough would also account for pelite deposition of the Glenummera. The amount of erosion of the Grampian Orogen in western Ireland during upper Derrylea-Glenummera was very small.

Cooling ages in Connemara range from 480 to 418 Ma with a maximum from 455 to 445 Ma; North Mayo cooling ages range from 481 to 421 Ma with most lying between 464 and 430 Ma. These are too young for the period of extensional denudation and must relate to erosion during the mid-Ordovician compressional Mayoian Phase (Dewey et al, 2015) that followed subduction polarity flip (Fig. 3). During this “Andean-style” phase of shortening above a north-dipping subduction zone, the non-marine Mweelrea Formation was deposited in the South Mayo Trough, which was shortened north-south; the Connemara Antiform and Clifden Steep belt were developed, the ultramafic-mafic complexes and quartz-diorite gneisses south of the Clifden Steep Belt were thrust south-south-east in retrocharriage

335 along the Mannin Thrust over silicic volcanics of the Glensaul arc, and the Oughterard
336 Granite was intruded along the eastern Twelve Bens Zone and Clifden Steep Belt. Both the
337 Mweelrea Group and the post-Mweelrea Derryveeny Formation contain boulders of
338 Connemara Dalradian lithologies indicating substantial erosional denudation during the
339 Mayoian phase. The South Connemara Series are interpreted as a trench hanging wall
340 accretionary complex above a north-dipping subduction subduction zone (Ryan and Dewey,
341 2004). Lineations and shear sense in the South Connemara Series indicate that the
342 convergence now incorporated a slightly sinistral sense contrasting with the slightly dextral
343 sense on the Mannin Thrust. The south-verging Omagh Thrust and the Highland Boundary
344 down bend (Shackleton 1958) may be Mayoian structures. We visualize the Mayoian (Dewey
345 et al, 2015) as a phase of Andean-style shortening above a north and probably gently-dipping
346 South Connemara subduction zone that continued to the Southern Uplands of Scotland.

347 Silurian sediments rest unconformably across the eroded Dalradian and the Ordovician
348 rocks of the South Mayo Trough. Andesite sills and tuffs indicate the continuance of north-
349 dipping subduction. Both Ordovician and Silurian rocks were deformed by sinistral
350 transpression with clockwise-transecting cleavages during the terminal closure of the Iapetus
351 Ocean in the late Silurian.

352 The new model

353

354 In essence, our model, based upon geology and numerical modeling, is that Connemara is not
355 a displaced terrane; the early Ordovician South Mayo Trough and north-facing arc overthrust,
356 northwards, an extended or hyperextended continental margin followed by a flip in
357 subduction polarity. A strong case can be made for the Dalradian being deposited on a
358 hyperextended margin as for the Fleur-de-Lys in Newfoundland (Van Staal et al, 2013).
359 First, the lack of a foreland basin associated with either Grampian or Scandian thrusting in
360 the British Isles can be only reasonably explained by the Laurentian margin (edge of the
361 Laurentian rifted margin not the shelf edge) having a low effective elastic thickness (Ryan
362 2008). Secondly, late Ediacaran gabbroic complexes and ultramafic detritus are interpreted
363 as marking an ocean-continent transition zone formed during hyperextension (Van Staal et al
364 2013; Dewey et al, 2015). Thirdly, the early Ordovician intra-oceanic arc in Tyrone was
365 developed on a micro-continent, the Central Inlier, which collided with the Laurentian
366 margin during the Grampian orogeny (Cooper et al. 2011). The Central Inlier is Laurentide
367 in character (Chew et al. 2008) but must have been separated from the Laurentian margin by

oceanic lithosphere to have generated the Grampian collision. Finally, the thickness of Dalradian sediment has been estimated at perhaps no more than 15 km in any one depo-centre (Stephenson et al. 2013). Although such sediment thicknesses are not recorded at modern continental margins (Mooney et al. 1998, it is clear that Dalradian deposition took place over perhaps more than 100 m.yr. and accumulated vast volumes of sediment. These observations are consistent with a sediment-rich, hyperextended margin with outlying microcontinents that had a hydrated mantle which led to low elastic thickness. We suggest that the development of the Laurentian rifted margin in Cryogenian to Ediacaran times may have resembled that of the northeast Atlantic during the Cretaceous (Lundin & Doré 2011).

