

The Silurian of North Galway and South Mayo



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Abstract Silurian rocks are present in three successor basins that have no spatial and probably no temporal overlap. The southernmost Killary Harbour-Joyce country succession everywhere masks the contact between the Ordovician rocks of the South Mayo Trough and the Connemara Dalradian. It was deposited in c 5 m.y. from mid-Telychian (Late Llandovery) to Sheinwoodian (mid-Wenlock). The succession shows rapid deepening from terrestrial through shallow marine to a deeper water turbidite dominated package and then a subsequent shallowing. There are significant provenance changes throughout the succession and detrita that relate to source areas that are no longer extant. The Croagh Patrick succession was deposited on Ordovician rocks of the South Mayo Trough that had already been folded to form the open Mweelrea-Partry Syncline. This quartzose succession of Laurentian provenance is poorly dated but is probably Llandovery. It is of shallow marine origin with some indications of more offshore conditions to the west and is strongly deformed. The northernmost Louisburgh-Clare Island succession is non-marine and rests unconformably on the Clew Bay Complex and is in faulted contact with the Croagh Patrick succession. The lower part is of Ludlow or Pridoli age. It is not currently possible to delimit the geometry or extent of any of the depositional basins in which these three disparate successions formed.

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1 Silurian

South Mayo has outcrops of three Silurian successions that differ markedly from each other. They are either physically or structurally separated and there is currently no clear evidence that there is any age overlap although this remains possible (Fig. 1). From south to north these are:

- Killary Harbour–Joyce Country succession
- Croagh Patrick succession
- Louisburgh–Clare Island succession.

The essential features of these three were summarised in Graham et al. (1989) which contains references to the early and pioneering work.

1.1 Killary Harbour–Joyce Country Succession (KHJC)

This is the best known and biostratigraphically best constrained of the three Silurian successions. It crops out in an east–west belt from the Atlantic coast to Loughs Mask and Corrib in the east everywhere masking the contact between the Connemara Dalradian to the south and the Ordovician arc and South Mayo Trough sequences to the north. The outline stratigraphy is shown in Fig. 2 The outcrop is bisected by the

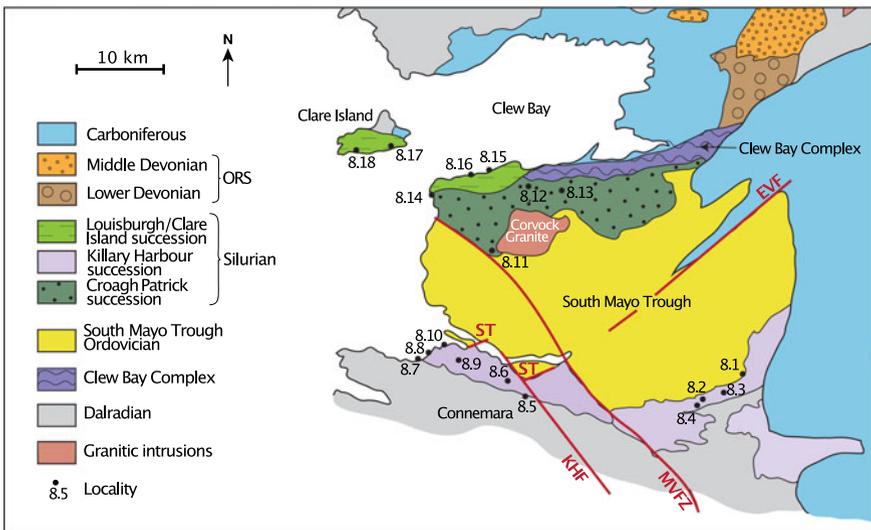


Fig. 1 General distribution of Silurian successions with field localities 8.1 to 8.18 shown. Abbreviations: EVF = Erriff Valley Fault; KHF = Killary Harbour Fault; MVFZ = Maam Valley Fault Zone; ST = Salrock Thrust

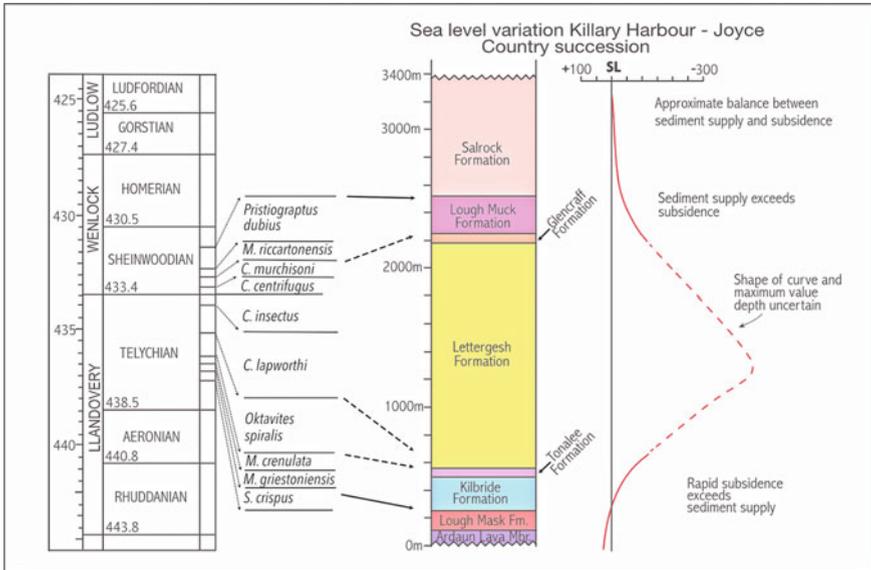


Fig. 2 Outline stratigraphy and interpreted sea level curve for the KHJC succession. The Silurian time scale and biostratigraphical control for the KHJC succession are shown on the left. Biostratigraphical data from Melchin et al. (2020) and Boydell (2012)

complex Maam Valley Fault Zone that is known to have significant post-Wenlock dextral displacement. However, there are also significant stratigraphic differences that occur from east to west where the changes approximate this fault zone suggesting that it had an earlier history.

The lower part of the succession (Lough Mask to Tonalee formations) is best developed to the east of the Maam Valley Fault Zone (Joyce Country) where it is much thicker than in areas west of the Maam Valley Fault Zone where it is still present but either thinner or truncated by contacts of younger age (McKerrow and Campbell 1960; Piper 1972). This sequence goes from terrestrial, in places with a basal conglomerate or breccia, through marginal and shallow marine to deep shelf and possibly beyond. The lowermost Lough Mask Formation can be seen to rest unconformably on the Dalradian to the south (Locs. 8.5 and 8.6) and on the Ordovician arc rocks to the north (Loc. 8.2). It also rests unconformably on the enigmatic Derryveeny Formation (Loc. 8.1) which may be of either Late Ordovician or early Silurian age (Graham and Badley 2021). It has been noted by Laird and McKerrow (1970) and Leake (2014) that the Dalradian rocks beneath the unconformity are stained red for several metres at many localities demonstrating that the basal Lough Mask Formation was deposited on a surface that had been exposed to erosion for a considerable time period. The presence of a distinctive and laterally extensive lava (Ardaun Lava Member) in the eastern part of the area and the laterally consistent nature of the Lough Mask Formation suggest that this surface had limited vertical

relief. The bulk of the Lough Mask Formation, which reaches up to 200 m in this eastern area, is formed by moderately well sorted feldspathic red sandstones that display both cross-bedding and flat bedding. Thin intervening mudrock horizons are red and show desiccation cracks and red mud clasts are present in many of the sandstones. These sandstones were interpreted as the deposits of bedload dominant rivers by Piper (1972). Piper (ibid. Fig. 5) provides the only substantial palaeocurrent data that suggest south-flowing rivers in this eastern area. The well sorted sediment in the Lough Mask Formation suggests a drainage basin of significant scale that would have extended well beyond the currently outcropping pre-Llandovery geology.

Recent detrital zircon data from Finny and Dooros demonstrate a significant young input that is only marginally older than the interpreted age of the Lough Mask Formation (Riggs et al. press). In thin section there is the common presence of fine-grained volcanic rock fragments that do not resemble anything seen in the older parts of the local stratigraphy. These are thought to be the likely carriers of the younger part of the detrital zircon spectrum which otherwise is consistent with a Laurentian origin.

The Ardaun Lava Member is a fine grained albite trachyte lava (keratophyre in many earlier publications) that reaches 115 m in thickness at Ardaun and on Dooros (Leake 2014). It can be traced northwards to the northern outcrop limits on the west side of Lough Mask but is seen to thin out and disappear westwards. Leake (2014) suggested that the lava was confined to valleys in the sub-Silurian land surface. The lateral extent with little obvious variation suggests that any such valleys must have been broad and of limited relief and also that the lava was of low viscosity. In the field the lava is distinctive but offers little information as in most places it is difficult to distinguish even the feldspar crystals. There are notable exceptions where coarse feldspar-phyric facies exist, but these are not common (Gardiner and Reynolds 1912; Graham 2021 Fig. SE12.6). The lack of internal variation makes it difficult to assess whether there are numerous or a very few flows, but evidence of inter-lava horizons has never been reported. It remains a puzzle as to why there is this one significant volcanic horizon in a succession which otherwise only contains thin tuffs and bentonites.

Piper (1972) demonstrated lateral variation in the thickness of the Lough Mask Formation and suggested a topography that had relief of hundreds of metres. It is difficult to reconcile this interpretation with the evidence from the eastern area that suggests deposition on a relatively flat braid plain.

West of the Maam Valley Fault Zone the Lough Mask Formation rests unconformably on the Dalradian commonly with a basal schist breccia (Locs. 8.5 and 8.6). Above this the feldspathic sandstones appear lithologically similar to the Lough Mask Formation seen in the east. However, their detrital zircon signature is markedly different with a predominance of Ordovician grains and a lack of the younger Silurian component (Riggs et al. in press). Moreover samples from the westernmost exposures (Loc. 8.6) contain some 8% of detrital zircons that have a typical peri-Gondwanan signature. There are no reliable published palaeocurrent data for the Lough Mask Formation west of the Maam Valley Fault Zone where it appears only to reach a few tens of metres in thickness but retains the characteristics of a fluvial succession.

Thus one must question the physical connectivity of the fluvial distribution systems between these two areas. Clearly more detailed work is needed here.

The contact with the overlying Kilbride Formation is gradational. It is defined by a change from feldspathic to more quartzose sandstones that is generally accompanied by a change from red to grey or green-grey colours. The Kilbride Formation represents the first marine strata in the succession and the lower part is characterised by the common presence of vertical trace fossils (*Skolithos*) indicative of deposition in high energy shallow marine environments (Loc. 8.2). Piper (1972) suggested a fourfold subdivision of this formation on the Kilbride peninsula where it reaches 320 m in thickness whilst subsequent work has shown that a threefold subdivision is mappable in this area (Graham and Badley 2021). Whilst there are few fossils in the lowest Finny Coarse Arenite Member, shelly faunas are common in the overlying Finny School Laminated Sandstone Member and the uppermost Drin Siltstone Member (Gardiner and Reynolds 1912; Donovan et al. 1992; Doyle 1994; Harper et al. 1995; Donovan and Harper 2003). Faunas described by Harper et al. (1995) indicate the upper part of the *griestoniensis* biozone of mid Telychian age. The faunas belong to the *Eocelia* and *Clorinda* depth communities of Ziegler et al (1968) that indicate shallow to mid-shelf conditions. A progressive deepening through the Kilbride Formation into the gradationally overlying Tonalee Formation is indicated both by the faunas and by the sedimentology. Sparse faunas from the Tonalee Formation (Doyle et al. 1990, 1991) indicate the deep outer shelf. The age of the Tonalee Formation is based on the stratigraphically overlying graptolite and sparse shelly fauna of the *crenulata* biozone (mid to late Telychian) described by Rickards (1973). The Tonalee Formation, which is up to 75 m thick on the Kilbride peninsula, is characterised by red mudrocks despite its outer shelf environment. Red marine horizons are known from elsewhere in Llandoverly strata of similar age (Ziegler and McKerrow 1975) and may reflect a widespread oceanic event that allowed oxidation of these sediments.

The contact with the overlying Lettergesh Formation is gradational but laterally variable and represents a significant change in provenance and in depositional processes. Piper (1967, 1970, 1972) regarded the lowest unit of the Lettergesh Formation as essentially a mudrock unit (Benbeg Member) with thick lenses of conglomerate that he termed the Gowlaun Member. Subsequent workers have retained the name Gowlaun Member for this lowest unit and have concentrated on the conglomeratic element (Locs. 8.5 and 8.6). It is evident on the geological map (Graham et al. 1989) that the base of the Gowlaun Member cuts across the lower formations in the stratigraphy such that it rests directly on the Connemara schists SW of Lough Fee at Alnagaighera. Laird and McKerrow (1970) give a thickness of 370 m here whereas Williams and O'Connor (1987) suggest a maximum thickness of 200 m south of Lough Fee.

There remains uncertainty both concerning the petrography of the clasts and the transport directions in what is essentially a single two dimensional section through the stratigraphy. McKerrow and Campbell (1960) state that the conglomerates are 80% quartzite clasts and 20% vein quartz and red chert, whereas Laird and McKerrow (1970), based on outcrops on the flanks of Lettershanbally recognise red and white quartzite (40–50%), sandstone and siltstone (30%), basic or intermediate volcanics

(15%) with much of the rest being jasper. Williams and O'Connor (1987) report pink and white psammite (55%), sedimentary clasts, mainly red sandstone, (25%) and fine grained basic to intermediate volcanics (20%) whereas Bluck and Leake (1986) note that the commonest clasts are pale pink sandstones rich in K-feldspar and suggest many of the clasts may be recycled from earlier conglomerates. Some of this disparity may reflect real lateral variation but some may also reflect the difficulty of distinguishing truly metamorphic quartzites from well cemented sandstones. Some more careful petrographic work is clearly needed here. The two reports of transport directions are by Piper (1970) based both on imbrication of conglomerate clasts and on cross-bedding in associated sandstones and Williams and O'Connor (1987) based on clast imbrication in the conglomerates. Both indicate flows from the north-east. Piper (1970) interpreted the conglomerates as filling deep water channels whereas O'Connor and Williams (1999) suggest a shallow water origin.

The nature of the relationships of the Gowlaun Member to the underlying strata has also been the subject of considerable discussion. Whilst all workers have suggested the presence of major channels in the Gowlaun Member, there is some uncertainty regarding the relative importance of erosive and laterally interfingering contacts. A diachronous base with persistent location of channels has been suggested by O'Connor and Williams (1987, 1999), Williams and O'Connor (1987) and Piper (1970). Based on exposures south of Lough Fee interfingering with Lough Mask and Kilbride Formation has been reported (Piper 1970; Williams and O'Connor 1987) and at Lettershanbally Gowlaun conglomerates overlie the Kilbride Fm but are divided in two by 8 m of red mudrock of the Tonalee Formation (Williams and O'Connor 1987; O'Connor and Williams 1999). Sandstones associated with the Gowlaun conglomerates are usually massive or slightly graded. These persistent interfingering contacts in this area just west of the Maam Fault zone are perhaps suggestive of some structural control on their location.

The overlying bulk of the Lettergesh Formation is more consistent in nature although it still poses many intriguing questions. Only the lower 800 m is seen east of the Maam Valley Fault Zone but over 1500 m are reported on the slopes of Benchoona (Laird and McKerrow 1970) where both the base and top of the formation can be seen. The formation is dominated by the deposits of sediment gravity flows, mainly high density turbidity currents (Loc. 8.4). Despite the extensive outcrop there are very few indications of flow directions. Piper (1972) reports flows to the west or south-west based on exposures south of Lough Nafuoey and Laird and McKerrow (1970) report flows to the south-east, south-west and south although no palaeocurrent data are presented. Graptolites from the Lettergesh Formation near Clonbur (Rickards and Smyth 1968) indicate a Wenlock age (*murchisoni* and *riccartonensis* biozones) (Sheinwoodian).

Petrographically the Lettergesh Formation is markedly different to anything seen lower in the succession. The commonest clasts are of intermediate to acidic volcanic clasts that can be seen in the coarser hand samples as distinctive red, pink, or purple weathering grains and are striking in thin section. The appearance of the volcanic clasts in these lithic arenites is very fresh and they do not resemble anything known from the local subjacent stratigraphy. These have been described by Williams et al.

(1992) who also note some clasts of volcanic glass and welded tuffs. They also note the presence of granitic clasts, serpentinites and detrital micas. They used published discriminant plots to suggest an arc source. The age and location of this arc source is unknown. Some detrital zircon data would clearly be useful here to investigate whether there is a very young component to the source area. Menuge et al. (1995) used a variety of reasoned assumptions along with Nd isotopic data to suggest that the arc was situated on Mesoproterozoic crust (1440–1600 Ma).

The upper contact of the Lettergesh Formation is gradational into the Glencraff Formation (60 m) seen west of the Maam Valley Fault Zone. This formation is characterised by finer-grained, thin-bedded sandstones and mudrocks that have been interpreted as outer shelf storm deposits (Nealon 1989; Nealon and Williams 1988) such that the shallowing of the environment must commence here or somewhere lower in the Lettergesh Formation. It is not possible to determine the maximum depth that this area reached during Lettergesh times.

The overlying Lough Muck Formation (340 m) indicates further shallowing and contains a shallow water fauna and evidence of bipolar currents (Williams and Nealon 1987) (Loc. 8.7). The faunas belong to the *Eocelia* community and indicate a mid-Wenlock age (Rickards and Smyth 1968). The overlying Salrock Formation (800 + m) (Loc. 8.8) is largely red coloured but has yielded some *Lingula* and poorly preserved gastropods (Laird and McKerrow 1970) indicating a continued marine influence. The depositional environment has been interpreted as a coastal plain but few details have been published. The faunas are not age diagnostic.

