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THE GEOLOGY OF THE KILBRIDE PENINSULA AND ADJACENT AREAS, COUNTY MAYO, AND ITS SIGNIFICANCE FOR REGIONAL GEOLOGICAL MODELS

JOHN R. GRAHAM and MICHAEL BADLEY

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Abstract

A new geological map and a partly revised lithostratigraphy are presented for the Kilbride Peninsula and the area immediately to the north in County Mayo in the west of Ireland. Volcanic arc rocks of the Lough Nafooey Group are unconformably overlain by late Floian mudrocks that were deposited after the cessation of volcanic activity and which did not receive any detritus from the Lough Nafooey arc. The unconformably overlying Darriwillian Rosroe Formation is similar in character to areas immediately to the west and north-east and shows a coarsening upward pattern. A south dipping Silurian succession everywhere masks the contact between the Lough Nafooey Group and the metamorphic rocks of Connemara. The Silurian succession shows progressive deepening from terrestrial sediments at the base to deep-water turbidites in the youngest strata seen. There are also important provenance changes throughout the Silurian succession. A widespread alkaline lava near the base is the only thick volcanic horizon seen in the succession. The structural geometry suggests that two large fault features (the Doon Rock and Clonbur faults) acted as a linked system during sedimentation and may have produced a point source for a clastic sediment fan of latest Ordovician or early Silurian age. This feature, termed the Derryveeny fan, contains coarse-grained metamorphic detritus from erosion of Connemara further to the south. A marked strike swing of the Silurian strata is attributed to post-Wenlock SSE directed contraction with reverse reactivation of the Derry Bay and Lettereeneen faults and associated deformation of their respective footwalls.

Introduction

South Mayo occupies a unique position in the Irish and British Caledonides in preserving Ordovician and Silurian sedimentary and volcanic rocks between outcrops of a Laurentian cover sequence (Dalradian Supergroup) that was deformed and metamorphosed by the Grampian Orogeny and now lies both to the north and the south. The region comprises early Ordovician volcanic arc rocks, a major early-mid Ordovician sedimentary basin and three different Silurian successions (Fig. 1).

The area considered here represents the easternmost outcrop of the southernmost Silurian succession, the Killary Harbour Joyce Country (KHJC) succession. The KHJC succession shows a marked strike swing from near east-west to almost north-south and there are indications from the airborne geophysical data (Tellus Data, Geological Survey Ireland) that there is a corresponding swing in the concealed basement rocks.

Just to the north-east of South Mayo in the south-west Ox Mountains there is also evidence for an important early Devonian (Lochkovian; 412 $\pm$ 0.8 Ma Chew

Fig. 1—Simplified geology of western Ireland showing the location of the study area. Ticks around margins of main geological map compilation refer to Irish National Grid. General location of study area in western Ireland indicated by box in map of Ireland (top left).

and Schaltegger 2005) granitic complex and small Devonian sedimentary basins associated with a major sinistral shear zone. It has recently been shown that much of the strong deformation affecting the Silurian rocks further north in the Croagh Patrick succession is of early Devonian age (Graham and Riggs 2021).

Understanding the nature and deformation history of these various elements is necessary to produce a coherent model of the evolution of this south-eastern margin of the Laurentian continent. The aims of this paper are to present a detailed map of the Kilbride Peninsula (Fig. 2) along with some modifications to the regional lithostratigraphy, particularly of the Silurian rocks and to describe and interpret the post-Wenlock structural development with reference to regionally established structural phases. This work is based primarily on a careful examination of the available field evidence and grid references cited throughout this report refer to the Irish National Grid. Elements concerning the Ordovician history have been discussed recently (Graham 2019) and are not the main concern of this contribution.

Stratigraphy

Lough Kilbride Formation

This consists everywhere of crushed and retrogressed impure psammites and semi-pelites with occasional lenses of metamorphosed ultrabasic rock. Whilst generally assigned to the Dalradian Supergroup, it is not clear how this unit fits into the established regional Dalradian lithostratigraphy (Leake 2014). It is faulted against the Ben Levy Formation which is thought to be part of the Southern Highland Group (Leake 2014). Graham *et al.* (1991) noted the presence of migmatites and discussed the minor differences between these and the clasts in the Derryveeny Formation.

Lough Nafuoey Group

The rocks of the Lough Nafuoey Group have been described by Gardiner & Reynolds (1912), Ryan *et al.* (1980) and Graham (2019). All three constituent formations are present on the Kilbride Peninsula and only a few points are noted here. The

Fig. 2—Geological map of the Kilbride Peninsula and Derry Bay area, with Paleozoic lithostratigraphic key on the left. DBF = Derry Bay Fault and DRF = Doon Rock Fault. Irish National Grid shown.

oldest unit (the Bencorragh Formation) displays the most primitive basaltic compositions. The overlying Finny Formation is more andesitic in nature with common volcanoclastic horizons. The youngest Knock Kilbride Formation marks a return to predominantly basaltic compositions, but with some rare acidic quartz-bearing levels in the upper part. Graham (2019) provides an assessment of the stratigraphy and stratigraphic relationships of the Knock Kilbride Formation to adjacent units.

Whilst it is possible to generate some rounded clasts on land, their common occurrence at numerous levels in the succession suggests rounding by wave action as a more likely origin (Fig. 3a). Several of the beds containing these clasts show well-developed grading (Fig. 3b) suggesting that deposition may have been in deeper water below storm wave base. The presence of quartz bearing igneous clasts and some sandstones in the Knock Kilbride Formation just south of Derry Bay (Ryan *et al.* 1980; Graham 2019 fig. 4) demonstrates that there were more evolved phases present within what is predominantly a basaltic to basaltic-andesite composition overall. Detrital zircon data from sandstones in the Knock Kilbride Formation shows the presence of some 1 Ga (Mesoproterozoic to Neoproterozoic) grains implying the availability of a continental source (personal communication Nancy Riggs 2019). Derived clasts from the Lough Nafooe Group described by Chew *et al.* (2007) suggest a similar interpretation.

