Rapid tectonic exhumation, detachment faulting and orogenic collapse in the Caledonides of western Ireland

Peter D. Clift, John F. Dewey, Amy E. Draut, David M. Chew, Maria Mange, Paul D. Ryan

*Department of Geology and Geophysics/MS 8, Woods Hole Oceanographic Institution, 360 Woods Hole Road, Woods Hole, MA 02543-1541, USA

bDepartment of Geology, 174 Physics/Geology Building, University of California, One Shields Avenue, Davis, CA 95616-8605, USA

cWoods Hole Oceanographic Institution-Massachusetts Institute of Technology Joint Program in Oceanography, Woods Hole, MA 02543, USA

dDepartment of Geology, Trinity College, Dublin 2, Ireland

eDepartment of Geology, National University of Ireland, Galway, Ireland

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Abstract

Collision of the oceanic Lough Nafooey Island Arc with the passive margin of Laurentia after 480 Ma in western Ireland resulted in the deformation, magmatism and metamorphism of the Grampian Orogeny, analogous to the modern Taiwan and Miocene New Guinea Orogens. After ~470 Ma, the metamorphosed Laurentian margin sediments (Dalradian Supergroup) now exposed in Connemara and North Mayo were cooled rapidly (>35 °C/m.y.) and exhumed to the surface. We propose that this exhumation occurred mainly as a result of an oceanward collapse of the colliding arc southwards, probably aided by subduction rollback, into the new trench formed after subduction polarity reversal following collision. The Achill Beg Fault, in particular, along the southern edge of the North Mayo Dalradian Terrane, separates very low-grade sedimentary rocks of the South Mayo Trough (Lough Nafooey forearc) and accreted sedimentary rocks of the Clew Bay Complex from high-grade Dalradian meta-sedimentary rocks, suggesting that this was a major detachment structure. In northern Connemara, the unconformity between the Dalradian and the Silurian cover probably represents an eroded major detachment surface, with the Renvyle–Bofin Slide as a related but subordinate structure. Blocks of sheared mafic and ultramafic rocks in the Dalradian immediately below this unconformity surface probably represent arc lower crustal and mantle rocks or fragments of a high level ophiolite sheet entrained along the detachment during exhumation.

Orogenic collapse was accompanied in the South Mayo Trough by coarse clastic sedimentation derived mostly from the exhuming Dalradian to the north and, to a lesser extent, from the Lough Nafooey Arc to the south. Sediment flow in the South Mayo Trough was dominantly axial, deepening toward the west. Volcanism associated with orogenic collapse (Rosroe and
Mweelrea Formations) is variably enriched in high field strength elements, suggesting a heterogeneous enriched mantle wedge under the new post-collisional continental arc.

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1. Introduction

Geochemical evidence from the bulk global composition of continental crust indicates that it was formed principally in subduction zone settings (e.g., Dewey and Windley, 1981; Ellam and Hawkesworth, 1988; Rudnick and Fountain, 1995). However, because of the loss of crust by tectonic erosion along many continental arc margins (e.g., Dewey, 1980; von Huene and Scholl, 1991), continued continental crustal growth must be largely achieved through the development of oceanic island arc complexes and their accretion to continental margins (Clift and Vannucchi, in press). Also, although arguments for subduction initiation along passive continental margins have been made (e.g., Erickson, 1993), arc–continent collision is also likely the principal origin for development of active continental margins (Dewey and Bird, 1970; Clift et al., 2003). The collision of Taiwan with the passive margin of southern China is the simplest known example of such a process in the modern oceans (e.g., Teng, 1990; Lundberg et al., 1997; Lallemand et al., 2001), yet, because of limited sampling in the adjacent Okinawa Trough and Ryukyu Arc, the rates of orogenesis, gravitational collapse and sedimentation in this area are known only in outline.

A well-dated example of arc–continent collision is known from the western Irish Caledonides. In the South Mayo Trough and adjacent metamorphic terranes of Connemara and North Mayo (Fig. 1), a clear Early Ordovician collision event between the Lough Nafooey Arc and the passive margin of Laurentia has been recognized (Dewey and Shackleton, 1984; Dewey and Ryan, 1990; van Staal et al., 1998; Dewey and Mange, 1999; Draut and Clift, 2001). New Guinea illustrates the Miocene collision of an arc with the north Australian continental margin (Davies et al., 1987). Here, arc/suprasubduction-zone ophiolite obduction developed the subjacent Bismarck Orogen, similar in size, duration and geology to the Grampian orogen (Dewey and Mange, 1999).

In this paper, we focus on the later stages of this collision by documenting the nature of orogenic collapse in this part of the Grampian orogenic belt. We further show how the tectonic and sedimentary processes that occurred during orogenic collapse are related directly to the changes in plate boundary zone strains linked to subduction polarity reversal.