Thus using the current geological time scale (Melchin et al. 2020) the whole of the Killary – Joyce country succession may represent only 5 Ma for a post-compactional thickness of more than 2500 m. The pattern of apparently rapid deepening where subsidence exceeds sediment supply followed by shallowing where the reverse is true is seen in several basin types. 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. 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. However, it is difficult to delimit either the basin shape or extent on the basis of what is currently known. There are no indications of typical basin margin facies such that the geographical extent of the original basin cannot be determined. Although subsequent outcrop belts commonly match original basin geometries this cannot be assumed here. Such palaeocurrent data as do exist are predominantly orthogonal to the current strike of the outcrop. There are therefore many unanswered questions concerning this succession. There are some suggestions that there were some important intrabasinal faults such as the Maam Valley Fault Zone (Mike Badley pers. comm.) and the Doon Rock Fault, but delimitation of their importance awaits more detailed investigation.

Two suites of intrusive rocks occur within this succession. There is a concentration of sills and dykes of microgranitic nature between Lough Fee and the coast which are

interpreted as being intruded into sediments that were not fully lithified (Mohr 1998). In the eastern part of the outcrop a series of doleritic sills appear to be associated with larger structures such as the Doon Rock Fault (Mohr 1990).

1.2 *Croagh Patrick Succession*

The rocks now assigned to the Croagh Patrick succession were originally considered to be part of the metamorphic basement (Dalradian) (Griffith 1838). The earliest workers were, not surprisingly, greatly influenced by the strong deformation displayed by these rocks and it was only clear that they were Silurian following discovery of faunas by the early Geological Survey geologists (Kinahan et al. 1876; Kilroe 1907a, b). Although the subject of ongoing research, little of biostratigraphic significance has been discovered since these early workers with the exception of Anderson (1960). A reassessment of the faunal collections by Williams and Harper (1991) has suggested that a Llandovery age is most likely rather than the original designation of Wenlock, but additional data are needed here. The succession rests unconformably on the Clew Bay Complex in the north and on Ordovician rocks of the South Mayo Trough in the south.

A stratigraphy of these rocks was presented by Anderson (1960) and Dewey (1963), the latter based on the eastern part of the outcrop, and subsequently supported and modified by Bickle et al. (1972) from the area around Croagh Patrick. Most subsequent workers have agreed that the detailed subdivisions evident in the area studied by Dewey (1963) are difficult to recognise throughout the whole outcrop. However, there is general agreement that the succession comprises a lower quartzose sandstone unit, in many places with a basal conglomerate, a middle more variable unit that contains significant amounts of mudrock, and an upper sandstone unit that is less pure than the lower one and locally slightly calcareous. This threefold subdivision presented in Graham et al. (1989) is shown in Fig. 3. Kelly and Max (1979) suggested that there was a unit of calcareous mudrocks and marbles present beneath the quartzose conglomerate of the Cregganbaun Formation at Derryheagh that they termed the Derryheagh Formation but subsequent work has shown that this cannot be substantiated.

The high level of deformation (Dewey 1967) and the possibility of structural excision or repetition of parts of the stratigraphy (Bickle et al. 1972) mean that there is the possibility of circular argument when looking at lateral variations in the succession. This probably also explains the large variation in thicknesses that have been reported for each of the formations and those shown in Fig. 3 should be treated as approximate. However, it does seem that the middle unit, the Bouris Formation, shows more sandy intercalations in the north-east and a more consistent muddy aspect in the western coastal sections (Loc. 8.12). The outcrop in the south-west near Cregganbaun also appears to show a somewhat sandier aspect at this level than the western coastal outcrop. However, exposure is very limited in the area west of the Corvock granite and the revised map pattern (Graham 2021) is only

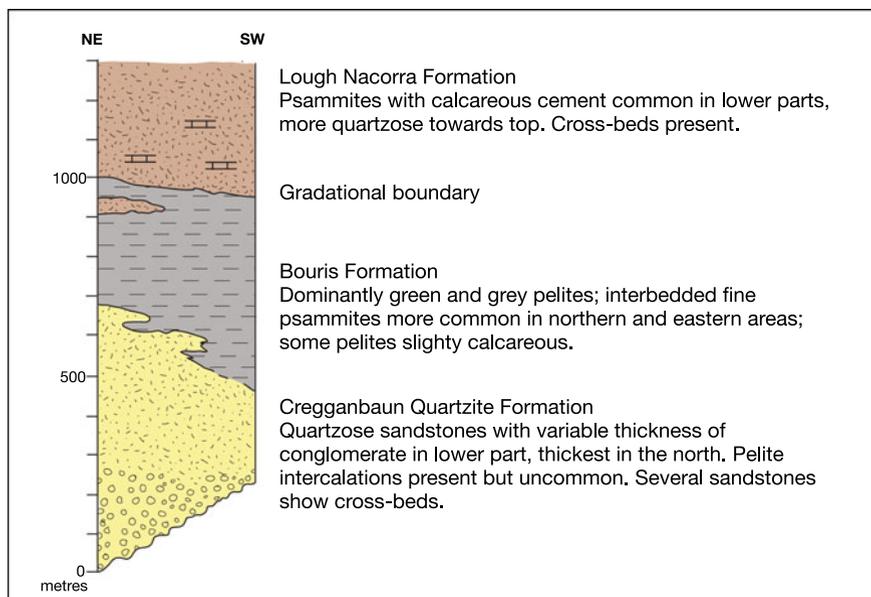


Fig. 3 Outline stratigraphy of the Croagh Patrick succession

one of several permissible representations. The tentative suggestion is that the area was sandier in the east and muddier, and presumably deeper water, in the west. This would be consistent with the few available palaeocurrent data given by Dewey (1963) suggesting flows from the east and north-east. The highly quartzose nature of the succession suggests derivation from the Laurentian margin of North Mayo. The detrital zircon data are dominated by Grenville and Laurentian grains but also contain a small percentage of Tonian grains (Riggs et al. in press). The succession is unusual in the context of South Mayo in that there is no clear evidence for contemporaneous volcanic activity. The Croagh Patrick succession is more strongly deformed than many of the Ordovician strata of the South Mayo Trough, particularly the southern limb of the Mweelrea–Partry syncline. It seems that the deformation is spatially controlled and it is thought most likely to relate to the position of major structures such as the Clew Bay Fault Zone (Highland Boundary Fault correlative). It has recently been shown that this deformation is of Lower Devonian age and the obvious questions relating to this succession concern its age and why there is such a high level of deformation. Work is in progress to delimit how the timing of this deformation which can be linked to the oblique collision history of this part of the Laurentian margin (Graham and Riggs 2021).

1.3 *Louisburgh–Clare Island Succession*

These rocks have variously been assigned to the Silurian and to the Old Red Sandstone (Bishopp 1950). They were investigated in detail by Phillips (1966, 1974) and Phillips et al. (1970) who established a stratigraphy that could be correlated between Clare Island and the mainland. This stratigraphy is shown in Fig. 4. The succession rests unconformably on rocks of the Clew Bay Complex (Loc. 8.15) on Clare Island and is in faulted contact with the Croagh Patrick succession to the south. The basal unit seen on Clare Island is the Kill Sandstone Formation with a local basal conglomerate dominated by Dalradian clasts. This has been interpreted as a fluvial unit by Maguire and Graham (1996). The overlying Strake Banded Formation is a dominantly red unit of mudrocks and sandstones that contains numerous volcanoclastic and volcanic horizons on Clare Island that pinch out eastwards such that volcanic levels are uncommon on the mainland. The bipolar current pattern noted by Phillips (1974) and interpreted as representing a tidal current regime was shown to be due to two different fluvial distribution systems by Maguire and Graham (1996). The volcanic source lay to the west of the current outcrop. The contact with the overlying Knockmore Sandstone Formation is best seen on the mainland and may represent a

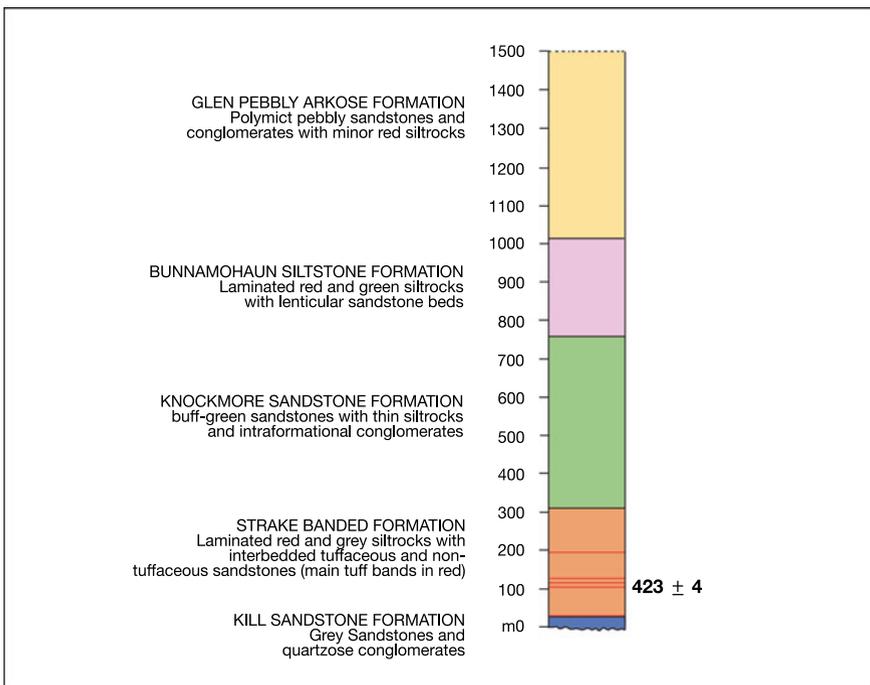


Fig. 4 Outline stratigraphy of the Louisburgh–Clare Island succession

time break within the succession although there is no indication of structural discordance (Loc. 8.13). The sandstones of the Knockmore Sandstone Formation are relatively fine-grained and well sorted implying that the fluvial system that delivered the sediment was of considerable length relative to the present outcrop. The overlying Bunnamohaun Siltstone Formation is interpreted as a flood plain deposit but with no significant difference in provenance.

There is a gradational contact up into the Glen Pebbly Arkose Formation which represents a significant coarsening of the sediment load and possibly a different provenance (Loc. 8.15). Although the petrography has been described to some extent by Phillips (1966; 1974) and Maguire (1989) there is much more information to be gleaned from a study of this formation. It has been suggested that most of the clasts can be matched with parts of the local Clew Bay geology.

The succession was interpreted as a marginal marine succession by Phillips (1974) based on the identification of bipolar current patterns, *Lingula* and some sea pens. The Silurian age was based on regional considerations and also on the presence of derived Silurian fossils in the uppermost Glen Pebbly Arkose Formation. This interpretation was rejected by Maguire and Graham (1996) who showed that the *Lingula* were spiral coprolites produced by fish (Gilmore 1992) and that the 'sea pens' were an enigmatic fossil initially described by Peach et al. (1899) from the Midland Valley of Scotland and termed *Glaucanome*. Re-assessment of these fossils by Graham and Evans (2001), who renamed them as *Peltoclados clarus*, has shown that they are of uncertain biological significance but are possibly related to charophytic algae. Unfortunately they provide no biostratigraphical information. Maguire and Graham (1996) reinterpreted the succession as being entirely terrestrial in origin.

A single fossil fish sample, no longer extant, from the Bunnamohaun Siltstone Formation was discovered by Dr D Palmer (Palmer et al. 1989) and identified as *Birkenia cf. elegans*. The general uncertainty of age ranges of early fish along with the cf specific assignation means that the suggested Wenlock age cannot be considered accurate. A first reliable age for the lower part of the succession (Strake Banded Formation) was recently presented by Graham et al. (2020) who demonstrated a Ludlow to Pridoli age (423 ± 4 Ma) for a tuff in the Strake Banded Formation. This indicates that there is no age overlap with the Killary Harbour – Joyce Country succession and there is most unlikely to be any overlap in age with the Croagh Patrick succession.

In the case of this basin the palaeocurrents are subparallel to the strike of the outcrop. However, there are no indications of basin margin facies such that the original scale of the depositional basin cannot be determined. The presence of a totally non-marine succession is part of a progression that continued into the Devonian as the Laurentian margin gradually stabilised and elevated during continued oblique collision (chapter “[Devonian and Carboniferous](#)”).

The location of a series of ultramafic minor intrusions into this succession appears to be spatially and genetically related to major faults (Upton et al. 2001).

2 Killary Harbour–Joyce Country Succession

2.1 Aim of Excursion

The aims of this excursion are to examine the evidence for the proposed deepening—shallowing basin fill; to examine provenance changes throughout the succession and to compare and contrast the successions developed in the eastern and western parts of the outcrop. This evidence can then be used to constrain models of basin development.

2.2 Locality 8.1: Derry Bay North (53.597583° , -9.434674°)

Access and other Information From Tourmakeady, take the R300 south towards Derry Bay, then take the small unnamed road that leads to the shore of Lough Mask at 53.597583° , -9.434674° ; the road is gated part-way - make sure to close the gate after passing through. There is some roadside parking just through the gate near a set of obvious exposures to the west of the road. These are typical, poorly sorted pebbly sandstones of the Ordovician Rosroe Formation that are dominated by volcanic clasts.

Proceed to the end of the road where there is a picnic site and parking (Fig. 5). Walk east to the lake shore. The first few outcrops are of the conglomeratic facies of the Derryveeny Formation. Sandstone layers demonstrate a northerly dip (Fig. 6a) and also provide reference horizons for examining clast orientations. Imbrication is visible from clast long axes in cross-section that consistently dip to the east more steeply than bedding indicating palaeoflow from roughly east to west here. Limited three dimensional exposure suggests that the longer dimensions seen in cross section are the b-axes of the clasts.

The Derryveeny Formation contains a large range of clast types (Fig. 6a, b), many of which have strong metamorphic fabrics. There are also granitic clasts without obvious fabrics and undeformed acidic porphyry clasts. Some of the metamorphic clasts show migmatitic textures (Fig. 6b, c) and contain sillimanite. Clasts are very large with average maximum clast size in some coarser layers exceeding 80 cm and some individual clasts reaching 1.2 m (Fig. 6c). This clast assemblage is interpreted as being locally derived from the Connemara massif. The metamorphic rock types are either present or likely to have been present locally in the Kilbride Formation that presently crops out just 2–3 km away on the southern side of the Kilbride Peninsula (Graham et al. 1991). The igneous clasts have been interpreted as parts of the Connemara magmatic arc, from undeformed near-surface volcanic rocks to deeper plutons.

At 53.597478° , -9.428097° , just north of a small stone pen, is a critical exposure that shows red feldspathic sandstone typical of the Silurian Lough Mask Formation resting unconformably on conglomerate of the Derryveeny Formation (Fig. 6d). The strikes of the two units are almost perpendicular. The precise age of the Derryveeny

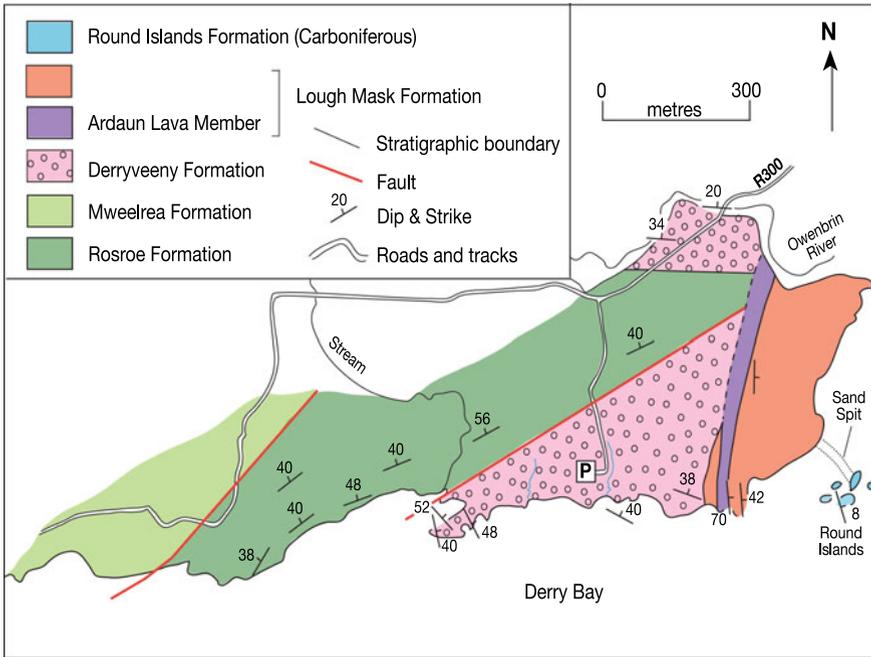


Fig. 5 Geological map of the area north of Derry Bay

Formation is not known, but the unconformity shows that it must be older than the late Telychian Lough Mask Formation, while clasts dated to $c. 462 \pm 7$ Ma (Middle Ordovician) and detrital zircons of $c. 450$ Ma (Late Ordovician) (Riggs et al. in press) indicate its maximum age. Thus, either a Late Ordovician or early Silurian age is possible.