Knock Kilbride Argillite Formation

Isolated exposures on the Knock Kilbride ridge have previously been noted by Gardiner and Reynolds

(1912), Dewey *et al.* (1970), Graham *et al.* (1989) and Graham (2019) but have never been formally described. These rocks are here termed the Knock Kilbride Argillite Formation and details of the type locality are shown in Figure 4. They consist of fine-grained siliciclastic sedimentary rocks which reach silt-grade at their coarsest. Thin, fine-grained laminae define the bedding. All outcrops have a splintery fracture in the field and a baked appearance that is attributed to the adjacent Glenbeg Felsite described below. The contact with the Lough Nafooe Group occurs in unexposed ground and thus the base of this formation is not seen. Dips are variable but exposure is not sufficient to establish any consistent fold geometries. A minimum of 10m of stratigraphy is present.

These rocks yielded graptolites which Dewey *et al.* (1970) assigned to the Chewtonian of the Australasian succession. This would equate to late Floian (*c.* 473–471Ma) of the current Ordovician time scale (Goldman *et al.* 2020), making them approximately equivalent in age to the Currarevagh Limestone Formation (Graham 2019) seen at the western end of Lough Nafooe. The absence of obvious volcanic debris suggests that they were deposited after the Lough Nafooe volcanic pile had been generated and they are interpreted to rest unconformably upon those rocks. The lack of any coarse-grained debris implies that there were no active local sediment sources and that deposition was in relatively quiet water. It is not possible to constrain the depth of this water other than it is likely to have been well below the limits of wave action as otherwise some clasts of the Lough Nafooe volcanic rocks would be expected to co-occur.

Fig. 3—Field images of rounded clasts in Lough Nafooe Group; hammer (circled) for scale in both images. (a) Graded bed of rounded clasts, Finny Formation (at grid reference 022592); (b) Volcanic conglomerates, Finny Formation dominated by rounded clasts (at grid reference 065593).

Fig. 4—(a) Sketch map of the outcrop of the Knock Kilbride Argillite Formation, with Irish National Grid coordinates shown. (b) Field appearance of the Knock Kilbride Argillite Formation at grid reference 047603.

Rosroe Formation

This formation can be traced from the Atlantic coast to the north-east of the Partry Mountains. Here it was previously erroneously given a different stratigraphic level and proposed as being younger than the Mweelrea Formation and termed the Maumtrasna Formation (Dewey 1963; McManus 1967). The formation has been described in some detail by Archer (1977), and Graham (1987, 2009). Graptolite faunas described by Skevington (1971) confirm a Darriwilian age. It is dominated by conglomerates,

pebbly sandstones and sandstones and overall shows a coarsening upward pattern (Graham 2009) that is seen throughout the whole outcrop from the west coast to the Partry Mountains. The clast assemblage is dominated by volcanic clasts with porphyries dominating in the lower portions and granitic clasts becoming more common upwards. Metamorphic debris, mainly psammites also becomes more common upwards but is present throughout. The coarser facies are best seen near the major road junction at grid reference M00036020 (Fig. 5).

Fig. 5—Coarse-grained facies of the Rosroe Formation near the road junction at grid reference M030020; the larger clasts left of the hammer (circled) are acid porphyries.

Fig. 6—Field image of the discordant contact (highlighted with yellow line) of the Glenbeg Felsite with the Lough Nafooe Group. Photograph taken at grid reference M04276031, looking approximately west.

Glenbeg Felsite

This coarse-grained quartz-feldspar porphyry was first described by Gardiner and Reynolds (1912). The western contact is clearly discordant to the layering in the Lough Nafooe Group (Fig. 6). There is no obvious sign of smaller grain sizes close to the mapped contact and the felsite appears to be homogeneous throughout. Whilst the age of this unit has not been established independently it must post-date the youngest date in the Lough Nafooe Group, which it intrudes with marked discordance, and must also post-date the Knock Kilbride Argillite Formation

which it clearly bakes. This would still allow it to be of similar age to some of the quartz-bearing rocks known from the Glensaul Group exposed some 5km to the north. Graptolites recovered from the Glensaul succession (Dewey *et al.* 1970) have been equated to the Castlemainian of the Australasian succession and the *Isograptus gibberulus* biozone of the British succession that would indicate a Dapingian age (*c.* 471.3 – 469.5 Ma; Goldman *et al.* 2020). A recent U-Pb zircon date of 468.8 ± 1.9 Ma has been obtained for this felsite (David Chew – personal communication 2021).

Derryveeney Formation

The Derryveeney Formation was first described by Graham *et al.* (1991) and is a coarse-grained clastic unit with a prominent conglomerate. It crops out along the northern shore of Derry Bay with some further patchy exposures adjacent to, and within, the Owenbrin River (Fig. 7). Maximum clast size locally exceeds 80 cm in diameter with occasional outsize clasts reaching 120 cm and thus local derivation is indicated (Fig. 8a). The clast assemblage has been described by Graham *et al.* (1991) and includes sillimanite-bearing migmatites as well as foliated granitoids, non-foliated granitoids and porphyries (Fig. 8b,c). It has been generally accepted as providing a sedimentary linkage between the metamorphic rocks

of Connemara and the South Mayo Trough (Clift *et al.* 2003; Draut *et al.* 2004; Graham *et al.* 1991).

The northern shore of Derry Bay provides excellent exposure of the coarse conglomerate facies with its typical clast assemblage and also clast imbrication (Fig. 8d) demonstrating an easterly to south-easterly provenance. This is particularly well displayed where sandstone beds and lenses are present in the sequence, indicating the regional bedding. The contact with the Rosroe Formation, which lies to the north, is not exposed and is marked by sporadic exposures of porphyry where it is inferred to intersect the shoreline (Fig. 7). Given the dips in the two formations this contact is interpreted to be a fault and the porphyry is inferred as being intruded along the fault zone. In a

Fig. 7—Detailed map of Ordovician and Silurian relationships north of Derry Bay. Irish National Grid (km squares) is shown for geographic reference.