2. Regional geology

The Lough Nafooey Arc forms the southern edge of the South Mayo Trough and comprises a series of earliest Ordovician basaltic lavas overlain by Tremadocian andesitic lavas and epiclastic breccias interbedded with pillowed flows, which are succeeded by an Arenig sequence of andesitic to rhyolitic lavas, breccias and volcaniclastic sediments. These rocks are associated with an ~ 6-km-thick series of Early-Middle Ordovician volcaniclastic and siliciclastic sedimentary rocks (Figs. 1 and 2). The sedimentary rocks in the South Mayo Trough accumulated prior to, during and after the arc–continent collision event. The oceanic Lough Nafooey Arc can be considered an along-strike equivalent of the Lushs Bight Arc of Newfoundland (e.g., Coish et al., 1982), and the Shelburne Falls Arc of New England (Karabinos et al., 1998). An up-section trend within the Lough Nafooey volcanic rocks to more siliceous and light rare earth element (LREE) enriched compositions is consistent with the arc colliding with the passive margin of Laurentia during the Early Ordovician (after 480 Ma; Draut and Clift, 2001). This is due to the progressively increasing recycling of LREE-enriched continental material through the subduction zone as the passive margin is subducted. Collision precipitated the Grampian Orogeny in the British Isles and the Taconic Orogeny in North America (e.g.,
Fig. 1. Regional geological map of western Ireland showing the Connemara and North Mayo metamorphic terranes separated by the South Mayo volcanic island arc terrane. The strike-slip faulted boundary between the Connemara and South Mayo terranes is buried under Silurian strata, while the Achill Beg Fault separates low grade arc and trench rocks of South Mayo from the high-grade rocks of North Mayo. CLW = Cashel–Lough Wheelan; DCD = Dawros–Currywongaun–Doughruagh.
Despite earlier work indicating a protracted Grampian Orogeny in Connemara (e.g., Elias et al., 1988; Cliff et al., 1996; Tanner et al., 1997), more recent studies have now demonstrated a duration of less than 15 m.y., with peak metamorphism at ~470 Ma in Connemara (Friedrich et al., 1999a,b; Dewey and Mange, 1999). Ar–Ar dating of the main nappe fabric in the Ox Mountains Dalradian suggests that cooling had started by at least 460–450 Ma in this area (Flowerdew et al., 2000). The Connemara and North Mayo Dalradian metamorphic terranes are considered to be metamorphosed fragments of the Laurentian margin (e.g., Lambert and McKerrow, 1976; Dewey and Shackleton, 1984; Harris et al., 1994). Connemara is now displaced from its original location and lies along strike and south of the units that comprise the Lough Nafouey Island Arc. This displacement cannot be the result of southward thrusting of high-grade Connemara over South Mayo because much of this has never exceeded anchi-metamorphic conditions. Rather, the position of Connemara today must have been achieved by post-Grampian strike-slip tectonism that affected the Laurentian margin [e.g., the Southern Uplands Fault, the Fair Head-Clew Bay Line (equivalent to the Highland Boundary Fault in Scotland) and the Great Glen Fault; Hutton, 1987].
The Connemara Terrane have reached close to its modern position before the Late Llanvirn to Lower Llandovery (464–443 Ma) based on current and provenance data from the Derryveeny Conglomerate (Graham et al., 1991). Additional later Silurian and Devonian strike-slip faulting through Clew Bay also displaced the South Mayo Trough relative to the North Mayo Dalradian (Hutton, 1987), but the amount of displacement was probably not large (Ryan et al., 1995).

Connemara is one of the best-dated segments in the Caledonian–Appalachian Orogen and differs from the North Mayo Dalradian in that the meta-sedimentary rocks are intruded by a number of Early-Mid Ordovician gabbros and quartz diorites (Leake, 1989). Trace element and Nd isotopic geochemical evidence shows that these gabbros were emplaced in a subduction setting, with substantial involvement of new mantle melts, relative to crustal recycling, in their petrogenesis (Draut et al., 2002, in press). Therefore, the Connemara Dalradian can be interpreted as both the deformed margin of Laurentia and the mid-crustal roots to a syn-collisional volcanic arc (e.g., Yardley et al., 1982).

Following peak metamorphism in the Connemara Dalradian, radiometric dating indicates that the orogen experienced rapid cooling (>35 °C/m.y.; Friedrich et al., 1999a,b), typically explained as a response to orogenic collapse. Power et al. (2001) used fluid inclusion techniques to estimate rates of exhumation in Connemara of at least 7 km in 10 m.y., similar to modern massifs that exhibit the fastest exhumation rates (e.g., Nanga Parbat; Zeitler et al., 1993). We now explore the exhumation and orogenic collapse of the Irish Dalradian and assess implications for the tectonic evolution of this area and for the process of arc–continent collision.

3. Detachment faulting

Low-angle extensional faulting synchronous with thrust faulting has been recognized as a common tectonic process during and immediately following orogeny. In the High Himalaya, high-grade metamorphic rocks were exhumed by orogen-perpendicular extension beneath the Zanskar and South Tibetan Detachments, synchronous with thrusting (e.g., Herren, 1987; Burchfiel et al., 1992). In western Norway, high-pressure and ultrahigh-pressure metamorphic rocks were exhumed beneath a gently dipping late orogenic detachment (Dewey et al., 1993). A similar situation is envisaged for the Irish Dalradian.