There is a gap in exposure before the next outcrop to the east, which is of the trachytic Ardaun Lava Member of the Lough Mask Formation. This widespread member is fine-grained and typically weathers with a pink or purple colour (Fig. 6e). Although there is a gap at the eastern end of this exposure, the lava must be at least 10 m thick here, assuming a constant dip in the Silurian strata.

The next exposure to the east is of red feldspathic sandstone of the Lough Mask Formation. The sandstone is cross-bedded (Fig. 6f) with apparent northerly derivation. The strata strike almost north–south, a $c. 70^\circ$ rotation from the western end of the Kilbride Peninsula. Palaeomagnetic studies have suggested that this swing in strike is a regional feature that is interpreted to have occurred in late Silurian times (Smethurst et al. 1994).

Return by the same route to the car park on the shores of Derry Bay.



Fig. 6 **a** Imbricated cobble conglomerate beneath sandstone lens **b** Migmatite clasts in Derryveeny Formation conglomerate **c** Poorly sorted Derryveeny conglomerate with outsize porphyry clast **d** Derryveeny Formation conglomerates, here dipping away from the camera, unconformably overlain by red sandstones of the Lough Mask Formation. The marked difference in strike is evident **e** Field appearance of the Ardaun Lava Member on a glaciated lakeshore exposure **f** Cross-bedded feldspathic sandstones of the Lough Mask Formation (foresets are visible just left of the hammer)

2.3 *Locality 8.2: Finny Church (53.567923°, -9.487486°)*

Access and other Information Park at Finny Church (53.570798°, -9.492675°) on the R300. Stops at this locality are adjacent to a moderately busy road so take care of traffic and wear high visibility clothing. Most stops involve entering private land through gates which should be carefully shut.

Walk east until the remnants of a small quarry are seen in a reddish-weathering sandstone, which provides fresh samples (53.567923°, -9.487486°). This rock is typical of the majority of the Lough Mask Formation and represents deposition in a fluvial environment. A set of small low-lying crags just to the west of the loose, fresh debris display the rocks in section (Fig. 7a) and cross bedding is visible, along with some thin, muddy partings and reworked red mud clasts. It is clear that this was one of the localities sampled for palaeomagnetic studies. In thin section these sandstones

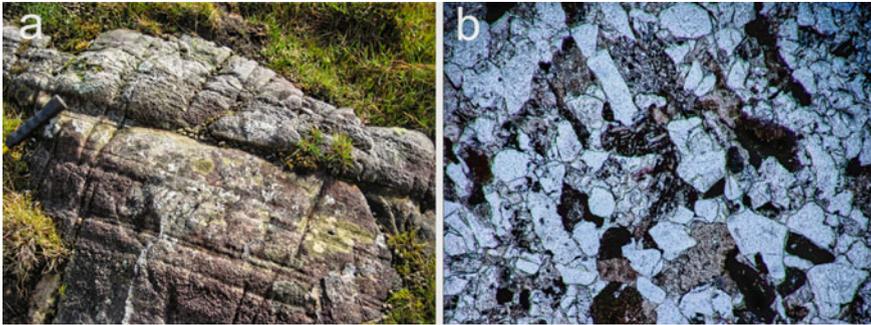


Fig. 7 a Red, feldspathic sandstones of the Lough Mask Formation b Thin section of red Lough Mask sandstone: note the iron enriched volcanic clasts and the iron oxide grain coatings that give rise to the red colour

display numerous fine-grained volcanic rock fragments (Fig. 7b). These volcanic rock fragments are thought to be the carriers of the young (Silurian) component of the detrital zircon profile (Riggs et al. in press).

Return to the road and round a small bend and then cross the road when it is safe to do so. Enter the field on the right through a metal gate and examine the low lying rocks that dip towards the river to the south. These rocks belong to the lower part of the Kilbride Formation and are pale grey rather than the red of the Lough Mask Formation. They represent the first marine strata in this transgressive sequence and are characterised by mainly horizontal or low-angle stratification that is interpreted as being wave generated (Fig. 8a). The beds also contain numerous, closely spaced vertical burrows (Fig. 8b). These have been named *Skolithos* and they represent dwelling burrows of filter feeders that lived in the high energy shallow marine conditions. These types of trace fossils occur in rocks from the Cambrian to the Holocene, but it is by no means certain that they were produced by the same types of organisms through geological time.



Fig. 8 a Thin bedded, grey, quartzose sandstones in the lower part of the Kilbride Formation b *Skolithos* bearing grey sandstones seen in profile, lower part of the Kilbride Formation

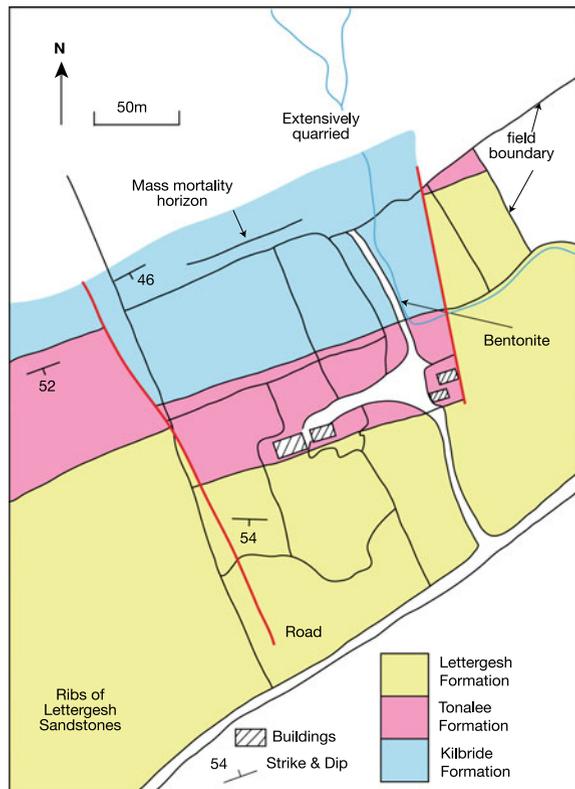
2.4 Locality 8.3: Kilbride (53.570084° , -9.451363°)

Access and other Information Park at the road junction on the R300 where a minor, unnamed road runs northeast ($53.570,084^\circ$, -9.451363°). Walk to the northeast along the minor road (Fig. 9).

Greywacke sandstones of the Lettergesh Formation are well exposed in the fields on the western side of the road where they form a series of low ridges. Continue to a large gateway at (53.572893° , -9.445347°) and then follow the track to the left passing through a series of farm buildings, beneath which are small exposures of the Tonalee Formation, and head towards the open hillside where there are visibly quarried areas.

On commencing the upslope track towards the quarries the ditch section on the right (E) side is through the middle and upper parts of the Kilbride Formation and also shows a thin, pale-weathering bentonite horizon (Fig. 10a). Just above the gate through the main boundary wall at 53.5747° , -9.4469° there are extensive and spectacular exposures through the fossiliferous sandstones and siltrocks of the Kilbride Formation (Fig. 10b, c). Some large bedding plane exposures are rich in fossil corals.

Fig. 9 Map of Kilbride locality



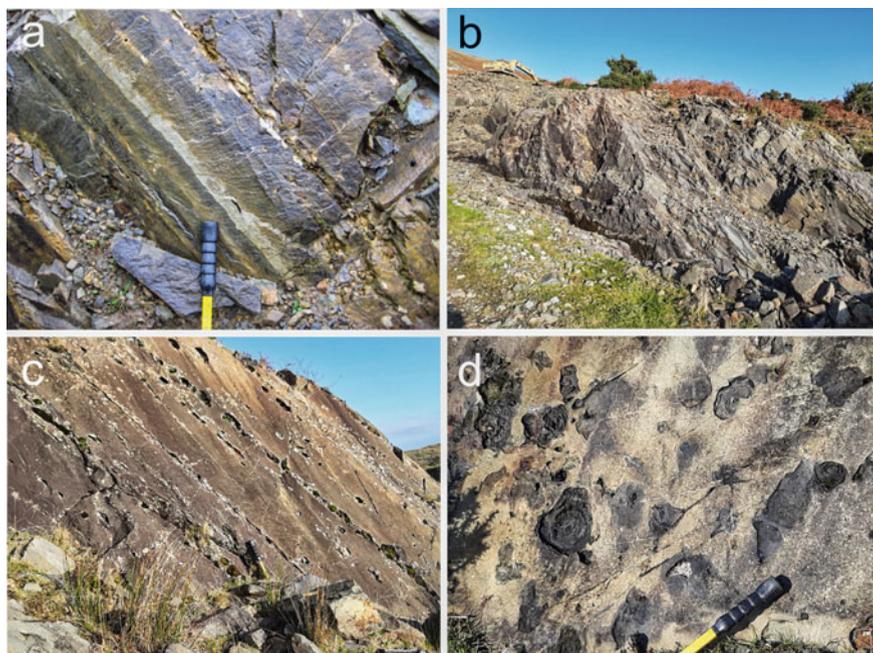


Fig. 10 a Bentonite in upper part of the Kilbride Formation b Quarried section in the middle part of the Kilbride Formation c Siltstones of Kilbride Formation with weathered out coral concentrations forming prominent horizons d Mass mortality horizon where corals are buried beneath thin, pale weathering ash layer rich in muscovite flakes

The farthest downhill of these has a thin volcanic ash layer (bentonite) covering it that is likely to have been responsible for mass mortality of the corals (Fig. 10d; Harper et al. 1995).

2.5 *Locality 8.4: Drin and Bencorragh (53.564764°, -9.493817°)*

Access and other Information Proceed down an unmarked minor road opposite Finny Church. After crossing a bridge over the Finny River continue around a bend to the left, then right for c. 800 m and park in a small layby (Fig. 11) at 53.564764°, -9.493817°.

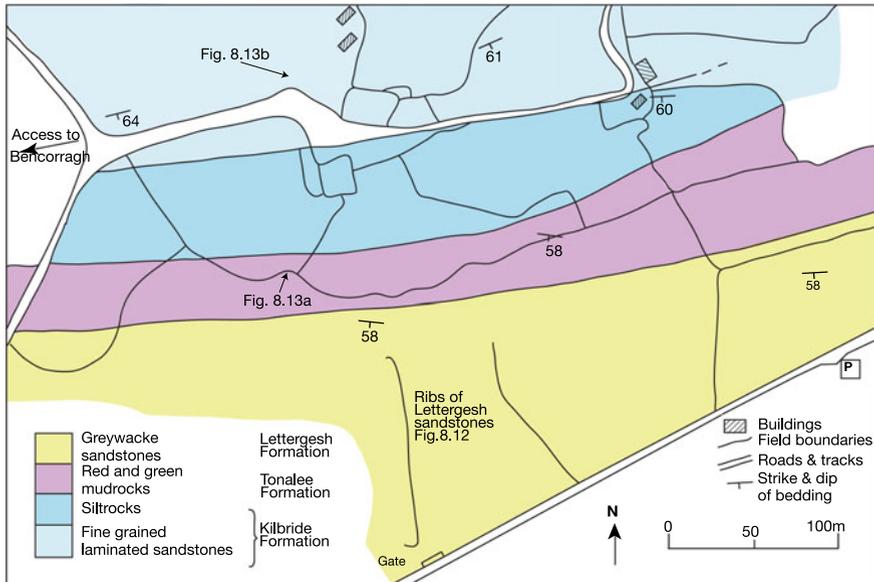


Fig. 11 Simplified geological map of Drin

2.5.1 Drin

Ribs of dipping beds of the Lettergesh Formation can be seen running down the hill from the west. Walk along the road for a further 300 m and access a field on the right via a gate at to examine the predominantly coarse-grained sandstones that are interpreted to have been deposited mainly by high-density turbidity currents. Massive, graded sandstones (Fig. 12a,b) commonly with vertical dewatering pipes, and stratified sandstones with parallel atenation and, less commonly, small scale cross stratification are present, with the massive graded portions consistently underlying the parallel laminated parts where they are part of the same bed (Fig. 12). Some of the coarser beds have erosive bases and/or are loaded into the beds below (Fig. 12c–e).

These greywacke sandstones are dark coloured on fresh surfaces and a variety of grain types are visible with a hand lens. Those with a distinctive reddish or pinkish tinge can be seen to be volcanic rock fragments in thin section (Fig. 12f) and grains of this type comprise a large proportion of the sandstones. They appear to be very fresh, first cycle detritus.

To examine a range of bed types and structures walk to the N-NW across the strike towards the line of a small stream and the edge of the small fields. On approaching the stream walk c.100 m upstream to larger exposures of red and green mudrocks of the Tonalee Formation in and adjacent to the stream (Fig. 13a) (53.565088°, -9.499031°). This formation forms a valuable marker horizon within the Killary-Joyce succession.

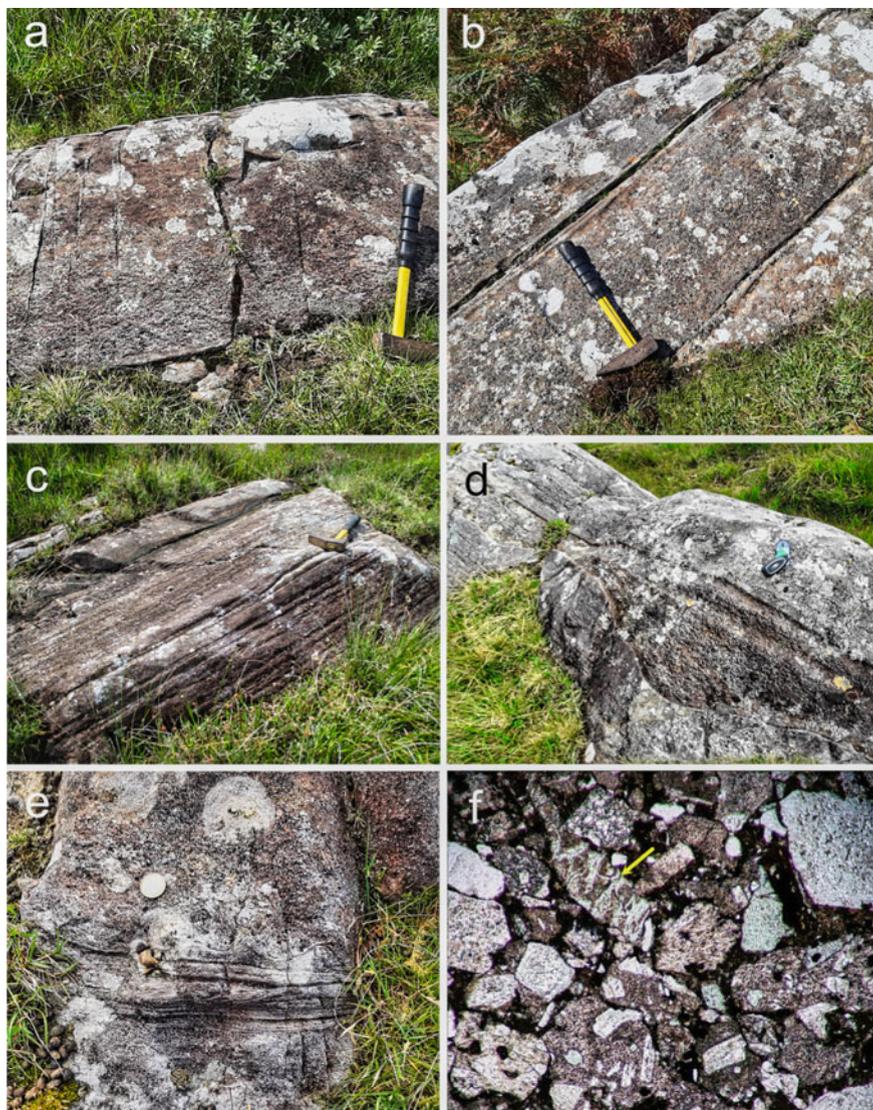


Fig. 12 Images from the lower part of the Lettergesh Formation: **a** Graded sandstone **b** Massive graded sandstone with thin layer of parallel lamination at the top and thin mud parting between this and the next sandstone **c** Amalgamated parallel laminated sandstones **d** Erosional scour filled with coarse sandstone showing size grading and parallel lamination in upper part beneath a sharp contact at the base of the next sandstone **e** Loading at the base of the coarse sandstone in the upper part of the image: the upper part of the graded sandstone beneath shows parallel lamination succeeded by small scale cross stratification produced by ripples **f** Thin section image (xpl0) from the Lettergesh sandstones at Drin. Note the dominance of feldspathic rock fragments; the clast marked by an arrow preserves some fiamme

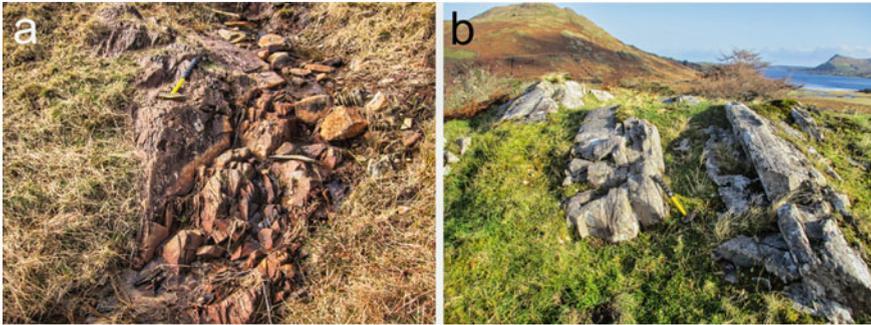


Fig. 13 a Typical red Tonalee Formation mudrocks b Laminated sandstones from the Finny School Laminated Sandstone Member of the Kilbride Formation; Kilbride peninsula in the background

Where a small track crosses the stream walk eastwards down through the succession that beneath the Tonalee Formation consists firstly of siltrocks with scattered fossil debris and then fine-grained laminated quartzose sandstones that are particularly well exposed next to an old NW trending track (Fig. 13b). Mapping of this area shows that these laminated sandstones of the Finny School Laminated Sandstone Member of the Kilbride Formation directly overlie the coarser-grained *Skolithos* bearing sandstones seen at Loc. 8.2. From here there is a direct walking route along the ridge crest to Bencorragh.