Fig. 8—Outcrop photographs for the Derryveeny Formation from the north shore of Derry Bay:

- (a) Typical clast assemblage of Derryveeny Formation at grid reference M047618;
- (b) Large boulder-scale porphyry clasts at M047618;
- (c) Sandstone lens and imbrication at M049618;
- (d) Metamorphic clasts with migmatitic textures at M048618.

regional context clear, unequivocal contacts between the Rosroe and Derryveeny formations have yet to be described. The Derryveeny Formation is considered to be younger on the basis of its clast assemblage, the younger dated clasts described by Graham *et al.* (1991) and the presence of *c.* 450 Ma (Katian) detrital zircons (Riggs *et al.* in press).

Silurian succession

The lithostratigraphy of the Silurian succession in the study area is based largely on pre-existing and well-established schemes (Fig. 9). Where new, lower-level subdivisions are proposed here they conform to accepted lithostratigraphical nomenclatural terminology.

Lough Mask Formation

This is the lowest formation of the Killary Harbour – Joyces Country Silurian succession. It contains two distinctive units in the lower part, namely a locally developed conglomerate unit first noted by Gardiner and Reynolds (1912) and an albite trachyte volcanic horizon. This was noted as being thickest at Ardaun

by Leake (2014) although he did not formally define this lava as a member. It was termed the Ardaun Lava Member by Geological Survey Ireland (Morris *et al.* 1995; McConnell *et al.* 2002; Long *et al.* 2005).

The base of the Lough Mask Formation rests unconformably on a variety of stratigraphic units. At M34005964 the basal conglomerate can be seen resting on the underlying Finny Formation of the Lough Nafooy Group. At M42706031 the basal conglomerate is not present but the lowest red sandstones of the Lough Mask Formation rest directly on weathered Glenbeg Felsite (Fig. 10a). At M54996177 red sandstones of the Lough Mask Formation overlie the conglomerates of the Derryveeny Formation (Fig. 10b).

The basal conglomerate, here termed the Kilmore Conglomerate Member, is well exposed along the southern slopes of the Knock Kilbride ridge and appears to be discontinuous, presumably occupying depressions in the Silurian landscape. The coarsest beds are present at M02635925 where boulder-scale clasts reach up to 55cm in diameter (Fig. 10c). Two plagiogranite clasts from this locality and locally derived from the Lough Nafooy

Gardiner and Reynolds 1912	Piper 1972	Graham <i>et al.</i> 1989 Morris <i>et al.</i> 1995; McConnell <i>et al.</i> 2002; Long <i>et al.</i> 2005	This paper
Doon Rock Grits	Lettergesh Formation	Lettergesh Formation	Lettergesh Formation
Purple Sandy Shale	Tonalee Formation	Tonalee Member	Tonalee Member
Finny School Beds (calcareous flags)	Kilbride Formation Div 4: Fossiliferous bioturbated silts Div 3: Sandstone and silt, bioclastic Div 2: Well sorted sandstones with <i>Skolithos</i> Div 1: Poorly sorted sandstones almost no fossils	Kilbride Formation	Drin Siltstone Mbr
Annelid Grits			Finny School Lam.Sst.Mbr
Red Sandstone			Finny Coarse Arenite Mbr
Basal conglomerate	Lough Mask Formation	Lough Mask Formation Ardaun lava Mbr	Lough Mask Formation Ardaun Lava Mbr Kilmore Conglomerate Member

Fig. 9—Comparison of stratigraphic terminology used for the Silurian strata in the south Mayo region by previous authors and the present contribution.

Group were analysed by Chew *et al.* (2007) and yielded ages of 489.9 +/- 3.1 and 487.8 +/- 2.3 Ma (late Cambrian to early Ordovician). The Kilmore Conglomerate Member has a maximum thickness of 40m. The nature of the clast assemblage varies along strike such that at the eastern end of the peninsula (0507063200) the clasts are dominated by felsite and quartzose sandstone. The felsite clasts appear to be identical to the subjacent Glenbeg Felsite; here the maximum clast sizes are typically 35cm (Fig. 10d).

The Ardaun Lava Member in places rests on the Kilmore Conglomerate Member and in others is separated from the subjacent strata by a small thickness of red sandstones. However, in many places the Ardaun Lava Member appears to rest directly on the underlying Lough Nafaoey Group with no intervening sediment. For the most part this member is fine-grained and homogenous in the field and with an aphanitic texture in hand sample. However, in some places prominent feldspar laths up to 8mm (Fig. 11a) in a fine-grained pink/purple groundmass are evident, as noted by Gardiner and Reynolds (1912). Elsewhere, unusual joint features occur which are filled with fine-grained red material

displaying slightly rounded shapes (Fig.11b). These were interpreted as potential pillow structures by McKerrow and Campbell (1960), however, this was refuted by Piper (1972) who suggested they were a later weathering feature. We concur with the latter interpretation. This lava member reaches at least 112m in terms of thickness at Ardaun just south of the Kilbride Peninsula (Leake 2014) and thins westwards along the southern flanks of the Bencorragh ridge south of Lough Nafaoey. Leake (2014) suggested that the thicker occurrences represent infilling of palaeovalleys. The marked lateral extent of this lava is puzzling and suggests a lava with a very low viscosity and also that any valleys on the Lough Mask Formation palaeo-surface must have had limited relief. The rock itself is quite pale in hand sample and has been described (McKerrow and Campbell 1960) as being strongly alkaline in composition; this may be an explanation for the low viscosity. The Ardaun Lava Member is also unusual in its isolated occurrence as no other lavas are known from this Silurian succession although several thin (cm scale) bentonites are present, particularly in the overlying Kilbride Formation (Harper *et al.* 1995; Batchelor

Fig. 10—Field photographs of the lower parts of the Lough Mask Formation:

- (a) Red sandstones of the Lough Mask Formation (labelled LMF) resting on weathered surface of the Glenbeg Felsite (labelled GF) at grid reference M043603;
- (b) Red sandstones of the Lough Mask Formation (white arrow) resting on conglomerates of the Derryveeney Formation at grid reference M055618;
- (c) Boulder conglomerate with plagiogranite clasts at M057593;
- (d) Conglomerates from the eastern end of the Kilbride Peninsula (grid reference M051604) dominated by well-rounded clasts of Glenbeg Felsite.