We suggest that the preservation of the South Mayo Trough, below sea-level, synchronously with its being thrust northwards above and across the Dalradian as it was being deformed and metamorphosed beneath means that this part of the Grampian Orogen was dense and relatively unsupported by lithospheric flexure, for the following reasons:

1. Loading by the high-density obducting arc/ophiolite slab (Waltham et al., 2008)
2. Rapid reversal (flip) of subduction polarity associated with extension of the upper slab behind the free face
3. The low elastic thickness of the rifted margin
4. The margin was thermally mature because arc-continent collision occurred about 90 my after the rift-drift transition.
5. Subducting large amounts of mafic rocks in a volcanic rifted margin (Ryan 2008).

This was enhanced by a high early Ordovician sea level, as revealed by widespread carbonate platforms (e.g. Durness, St. George, Stockbridge). An explanation for how segments of an orogen that was elsewhere being deeply eroded could have been below sea level is given by Ryan and Dewey (2011), who draw parallels with the lateral transport of sediment from the 'mature' Taiwan orogen south-westwards into the 'nascent' arc-continent collision in the South China Sea (Fig. 2).

Thus, the Grampian Orogeny in Connemara occurred below sea level initially without mountains but with early detritus being supplied laterally from the evolving orogen that lay to the east (Ryan & Dewey 2011). The Orogen was partially denuded by extensional detachment (s) during upper Derrylea times and heavily eroded during the post-Grampian Mayoian phase. The obducting arc provided the heat for the Grampian metamorphism, which was advected by the voluminous intrusion of calc-alkaline mafic/ultramafic magmas. From Letterbrock to the end of Derrylea deposition, an obducted fore-arc ophiolite sheet,

402 between the South Mayo Trough and the Killadangan accretionary prism was progressively
403 eroded, and the mainly ultramafic remnants were overthrust and telescoped to the narrow
404 remnant of the Deerpark Complex.

405 Hence, the Grampian Orogeny in Connemara comprised north-verging fold nappes in a
406 “shear carpet” below the overthrusting arc which also provided both the D3 calc alkaline
407 magmatism and advective heat for the metamorphism, migmatization, and melting, whose
408 intensity diminishes northward. Fore-arc basin sedimentation in the South Mayo Trough
409 continued “piggy-back” in the overthrusting arc synchronously with the Grampian Orogeny
410 beneath; hence, arc obduction and the subjacent developing orogeny were almost wholly
411 below sea level. Only parts of the fore-arc ophiolite, of which the Deer Park Complex is a
412 remnant, were being eroded from about 477 Ma until about 460 Ma (Dewey and Mange,
413 1999). Modest extensional denudation of the Grampian Orogen began at about 466 Ma and
414 major erosional denudation began at about 464 Ma and continued through the “Andean”
415 Mayoian phase until about 445 Ma shortly after which a blanket of Silurian sediment was laid
416 down unconformably across the whole region. We suggest that the CB/HBF line was an
417 abutment that formed a barrier to further northward arc obduction and north-verging D2/D3
418 nappes.

419 We emphasize that our model is strictly for the Grampian event of western Ireland south of
420 Achill Island. This raises the further problem of the mechanism(s) that formed the nappe
421 structure of the main Dalradian zone north of the CB/HBF in Ireland and Scotland and
422 accounts for its metamorphism.

423 If the model is admissible, Grampian deformation and metamorphism in Connemara should
424 be slightly older than in North Mayo but geochronological data are insufficient, now, to
425 determine the precise relative ages of structure and metamorphism in the two areas. We now
426 develop a quantitative model to test the viability of the geological model.

428 **Numerical model.**

429
430 We have constructed a numerical experiment (Fig. 4) to model the evolution of the western
431 Ireland segment of the Grampian Orogen, where we emplace a hot hanging wall over a cold
432 footwall. Our aim is to examine the thermal response of the footwall with time and whether
433 such a system might produce the metamorphic conditions reported in Connemara. This is not
434 intended to be a full geodynamic model for Connemara because there are too many

unknowns. Rather we wish to test the admissibility of our hypothesis.

The two-dimensional (2D) kinematic flexural model used by Ryan (2008) is linked to a transient finite element (FE) thermal model (see Ryan and Dewey 1997 for details) to investigate the likely thermal consequences of emplacing a hot hanging wall over a cool footwall. After each time step (0.01 m.yr.) in the kinematic thrust model, each data point and its properties (density, heat productivity, temperature at the previous time step, conductivity) are mapped to the nearest node in a quadrilateral matrix, which is then solved using the FE method for the nodal temperature. The computed temperatures are then mapped back from the FE matrix to the kinematic matrix and the process repeated.