Provenance exercise for the KH-JC succession (Finny Church and Drin)

- (1) What information can you determine in the field concerning the provenance of the Lough Mask Formation?
- (2) How do the sandstones with the *Skolithos* burrows in the Kilbride Formation differ compositionally from the sandstones of the Lough Mask Formation?
- (3) To what do you attribute this difference?
- (4) What can you determine in the field concerning the composition of the Lettergesh sandstones?
- (5) How do you interpret the provenance changes seen to occur through the succession?
- (6) What further information is needed to support your interpretation?

This exercise is best accompanied by examination of thin sections under the microscope. An indication of some of the major differences is given by comparing Figs. 7b and 12f.

2.5.2 Bencorragh

For the ascent of Bencorragh which has spectacular exposures and views allow at least an hour and a half. Continue straight up the indistinct old track as far as the curved boundary wall and cross the fence here (arrow on Fig. 11). Follow the crest of the ridge to the summit of Bencorragh. Exposures near the summit of Bencorragh provide the best examples of pillow lavas seen anywhere in Ireland (Fig. 14). The structure of the pillows seen here and in the crag faces just to the south show that the lavas consistently dip steeply and young to the north (Fig. 14a–c). The pillows are elongate, showing that they were lava tubes and locally have spectacular radial vesicles infilled with quartz and epidote. The pillows here record a greenschist facies assembly, whilst those at higher stratigraphic levels (Loc 6.15) are anchimetamorphic which may reflect burial metamorphism within the volcanic pile (Ryan et al. 1980).

There are fine views from here of the almost flat Maumtrasna Plateau to the north, the trace of the Derry Bay Fault on the north side of Lough Nafooney (Fig. 14d), and Lough Mask and the flat lying Carboniferous limestone lowlands to the east. Scattered exposures of basal Carboniferous conglomerates and sandstones with gentle dips are present on the surface of the plateau. There is considerable debate as to whether the Maumtrasna Plateau represents the result of Variscan faulting or whether it is due to later Tertiary uplift (Dewey 2000; Worthington and Walsh 2011). Return is by the same route.

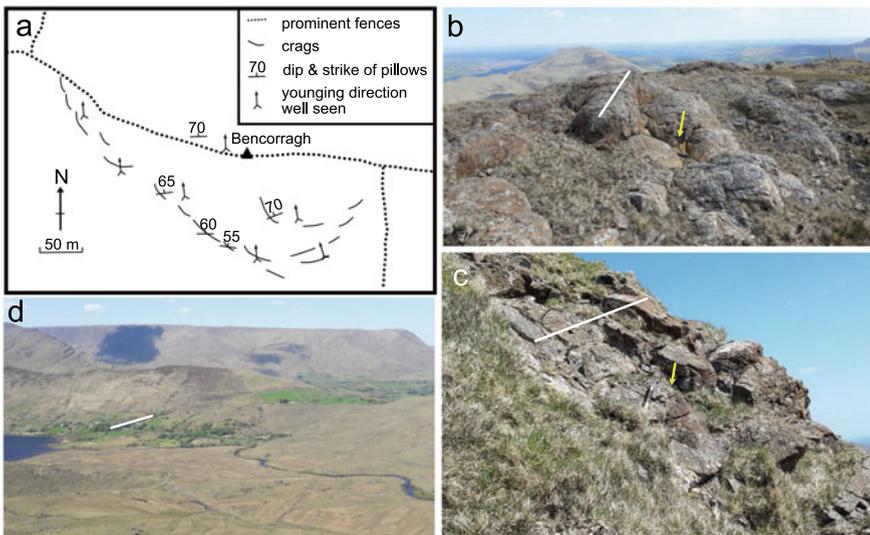


Fig. 14 a Sketch map of localities near Bencorragh summit b Pillow lavas on the summit of Bencorragh. Beds dip steeply to and young to the left (north) and the yellow line approximates dip and the white line marks strike on (b) and (c) c Pillow lavas seen in profile in the crags south of Bencorragh d Maumtrasna Plateau seen from Bencorragh. The scar in the middle ground (indicated by white line) marks the course of the Derry Bay Fault

2.6 Locality 8.5: Owenduff Bridge (53.573714°, -9.794439°)

Access and other Information Take the N59 west from Leenane and park at Owenduff bridge on the wide verge on the side of the road (53.573714°, -9.794439°). This is a main road on which traffic moves quickly so take great care and wear high visibility clothing.

This locality allows examination of the lower part of the Killary Harbour – Joyce Country succession and its relationship to the metamorphic rocks of Connemara. Walk west after parking across the bridge for about 40 m. Here, Dalradian psammites with common quartz veins are exposed on either side of the road. Now walk back to the exposures adjacent to the bridge. These are immature breccias, the lowermost being dominated by locally derived Dalradian clasts (Fig. 15a). Above this bedding is readily discernible and locally clasts show good imbrication indicating approximately westerly flow (Fig. 15b). The overabundance of vein quartz and the moderate sorting indicate that these are not simply local scree deposits but that the sediment had undergone a degree of sorting and segregation. These breccias are interpreted as infilling depressions on an irregular eroded surface of Dalradian rocks.

Continue eastwards along the road. Rocks exposed just to the north of the road are well-sorted, grey-green sandstone that contains some shell fragments. These are part of the Kilbride Formation, which, along with the Lough Mask Formation, is relatively thin in this area being together a maximum of a few tens of metres.

Continue towards Leenane to the next prominent crags adjacent to the road (53.574237°, -9.792715°), where there is a series of well-rounded cobble conglomerates and interbedded sandstones. The most common clast types are pale-weathering sandstones and pale porphyries. (Fig. 16a, b). Vein quartz is notably absent or rare and there is a lack of clasts that can be matched to the Dalradian basement. Despite their well-rounded nature, the clasts display imbrication (Fig. 16c) that suggests flow from northeast to southwest. These rocks have been assigned to the Gowlaun Conglomerate Member that forms the basal part of the Lettergesh Formation.

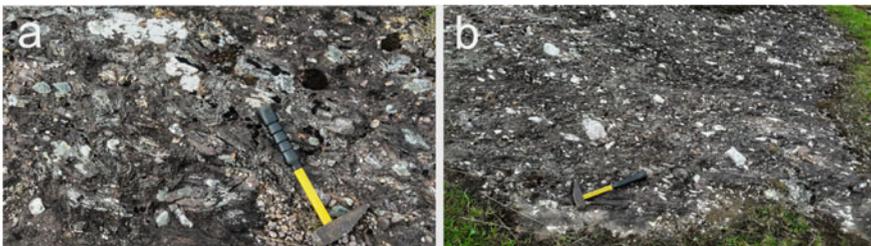


Fig. 15 a Basal breccias of the Lough Mask Formation dominated by Dalradian schist clasts b Breccias of the lower part of the Lough Mask Formation: note the bedding, the common presence of vein quartz, and the imbrication of elongate clasts that dip to the right at steeper angles than bedding

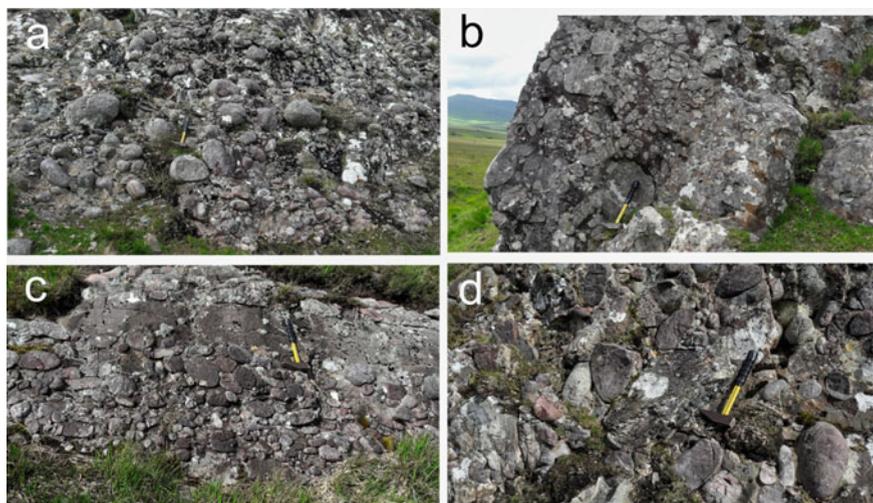


Fig. 16 a, b Close-packed texture of the Gowlaun Conglomerate c Imbrication of clasts dipping more steeply to the right (northeast) than bedding d Large, poorly rounded clast of Dalradian schist (just left of hammer)

Walk northwest across the bog to a large prominent crag at (53.574425°, -9.793559°). At the western end of this exposure, a large (>50 cm) clast of quartz-veined psammite is present that is not rounded and may have been acquired from the local basement (Fig. 16d). The source of the majority of the clasts is not known and they may represent a part of the succession that is not otherwise preserved.

2.7 *Locality 8.6: Lough Fee: (53.592468°, -9.831395°)*

Access and other information This is a viewing stop of the hillside south of Lough Fee and Lough Muck. There are numerous possible places to pull off at the side of the road, the largest being just after passing a small, wooded peninsula at 53.592468°, -9.831395°.

A series microgranitic intrusive rocks are present in the area from Lough Fee to the Atlantic coast. These have been described by Mohr (1998) who suggested they were intruded into sediments that were only moderately lithified. The thickest of these sills is the Benchoona sill that forms an impressive hill to the south of Lough Fee (Fig. 17) where it reaches a maximum thickness of 330 m. The sill thins markedly against the Letterfrack fault and Mohr (1998) suggests that intrusion overlapped with tilting of the Silurian succession and movement on the Letterfrack fault. An example of one of the thinner sills can be examined at locality 8.8.

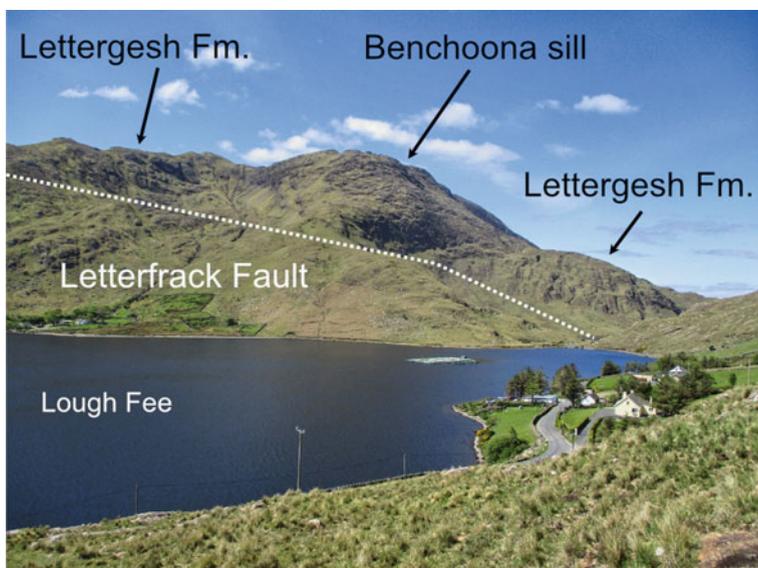


Fig. 17 View of the Benchoona sill and the surrounding Lettergesh Formation sediments at the south-west end of Lough Fee

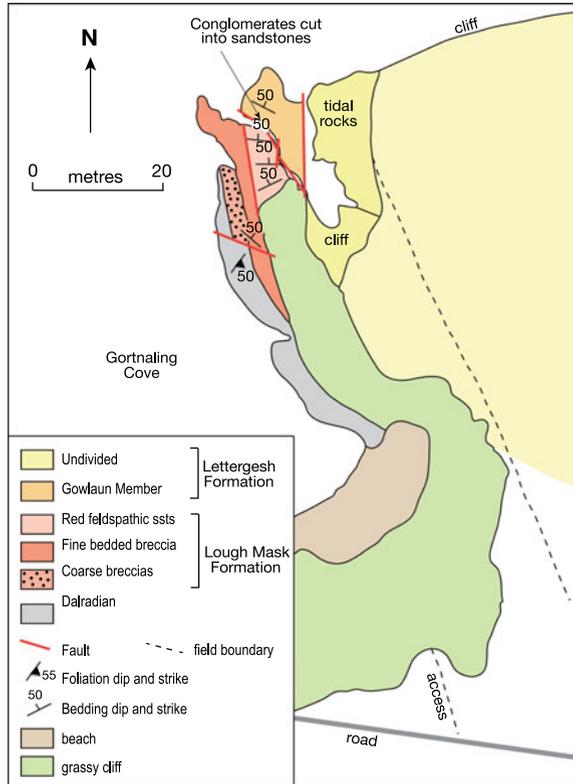
2.8 *Locality 8.7: Gortnaling (53.598628°, -9.912364°)*

Access and other Information From Leenane, head west on the N59 and then turn right onto an unnamed road signposted for Tully Cross. Some parking is usually available outside the national school in Gowlaun (53.598628°, -9.912364°). Walk southwest along the road to a stone-faced bungalow with a track just beyond it. Enter the field opposite (53.597450°, -9.917221°) containing two large trees and walk down to the east side of Gortnaling Cove (Fig. 18). The section can be accessed by carefully descending a low grassy cliff at the seaward end of the field; take great care if it is wet.

This locality allows examination of the relation of the basal parts of the Killary Harbour – Joyce Country succession with the metamorphic rocks of Connemara.

Although there is considerable faulting in this area, the contact between the Dalradian and the base of the Silurian can be seen (Fig. 19a). Large blocks of heavily serpentinised ultramafic rocks containing bastite pseudomorphs after orthorhombic pyroxene suggesting a harzburgite origin occur at the contact (Fig. 19a, b) which also contains locally derived Dalradian material. The Dalradian beneath comprises upper greenschist-facies semi-pelitic psammites with thin foliation-parallel quartz sheets. The basal few decimetres of the Silurian sequence are dominated by locally derived Dalradian clasts (Fig. 19b). Above this are bedded breccias, richer in vein-quartz clasts (Fig. 19b, c), similar to those seen at Owenduff Bridge (Loc. 8.5). These breccias are the basal part of the Lough Mask Formation. There are two interpretations

Fig. 18 Geological map of Gortnaling Cove



for this contact (see Basal Silurian Exercise below). Firstly, that it is an unconformity modified by subsequent deformation or secondly that this is a weathered low-angle extensional shear zone.

On most of the foreshore, the basal breccias are separated by a fault from a series of well-bedded medium- to coarse-grained feldspathic sandstones that are assigned to the Lough Mask Formation (Fig. 19d) but a conformable stratigraphic contact is visible just beneath the steep grassy cliff. These feldspathic sandstones are separated by further faults from a series of conglomerates that have a very different clast assemblage to the breccias of the basal Lough Mask Formation. The conglomerates have been assigned to the Gowlaun Member of the Lettergish Formation (Fig. 19e, f). They continue to the edge of a steep inaccessible cliff, beyond which well-bedded sandstones and mudrocks of the Lettergish Formation are visible in the cliff sections.

It is not clear if the Kilbride Formation has been excised by the numerous faults, was erosively removed in Gowlaun times, or was never deposited here. The faulting also means that the thickness of the Gowlaun Member here is not known; it reaches its maximum thickness on Altnageera, some 3 km inland, estimated at 370 m by Laird and McKerrow (1970), where it appears to have cut through the Lough Mask Formation to the Dalradian basement. The clast assemblage in the Gowlaun Member

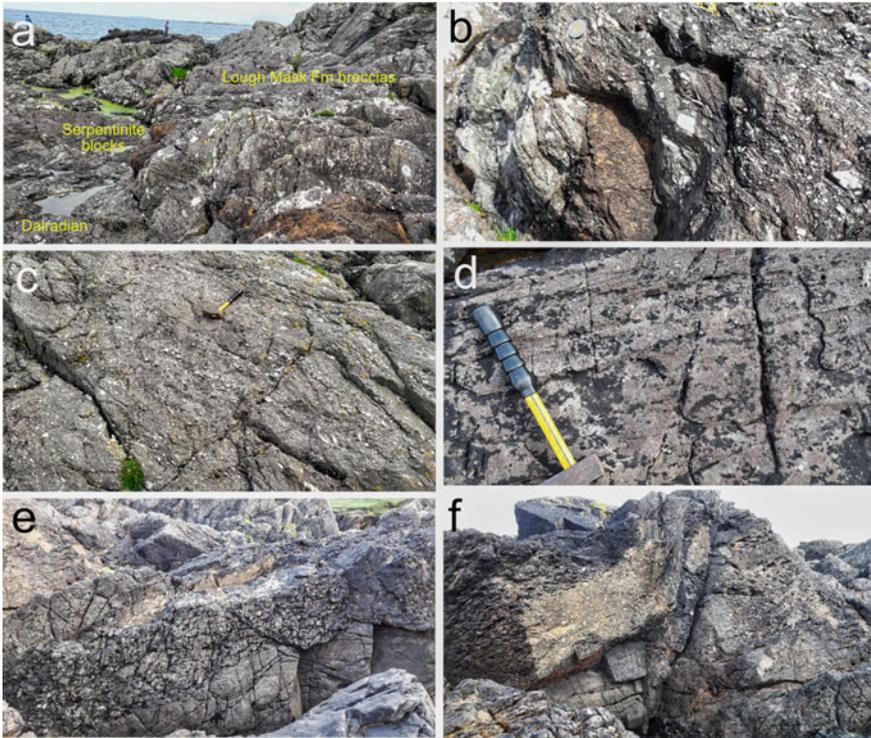


Fig. 19 **a** Unconformity between Dalradian schists (bottom left) and breccias of the Lough Mask Formation. Note the large, brown-weathering blocks of serpentinite at the unconformity surface **b** Close up view of the unconformity looking west; Dalradian is on the left with prominent serpentinite blocks at the unconformity; coarse grained breccias of the lower part of the Lough Mask Formation are to the right **c** Well bedded fine grained breccias in the basal part of the Lough Mask Formation; note the large amount of vein quartz **d** Coarse, feldspathic sandstones of the Lough Mask Formation **e** Coarse conglomerates of the Gowlaun Member cutting into sandstones at side of fault gully shown on Fig. 18 **f** Conglomerates of the Gowlaun Member exposed on the side of the fault gully shown in Fig. 18 Note the angular clasts which are of Dalradian schists

here is very different to that seen near Owenduff Bridge, as clasts are more angular and include numerous Dalradian schist clasts. This could be interpreted as resulting from collapse of submarine canyon walls of schist as the Gowlaun currents flowed through the canyon that was cut into the basement. Unfortunately, there is no control, from what is essentially a two-dimensional exposure, of the overall orientation of this channel and the sediment transport direction from the northeast is only derived from exposures south of Lough Fee (Williams and O'Connor 1987).