Fig. 11—Field photographs showing features of the Lough Mask Formation:

- (a) Feldspar-phyric facies of the Ardaun Lava Member at grid reference M052650;
- (b) 'Pseudo-pillows' produced by weathering at M057618. Hammer circled for scale.

et al. 2003). The member is also well exposed on the northern shore of Derry Bay (Fig. 7).

The main part of the Lough Mask Formation consists of relatively well-sorted, red, feldspathic sandstones that display horizontal bedding (Fig. 12a) or cross-bedding (Fig. 12b) with minor muddy horizons (Fig. 12c). Except for the basal Kilmore Conglomerate Member, described above, there is little material that exceeds coarse sand-grade. Where the thin muddy levels are well exposed they commonly display evidence for desiccation which is consistent with the proposed fluvial origin of the formation (Piper 1967, 1972). Palaeocurrent directions derived by Piper (1972, Fig.5) from cross-bedded sandstones suggested a northerly source for the sand. The Lough Mask Formation crops out over a very substantial area (at least 300km²) with only limited variation in facies implying the presence of

a substantive sand-dominant fluvial plain with little topography. The relatively well-sorted sediment suggests a river system of some considerable length and a reasonably large drainage basin. The formation is assigned a Telychian age on the basis of faunas in the conformably overlying Kilbride Formation.

In thin section the feldspars occur as monomineralic grains but also as phenocrysts within volcanic rock fragments (Fig. 12d). These phenocrysts are mainly oligoclase or andesine in composition. The volcanic clasts do not obviously match any of the known horizons within the Ordovician succession of the South Mayo Trough. Detrital zircon data show a number of younger grains (Riggs *et al.* in press) suggesting the presence of an igneous source component that is no longer extant but which is significantly younger than the adjacent South Mayo Trough succession and of early Silurian age. Whilst the detrital

Fig. 12—Sedimentary structures and petrography of the Lough Mask Formation:

- (a) Flat bedded sandstones at grid reference M015586, hammer handle circled for scale;
- (b) Cross-bedded red sandstones at M052620;
- (c) red mudrocks with desiccation cracks at M015586;
- (d) Thin-section photomicrograph of sandstone unit with iron-enriched volcanic grains. Field of view 4mm approximately.

zircons cannot be unambiguously assigned to phases seen in thin section, it seems most likely that these are related to the volcanic grains. The source areas of this relatively large drainage basin may now be buried or may have been removed by subsequent erosion.

Kilbride Formation

The base of the Kilbride Formation is defined by the change from feldspathic to quartzose sandstones. This approximately coincides with a change from red to grey colours in most places, but is locally complicated by the presence of sandstones with a slight greenish hue; the mineralogical change is preferred in defining the base of the formation over the more nebulous colour change. Herein we review the nature

of the Kilbride Formation and propose subdivision into three newly named members (Fig. 9). These subdivisions can be mapped throughout the area of the Kilbride peninsula although it is not clear if they can be recognised further to the west. Piper (1972) recognised four subdivisions but the distinction between his lower two subunits is not mappable and if these are combined then his stratigraphic scheme approximately matches that proposed here.

The lowest, coarsest grained member, here termed the **Finny Coarse Arenite Member**, is characterised by medium- to coarse-grained sandstones that are characterised by numerous horizons displaying closely spaced *Skolithos* vertical burrows (Fig. 13a,b). The type section is taken just east of

Fig. 13—Outcrop features of the Finny Coarse Arenite Member of the Kilbride Formation:
 (a) typical thin to medium-scale sandstone beds which are flat to low-angle in terms of orientation at grid reference M017585;
 (b) Vein quartz-rich pebbly sandstones at M049603;
 (c) *Skolithos* vertical burrows in section and plan at M016585.

Finny Church between M01855860 and M01905847 where 120m of this member are present.

In a few places, such as 0490060330, granule and pebble rich sandstones occur with the coarse clasts being of vein quartz (Fig. 13c). *Skolithos* is a trace fossil recording a behavioural pattern characteristic of nearshore high-energy shallow marine conditions. Primary sedimentary structures, where preserved, are dominated by horizontal to low angle lamination (Fig. 13a) that are interpreted to be the product of strong wave action.

In thin section these sandstones are markedly more quartzose than those of the underlying Lough Mask Formation. The difference could be attributed to the effects of prolonged reworking in the coastal zone rather than to any difference in provenance.

The middle member of the Kilbride Formation, here termed the **Finny School Laminated Sandstone**

Member, is characterised by the presence of fine-grained quartzose sandstones (Fig. 14a) with subordinate muddy horizons. The type section is between M05026000 and M05165985 where 148m of this member are present. The base is gradational and is taken where fine-grained sandstones become dominant. A variety of shallow marine shelly fossils have been described from this level (Gardiner and Reynolds 1912; Doyle 1994; Harper *et al.* 1995; Harper and Donovan 2007) in particular brachiopods and rugose corals (Fig. 14b). Primary sedimentary structures are dominated by subparallel lamination and ripple-scale cross stratification. Some of the ripples are indicative of wave action (Fig. 14c). A few examples of low angle undulose lamination that are consistent with descriptions of hummocky cross stratification also occur. Beds are generally thinner than in the underlying member and horizontal burrows are much more common.

Fig. 14—Field photographs of the upper parts of the Kilbride Formation:

- (a) Fine-grained laminated sandstones in the Finny School Laminated Sandstone Member at grid reference M042593. Weathered out horizons are those rich in coral fossils. Hammer (circled) for scale;
- (b) Scattered corals, typical of the Finny School Member, on a bedding surface overlain by thin, pale-weathering tuff layer (grid reference M042592);
- (c) Small scale wave ripples on bedding plane, Finny School Member at M043593;
- (d) Thin pale-weathering bentonite in the Drin Siltstone Member at M042592.