The hanging wall is 30 km thick with a geotherm of $45^{\circ}\text{C.km}^{-1}$ in the top 15 km and $18^{\circ}\text{C.km}^{-1}$ in the lower 15 km, giving a temperature of 945°C at its base. The footwall is also 30 km thick with an initial geotherm of $22^{\circ}\text{C.km}^{-1}$ for the top 15 km and $10^{\circ}\text{C.km}^{-1}$ for the lower 15 km, giving a Moho temperature of 450°C . Thrusting lasted for 6 my. at a velocity of 30 mm.yr^{-1} , giving an orogen 180 km wide. Because thrusting is believed to have been below sea level, erosion is not taken into account. Topography is compensated using flexural isostasy with an elastic thickness of 2 km. Other assumptions used in this modeling are given in Table 1. The results are presented as a cross-section in figure 4A and a set of PTt paths for a given node in the model (Fig. 4B). Each point represents the average temperature and pressure for 10 time steps (100,000 yr.).

The model predicts that, in an arc-continent collision where a hot hanging wall (arc) is emplaced over a cold foot wall (continental margin) in a short-lived orogenic event ($\sim 6\text{ my.}$), the resultant pressure, temperature, time (PTt) path depends on the position of the sampled locality within the footwall with respect to the hanging wall (Fig. 4B). A node that initially lay 30 km in front of the thrust tip but at a depth of 20 km below the thrust footwall does not heat significantly until the last few time steps and remains in the high-pressure, low-temperature field. The slight initial cooling reflects the fact that the assumed geotherm was very slightly higher than the equilibrium geotherm for the footwall. A node in a similar horizontal position that lay only 7 km beneath the thrust falls into the 'Barrovian field', but stays in the kyanite stability field. A node 4 km above, that is at 3 km below the thrust, heats most rapidly and passes through the alumino-silicate triple point and into the sillimanite stability field (Figure 4B).

The modeling indicates that Barrovian PT conditions can be obtained in a short period ($<5\text{ m.yr.}$). These conditions are, however, only achieved in the upper 7 km of the footwall with

highest temperatures immediately beneath the thrust. This rapid heating is attributed to the fact that, as a given segment of the 'arc' cools by conduction into the footwall, it is replaced by a new segment of hot arc. The upper 7 km of the footwall would comprise the sedimentary cover. It should be noted that this model can only be applied to Connemara because, in north Mayo, the metamorphic grade, including temperature, increases towards the basement.

Conclusions

We confirm that it is likely that the Grampian orogeny in western Ireland was the result of a short-lived Ordovician arc-continent collision, which initially took place below sea-level (Fig. 4). We argue that Connemara was thrust over a hyper-extended Laurentian margin and is essentially in place with respect to the rest of the Orogen. Grampian metamorphism was due to advected heat from the hanging wall arc nappe. A numerical model shows this is an admissible scenario. The model predicts that the PTt path beneath the arc nappe depends on location within the footwall. We emphasize that regional metamorphism in the Grampian orogeny was not produced by one single mechanism. Compare for example the explanation of Viete et al. (2010) for the Buchan zone with the current model for Connemara. The relative contributions of these and other mechanisms (for example: England & Thompson (1984); Warren and Ellis, 1996; Lin (2000)) must all be considered in the context of the regional geology.

We believe that the view of Connemara as a displaced terrane has held back its understanding. The terrane concept (Coney, Jones, and Monger, 1980) can be of great value in the objective description of adjacent terrains that differ fundamentally. It may help in recognizing that they may have originated perhaps thousands of kilometres from each other, and to avoid meaningless tectonic cross-sections (Van Staal et al, 1998). On the other hand, a militant terrane obsession can lead to the overzealous assumption that every terrain is a terrane, which can lead to an arid and aimless patchwork geo-quilt and the fruitless dissection of an orogen leading to the obfuscation of tectonic meaning (Sengor and Dewey, 1990). As a rote dogma, the terrane concept is unhelpful, sometimes dangerous in tectonics. The term terrane tectonics has been used to legitimize the terrane dogma. There is no such thing as terrane tectonics; the displacement of terranes, their provenance, and resting place, is a natural consequence of plate boundary evolution (Sengor and Dewey, 1990; Van Staal et al,

500 1998).

501 Lastly, there are many both subtle and substantial differences in the geology and tectonic
502 style along the Laurentian margin of the Appalachian/Caledonian border zone such as timing
503 of Ordovician events, the presence of absence of obducted ophiolites and foreland basins.
504 The Grampian/Taconic arc(s)- continent collision(s) were clearly not greatly exotic to
505 Laurentia because they contain Laurentian Cambro-Ordovician faunas. Differences in
506 orogenic geometry and timing are probably the result of along-strike differences in the pre-
507 collisional map geometry and lithospheric structure of the rifted margin and arc(s).