In Connemara, exhumation is also achieved by synchronous thrusting and detachment faulting that combine to extrude deeply buried meta-sedimentary rocks to the surface. The Mannin Thrust places the Dalradian towards the south over anchizone metarhyolites of the Delaney Dome Formation (Fig. 1), a deformed equivalent of the syn-collisional arc sequence, the Tourmakeady Volcanic Group (Dewey and Mange, 1999; Draut and Clift, 2002). This Delaney Dome arc fragment must have been transposed into its present location with the Connemara Dalradian, after the Grampian Orogeny. South southeasterly motion on the Mannin Thrust may be constrained relative to the formation of other regional structures, post-dating the D3 fabric and pre-dating the D4 fabric defined by Leake et al. (1983) and Tanner et al. (1989). Movement on the thrust is indirectly constrained by isotopic dating of the syn-orogenic arc intrusive rocks to 470–462 Ma (Friedrich et al., 1999b) and is considered to date from the period of rapid cooling in Connemara, i.e., post-dating peak metamorphism. Motion on the Mannin Thrust may have been related to the early phases of subduction polarity reversal (Dewey and Mange, 1999). Identification of related extensional detachment has been more controversial. We present here newly recognized evidence for major detachment faults in North Mayo and Connemara.

3.1. Detachment faulting in North Mayo and Achill Island

A key feature of all major detachment systems is the presence of a significant metamorphic contrast, with low-grade rocks in the hanging wall and higher-grade exhumed rocks in the footwall. Across Clew Bay, a clear difference in grade has long been recognized between the low-grade South Mayo Trough and the higher-grade Dalradian in North Mayo. Much of the contact is covered by Silurian and Carboniferous sedimentary rocks (Fig. 1), except on the island of Achill Beg, located in NW Clew Bay (Figs. 1 and 3), where a major high-angle fault, the Achill Beg Fault,
Fig. 3. Geological map of Achill Beg Island and the boundary between the relatively low-grade metamorphic rocks of the South Achill Beg Formation, essentially part of the Clew Bay Accretionary Complex and the high-grade rocks of the North Mayo Dalradian. Section through A–A' is shown in Fig. 4. Modified after Chew (2001).
places accretionary complex sedimentary rocks of the Clew Bay Complex under the youngest Dalradian rocks seen in the North Mayo inlier—the upper Argyll Group (Chew, 2003). Although the Fault has been reactivated since the Carboniferous (Chew et al., in press), both the Clew Bay Complex and the Dalradian on Achill Beg show a dominant northerly dipping structural fabric (45–60°N; Fig. 4), as does the Clew Bay Complex on the southern edge of Clew Bay, west of Westport (Fig. 1).

Gravity (Ryan et al., 1983) and deep-penetrating reflection seismic (Klemperer et al., 1991) studies show that the Clew Bay Complex is associated with a north-dipping fabric that can be traced to the Moho, implying that post-orogenic extension affected the whole of the continental crust. At outcrop, the north-dipping fabric is observed to be a penetrative shear fabric within metamorphosed clastic sedimentary rocks. Furthermore, to the north, Dalradian metamorphic rocks of North Mayo (now in the hanging wall of this structure) preserve an earlier south-dipping fabric that is not observed south of Clew Bay that is attributed to the Grampian event. These fabrics are consistent with structural arguments about the initial vergence of the Grampian nappes, i.e., the top to the north tectonic transport during D1 and D2 at least in South Achill Island (Fig. 5C).

The northern boundary of the Achill Beg Shear Zone, which we tie to D3 and D4 deformation during cooling, is not sharply defined, but instead, D3 structures become gradually less intense to the north. Two discrete elements have been recognized in the D3 deformation episode in North Mayo and Achill Island: asymmetrical buckle folds with axial planes anticlockwise to the S2 foliation (Figs. 5A and C) and extensional crenulation cleavages (Platt and Vissers, 1980) that cut the S2 foliation in a clockwise sense (Chew et al., in press). The main S2 foliation is generally defined by muscovite, chlorite and equigranular quartz grains with interlobate grain boundaries. The later extensional crenulation cleavages make an angle of about 29° with the S2 foliation in a clockwise direction (Fig. 5B) and consistently give a dextral sense of shear. Identical in style to the normal-slip crenulations of Dennis and Secor (1990), they are believed to be broadly contemporaneous with the F3 asymmetric buckle folds based on the absence of apparent overprinting relationships. On a vertical surface, the extensional shear bands give a

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**Fig. 4.** Geological cross section through Achill Island (after Chew, 2001) showing the south-vergent asymmetry of the D2 deformation in the Dalradian, contrasting with the NNW-vergent D1 deformation. See Fig. 3 for location of section. Modified after Chew (2001).
down to the south shear sense, consistent with a detachment fault of this orientation.

Near Westport, Graham et al. (1989) mapped the accretionary complex rocks of the Clew Bay Complex as dipping north and structurally overlying the rocks of the South Mayo Trough. This is unusual because given the geometry of modern accretionary complexes, the forearc basin might be expected to overlie the accretionary wedge, whose tectonic fabric would dominantly parallel the dip of the subduction zone, i.e., dip towards the arc volcanic front, not away from it, as it does in the modern setting. The current steep north-
dipping fabric of the Clew Bay Complex implies shear and accretion in a north-dipping subduction zone, inconsistent with the subduction polarity inferred from the South Mayo Trough and with the relative location of the arc volcanic rocks of the Lough Nafooey and Tourmakeady Volcanic Groups. The modern dip of the tectonic fabric within the Clew Bay Complex and its overlying relationship with the South Mayo Trough can, however, be understood if it is recognized that the entire region has been tilted and overturned following exhumation, as a result of the D3 dextral shearing described above.