Some thin tuffs are known from this member and Harper *et al.* (2003) describe a spectacular example whereby the original submarine ash fall caused the mass mortality of corals (Fig. 14b). Little primary mineralogy remains from these tuffs (Batchelor *et al.* 2003), which are mainly indurated bentonites just a few cm thick.

The base of the third member, here termed the **Drin Siltstone Member**, is also gradational and is defined where silt grade rocks become dominant. These grey siltstones contain numerous fossils, especially corals and brachiopods. Horizontal burrows are extremely common. Thin bentonites are also present in this member (Fig. 14d). The type section is taken just west of the Finny River at Drin between L09805836 and L09745829 where 52m of this member are present. The type section is described in Graham 2021 and Graham *et al.* (in press).

The Kilbride Formation is interpreted as a transgressive sequence in which subsidence only marginally outstripped sediment supply. Interpretation of the faunas in the Finny School Member, which belong largely to the *Eocelia* and *Clorinda* communities of Ziegler *et al.* (1968) suggests water depths of at least 50m for this shelf succession. However, there is much dispute about interpreting water depths from these assemblages such that ranges from 50–250m have been suggested for the same assemblage (e.g. Brett *et al.* 1993; Cocks and McKerrow 1984; Ziegler *et al.* 1968). The lower part of the range seems more reasonable. A general east-west orientation of the shoreline was inferred by Piper (1972) presumably based on the general northern derivation of the fluvial Lough Mask Formation, and an interpretation of ENE oriented faults as synsedimentary basin controlling faults. There is little within the Kilbride Formation to provide any independent verification of shoreline orientation.

Tonalee Formation

The Tonalee Formation comprises red, green and grey mudrocks, the red coloured ones forming a distinctive mapping horizon. Although the presence of a red/purple mudrock unit was recognised by most early works, e.g. Gardiner and Reynolds (1912), McKerrow and Campbell (1960) it was referred to as 'Purple sandy shale'. It was first formally defined by Piper (1967) with the base defined by the advent of strongly coloured mudrocks that typically have a red or green hue (Fig. 15). Graham *et al.* (1989) considered this to be a member of the Kilbride Formation, but this cannot be justified as the unit fulfils all the requirements for formation status. Although the red

mudrocks (Fig. 15a,b) are the most common and distinctive in the field, there is not a simple clear pattern of red and green colours. The strong colouration is attributed to the iron content. Although in general the red mudrocks tend to underlie the green (Fig. 15c,d) there is also lateral and vertical gradation of one to the other. The formation contains an unusual, 'stunted' fauna (Doyle *et al.* 1990) and is interpreted as distal *Clorinda* community representing deposition in an outer shelf environment. Red colours in shallow marine environments are unusual and have often been linked to major oceanic events related to oxygenation. Similar red mudrock horizons are known from other Silurian successions that appear to be of approximately the same age (Ziegler and McKerrow 1975). Overall the Tonalee Formation is interpreted as being deposited during a period of deepening during which subsidence +/- eustasy outstripped sediment supply.

Near Doon Rock c. 10m of grey mudrocks of the Tonalee Formation were interpreted as equating with the Benbeg Mudrock Member of the Lettergesh Formation by Piper (1972), and Rickards (1973). Whilst this correlation may be true it is very difficult to test and is certainly not mappable. Thus any green/grey mudrocks above the red mudrocks are all included in the Tonalee Formation (an approach also adopted by Leake 2014). Overall the Tonalee Formation is relatively thin (maximum 75m) and in many places there is very little thickness between the last seen red mudrocks and the first sandstones of the overlying Lettergesh Formation.

Lettergesh Formation

This formation is characterised by medium- to coarse-grained immature sandstones (greywackes) that commonly form a series of prominent ribs in the landscape (Fig. 16a,b). The base is gradational within a few metres over which sandstones thicken markedly into beds that are typically up to 1.5m thick. This formation is at least 700m thick on the Kilbride Peninsula where the top is not seen and reaches more than 1500m in areas further west (Graham 2021). It can be mapped over an area of at least 250 km² representing a very substantial volume of sediment. Late Telychian faunas are known from the base of the Lettergesh Formation and the overlying Lough Muck Formation seen further west is of Sheinwoodian (early Wenlock) age (Graham *et al.* in press).

Normally graded bedding is common (Fig. 16c) in the Lettergesh Formation, but several also display parallel lamination (Fig. 16d) or, less commonly,

Fig. 15—Outcrop features of the Tonalee Formation:

- (a) Red mudrocks in large roadside exposure at grid reference M027586. Hammer (circled) for scale;
- (b) Typical small exposure of red mudrocks at M047594;
- (c) Grey-green mudrocks exposed in a small quarry at M025586. The thin white weathering bands are bentonites and the subvertical structure just left of the hammer is a spaced cleavage;
- (d) Green mudrocks of Tonalee Formation (at grid reference M025586) the finer horizons display a weak spaced cleavage.

cross stratification. Dewatering structures are also common. The most striking feature in the field is the generally dark colouration and the presence of pink and purple rock fragments that are visible with a hand lens. These sandstones are compositionally distinct from anything lower in the succession. In thin section the clasts are dominated by feldspathic rock fragments that have a very fresh appearance (Fig. 16e,f). The feldspar phenocrysts are mainly andesine in composition. Although these clasts dominate the rock fragments seen in thin section, the rocks also contain clasts of serpentinite, quartzose plutonic igneous rocks, undulose quartz, microcline, opaques and heavy minerals (see also Menuge *et al.* 1995; Williams *et al.* 1992).

The petrography and geochemistry of the Lettergesh Formation was investigated by Menuge *et al.* (1995) and Williams *et al.* (1992) in an attempt to establish its provenance giving somewhat

inconclusive results. There is no clear match for the remarkably fresh volcanic clasts in the local regional geology and these are inferred to be derived from an area that is no longer extant or is buried beneath younger strata. Palaeocurrent data are limited and the above authors quote data from Laird (1969) from further west than the area under consideration here implying a derivation from the north or north-west. If the earlier suggestion (Piper 1972) of an overall east-west shoreline parallel to the current structural grain is accepted, then a largely axial east to west flow direction seems just as likely, but there is no body of palaeocurrent data to support either interpretation. There are potential source areas for the serpentinite and granitic clasts to both north and south of the current outcrop.