508

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510

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Figure captions

879

880 1.1. A. Simplified tectonic map of the British and Irish Caledonides north of the
881 Iapetus Suture; B. Simplified geological map of the western Irish Caledonides; C.
882 Outline section of the western Irish Caledonides. Modified from Dewey, 2005

883 2.2. Comparison of main tectonic zones of Taiwan and the Grampians. Both orogens
884 are plotted using the UTM projection (Taiwan, zone 51 and the Grampians, zone 29)
885 and at the same scale. The maps are rotated so that the sutures are broadly parallel.
886 The foreland lies to the top of the plots and the ocean to the bottom.

887 3.3. Major events, facies, and timing in the British and Irish Caledonides north of the
888 Iapetus Suture. Modified from Dewey and Mange, 1999 and Dewey et al, 2015

889 4.4. A. Cross-section illustrating the result of the arc obduction model. B. Pressure,
890 temperature, time (PTt) paths derived from the numerical model described in the text.
891 Each point represents the average values for a given node for ten time steps, which is
892 100,00 years. The aluminium silicate stability fields are shown.

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896

897 Table 1.

Thrust model assumptions	
Elastic thickness of hanging wall (arc)	2.0 km
Elastic thickness of foot wall (margin)	2.0 km
specific gravity for foreland basin fill replacing mantle	2200.0 kg.m ⁻³
Specific gravity for crust	2775.0 kg.m ⁻³
Width of model	750 km
Distance to tip of ramp from left hand (arc) side of model	420 km
Dip of ramp	14.4°
Horizontal dimension of cells	300 m
Vertical dimension of cells	300 m
Rate of thrusting	30.0 mm.yr ⁻¹
Duration of thrusting	6.0 m.yr.
Erosion constant	0.0
Model for motion over ramp	flexural isostasy
Assumptions for the FE thermal routine	
Minimum value in thrust model mapped to FE grid	200.0 km
Maximum value in thrust model mapped to FE grid	700.0 km
Number of horizontal grid nodes	100
Horizontal spacing of quadrilateral grid nodes	5000.0 m
Number of vertical grid nodes	100
Vertical spacing of quadrilateral grid nodes	300.0 m to 600.0 m
Footwall depth to ‘Conrad’ disconuity	15.0 km
Footwall initial geotherm [C.m ⁻¹] above and below ‘Conrad’	2.2E-02 (above) 1.0E-02 (below)
Footwall heat productivity [A/rho.Cp] above and below ‘Conrad’	4.0E-13 (above) 2.0E-13 (below)

Footwall diffusivity [$\text{m}^2.\text{s}$] above and below 'Conrad'	7.83E-07 (above) 7.83E-07 (below)
Hanging wall depth to 'Conrad'	15.0 km
Hanging wall initial geotherm [C.m^{-1}] above and below Conrad'	4.5E-02 (above) 1.8E-02 (below)
Hanging wall heat productivity [$\text{A}/\rho\text{Cp}$] above and below 'Conrad'	4.0E-13 (above) 2.0E-13 (below)
Hanging wall diffusivity [$\text{m}^2.\text{s}$] above and below 'Conrad'	7.83E-07 (above) 7.83E-07 (below)
Boundary conditions, fixed temperatures: at the surface; on the hanging wall side of thrust; and on the footwall side of thrust.	10 °C; 945 °C; 450 °C

898

Draft

Figure 2.

- BH Bohaun

BC Betts Cove

BL Ben Levy

BOIC Bay of Islands Complex

BU Bunnacuneen

CP Croagh Patrick

DN Durness

DV Derryveeney

GL Glensaul

GM Glenummera

GT Goose Tickle

K Killadangan

LB Letterbrock

LN Lough Nattooey

LT Lettergesh

LP Long Point

MD McDuff

MW Mweelrea
- NB New Bay

PL Point Leamington

RR Rosroe

SG Saint George

SA Snook's Arm

SH Sheeffry

TH Table Head

UD Upper Derrylea
- A Stages

B graptalite zones

C Newfoundland shelf

D Notre Dame arc

E Scotland shelf

F Grampian Highlands

G Connemara

H North } South Mayo

I South } Trough

J Tyrone

K Ballantrae

L Shetland

M Southern Uplands
- LD Llandoverly

AS Ashgill

CA Caradoc

LL Llanvirn

AR Arenig

TR Tremadoc

UC Upper Cambrian
- + granite

x tonalite

• ophiolite

■ sole

↔ extension

⇐ ophiolite obduction

⋈ accretionary prism

Figure 4A