The basal breccias at Gortnaling and Owenduff Bridge (loc. 8.5) are part of a carapace of clast-supported breccias that underlie all the Silurian deposits of South North Galway where they rest upon the Dalradian of Connemara (Williams and Rice 1989; Leake 2014). The high concentration of quartz suggests that these breccias

may represent a lag deposit on an erosion surface. Williams and Rice (1989) identify sections at the local base of the Silurian, including Gortnaling, where fault rocks become progressively infiltrated with sediment up section. They attribute this to the breccia having developed along a regional low-angle extensional detachment associated with the exhumation of the Connemara Massif. Clift et al. (2004) suggest that this crustal scale extensional detachment entrained mafic and ultramafic blocks whilst it was active during the Mid-Late Ordovician and was then partially eroded prior to Silurian deposition. Leake (2014) offers an alternative explanation and argues that the quartz rich breccias are due to the preferential preservation of the more resistant material and that the deformation fabrics in parts of the breccia are due to subsequent intra-Silurian folding.

Basal Silurian exercise

The nature of the sub-Silurian unconformity is regionally important in assessing the post-Grampian history of Connemara and the origin of the Killary Harbour–Joyce Country depositional basin. The lowest Silurian sediments have been interpreted both as simple sedimentary breccias overlying an irregular but largely peneplaned surface and also as erosional remnants of a major extensional detachment within the Dalradian succession.

This exercise requires examination of both locality 8.5 (Owenduff Bridge) and locality 8.7 (Gortnaling Cove). The assessment of the field evidence can be enhanced by using information from some key published sources (Chew and Van Staal 2014; Clift et al. 2004; Friedrich and Hodges 2016; Geological Survey of Ireland—www.gsi.ie; Leake 2014; Williams and Rice 1989). What additional field data/samples would you collect to further answer questions you have raised in the field?

Owenduff Bridge

- (1) What sedimentary structures are observed in the breccias?
- (2) What information can be gleaned from these structures?
- (3) What is the composition of the breccias?
- (4) How do you produce a composition of this nature?

Gortnaling

- (1) Describe the nature of the contact between the Dalradian and the Silurian. What type of contact is this?
- (2) Why are serpentinites concentrated at or near the contact?
- (3) What is the relationship of the serpentinites to the enclosing Dalradian?
- (4) How far beneath the contact are the serpentinites found?
- (5) What is the nature of the structure in the Dalradian beneath the contact; is there any evidence for high strain zones?

- (6) Construct the lower part of the Silurian stratigraphy based on these exposures. Be careful to base the summation on demonstrable unfaulted contacts.
- (7) How does this succession compare to that seen in the eastern part of the outcrop (Lough Mask and Lough Corrib areas) and at Owenduff Bridge?

Provenance of the Gowlaun Conglomerate

This exercise can be carried out safely at Owenduff Bridge where there are numerous large exposures to accommodate a student group. If safety conditions can be satisfied the exercise can be repeated at Gortnaling although available exposures are more limited.

- (1) Should size and shape of clasts be measured? Why might this be important?
- (2) What transport distance is needed to accomplish the level of rounding displayed by the clasts?
- (3) How well can a maximum transport distance be constrained?
- (4) Devise a sampling strategy for accurately estimating the clast composition of the Gowlaun Conglomerate?
- (5) What criteria would you use in the field to distinguish between quartzose sandstones and metamorphic quartzites?
- (6) In which direction did the source area lay?
- (7) What is the best reconstruction you can make of the composition of the source area?
- (8) Does the information from Owenduff Bridge give the same answer as that from Gortnaling?

2.9 Locality 8.8: Lettergesh Beach: (53.602154°, -9.908356°)

Access and other information From locality 8.7 take a short drive north to the signposted beach car park at Lettergesh (53.602154°, -9.908356°). From here walk 110 m right (north) to the first headland.

Sandstones of the Lettergesh Formation are intruded by one of the many microgranitic sills that are common in this area (Fig. 20a). There is some evidence of baking of the Lettergesh sediments, in the form of irregular green-weathering patches in the sandstones beneath the sill (Fig. 20b). There are no published details of the mineralogical changes involved.



Fig. 20 a Sandstones of the Lettergesh Formation overlain by microgranitic sill b Contact metamorphic effects in Lettergesh Formation sandstones

2.10 *Locality 8.9: Salrock and Salrock School (53.602185°, -9.857188°)*

Access and other Information Parking is available on the Lough Muck side of the road near the old Salrock School (now a private house) at 53.602185°, -9.857188°. Walk back along the road to the east.

2.10.1 **Salrock School**

These localities allow examination of the shallowing upward part of the Killary Harbour – Joyce Country succession. Several good roadside exposure here show the essential characters of the Glencraff Formation (Fig. 21). This formation consists of



Fig. 21 Thin bedded sandstones and mudrocks of the Glencraff Formation, Salrock School

c. 60 m of parallel-sided thin sandstones interbedded with grey mudrocks. They are in marked contrast to the thick-bedded turbidites of the Lettergesh Formation below and the more lenticular interbedded sandstones and mudrocks of the Lough Muck Formation above. These sandstones have been interpreted as turbidites by Laird and McKerrow (1970) and as outer shelf storm deposits by Nealon (1989).

2.10.2 Salrock

Return a little to the east and turn left on an unnamed road to Rosroe Pier. Just after this road crosses the crest of a ridge and some large pine trees appear on the right hand side, there is parking for several vehicles on the left side of the road (53.602388°, -9.851000°). Access the open hillside to the left, keeping to the left of a telegraph pole and then keep near to the crest of the ridge.

This exposes both the mudrock-dominant (Fig. 22a) and sandstone-dominant (Fig. 22b) facies of the Lough Muck Formation and also some interesting large-scale structures. These consist of packages of beds that are discordant, often subtly, to those beneath. Examples where the younger beds are asymptotic to a basal surface and also those where the upper beds are steeper and markedly discordant are seen. In many cases the beds just above the discordances are deformed by soft-sediment deformation, but in others they are not (Fig. 23). These structures have variably been interpreted as rotational slump scars (Laird 1968) or drapes of tidal channels (Williams and Nealon 1987). Whichever interpretation is accepted basically defines where the slope to shelf transition occurs in what is generally a shallowing-upward sequence (Fig. 2).

After returning to the parking it is worth a short drive down the road for a panoramic view of the Salrock Thrust where Ordovician rocks of the Rosroe Formation are thrust over the Salrock Formation of the Killary Harbour–Joyce Country succession (Fig. 24).

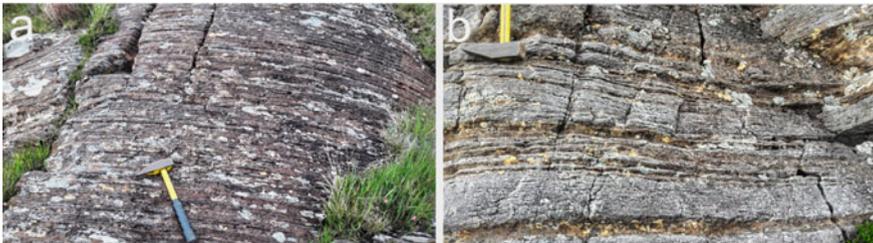


Fig. 22 a Thin bedded facies of the Lough Muck Formation b 8.7.3 Sandstone rich facies of the Lough Muck Formation

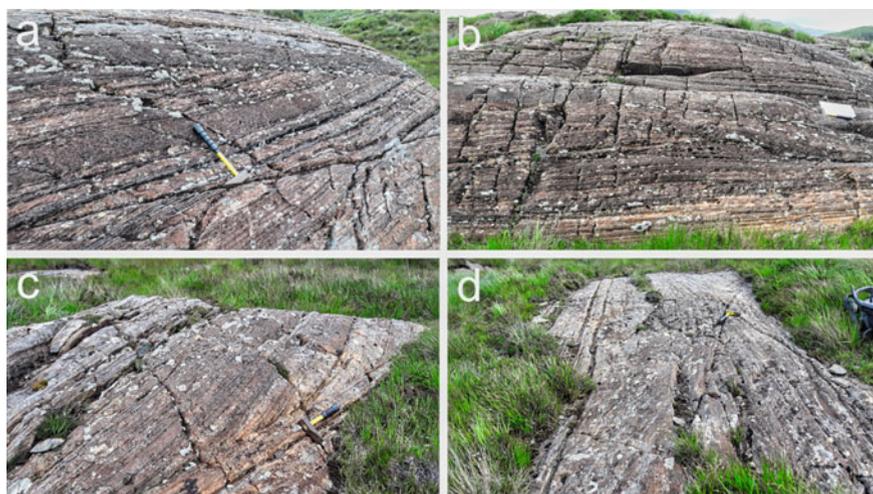


Fig. 23 **a** Rotated package of sandstone dominant facies with clear truncation at its upper surface **b** Large gently discordant bed packages **c** Bed package showing asymptotic discordance at its lower surface **d** Large rotated package with curved profile; the beds on the left provide the regional horizontal

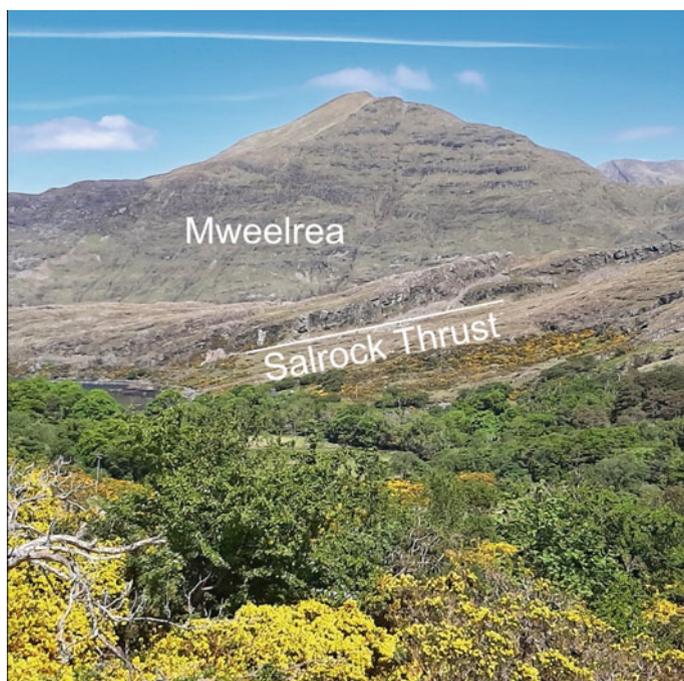


Fig. 24 Panoramic view of the Salrock Thrust. Killary Harbour is hidden from view but the gentle dips of the South Mayo Syncline are evident in Mweelrea to the north

2.11 Locality 8.10: Glassilaun (53.614860°, -9.874965°)

Access and other Information From Leenane take the N59 and then turn right onto the unnamed road towards Tully Cross. About 2 km beyond the western end of Lough Muck take the small, signposted road to Glassilaun Beach, where there is abundant parking. There are good sections at either end of the beach and in the small group of rocks in the central part approximately half tide or lower is needed to access and examine them.

This beach has excellent exposures of the Salrock Formation, the uppermost part of the Killary Harbour–Joyce Country succession. The Salrock Formation is dominated by red and purple mudrocks (Fig. 25a, b) and interbedded sandstones (Fig. 25b, d) but it also contains numerous green mudrocks, especially where the sandstones are thicker. This colour variation is thought to be secondary as it does not always follow bedding (Fig. 25c). It is probable that the whole section was initially red and that reduction of the iron-bearing minerals occurred during later fluid movement, which would have been greatest through the more permeable thicker sandstone horizons. The occasional presence of *Lingula* and gastropods without any truly open marine fossils suggests that these rocks were deposited in marginal marine mudflats.

The formation is intruded by several microgranite sills, a good example being visible in the rocks near the centre of the beach (Fig. 26).

An excellent example of antitaxial, extensional veins occurs in the first, low, smooth outcrops at the eastern end (53.615701°, -9.876259°) of the fine sandy beach,

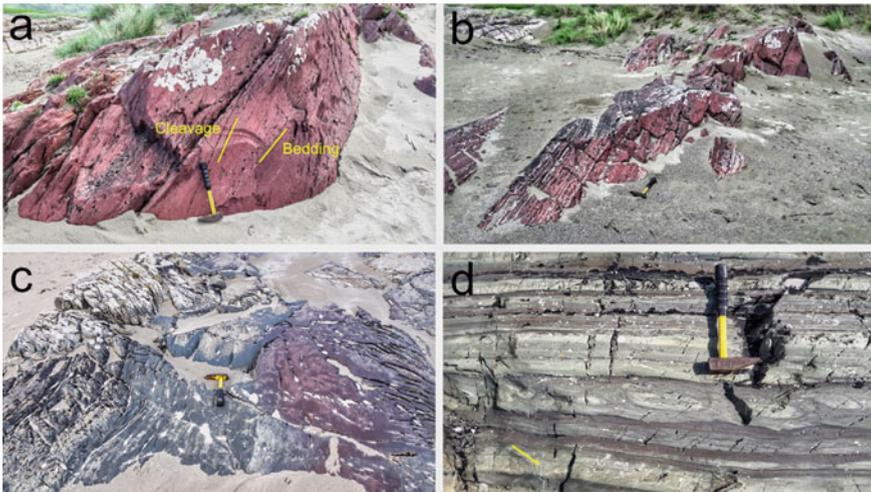


Fig. 25 a Homogenous red mudrocks of the Salrock Formation b Homogenous red mudrocks of the Salrock Formation interbedded with paler coloured thin bedded sandstones c Thick green sandstone (left) with homogenous red mudrocks to the right: the mudrocks on which the hammer rests have undergone secondary reduction d Thin bedded red mudrocks interbedded with thin non-red sandstones a thin horizon of soft sediment deformation is just below the hammer head



Fig. 26 Microgranite sill (hammer rests on this) cutting thin bedded mudrocks and sandstones of the Salrock Formation

125 m northwest of the carpark, where hard, grey-green, fine-grained sandstones grade into interbedded red–purple mudrocks of the Salrock Formation (Fig. 27a, d). A striking feature of the vein-fill mineralogy is that it is related systematically to the mineralogy of the alternating bands of quartz-rich sandstones and red–purple mudrocks, quartz in the sandstone veins and chlorite in the mudrock veins (Fig. 27a); veins are antitaxial. This indicates that the vein-fill “fed” on the chemistry of the immediate vein wall, an example of the “substrate effect” (Lander and Laubach 2015) and that the veins grew incrementally with no through-going gap, no consequent

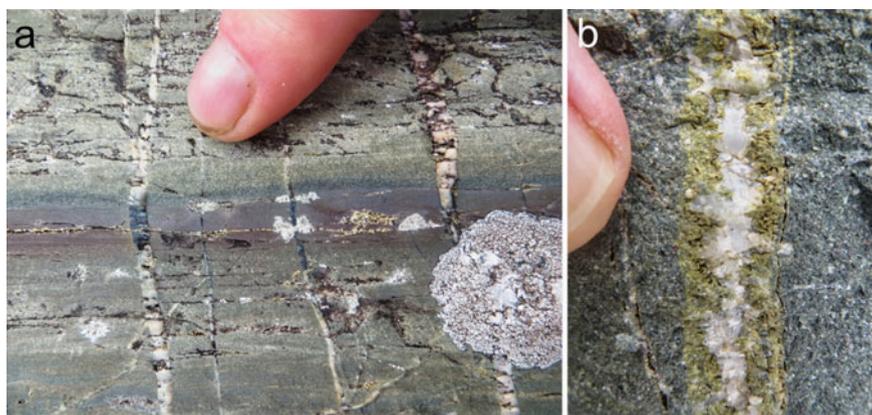


Fig. 27 **a** Vein whose fill mineralogy is related to that of the bedrock, quartz in the sandstone and chlorite in the mudstone **b** Vein with antitaxial epidote rims and vuggy quartz later stage fill

fluid transport, and in the solid state. It is probable that these veins developed during regional transtension (see Loc 8.14).