Fig. 7 shows the proposed model in which the region around northern Clew Bay has been rotated, while not apparently affecting the main part of the South Mayo Trough. Likely, the rotation is linked to transpressional deformation, whose age is not constrained by this study. Sedimentary structures and biostratigraphy along the northern arm of the South Mayo Trough demonstrate that this is not overturned, although the strata may have been more north-dipping when originally deposited. The contact between the strongly rotated Clew Bay region and the South Mayo Trough is now covered by Silurian sequences exposed west of Westport (Fig. 1). Their location in this belt may reflect the presence of a major fault in that area, decoupling the South Mayo Trough and the Clew Bay Complex.

Hence, prior to late Grampian (D3) dextral shearing, the present-day subvertical, north-dipping Dalradian...
nappes would have originally been flat-lying along the northern margin of Clew Bay (e.g., Sanderson et al., 1980; Chew, 2003; Fig. 4). Consequently, we infer that the original dip of the Achill Beg Fault and the tectonic fabric of the Clew Bay Complex were not steeply towards the north but, instead, towards the south. In this reconstructed orientation, the Clew Bay Complex along the southern edge of Clay Bay dips southward under the South Mayo Trough, consistent with accretion in a south-dipping subduction zone. Also, on Achill Beg, the low-grade Clew Bay Complex (Fig. 6C) would have originally overlain the high-grade Dalradian (Fig. 6B), thus implying late extension not shortening across the Achill Beg Fault. Brittle, late-stage shear-sense indicators along the fault (Fig. 6A) that indicate a thrusting motion in the present sense (i.e., top to the SSE; Fig. 5A) imply a top to the south-southeast extension after restoration.

Once the effects of later deformation have been removed, the original geometry of the collision zone in the region is more apparent. The dominant, high-strain deformation event in North Mayo (D1) is associated with bedding-parallel shear zones with a NNW-directed transport direction (Chew, 2001, 2003). In contrast, the D2 event that caused much of the large-scale folding observed has a clear southward vergence. NNW-directed transport in the Dalradian and Clew Bay Complex is consistent with a collision between a passive margin and a south-dipping subduction zone (Dewey and Ryan, 1990). That the upper Argyll Group meta-sedimentary rocks are juxtaposed against the Clew Bay Complex also make geodynamic sense in that these are recognized as the youngest units within the Dalradian stratigraphy in western Ireland. Consequently, it is the Clew Bay Complex and the upper Argyll Group meta-sedimentary rocks of the North Mayo Dalradian that would have been immediately overthrust by the accretionary wedge of a colliding arc. Having been overthrust, deformed and meta-

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**Fig. 7.** Diagram showing how rotation about a horizontal axis, driven by transpressional tectonics in the Clew Bay area, may have caused the reversal of dip on the Achill Beg Fault, as well as placing the Clew Bay Complex enigmatically over the South Mayo Trough. Restoration of this region to their original orientations results in tectonic relationships more consistent with what is known from modern subduction zone.
morphosed, the upper Argyll Group was still at the top of the Dalradian structural stack when a detachment fault, exploiting a location close to, or along the original overthrust, brought the upper Argyll Group back to the surface.

3.2. Detachment faulting in Connemara

The nature of detachment faulting in northern Connemara has been a source of controversy. Wellings (1998) proposed that extension along an east-west trending, north-dipping tectonic discontinuity through northern Connemara, known as the Renvyle–Bofin Slide, was responsible for exhumation of the main Dalradian of the Twelve Bens, whereas Williams and Rice (1989) favored a role for low-angle extensional faults south of Connemara. Although the Renvyle–Bofin Slide is a major extensional structure, it is not considered to be the master structure because no major metamorphic break is observed across it. Because of the strike-slip emplacement of Connemara south of the South Mayo Trough, it is possible that the original root zone of the detachments was not preserved within this block or has been buried by later sedimentation. By comparison with North Mayo, a detachment might be expected to separate high-grade rocks in Connemara from a lower grade arc towards the south, similar to the model proposed Williams and Rice (1989). This southern repeat of the arc is not well preserved, but is likely represented by the rhyolites of the Delaney Dome Formation that correlate with the arc volcanic rocks of the Tourmakeady Formation (Dewey and Mange, 1999; Draut and Clift, 2002). However, the hypothesis that detachment faults in Connemara should lie along its southern edge assumes that the Connemara block has not been rotated within the strike-slip zone since exhumation. Paleomagnetic and GPS studies of active strike-slip margins clearly demonstrate that major block rotations are to be expected in such areas (e.g., Transverse Ranges, California, Nicholson et al., 1994; Aegean Sea, Clarke et al., 1998). Indeed, the top-to-the-north geometry of the Renvyle–Bofin Slide and the southward motion on the Mannin Thrust are consistent with a major north-dipping detachment along the northern edge of the Connemara Dalradian. This scenario also compares closely with the High Himalaya exhumation along a southward-verging Main Central Thrust and a northward extending South Tibetan Detachment, both with north-dipping geometries.