Thus the Lettergesh Formation is interpreted as having been deposited in relatively deep water by a combination of sediment gravity flows in a basin that

Fig. 16—Outcrop and petrographic features of the Lettergesh Formation:

- (a) Typical weathering style of the unit in the field looking eastwards - the prominent ridge labelled DR is Doon Rock;
- (b) Ribbed beds of sandstone outcropping at grid reference M050595;
- (c) Size-graded sandstone at M050595;
- (d) Parallel lamination at M050595;
- (e, f) Thin-section photomicrograph images of sandstone. LV = lithic volcanic grains, F = lithic volcanic grain with fiamme and M = metamorphic grain. Field of view of both images is approximately 4mm.

had deepened substantially during the deposition of the Tonalee Formation before tapping an extensive sediment source that was not previously available represented by the Lettergesh Formation. This is the youngest Silurian formation seen in this area but in

areas further west an upward shallowing sequence is seen (Laird and McKerrow 1967; Graham *et al.* 1989; Graham in press) indicating that sediment supply eventually exceeded subsidence. Whilst this is a typical pattern seen in many foreland basins, there

are no indications in the regional geology of the Laurentian margin to suggest this as an explanation (Graham *et al.* in press). The pattern is also common in many pull-apart basins seen in transcurrent margins and given the indications for oblique collision in Silurian times (Dewey and Strachan 2003; Waldron *et al.* 2014) this may be a more likely explanation.

Carboniferous

Carboniferous strata rest unconformably on the older Paleozoic rocks in the region of South Mayo. On the Maumtrasna Plateau, some 5km north-west of the study area, gently dipping conglomerates and sandstones of Mississippian age rest unconformably on the Mweelrea Formation of the South Mayo Ordovician succession at an elevation of *c.* 600m. The Geological Survey Ireland map (2021) assigns these rocks to the Moy Sandstone Formation, although they bear little resemblance to the Moy Sandstone at its type area near Castlebar (Long *et al.* 1992). At the northern end of Lough Mask, Mississippian quartzose pebble conglomerates and sandstones age rest unconformably on Silurian rocks of the Killary Harbour succession and on sandstones of the Rosroe Formation at an elevation of *c.* 50m.

South of Lough Mask, Carboniferous rocks are faulted against the Dalradian and the Killary Harbour Silurian. However, at Round Islands, conglomerates that are very similar to those exposed on the Maumtrasna Plateau appear to rest unconformably on the Killary Harbour Silurian succession at lake level (Fig. 16). However, these rocks are not present on either the Lusteen Islands or on the south side of Derry Bay suggesting that they are faulted against the older rocks in this area (Fig. 2).

These rocks are here termed the Round Islands Conglomerate Formation. This is also a more appropriate designation for the rocks exposed on the Maumtrasna plateau which are of similar facies. The type section is taken at Round Islands between M06016175 and M06206179, where about 45m of coarse-grained sediments are exposed. The conglomerates (Fig. 17a-c) are dominated by clasts of metamorphic rocks, mainly psammites but also contain grey-green sandstones that resemble those of the underlying Silurian succession and undeformed porphyries. The conglomerates have a sandy matrix and are interbedded with coarse-grained sandstones, some of which display cross bedding (Fig. 17d).

Fig. 17—Field photographs of the Carboniferous-aged Round Islands Conglomerate Formation:
 (a) Conglomerates exposed on Round Island, with Lusteen Islands visible in the background (grid reference M062618);
 (b) Clast-supported conglomerate at M061618;
 (c) Poorly-sorted conglomerate with conspicuous sandy matrix at M061618;
 (d) Trough cross-bedded sandstones at M061616.

Structure

The basic structure (Fig. 18) shows a north-dipping Ordovician succession that forms part of the southern limb of the South Mayo syncline, a mainly southerly dipping Silurian succession that rests unconformably on these Ordovician rocks and a southern block that is part of the Connemara Dalradian succession. In common with the whole region from Lough Mask to the west coast the Silurian rocks obscure the contact between Ordovician strata and the Connemara Dalradian. The nature of this important relationship thus cannot be elucidated based on this area alone.

This paper focusses on structures developed post-Wenlock although clearly older rocks were also affected. With the exception of some small-scale folds adjacent to the Doon Rock Fault (Graham 2021) there are no minor folds in the Kilbride area affecting the Silurian rocks, which form a simple south-dipping succession in the western part of the area with progressive strike swing to the east such that dips in the easternmost part of the area are to the east. Cleavage is only developed in the finer lithologies of the Drin Siltstone Member of the Kilbride Formation and the Tonalee Formation and is everywhere steeper than bedding. A series of mainly NW trending faults have normal displacement

downthrowing to the east and those that are exposed have well-developed quartz breccias. The less numerous NNE trending faults have offsets which also suggest normal displacements.

There are three major parts of the structure that shed light on the structural development of South Mayo. These are the Doon Rock Fault, the Derry Bay Fault, and the marked strike swings of the Silurian strata and these are considered below.

The Doon Rock Fault

The ENE trending Doon Rock Fault, for much of its mapped length, juxtaposes Silurian sediments against Dalradian basement in its southern wall. To the SW of the Kilbride Peninsula the fault trace cannot be followed in poorly exposed ground where Lettergesh Formation is juxtaposed. At its northeastern extremity in the low-lying ground of the Kilbride Peninsula, however, the Lough Mask Formation overlies the Dalradian with dips to the north and east, (Gardiner and Reynolds 1912; Fig.2), a pattern of stratal dips commonly seen in normal fault footwalls as displacement decreases towards the fault tip (Gibson *et al.* 1989). A similar but more complete pattern of radiating stratal dips of Lough Mask, Kilbride and Lettergesh formations is seen towards the western portion of the Clonbur

Fig. 18—Structural cross section across the study area: line of section is shown on Figure 21. Silurian is uncoloured.