Veins in the calcareous greywackes of the underlying Lettergesh Formation, are particularly well seen in a small quarry with a mobile telephone mast on the west side of the Leenane-Clifden road 200 yards south of the Lettergesh turnoff (53.579563°, -9.786943°). These show epidote rims and centre fills of quartz, antitaxial in the epidote stage and vug-fill in the later quartz stage (Fig. 27b).

3 Croagh Patrick Succession

3.1 *Aim of Excursion*

The aim of this excursion is to examine the stratigraphy of the strongly deformed Croagh Patrick succession and to show the relationship to the underlying Ordovician and to some of the major faults in the area.

3.2 *Locality 8.11: Derryheagh and Cregganbaun* (53.695560°, -9.799678°)

Access and other Information Take the R335 south from Louisburgh as far as (53.695560°, -9.799678°) where parking is available (Fig. 28). From the parking spot walk north along the road and enter via the gate on the right just before the rendered stone wall.

Exposures to the west of the large barn are of the Cregganbaun Conglomerate (Fig. 29a, b) which forms the basal unit of the Croagh Patrick succession. This contains well-rounded clasts up to 35 cm across of pink and pale quartzite and psammite. Rare interbedded sandstones (Fig. 29c) define bedding, which strikes about 080 and dips 42° north. This is discordant to bedding in the Sheeffry Formation to the east. There is an obvious cleavage in the sandier layers and the near-vertical alignment of clasts in parts of the conglomerate is tectonic rather than a primary sedimentary fabric. Exposures to the north are of compact quartzose sandstone, the texture of which is in part due to baking by the Corvock granite. These rocks are part of the Cregganbaun Quartzite Formation although they lack the very pale, almost white appearance seen elsewhere, e.g. Kilgeever (Loc. 8.12).

Return to the parking and drive northwards towards Cregganbaun School. Just beyond the road junction to Killeen there is a large parking area on the west side of the road (53.703535°, -9.808185°). In this area, fine grained, pale-weathering sandstones and siltrocks that are part of the Bouris Formation locally contain shell debris that contains some identifiable coral and brachiopods fragments, mainly preserved

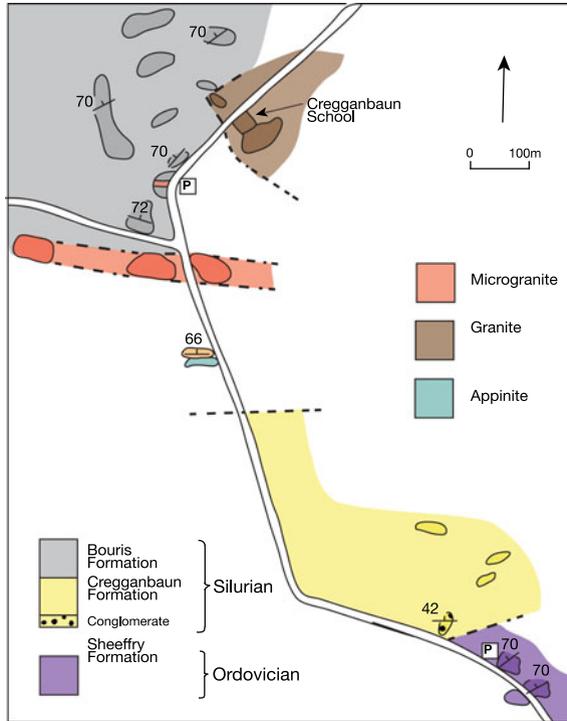


Fig. 28 Simplified map of the Derryheagh/Cregganbaun area

as moulds. A small felsitic intrusion is also present. From here, walk towards Cregganbaun School and, just before reaching it, enter the open moorland to the south of the school. There are abundant exposures of the Corvock Granite here (Fig. 28), which is even-grained and quartz-rich and has caused widespread thermal alteration in the area. The granite has been dated at 410 ± 4 Ma (Graham and Riggs 2021) (Lower Devonian) and at 387 ± 12 Ma, approximately Middle Devonian but with large error (O’Connor 1989). It clearly post-dates the Silurian rocks and has caused widespread thermal alteration in the area.

Just opposite the school (53.704526° , -9.806506°) a small trackway provides access to a large area of open moorland. Some granite is exposed near the entrance to the moorland. Walk westwards across numerous exposures of Bouris Formation until reaching a marked break in slope and then south across strike to see the typical features of the Bouris Formation (Fig. 29d–f). The formation is somewhat sandier here than in the exposures to be visited at Emlagh (Locality 8.14).

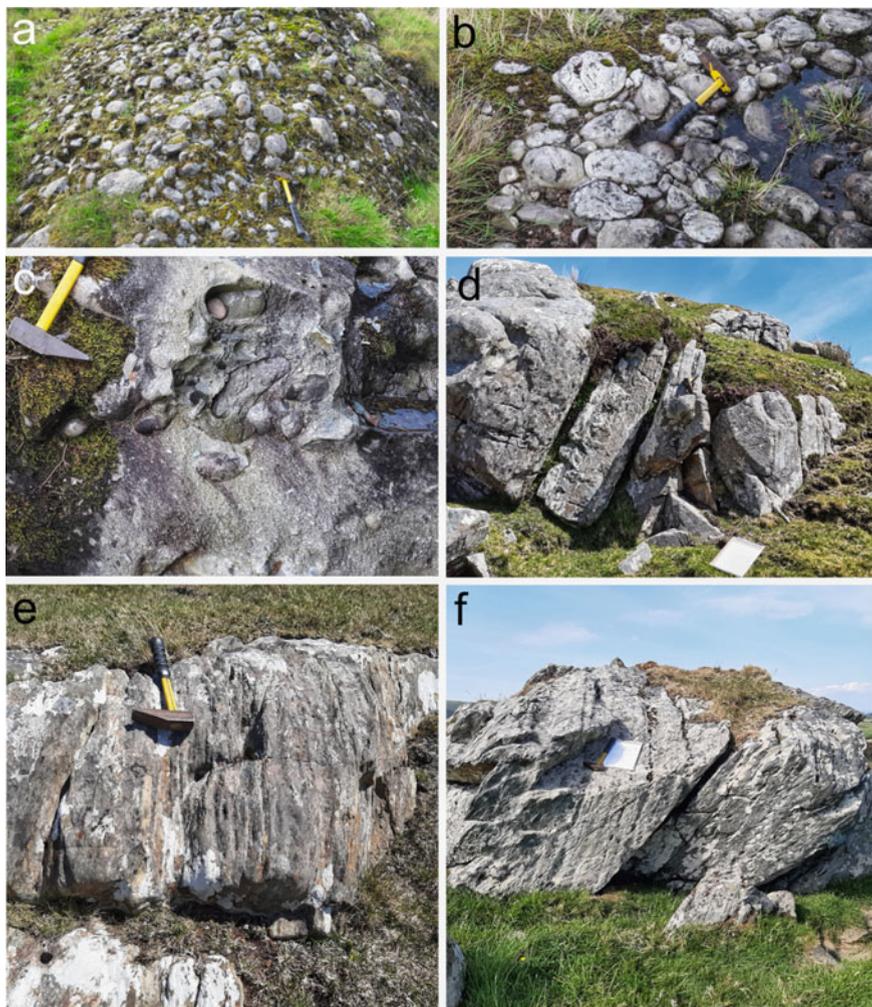


Fig. 29 a Cregganbaun Conglomerate at Derryheagh b Cregganbaun Conglomerate at Derryheagh with closely packed clasts of quartzite c Isolated cobbles in strongly deformed sandy matrix, Cregganbaun Conglomerate, Derryheagh d Fine grained sandstones in Bouris Formation e Typical muddy Bouris Formation bedding is subvertical and cleavage dips more gently to the left f Thin bedded sandstones in muddy Bouris Formation bedding

3.3 *Locality 8.12: Kilgeever (53.765071°^o, -9.765410°^o)*

Access and other Information Entering Louisburgh on the R335 from Westport, turn left onto Chapel Street at the crossroads in the centre of the village. Go straight for about 2 km and then fork right at a brown sign for Clew Bay Archaeological Site 10 and Kilgeever cemetery. There is abundant parking opposite the cemetery

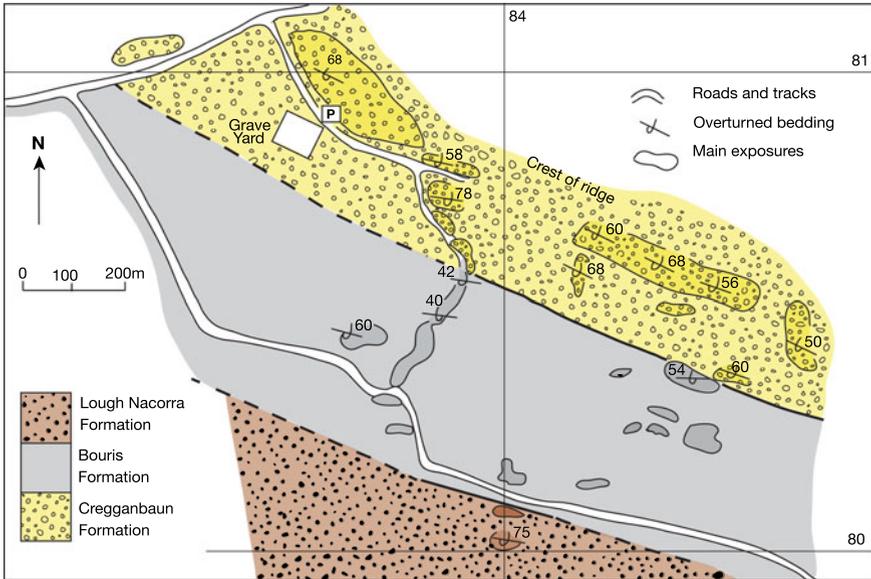


Fig. 30 Simplified geological map of Kilgeever area

(53.765071°, -9.765410°), where there is a large quarry exposure (Fig. 30). The ridge can be accessed via a small steep path opposite the eastern end of the cemetery.

The rock is quartzite that is strongly deformed such that it is difficult to determine original sedimentary structures. A few preserved cross-beds indicate that younging is to the south and that the bedding is overturned. The purest, white-weathering quartzites are seen near the top of the ridge (Fig. 31a). In general, thicker, more quartzose beds dominate the northern part of the exposure and to the south, younger beds are thinner.

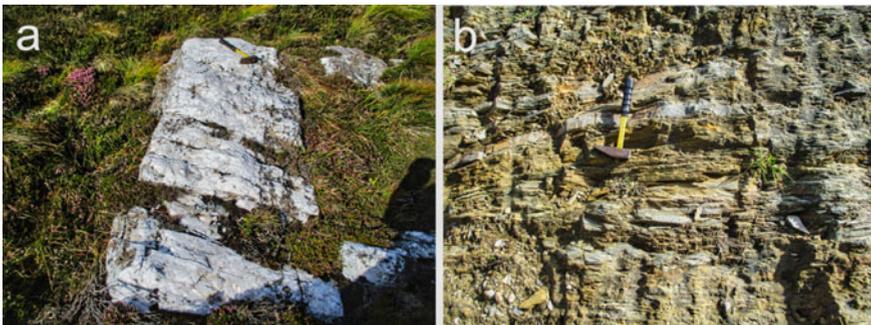


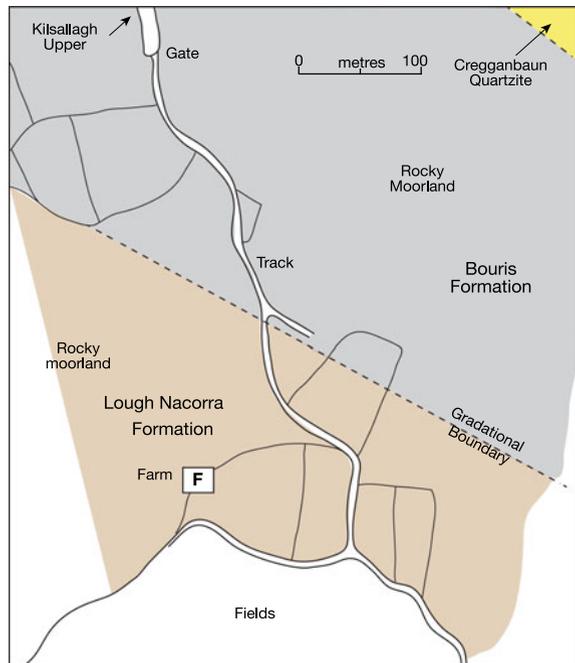
Fig. 31 a Pure white quartzites on ridge of Kilgeever Hill b Flaggy quartzites, psammites and pelites in the Cregganbaun Quartzite Formation

From the main car park, continue east along the track to a second quarry on its north side. The upper part of the quarry face is mainly quartzite, with increasing admixture of finer-grained pelitic layers towards the base (younger beds) (Figs. 31b). The pelitic layers have a soapy feel but do not have any megascopic new mineral growth. This unit lies within the Cregganbaun Quartzite Formation as more quartzites are present to the south. A cross-section exposed in an old track to the south shows that the Cregganbaun Quartzite passes transitionally upward into the finer grained Bouris Formation (Fig. 30). There are fine views to the south of the Sheeffry hills, the Doo Lough gap through which run the Maam Valley Fault Zone, and Mweelrea.

3.4 Locality 8.13: Kilsallagh Upper (53.763179°, -9.705105°)

Access and other Information Take the L5880 from Lecanvey and after c. 1 km take the next left, driving uphill to Kilsallagh Upper. Park in the large car park (53.763179°, -9.705105°), or at the roadside at the end of the ridge to the east, which marks an alternative access route to Croagh Patrick (Fig. 32). The ridge is formed by the

Fig. 32 Simplified geological map of Kilsallagh Upper



Cregganbaun Formation, which provides the pale debris for the extensive screens.

The purpose of this stop is to examine some easily accessible sections in the Lough Nacorra Formation as well as enjoying some spectacular views of South Mayo geology and scenery. Walk southwards from the car park past a few houses and then through gates and a farmyard, keeping to the metallised track. Be sure to shut the gates. Just through the farmyard, outcrops near a small stone shed on the east side of the track are of the mainly pelitic Bouris Formation. The dip is steeply northwards but the rocks are overturned and young to the south (Fig. 33a).

Continue up the track through further gates, as far as the ridge crest. Extensive exposures demonstrate the gradational passage from the Bouris Formation to the Lough Nacorra Formation. There is a consistent overall dip to the north in rocks that are overturned on the northern limb of the Croagh Patrick Syncline. The rocks are strongly deformed and contain numerous minor parasitic and kink folds. However, primary way-up evidence such as truncated small-scale cross-bedding can be found in the coarser horizons (Fig. 33b). On the southern side of the ridge, towards an isolated farmhouse, the succession is dominated by well sorted, fine- to medium-grained psammities (Fig. 33c) many of which are dominated by parallel lamination.

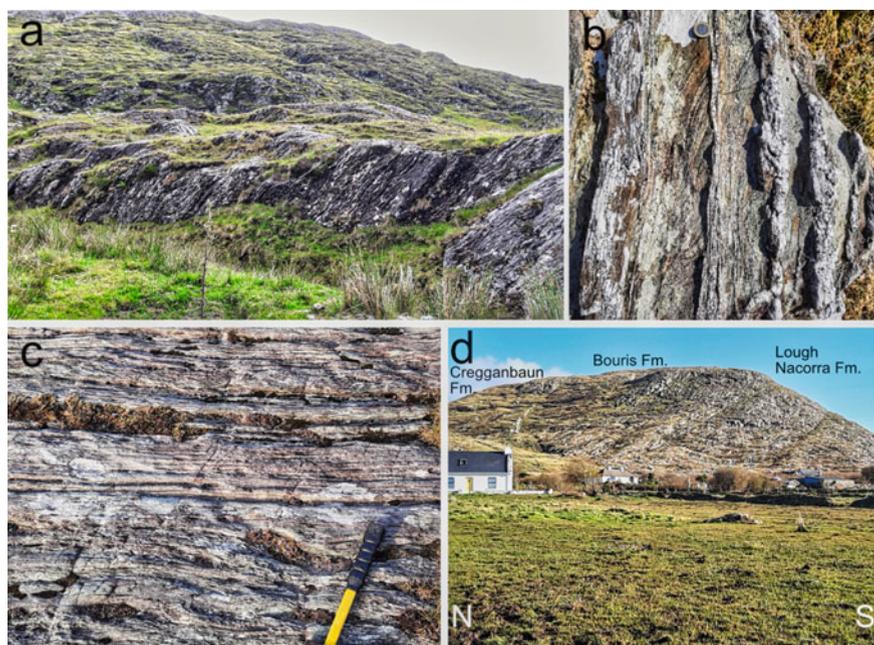


Fig. 33 a Bouris Formation exposure looking east, the bedding can be seen dipping moderately to the left (north) but is overturned and younging is to the south b truncated cross-beds giving primary way-up evidence, Lough Nacorra Formation c typical psammitic Lough Nacorra Formation dominated by flat lamination d Silurian stratigraphy exposed on the southern side of the Croagh Patrick ridge

There are excellent views from here to the north, south and west and the eastward continuation of the Lough Nacorra outcrop is evident in the hillside to the east (Fig. 33d).