We propose that fragments of a detachment surface are mapped close to and along the unconformity between the Dalradian and the overlying Silurian sedimentary rocks, along the northern edge of Connemara (Fig. 8). There is a preferential development of serpentinite, ultramafic and mafic blocks along, and just south of this contact but not within the main outcrop of the Connemara Dalradian. These mafic and ultramafic rocks, which include coarse-grained gabbros (Fig. 5D), occasionally cut by dykes of ophitic meta-dolerite, form coherent, relatively undeformed pods 10–200 m across, surrounded by strongly sheared Dalradian metasedimentary rocks.

The coarse-grained character of most of the gabbro blocks (grains >1 cm across) is inconsistent with an alternative origin in which the small mafic bodies were intruded into the sedimentary rocks and then deformed. The coarse grain size of some of the gabbros indicates original slow cooling within a large intrusion, followed by tectonic dismembering. In this respect, they contrast with the clearly intruded, kilometer-scale Cashel–Lough Wheelan and Dawros–Currywongaun–Doughruagh gabbro bodies (Leake, 1986; Fig. 1), although some smaller intrusions, complete with chilled margins, related to these larger bodies are also noted. Furthermore, the fact that such mafic and ultramafic bodies are only found either close to the unconformable northern contact of the Connemara Dalradian or close to the Achill Beg Fault is difficult to reconcile with an original intrusive origin. The serpentinized peridotites, moreover, have a tectonized internal texture consistent with a mantle origin rather than as an ultramafic intrusive. Because the bulk of the Dalradian outcrop comprises metasedimentary rocks, the occurrence of small mafic and ultramafic rocks only at the structural top suggests that these have been emplaced tectonically.

We suggest that the unconformity represents an exhumed and partly eroded detachment surface. In this scenario, the presence of lower crustal or mantle rocks can be explained as blocks entrained along a crustal scale structure that brings Dalradian rocks to
the surface from beneath the colliding arc. The hanging wall was completely removed and the exposed metamorphic rocks were covered by the fluvialite Silurian Lough Mask Formation. This relationship might be consistent with a “rolling hinge” type of detachment (Buck, 1988). Metamorphic core complexes in the US Basin and Range and those on slow-spreading mid-ocean ridges expose deeply buried rocks at the surface where they may be eroded and transgressed by sediments.

The marine Kilbride and Lettergesh Formations, which transgress over the Dalradian, are dated as

Fig. 8. Geological map of the NW Connemara coast showing the Early Silurian Kilbride and Lettergesh Formations lying unconformably over Dalradian metasedimentary rocks. Note the preferential occurrence of mafic and ultramafic pods along the unconformity contact.
Upper Llandovery (435–420 Ma) implying a significant hiatus between the time of most rapid cooling (470–455 Ma; Friedrich et al., 1999b) and final transgression. However, this time gap may be less than it initially appears. Although the rocks cooled rapidly through the biotite Ar closure temperature (~ 300 °C; Lovera et al., 1989), exhumation at shallower levels after 455 Ma below the closure temperature could have continued at slower rate. This would reduce the amount of time that the detachment would have been exposed at the surface and subject to erosion prior to Silurian transgression.

### 4. Sedimentary response to collapse

Orogenic exhumation in western Ireland was accompanied by erosion, resulting in rapid, coarse-grained sedimentation preserved as the Rosroe, Maumtrasna and Derrylea Formations within the South Mayo Trough (Fig. 2). On the south side of the South Mayo Trough, the Rosroe Formation is dated as Early Llanvirn (lower artus graptolite zone, 467–464 Ma according to the time scale of Tucker and McKerrow, 1995). It comprises very coarse conglomerates and sandstones, including abundant granite and volcanic clasts (Archer, 1977; Fig. 9B–D). The Rosroe Formation was interpreted originally to represent the deposits of large submarine fan deltas eroding a volcanic and plutonic arc source south of the modern outcrop region (Fig. 1; Archer, 1977, 1984). The Rosroe Formation has been correlated with the Derrylea Formation on the northern limb of the South Mayo Trough (Dewey, 1963; Dewey and Ryan, 1990; Fig. 2), although Williams (2002) considered the Derrylea Formation to have been a separate system, deposited in a different subbasin. Up-section, the depositional environment of the South Mayo Trough shallows, culminating in the middle Llanvirn Mweelrea Formation, which comprises a >3-km-thick package of west-flowing fluvial sandstones derived from a rapidly eroding Dalradian source (Pudsey, 1984).

The sedimentary system in western Ireland related to Dalradian exhumation bears many similarities in terms of facies and relationships to related tectonic units with the sedimentation associated with exhumation in the Taiwan arc–continent collision zone. In Taiwan, alluvial fans derive material from the exhumed metamorphic rocks of the Central Ranges, where sediment eroded from the collisional orogen is washed along-strike from the alluvial Ilan Plain, through the Huapingshu Canyon into the post-orogenic collapse basin of the Okinawa Trough (e.g., Yu and Hong, 1993). A depositional model for the South Mayo Trough featuring two canyons, one in the center and one in the east of the southern margin of the basin (Archer, 1977), is consistent with this modern analogue. Pleistocene sedimentation rates in the southern Okinawa Trough exceed 325 cm/k.y. at ODP Site 1202 (Salisbury et al., 2001). In comparison, Graham et al. (1989) estimated 1350 m of Rosroe Formation deposited at 464–467 Ma, a long-term average rate of >45 cm/k.y., also a very high rate of accumulation.