Fault (Fig. 18a,b) *c.* 4km SE of the Doon Rock Fault's eastern tip. The proximity of the two faults and their respective westward and eastward decreasing displacements to a fault tip (Fig. 19a,b) strongly indicates that the faults are part of the same system and linked by an intervening relay zone (Athmer and Luthi 2011; Hemelsdaël and Ford 2016). Piper (1972) reports the absence of Ordovician clasts in the lowest Lough Mask Formation fluvial sediments resting on Connemara Schists south of the Doon Rock Fault, whereas north of the fault where

Lough Mask Formation overlies Lough Nafoeey Group Ordovician, but not Dalradian, clasts occur. This is a provenance signature anticipated in the sediments fringing an active normal fault experiencing footwall uplift and hanging wall subsidence. Initial fault movement occurred in a sub-aerial environment with Doon Rock footwall creating a drainage divide; its hanging wall, with a southerly palaeoslope receiving Lough Nafoeey Group volcanic clasts from exposures at the next footwall to the north. During the deposition of the Lough

Fig. 19—(a) Schematic map diagram of the linked Interpretation of the Doon Rock, Clonbur, and Lough Mask, Dooros, Currarevagh faults. Black arrows represent generalised dips; (b) Sketch diagram of a relay zone, after Hemelsdaël and Ford (2014) (c) Reconstruction of the Derryveeny fan (after Graham et al. 1991).

Mask Formation, a southward flowing river system established itself over the Doon Rock Fault footwall. Ordovician clasts derived from the north were noted by Piper (1972) in the Kilbride Formation. Extrapolation of the base Lough Mask Formation dip and strike measurements in the hanging wall has been used to estimate synsedimentary Silurian northward downthrow of *c.* 700–800m. The footwall sequence of Lough Mask Formation (Ardaun Lava Member) through Kilbride Formation and up to Lettergesh Formation is more than 500m thick. While clearly locally important for controlling basin architecture, the Doon Rock Fault was not a main driver of Silurian basin subsidence. The presence of the lower parts of the Lough Mask Formation in the footwalls of both the Doon Rock and Clonbur faults indicates that these were not significantly emergent. Silurian basin subsidence was likely driven by much longer-wavelength processes beyond the immediate study area.

If the interpretation that the Doon Rock and Clonbur faults were linked by a relay is accepted, then the position and nature of the Derryveeny Formation is interesting. The Doon Rock/Clonbur fault relay is strategically located to provide a point source for the Derryveeny Formation (Fig. 19c) almost in the position originally postulated by Graham *et al.* (1991) on totally independent criteria. An early Silurian age for the Derryveeny Formation is entirely possible based on the available data. However, some fault-related deformation of this formation prior to the deposition of the upper Telychian Lough Mask Formation would be necessary to explain the observed field relationships. This could indicate that the Doon Rock/Clonbur fault relay had an earlier history as a ‘jog’ in the evolving South Mayo Trough/Connemara boundary prior to their Silurian extensional history.

Thus, the Doon Rock Fault is interpreted to have acted as a synsedimentary normal fault with downthrow to the north during the Silurian. This structural feature today has a mapped length of >11km, a downthrow of >700m to the north and a well-developed hanging wall syncline. The presence of both the lower parts of the Lough Mask Formation shows that there was no significantly emergent footwall. Despite the synsedimentary nature of the Doon Rock and Clonbur faults the displacements appear to be relatively modest and these are unlikely to have been the major basin bounding faults which are presumed to lie outwith the present outcrop. The regional north to south palaeoslope indicated by the Lough Mask Formation suggests that these lay to the north.

The Doon Rock Fault has previously appeared as a significant structure in many reconstructions of the Irish Caledonides. Whilst it almost certainly was an important early Ordovician structure, the field data do not offer any great support for this being the case in Silurian times. Viewing its later history as an intrabasinal Silurian fault seems to be the most parsimonious interpretation of the available data.

The sub-Silurian unconformity of Dooros and Currarevagh on the shores of Lough Corrib occur at similar elevations to the Doon Rock and Clonbur footwalls indicating that they can be used as a proxy for the local Silurian structural ‘regional’. The Lough Mask – Dooros – Currarevagh Fault (Fig. 19a) clearly has some post-Carboniferous displacement but it is currently not possible to delimit its total movement history.

The Derry Bay Fault

This is a major structure that can be traced westwards to Bunnacuneen at the western end of Lough Nafooe. Here the situation is complex and it appears that the structure links into the Salrock Thrust/Bencraff Fault further west (McKerrow and Campbell 1960) by means of a footwall shortcut fault (Turner and Williams 2004) with a slice of Rosroe Formation bound on one side by a thrust and on the other by a normal fault. However discussion of these structures further west are beyond the scope of this paper.

The regionally widespread Mweelrea Formation that crops out in the north-west of this area (Fig. 2) is characterised by a series of marker ignimbrites. These are absent on the north side of Lough Nafooe and are inferred to be cut out by the Derry Bay Fault. The fault forms an impressive gully just west of Derry Bay (Fig. 20) and can be mapped as far as M040625 from where lack of exposure prohibits further tracing. However, it is clear that it does not trace eastwards from here as there is reasonable outcrop control. The fault is inferred to bend northward and link to the Lettereen Fault that is well documented north of the Owenbrin Valley (Fig. 7; McManus 1972). Along this latter fault beds are steeply overturned towards the west. There is considerable dragging along the faults that led to warping of beds and a shatter belt (McManus 1967). The fault configuration predicts a highly oblique displacement vector. The Derry Bay and Lettereen faults are interpreted as part of a linked fault system that was also active during deposition of the Mweelrea Formation (Fig. 21a). The Derry Bay Fault is interpreted as the main extensional fault

Fig. 20—Derry Bay Fault gully (highlighted with white line) with Maumtrasna plateau in the background. Photograph taken from Bencorragh (grid reference L985584) looking north.

with the Letttereeneen Fault acting as a lateral wall. This whose geometry is almost certainly controlled in large part by the rigid volcanic blocks of the Lough Nafooe and Glensaul groups.