3.5 *Locality 8.14: Emlagh Point (53.744148°, -9.897374°)*

Access and other Information From Louisburgh, take the R355 south heading for Killeen and the Lost Valley. After about 5 km turn right (signposted Doogmakeon) at 53.739195°, -9.851912° and continue to the end of the road where there is plentiful parking at 53.744148°, -9.897374°. Continue down track to beach. A low tide is necessary to study these outcrops. This locality affords a traverse from the polyphase, strongly sheared, Bouris Formation with subvertical foliation, through the north-dipping Emlagh Fault, to the non-metamorphosed sediments of the Louisburgh-Clare Island succession (Fig. 4). The Emlagh Fault is sinistral normal, so the Bouris Formation is in the footwall and the Louisburgh-Clare Island succession forms the hanging wall.

The footwall rocks are superbly exposed from Gortnagarryan Strand to the tip of Emlagh Point first in distributed outcrops then on a continuous wave-cut platform. Bedding is transposed into parallelism with the sub-vertical foliation to form a shear banding with stripes of pelite and fine psammite. On the headland just opposite the parking two small, irregular, tonalite intrusions and several aplite veins are affected by the foliation (53.744204°, -9.899294°); the Corvock granite 10 km to the east is the likely source of these intrusions. The banding is the first-phase foliation in the footwall. It is almost penetrative, but lenses of less-deformed fine psammite are preserved and, in a few places, show current cross-bedding that consistently indicates younging to the north.

On the north side of Emlagh Point, the north-dipping Emlagh Fault is exposed on the foreshore (Figs. 34 and 35). The rocks exposed north of the fault belong to the Strake Banded Formation characterised by red mudrocks and sandstones. In this area there are also three levels at which calcareous laminites occur and these form useful local markers (Maguire 1989). Detrital zircon from sandstones here are mainly rounded purple zircons of probable Grenville age and euhedral grains that indicate that volcanism continued into the Silurian (Dewey and Mange 1999), which has been confirmed by Riggs et al. (in press). We suggest that the best way to follow the geology here is to work westwards along the fore-shore outcrops and wave-cut platform in the Bouris formation, turn north to the north side of Emlagh Point, then eastwards to the outcrop of the Emlagh Fault and its hanging wall (Figs. 34 and 35a).

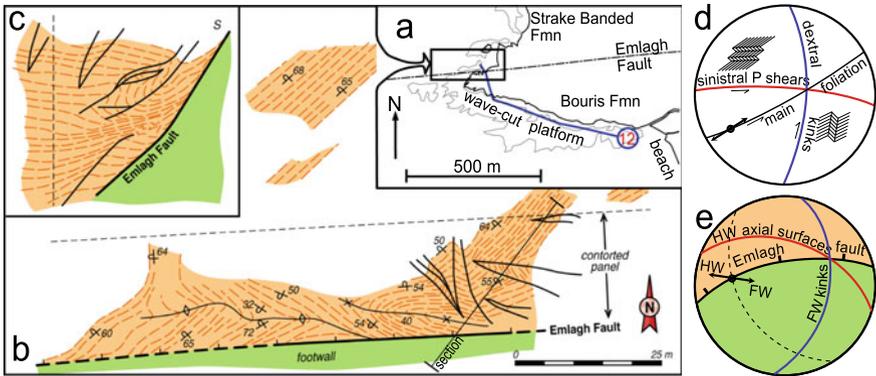


Fig. 34 **a** Location map for locality 8.14 showing traverse (blue line) **b** Structural map of the Strake Banded Formation in the hanging wall of the Emlagh Fault **c** NE–SW section through the Emlagh Fault. The dashed line shows the edge of the severely contorted panel. **d** main fabric elements of the Bouris Formation (footwall) **e** Main fabric elements of the Strake Banded Formation (hanging wall)

The Emlagh Point outcrops constitute a fine example of the effects of late Silurian–early Devonian sinistral transtension superimposed on a transpressional then a strike-slip milieu. Structures throughout the South Mayo Trough show this sinistral structural sequence of transpression with cleavage and early, gently-plunging open to tight folds at the meso-scale, evolving through strike-slip east–west shear zones to transtension with structures ranging from large steeply-plunging open folds to a variety of outcrop scale minor structures. We suggest that this sequence is a result of a changing slip direction across the sinistral collision zone between the Laurentian and Avalonian continents during the late Silurian–early Devonian. In the Bouris Formation which outcrops in the footwall of the Emlagh Fault, the vertical shear foliation is coincident with transposed bedding and an early cleavage, which gives the rock its stripy character. Sheets of laminated quartz with a sub-horizontal fibre lineation are parallel with foliation, and the foliation is folded by steeply-plunging sinistral tight to isoclinal folds (Fig. 35b). Dextral kink bands (Fig. 35c) and sinistral P folds (Fig. 35d) indicate sinistral transtension. The northeast-striking foliation suggests that it lies in the short limb of a transtensional fold typical of the South Mayo Trough. The absence of SC structures, so common in the Deer Park to the east, is typical of transtensional shear zones. SC structures can only form in a thinning transpressional shear zone, whereas kink bands and P structures can form only in a widening transpressional shear zone (Dewey and Ryan, in preparation). This is because shear zones thin in transpression and thicken in transtension. Late dextral kink bands are common through the South Mayo Trough in slates; they formed in the sinistral transtension final phase of regional deformation. They are especially well-developed in the slates of the Glenummera Formation and in the red slates of the Salrock Formation at Glassilaun beach.



Fig. 35 **a** General view looking east-northeast of the Emlagh Fault whose trace is marked with a dotted line **b** isoclinal folds in laminated quartz sheet, Bouris Formation **c** dextral kink bands and **d** sinistral 'P' shears in the main shear fabric of the Bouris Formation **e** increase in fold intensity in the Strake Banded Formation (left hand side) towards the Emlagh Fault (dashed line) **f** contorted panel (see Fig. 34b) in the Strake Banded Formation within 2 m of the Emlagh Fault

The Emlagh Fault is planar, dips north at about 65° , and is heavily silicified to a very tough rock in a band about ten centimetres wide. We have not seen slickensides along the Fault. The hanging wall Strake Banded Formation is mostly inverted with a super-posed east-plunging antiform and synform whose axial surfaces strike at about 20° clockwise to the Emlagh Fault. Intensity of folding in the hanging wall increases towards the fault (Fig. 35e) until, in an approximately 2 m zone along the Fault, there are very tight refolded folds arranged in phacoids and lozenges (Fig. 35f).

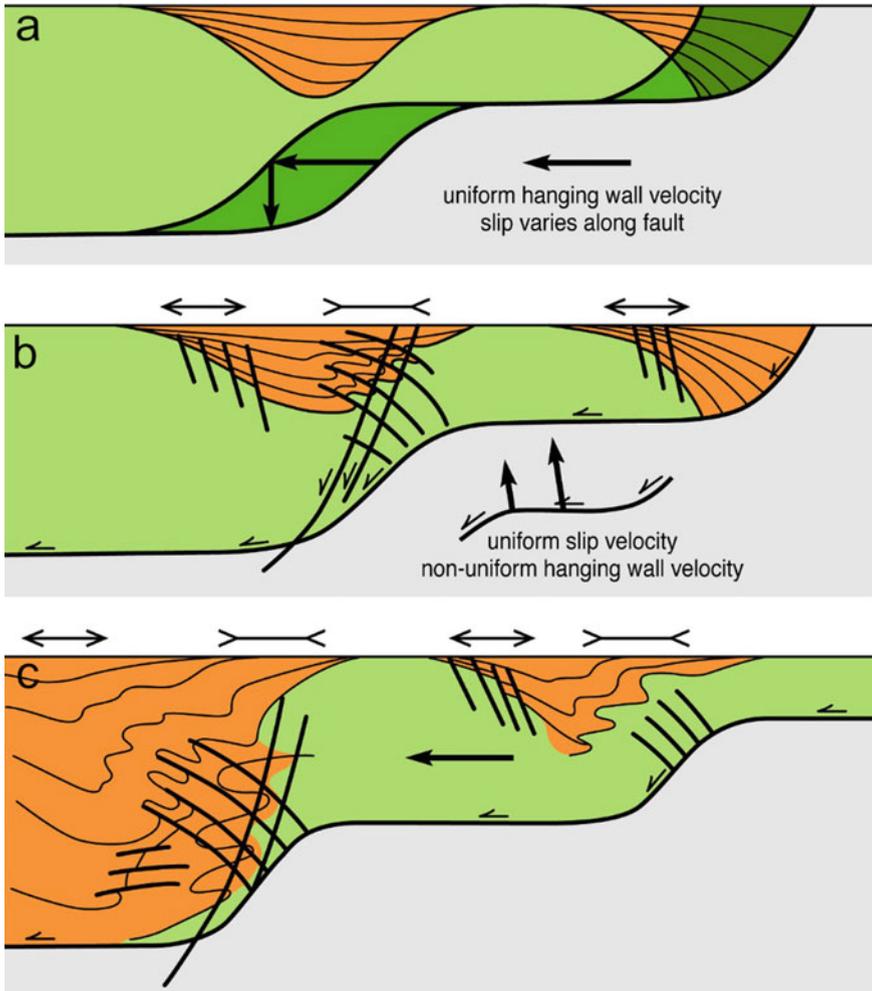


Fig. 36 Schematic diagram showing the structural development of basins in the upper part of the brittle lid above a normal fault with ramps and flats (see text for details)

The kinematics of the Emlagh structure is illustrated in Wulff Net stereo-projections in Fig. 34d, e. In the footwall (Fig. 34d), the sinistral P shears and dextral kink bands form a conjugate pair across the sinistral shear foliation with which they share a steeply-plunging intersection lineation. The slip direction on the shear foliation (black dot), from sinistral isoclinal and quartz fibre, plunges gently to the southwest. In Fig. 35e, kink bands in the footwall in a zone some 10 m wide adjacent to the fault dip to the east at a slightly shallower inclination than those farther away from the Fault, and fold axial surfaces in the hanging wall dip at about 45°, are clockwise-transsecting with respect to the Fault; kinks, folds, and Fault have a common intersection. This

suggests an origin in sinistral transtension with a sinistral-normal slip direction on the Fault and a change from sinistral strike slip to sinistral transtension. An earlier regional sinistral transpression is not seen at Emlagh Point but is widely-developed across the South Mayo Trough where it generated the first cleavage (see Loc 6.11).

The stratal inversion of the hanging wall adjacent to the Emlagh Fault before the superposition of the transtensional structures is not seen elsewhere in the Clare Island-Louisburgh Basin and may be a result of a large-scale non-planarity of the Emlagh Fault. Where a normal fault has flats and ramps (Fig. 36a), asymmetric basins form above blind and surface-intersecting ramps. Because of the downward motion and slower forward velocity of basin fill above a blind ramp, counter-intuitive thrusting and overfolding develop, and normal faults develop at the ramp to normal transition (Fig. 36b). Very complicated superimposed fold and fault patterns may develop (Fig. 36c).

Exercise: Structure of the northern Silurian successions

Using the information acquired in the field at localities 8.12 to 8.18, locality 6.1 and Fig. 37.

- (1) Draw a series of sketch N-S sections to illustrate the structure of the Croagh Patrick and Louisburgh-Clare Island successions.
- (2) In what geological settings might such structural profiles develop?

4 Louisburgh–Clare Island Succession

4.1 Aim of Excursion

The aim of this excursion is to examine the stratigraphy and paleoenvironments of the Louisburgh–Clare Island succession, its relationship with the underlying rocks of the Clew Bay Complex and its subsequent deformation history. A summary map is shown in Fig. 37.

4.2 Locality 8.15: Shivlagh Rocks (53.777794°, –9.796047°)

Access and other Information Proceeding north-east from the centre of Louisburgh fork left at the Garda Station and then straight (northeast) until the road bends 90° left, then 90° right and descends to a small stream where there is limited parking at (53.777794°, –9.796047°). Just over the stream, a stile and short path access the coast near Shivlagh Rocks (Fig. 38). At least half tide is needed to study this section.

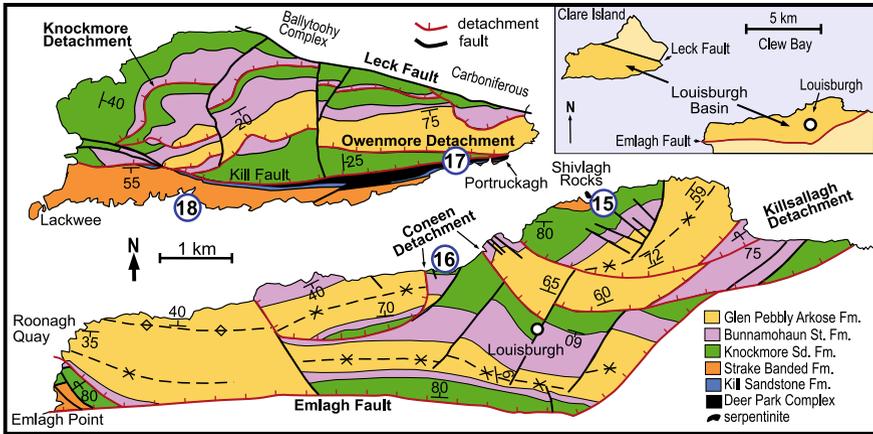
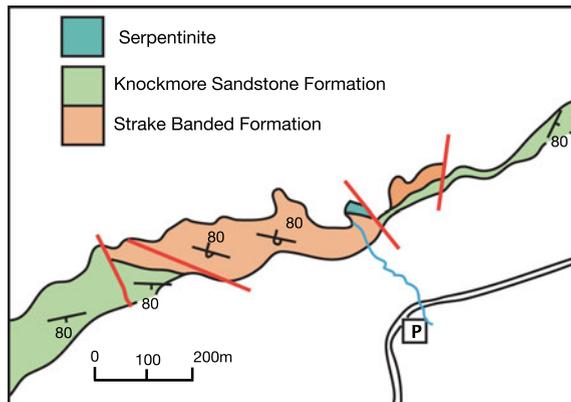


Fig. 37 Summary geological map of the Louisburgh–Clare Island succession with localities 8.15 to 8.18 shown by circled numbers ‘15’ – ‘18’ respectively. Abbreviations used: St. = Siltstone; Sd. = Sandstone; Fm. = Formation

Fig. 38 Geological map of the Shivlagh rocks area



Examine the cliff section on the east side of the bay, which is formed of red mudrocks and thin sandstones of the Strake Banded Formation, the lowest part of the Louisburgh–Clare Island succession seen on the mainland. A prominent yellow-weathering bed in the cliff that is offset by a shallowly north-dipping normal fault is a tuffaceous sandstone (Fig. 39a). This is the only thick bed of this type seen on the mainland, in contrast to the outcrop further west on Clare Island where they are more common. The upstanding ridge of tidal rocks seaward of here is formed by a much-altered serpentinite intrusion that has caused discolouration of the adjacent Strake Banded Formation. The intrusion is cut off by a fault to the east, but this part of the coastline is not easily accessible.



Fig. 39 **a** Pale weathering tuffaceous sandstone within the mainly red mudrocks of the Strake Banded Formation. The white line indicates the trace of the low angle normal fault. The line is broken where the fault is obscured by material in the foreground. Beds are overturned and young to the right **b** Interbedded red mudrocks and grey sandstones, Strake Banded Formation **c** Contact between the red mudrocks of the Strake Banded Formation (left) and the granule rich grey-green sandstones of the Knockmore Sandstone Formation (right) **d** Typical field appearance of the Knockmore Sandstone Formation on the foreshore exposure. The hammer rests on a thin bedded portion with desiccated mudrocks. Only the major bedding planes stand out **e** Flat laminated sandstone on wave polished surface **f** Intraformational mud clasts in flat laminated sandstones on wave polished surface.

Return to the boulder beach and walk westwards through typical Strake Banded Formation. Beds are mainly overturned and dip to the north but young to the south (Fig. 39b). In the first rocky bay, small grey dykes can be seen cross-cutting the layering. These dykes are themselves faulted, very fine-grained and appear to lack chilled margins. These have also been described as being of serpentinite composition (Phillips et al. 1970).

At the next headland there are several small faults, but just beyond it a clear stratigraphic contact can be seen between the Knockmore Sandstone Formation and the Strake Banded Formation (53.778877° , -9.803201°). The base of the Knockmore Sandstone Formation is sharp and erosive, locally rich in quartz pebbles and cross-bedded (Fig. 39c). Although there is no obvious structural discordance, there may be a significant time gap here, as there is a major change in the style of sedimentation. Above the coarse basal bed, the sandstones are finer grained and dominated by flat and low-angle lamination with only occasional cross-beds. On most of the coastal exposure, it is only the major bedding planes that weather out (Fig. 39d) and the sandstones show little apparent internal structure, but fine lamination is visible on the wave polished rocks (Fig. 39e, f). Mudrock horizons are relatively thin and commonly show desiccation cracks, emphasising that the sediment surfaces were commonly exposed. The sandstones are interpreted as fluvial deposits.

4.3 *Locality 8.16: Cooneen Harbour* (53.770229° , -9.830518°)

Access and other Information Parking is available for a few cars at Cooneen Harbour (53.770229° , -9.830518°). For more or larger vehicles use the beach car park at Carrowmore Strand (53.769422° , -9.824973°) and walk across the beach. Walk down the slipway onto the beach.

The rocks exposed on the foreshore at the western end of the beach (Figs. 40 and 41a) are probably the best exposures of the Bunnamohaun Siltstone Formation on the mainland for demonstrating internal structures.