Lundberg and Dorsey (1990) demonstrated that rapid Quaternary uplift of the Coastal Range, interpreted as a fragment of the accreted Luzon Arc (e.g., Dorsey, 1992), has resulted in proximal sedimentation in the Longitudinal Valley overlying the accreted arc and forearc. The Longitudinal Valley is thus comparable with the syn-collisional South Mayo Trough. Although erosion rates in the Coastal Range are high, those in the higher and more extensive Central Range of the Taiwan Orogen are greater and contribute the bulk of the sediment reaching the Okinawa Trough (Lundberg and Dorsey, 1990). This parallels the situation in South Mayo where a rapid influx of material eroded from the exhuming Dalradian metamorphic rocks is found throughout the basin, recognized on the basis of the high-grade metamorphic minerals (Dewey and Mange, 1999), as well as the Pb isotopic composition of the detrital K-feldspar grains (Clift et al., 2003).

#### 4.1. Source of sediment

The provenance of sediment during orogenic collapse in the Irish Caledonides has been a source of controversy. Apart from the apparent arc source to the Rosroe Formation, Dewey and Shackleton (1984) recognized the influx of ophiolitic material in the upper parts of the South Mayo Trough, which they related to the progressive unroofing of the forearc basement, now preserved as the Deer Park Complex,
a mafic/ultramafic part of the Clew Bay Complex (Fig. 1). Chemical data from the sediments of the South Mayo Trough (Wrafter and Graham, 1989) show a progressive increase in Cr, Ni and Mg up-section into the Derrylea Formation, although these values drop in the middle of this unit. Dewey and Mange (1999) correlated this drop with the first appearance of high-grade metamorphic minerals (garnet, hornblende, staurolite and sillimanite) in the middle of the Rosroe and Derrylea Formations, which they related to an initial influx of detritus from a newly exposed Dalradian source located to the north, i.e., North Mayo. The sudden arrival of staurolite in the upper Derrylea Formation, following erosion of an ophiolitic source, suggests rapid exhumation of the deformed Laurentian passive margin within a metamorphic complex.

Clift et al. (2002) examined the trace element composition of granite boulders and the Pb isotopic character of K-feldspar grains in the Rosroe Formation and inferred a Laurentian (i.e., Dalradian, rather than an arc) source, in accordance with the model of Dewey and Mange (1999). These boulders are mainly of high-level quartz-rich, minimum melt type granites that were, presumably, part of the cover to the collapsing metamorphic pile. Paleo-current analysis suggested that the Dalradian source was located towards the NE, i.e., North Mayo (Fig. 9).
At outcrop, the provenance of the Rosroe and associated formations is apparent. Along the southern edge of Killary Harbour, the boulder conglomerates are dominated by granite clasts with only minor lava fragments (Fig. 9C). In contrast, at Lough Nafooey, the proportion of lava, both fresh and altered, is much higher (Fig. 9B). Both types of deposit contrast with the younger (Llanvirn to Lower Llandovery; 464–443 Ma) Derryveeny Conglomerate (Figs. 2 and 9D), which contains abundant schist and foliated granite clasts and granites similar to those seen in the Rosroe Formation. The provenance of sediments deposited during exhumation is not uniform, but shows a dominant influx from the North Mayo Dalradian and equivalent sources to the NE (e.g., Ox Mountains, southern Donegal), with variable, subsidiary input from the Lough Nafooey Arc.

4.2. Sediment transport

The patterns of sediment dispersal during exhumation were summarized by Dewey and Mange (1999) and Clift et al. (2002) (Fig. 10), combining paleocurrent data from across the South Mayo Trough.
Although some S–N flow is apparent along the southern edge of the basin, a more axial flow towards the west is seen in the central parts of the trough. Williams (2002) argued that the presence of finer-grained rocks in the Derrylea Formation, north of the boulder conglomerates of the Rosroe Formation, precluded a sediment source to the north of the trough. However, if the sediment flux is dominantly axial, lateral changes in grain size could simply reflect differences in tectonic subsidence rates focusing coarser sediments into the depocenters. The sedimentary facies support the idea of basin deepening and fining towards the SW. Fig. 9A shows the sands and shales of the Rosroe Formation close to Rosroe village (Fig. 1). These channel sands imply a more distal, deeper water environment than the dominant fanglomerate facies observed further east and north (Fig. 9B and C).