The marked strike swing of the Silurian strata north of the Doon Rock Fault

This is evident on the regional geological map (Fig. 2) and the Silurian outcrop continues uninterrupted across Derry Bay indicating that no major post-Silurian structure runs through the bay. This strike swing is thought to have a different origin to that seen in the footwalls of the Doon Rock and Clonbur faults. Post-Wenlock contractional deformation resulted in reactivation of extant faults and fractures such as the Derry Bay Fault (McKerrow and Campbell 1960), evidence for which is well seen in the area immediately south of that described here (Leake 2014). During this deformation the Doon Rock Fault acted as a buttress against which structures to north and south shortened along a vector approximately orthogonal to the trend of the Derry Bay Fault (Fig. 21). This resulted in inversion of the Ordovician Mweelrea Basin utilising the reverse-reactivated Derry Bay and Letttereeneen faults, which respectively created the steep southward dips of the Silurian sequence on the Kilbride Peninsula

and eastward tilting of the Silurian sequence along Lough Mask's southwestern shore in their respective footwalls.

There is palaeomagnetic evidence for long-term clockwise rotation of Connemara of $c. 40^\circ$ between Derry Bay and Salrock on the west coast. The South Mayo Trough did not rotate relative to the Laurentian foreland of North Mayo (Smethurst *et al.* 1994). Much of this rotation is interpreted as occurring during this post-Wenlock phase being facilitated by the distribution of pre-Silurian basement blocks. To the immediate southeast of the Kilbride Peninsula, the Clonbur Fault footwall, and Silurian sequences on Dooros and at Currarevagh, do not appear to have experienced that same intensity of post-Wenlock deformation seen in Joyce Country (Leake 2014) and Kilbride. This may be a consequence of lying in the strain shadow of the rigid blocks of volcanic rocks of Lough Nafooe and Glensaul and being eastward of the area experiencing rotation.

Timing of post-Wenlock deformation

The generation of mainly east-west oriented folds with associated weak cleavage is clearly post-Wenlock in age. Leake (2014) argues that this deformation can be tightly constrained as 422.5 ± 1.7 Ma (Ludlow-Pridoli). This is based on the lack of

Fig. 21—Structural configuration and timing of movements. ABC Line of section shown in Figure 18. Large southeast directed black arrow: indicative vector of post-Wenlock contraction. CF = Clonbur Fault, DBF = Derry Bay Fault, DRF = Doon Rock Fault, LF = Lettereen Fault, LMDC = Lough Mask Dooros Currarevagh Fault, MVF = Maum Valley Fault system, sSu = sub-Silurian Unconformity. Tellus geophysical data sourced from Geological Survey Ireland.

deformation in the Omev Granite, located *c.* 40km west of Joyce's Country and the Kilbride Peninsula. This granite body occurs in the axial region of the Grampian D4 (*c.* 464 Ma) Connemara Antiform, which folds Dalradian rocks. External contacts of this pluton are mostly concordant to the limbs and hinge of the Connemara Antiform (McCarthy 2015) which here, does not appear to have been affected by post-Wenlock northward tilting of the northern limb of the Connemara Antiform and overlying Silurian strata that occurred in north Connemara, west of the Maam Valley Fault zone (Badley 2014). At Currarevagh, on the southern shore of Lough Corrib, a north dipping outlier of Lough Mask and Kilbride formations, passes unaffected across the Connemara Antiform. We surmise that the axial region of the Connemara Antiform may not have been further deformed during the post-Wenlock episode and conclude that lack of deformation of the Omev Granite is equivocal in constraining the

age of post-Wenlock deformation in the region. The term Scandian refers to the near orthogonal collision of Baltica and Laurentia. It has clear spatial limits and Graham and Riggs (2021) argue that the use of the term is inappropriate for areas south of the Great Glen Fault in Scotland. They also noted both that the geometry of the Bohaun Shear zone just north of this area was consistent with the geometry of the demonstrably Devonian structures affecting the Croagh Patrick Silurian succession and that the level of deformation decreased southwards from Clew Bay. The movement on this shear zone transfers to a series of N-S normal faults, especially the Lettereen Fault, at the western end of the Partry Mountains. The marked strike swing shown by the Silurian on the western side of Lough Mask to an almost north-south orientation is, in our view, best interpreted to reflect the effects of inversion on the Lettereen Fault. Thus the deformation cannot be more tightly constrained than post-Wenlock and

pre-Carboniferous and there remains the possibility that this deformation is Devonian in age.

Conclusions

The late Cambrian to early Ordovician rocks of the Lough Nafooe volcanic arc are unconformably overlain by quiet water mudrocks of late Floian age in this area. The unconformably overlying conglomeratic Rosroe Formation is similar in character to its outcrop to the west and north-east. This several hundred-metre-thick coarse clastic unit of Darriwilian age reflects the steep slopes and rapid uplift of Connemara to the south which acted as the source area.

A south dipping Silurian succession masks the contact between the Dalradian metamorphic rocks of Connemara and the Lough Nafooe volcanic arc. A coherent stratigraphy is present and laterally traceable in the Silurian of the Kilbride Peninsula, permitting a tripartite subdivision of the Kilbride Formation that is not possible in areas west of the Maum Fault zone. The succession shows evidence for progressive deepening as subsidence likely exceeded sediment supply going from terrestrial to off shelf depths. There are also significant provenance changes throughout the Llandovery (Telychian Stage) to early Wenlock (Sheinwoodian Stage) sequence, between the lowermost fluvial Lough Mask Formation and the uppermost, turbiditic Lettergesh Formation. It is not currently possible to define either the scale or geometry of the Silurian depositional basin.

Analysis of the main structural elements suggests that the Doon Rock and Clonbur faults formed a linked system during Silurian sedimentation. It is possible that a relay zone between them facilitated a point source access for the feeder to the Derryveeny fan which would, by implication, be of early Silurian age, or prior to Silurian extension, a 'jog' in the evolving South Mayo Trough / Connemara boundary. The Derry Bay fault that links westwards into the Salrock/Bencraff faults is interpreted as linking to the Lettereeneen Fault at its eastern end, these geometries being largely controlled by rigid blocks produced by the Lough Nafooe volcanic arc.

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