5. Magmatic response to collapse

Orogenic collapse and the establishment of an active margin following the Grampian Orogeny was accompanied by continued volcanism preserved as tuffs within the Rosroe and overlying Mweelrea Formation (Fig. 2). Like the preceding Tourmakeady Volcanic Group, which was erupted prior to and during peak metamorphism, these are high-silica tuffs, up to 75% SiO₂ (Clift and Ryan, 1994). Draut and

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Fig. 11. Trace element discrimination diagram showing the wide range of REE and HFSE enrichment in tuffs from the Rosroe and Mweelrea Formations compared to similar post-orogenic lavas from Taiwan (data from Chen et al., 1995; Shinjo, 1999). Note that lavas from both these settings are very enriched in HFSEs compared to either the continental crust average and to oceanic arc melts. Tonga field is for a range of major element glass compositions erupted since 7 Ma (Clift and Dixon, 1994). Tourmakeady and Lough Nafooey Group data are from Draut and Clift (2001). Compositions of N-MORB, mantle and average continental crust are from Rudnick and Fountain (1995).
Clift (2001) demonstrated that, whereas the Rosroe and Mweelrea tuffs show similar high light rare earth element (LREE) enrichment compared with the Tourmakeady Volcanic Group, they have a wider range of relative enrichment in the high field strength elements (HFSE; Fig. 11). Williams (2002) suggested that the tuffs of the Rosroe Formation were erupted in an oceanic island arc, but a comparison between siliceous volcanic glass from a typical Neogene oceanic arc, such as Tonga, and the Rosroe Formation shows that the Rosroe Formation is much more enriched in REEs and HFSEs. In contrast, there is a significant overlap between the Lough Nafooey Group, erupted before arc–continent collision, and the Tonga Arc. Draut and Clift (2001) linked this change from the basaltic, LREE-depleted Lough Nafooey to high-silica, LREE-enriched Rosroe chemistry with the arc–continent collision.

The degree of continental crust recycling through the collisional arc is best demonstrated through the application of isotope chemical techniques, which are not affected by fractional crystallization, as are the REEs and HFSEs. Neodymium isotope data show that magmatism during orogenic collapse in South Mayo involved significant remelting of the continental crust. Initial \( ^{143} \text{Nd} / ^{144} \text{Nd} \) values of \(-8.4\) to \(-10.6\) reported by Draut and Clift (2001) from the Tourmakeady Volcanic Formation, Rosroe Formation and Mweelrea Formation (472–466 Ma) require significant mixing of radiogenic continental crust (Dalradian \( ^{143} \text{Nd} / ^{144} \text{Nd} \approx -12 \) to \(-22\); O’Nions et al., 1983; Frost and O’Nions, 1985; Jagger, 1985) with a typical oceanic end member with \( ^{143} \text{Nd} / ^{144} \text{Nd} \) values of \(+8\) to \(+10\). The wide range of HFSE and LREE enrichments observed in the Rosroe and Mweelrea Formation tuffs points to a very heterogeneous source compared with even the syn-collisional Tourmakeady Volcanic Group. The scatter may reflect involvement of more enriched mantle sources contrasted to that feeding the Tourmakeady Volcanic Group. Extensional collapse of the orogen coupled with subduction polarity reversal would change the flow of mantle under the orogen and could draw in less depleted mantle material under the volcanic arc. Alternatively, gravitational loss of a dense arc lower crust during collision could also provide space for upwelling and influx of fresh mantle material under the volcanic roots of the arc.

6. Discussion

The processes and effects of extensional collapse in the Irish Caledonides after the Grampian Orogeny bear similarities to other documented collisional belts (Dewey, 1988), especially the Taiwan–China collisional orogen (Teng, 1996; Lee et al., 1997). Taiwan, like the Grampian Orogen, is an oceanic arc–continental collisional environment involving subduction polarity reversal and exhumation of a metamorphosed continental margin sequence through the action of major detachment faulting (Teng, 1996; Clift et al., 2003). In Taiwan, the new continental Ryukyu island arc is built on the remnants of the oceanic Luzon Arc. In Connemara, the arc volcanic front of the succeeding continental arc is not exposed, but is known along strike in Newfoundland as the Notre Dame Arc. The lack of the arc in Ireland is presumed to reflect tectonic excision during margin-parallel strike-slip faulting. The Southern Upland accretionary complex exposed in Scotland and Northern Ireland provided evidence that a north-dipping subduction zone was developed along this part of the Laurentian margin (van Staal et al., 1998; Leggett et al., 1983).

Several tectonic processes may drive extensional collapse following the metamorphic peak. Dewey et al. (1993) invoked lower crustal loss to explain rapid surface uplift and post-orogenic extension along major detachment faults following eclogitization in the Norwegian Caledonides. Subsequently, Krabbendam and Dewey (1999) invoked exhumation of the Norwegian eclogites in a sinistral transtensional pull-apart setting. We consider both of these models to be highly unlikely for exhumation in western Ireland. In any case, because no arc lower crustal rocks are exposed in western Ireland, any such hypothesis would be speculative. Geophysical modeling of different lower crustal lithologies and thermal regimes raises the possibility of lower crustal loss and surface uplift even without the formation of eclogite in arc settings (Jull and Kelemen, 2001). However, Clift et al. (2003) calculated that, given typical ocean arc crustal thicknesses (20–25 km), loss of an ultramafic lower crust that had not been eclogitized could be expected to drive <10\% of the topography in a collisional range. Thus, other tectonic mechanisms may be required to explain the degree of exhumation observed in western Ireland (>25 km; Friedrich et al., 1999b).
Orogenic extension is caused by the topographic load, facilitated by the low viscosity of the orogenic lower crust. For the collision of an oceanic arc into a rifted continental margin, once the compressive forces that formed the mountains are released from the thrust belt by renewed subduction following polarity reversal, there is a tendency for the structural stack to collapse and extend under its own weight. The trench thus forms a free space into which the orogen can collapse, especially if aided by subduction rollback (Dewey, 1980), triggering extension of the deformed arc and passive margin sequences (Fig. 12; Teng, 1996). Detachment faulting is a common feature in the Dalradian of the British Isles, where exposure has permitted its recognition. Farther northeast of our focus area, the Dalradian rocks in both the Ox Mountains Inlier and southern Donegal are exhumed along reactivated shear zones (the North Ox Mountains Slide, Flowerdew, 1998; the Lough Derg Slide, Alsop, 1991; Alsop and Hutton, 1993). In northwest Scotland, Powell and Glendinning (1990) documented the reactivation of thrusts as extensional faults, similar to our proposed motion on the Achill Beg Fault.

It is possible that some juxtaposition of high and low-grade rocks in the Clew Bay region is caused by Silurian sinistral strike-slip faulting. Such faulting is pervasive in parts of Clew Bay, but does not, by itself, explain the key juxtaposition of high- and low-grade units that requires greater relative exhumation in North Mayo and Achill Island, compared with the South Mayo Trough. Most of the cooling in Connemara and North Mayo is, moreover, too old to have been driven by the younger strike-slip faulting.

Sedimentation during exhumation was dominated by erosion of the metamorphosed continental margin series (Dalradian Supergroup). Although the cooling ages (460–450 Ma; Flowerdew et al., 2000) of the Ox Mountain Dalradian are slightly younger than the age of Rosroe sedimentation (467–464 Ma), this discrepancy may reflect moderate along-strike variability in the timing and rate of exhumation. This is, however, not required because the rocks now exposed in North Mayo are clearly not the source of the sediment but represent deeper levels of the source that was being eroded at the time of deposition of the Rosroe Formation. Geodynamic models of mass motion through orogenic belts (e.g., Willett et al., 1993; Royden, 1996) suggest that erosion can result in large fluxes of material from the subducting/colliding plate (in this case Laurentia), without erosional unroofing of any deeper structural level at any one place through time. Thus, the cooling ages of detrital minerals within the eroded sediment series would become younger up-section. The cooling age preserved at the surface in the source terrain after the end of rapid post-orogenic sedimentation will record the time when that package of igneous or metamorphic rock passed through the closure temperature of the minerals analyzed. This age must postdate the start of sedimentation. Depending on whether the source cooling is driven by erosion or tectonic exhumation, the cooling age of that source may also postdate the end of sedimentation in a syn-orogenic basin, especially if this becomes filled, so that additional eroded sediment will not accumulate but, instead, is transported oceanward and/or along strike.

7. Conclusions

Orogenic collapse of the Grampian Orogeny in western Ireland is inferred to have been rapid, with radiometric data suggesting 10–15 km of exhumation achieved between 470 and 460 Ma (Friedrich et al., 1999b; Power et al., 2001). We propose that rapid exhumation resulted from detachment faulting. A south-dipping, now overturned, north-dipping Achill Beg Fault is considered to represent a key structure unroofing the North Mayo Dalradian from under the low-grade rocks of the Clew Bay Complex and South Mayo Trough. In Connemara, the hanging wall of the detachment is not preserved, but the detachment surface corresponds, at least locally, to the Silurian unconformity along the north side of the Connemara Dalradian. Mafic and ultramafic blocks
485 Ma
Active oceanic subduction

480 Ma
Start of arc-continent collision
Compression and metamorphism

470 Ma
Exhumation of metamorphic rocks

450-440 Ma
Later marine transgression over eroded detachment

Lough Nafooey Arc
South Mayo Trough
Claw Bay Accretionary Complex
Laurentian passive margin
Laurentian craton

S
sealevel
Arc upper crust
Oceanic crust
continental crust

Arc lower crust and mantle
entrained along the detachment fault are now preserved along the unconformity. The Renvyle–Bofin Slide is considered to be a subordinate structure to this master detachment. Alsop (1991) and Flowerdew et al. (2000) have described similar exhumation along strike in the Grampian Orogen. It is likely that Ordovician exhumation occurred in the Taconic Belt of the Northern Appalachians from New York to Newfoundland. To date, such exhumation structures have not been described in detail, although Silurian–Devonian external detachments have been recognized in Vermont (Karabinos, personal communication, 2003).

Our basic model is that extensional collapse and exhumation in western Ireland was facilitated and caused by the change in stress driven by subduction polarity reversal, quite dissimilar from the transnational exhumation of eclogites documented in the Silurian of Norway (Krabbendam and Dewey, 1999). Influx of metamorphic detritus into the South Mayo Trough at 467–464 Ma marked the start of exhumation, with most sediment derived from the deformed Laurentian margin rather than from the colliding volcanic arc. Erosion was rapid and shed debris into a marginal-parallel trough as fan deltas, feeding submarine fans that flowed towards the west. Synchronous magmatism showed extreme HFSE and LREE enrichment contrasted to earlier volcanism. Volcanic chemistry implies petrogenesis in a continental subduction setting, with a heterogeneous, locally enriched upper mantle source.

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