The formation here is dominated by red mudrocks consisting of deep-red silts thinly interbedded with laminae of coarser red silt to fine sand. These mudrocks are interbedded with packages dominated by fine grained red sandstones. The red mudrocks contain some ripple structures in the coarsest bands, some of which are quite symmetrical and may have been generated by wave action (Fig. 41b). There

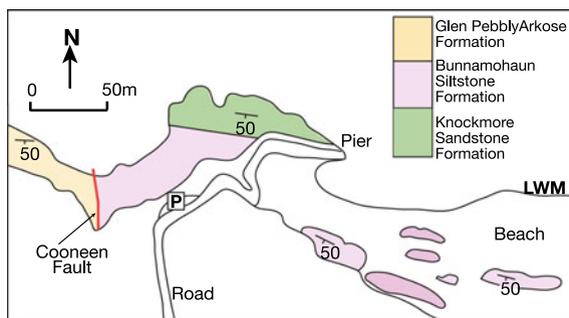


Fig. 40 Sketch map of the Cooneen Harbour coastal section

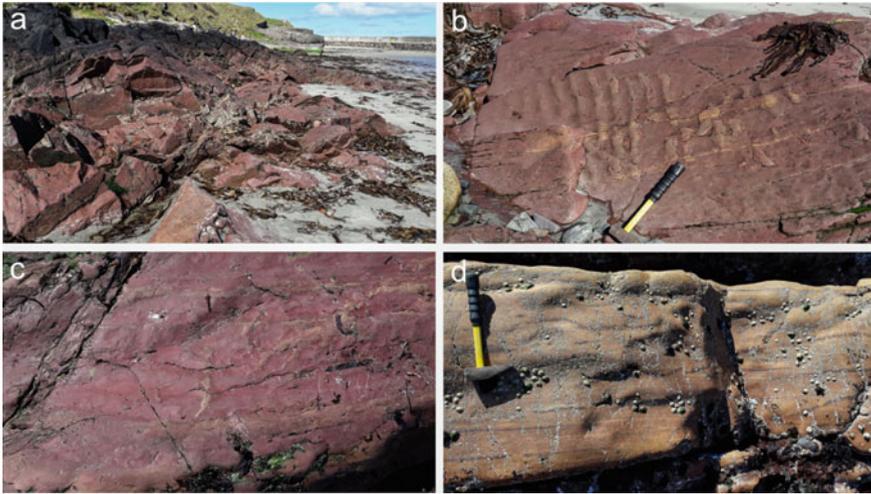


Fig. 41 **a** Bunnomohaun Siltstone Formation at Cooneen Harbour. The foreground is dominated by red mudrocks with thin sandstones more evident towards the back of the beach **b** Wave ripples exposed on a bedding plane surface **c** Typical bedding scale in red mudrocks cross-cutting sandier segregations are either desiccation crack fills or dewatering structures **d** Knockmore Sandstone Formation at Cooneen Pier with heavy mineral bands

are numerous desiccation-crack fills seen in cross-section as well as a variety of generally more irregular dewatering structures (Fig. 41c). The rocks are interpreted as flood plain deposits that repeatedly dried out; the few wave-generated ripples are interpreted to have formed when there was sufficient water depth after floods. The sandier horizons probably represent temporary influx of the channel systems present on the flood plain.

Either go around the end of the pier if the tide is low or cross the pier onto the rocks on the north side. The rocks are the upper part of the Knockmore Sandstone Formation and the contact with the overlying Bunnamohaun Siltstone Formation here runs mainly under the pier. The sandstone here differs slightly from the formation elsewhere in being brownish rather than green/grey but is similar in other aspects. Some heavy mineral bands are evident in the sandstones (Fig. 41d), which are mainly flat-laminated but locally cross-bedded. Thin grey laminite bands, which are common near the top of this formation elsewhere, are absent here although they are known from just behind Cooneen House some 300 m away. Follow these sandstones around into the cove to the west of the pier, where the contact with the Bunnamohaun Siltstone Formation can be seen.

A marked cleft on the west side of this cove marks the trace of the Cooneen Fault (53.770109°, -9.832105°). The fault dips west at about 60° and younger rocks of the Glen Pebbly Arkose Formation are present in the hanging wall (west side) (Fig. 42). The simplest explanation is that this is a normal fault, although it has previously been referred to as the Cooneen Thrust (Phillips et al. 1970).



Fig. 42 Gently right dipping trace of the Cooneen Fault; the footwall rocks to the left belong to the Bunnamohaun Siltstone Formation and the hanging wall rocks to the right belong to the younger Glen Pebbly Arkose Formation

4.4 Locality 8.17: Clare Island Southeast (53.795999°, -9.957834°)

Access and other Information From the harbour, walk west towards Kill. Pass three closely spaced houses on the right and then just before the next house on the left enter through a gate (53.799131°, -9.959510°) to follow a track diagonally left upslope, then walk due south, parallel to the field boundary to the headland of Portruckagh

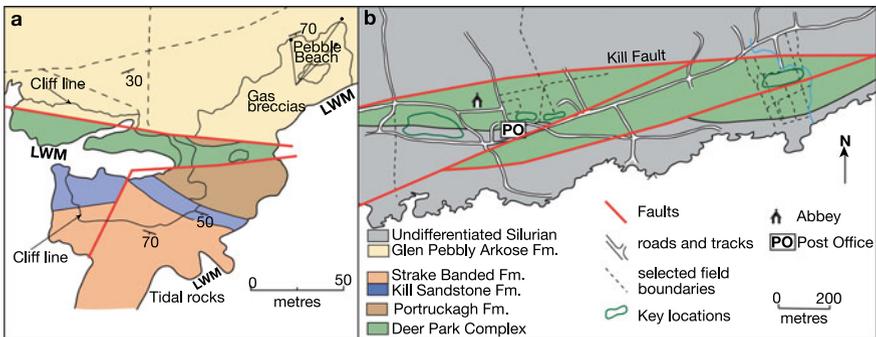


Fig. 43 **a** Detailed map of the Portruckagh locality **b** Simplified map of the area between Portruckagh and Kill showing the key exposures described in the text



Fig. 44 a Kill Fault zone, Portruckagh. The hammer rests on reddened Glen Pebbly Arkose Formation; the lower part of the image is of sheared Portruckagh Formation b Sheared Portruckagh Formation in Kill Fault zone, Portruckagh c Gas breccia in Glen Pebbly Arkose Formation, Portruckagh d Strongly discordant gas breccias in Glen Pebbly Arkose Formation, Portruckagh; the white line represents bedding

(Fig. 43a). Access the cove on the east side with fine views over Clew Bay, Croagh Patrick, Sheeffry Hills and Mweelrea.

These localities expose fragments of the Clew Bay and Deer Park complexes (see chapter “[The Ordovician Fore-arc and Arc Complex](#)”) and the lower part of the Louisburgh-Clare Island succession, within a major fault zone. The north side of the cove has magnificent exposure of the Kill Fault (53.795999° , -9.957834°) (Fig. 44a, b). Broken grey sandstone clasts, some containing quartz veining, in a sheared muddy matrix appear to be altered versions of the Portruckagh Formation, which is thought to be a low-grade part of the Clew Bay Complex. At the base of the cliff this sheared rock is in contact with brecciated Glen Pebbly Arkose Formation that is locally reddened. There is no veining in the Kill Fault Zone, presumably due to the impermeable and easily deformed muddy matrix.

Walk east to the next small cove with a pebbly beach. On this traverse there are numerous examples of brecciated Glen Pebbly Arkose Formation, with many breccia zones strongly discordant to bedding (53.796282° , -9.957078°) (Fig. 43c, d). These breccia zones are not confined to areas immediately adjacent to the Kill Fault, but can be found some distance from it. These unusual rocks have been interpreted as gas breccias (Phillips 1974), with the Kill Fault zone acting as the conduit from depth for the volatiles.

Return to the beach at Portruckagh, where the northernmost exposures are of low grade sandstones and mudrocks of the Portruckagh Formation. To the south

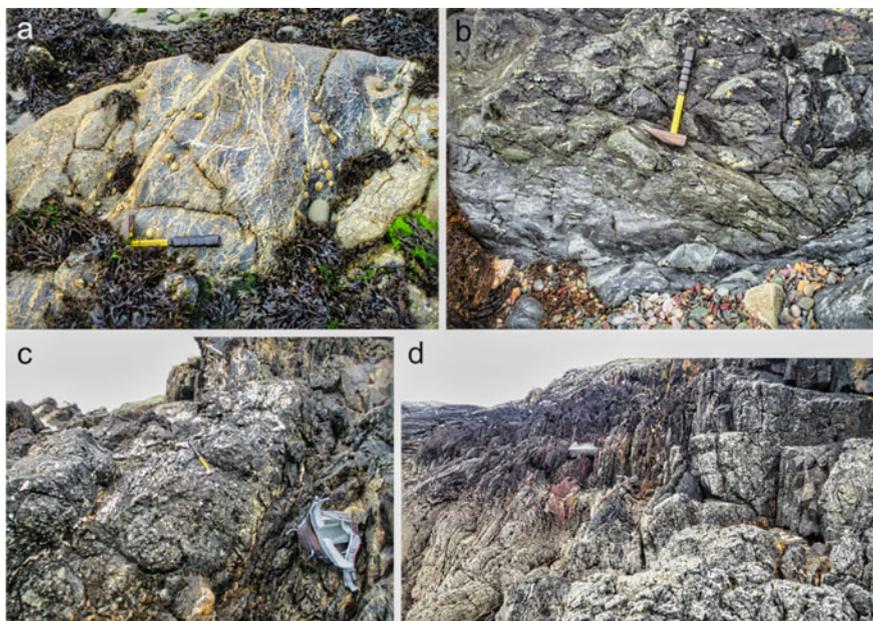


Fig. 45 **a** Veined serpentinite, Portruckagh **b** Dismembered sandstones and mudrocks of Portruckagh Formation, Portruckagh **c** Near vertically dipping Kill Sandstone Formation (left) resting unconformably on Portruckagh Formation (beneath rucksack), Portruckagh **d** Vertically dipping Kill Sandstone Formation (right) passing upwards into red mudrocks of the Stake Banded Formation (left), Portruckagh; beds young to the left (south)

of these is a sliver of strongly veined and altered serpentinite (Fig. 45a), which has a sharp contact to the south with a more extensive outcrop of the Portruckagh Formation. The latter consists of dark-coloured sandstones and grey mudrocks of low metamorphic grade (Fig. 45b) The rocks are cleaved but not schistose and bedding is readily distinguished. Access the headland on the south side of the beach, where more of the Portruckagh Formation is exposed. Finer grained portions show small-scale east-plunging folds and numerous small faults.

On the east-facing headland, a zone of sandstones with extensive quartz veining marks the base of the Kill Sandstone Formation, with the location of the quartz veins presumably determined by the more permeable nature of the strata (Fig. 45c). A thin conglomerate, less than a metre thick, is locally present at this steep, slightly overturned unconformity. In the cliff section to the west, the Kill Sandstone Formation passes gradationally into thin-bedded red mudrocks and sandstones of the Strake Banded Formation (Fig. 45d).

Return across the headland to the narrow isthmus connecting it to the main part of the island. In situ serpentinite can be examined on a thin ridge that juts into the bay to the west. Glen Pebbly Arkose Formation is visible in the cliffs on the north side of this cove and the Kill Fault can be seen in the low tidal rocks although it is not safe to access here. Return to the road by the same route used to get to Portruckagh.

Walk west along the road for 800 m, passing a black barn and then one more house on the right and then look for a large (c. 80 m long) exposure below the road towards the sea at Gurtin (Fig. 43b) (53.794322° , -9.974841°). Access it through a gate at 53.795776° , -9.975029° . The exposure is composed of amphibolite that in places has a strong tectonic fabric produced by mineral alignment. There are also parts that were originally sediments that are now metamorphosed to pelites with some quartzose sandy layers Phillips (1973).

Return to the road and continue west for c. 900 m towards the abbey. Enter the last field on the right before the fork right to the shop and abbey. The lowest part of the exposure is formed of metasedimentary rock with obvious large muscovites, quartz and locally garnets. The upper crags are of amphibolite. Return to the road and enter the next field, through the gate, to see further examples of amphibolite, most showing a clear tectonic fabric but with more massive parts.

Collectively these three localities show rocks that are interpreted to be part of an ophiolite and its associated sedimentary envelope referred to as the Deer Park Complex.

Return to the main road and walk west past the turn to the abbey and a cross-roads and then enter the large field on the right hand side through a gate near its western end (53.792413° , -9.993151°). The small ridge of exposures closest to the road is of veined, quartzose sandstone of the Kill Sandstone Formation. The next ridge of exposures to the north comprises spectacular examples of the Kill Conglomerate, which forms the basal part of the Silurian succession (Fig. 46a). The conglomerate is dominated by well-rounded clasts of quartzite up to 40 cm across, but there are also large clasts of vein quartz and, less commonly, jasper. A few small clasts of amphibolite are also present. The quartzite clasts are interpreted as fragments of the Dalradian metasedimentary rocks that are currently exposed along the northern side of Clew Bay. The next ridge to the north is an excellent example of amphibolite, parts of which have a strong tectonic fabric (Fig. 46b) that is steeply dipping and



Fig. 46 a Coarse-grained Kill Conglomerate, west of Abbey, Kill b Fine scale striping in amphibolite, Kill

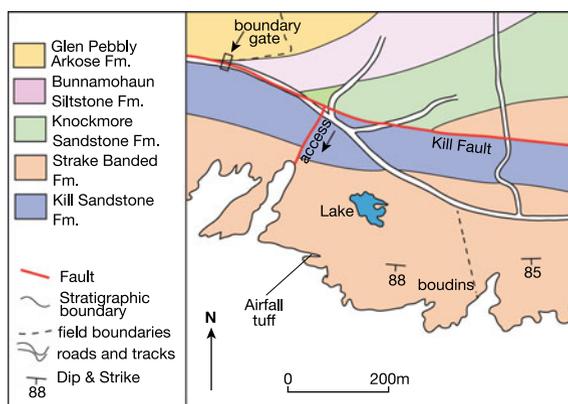
striking roughly east–west, but other parts are less deformed and have more of the appearance of metabasites.

4.5 *Locality 8.18: Clare Island Southwest (53.792903°, –10.018950°)*

Access and other Information From the harbour, walk west for just over 4 km towards the main boundary fence, which is marked by a large prominent wall across the hillside to the north built as part of the famine relief project and is marked on the road by a cattle grid. Just before this, where a stream crosses the road, enter the fields to the south via a gate (53.792903°, –10.018950°) and walk parallel with the wall on the west side as far as the coast (Fig. 47).

Extensive coastal exposure here is of steeply dipping Strake Banded Formation. There is abundant evidence from truncated cross-strata and graded beds that the rocks consistently young to the south (Graham 2001). The formation consists of three main rock types: purple mudrocks; fine grained, mainly grey or purple sandstones; and pale-weathering, coarser grained sandstones. The pale-weathering sandstones contain abundant tuffaceous fragments and were derived from the reworking of tuffs; some of these have associated ash-fall tuffs that are commonly graded (Fig. 48a). U–Pb zircon dating of one of these tuffs (53.790180°, -10.018412°) has yielded an age of 423 ± 4 Ma (Graham et al. 2020), a late Silurian (Ludfordian to Pridoli) age. Palaeocurrent indicators from these tuffaceous sandstones (Fig. 48b) indicate transport from west to east, suggesting that the volcanic centre lay to the west. In contrast, the grey/purple sandstones show palaeocurrents from the east (Fig. 48c), as do currents in the finer grained sediments.

Fig. 47 Sketch geological map of Brockal



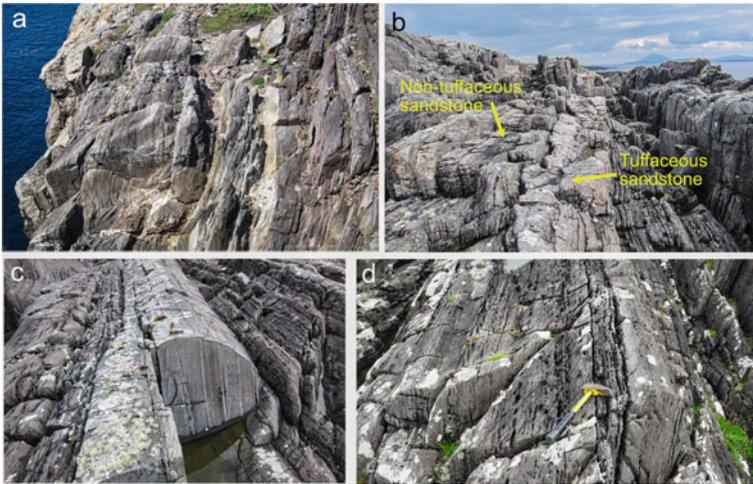


Fig. 48 **a** White weathering, graded, airfall tuff in Strake Banded Formation, Brockal. Beds are near vertical and young to the left **b** Erosive base to pale weathering tuffaceous sandstone, Strake Banded Formation, Brockal **c** Grey weathering, non-tuffaceous sandstone, Strake Banded Formation, Brockal: beds young to the right **d** Prominent, clockwise-transsecting cleavage in mudrocks and thin sandstones of the Strake Banded Formation, Brockal, looking west: beds young to the left

The rocks here are probably sandwiched between two major faults, the Kill Fault to the north and one lying offshore to the south. This is the likely reason for the very steep dips. Although folds are not seen, the rocks contain a strong cleavage and the intersection lineation plunges moderately to steeply east. In plan view, cleavage is consistently clockwise of bedding (Fig. 48d). The structures are interpreted as due to compression that was oblique to the main faults with an overall sinistral sense of displacement. There is also strong boudinage of sandstone beds, best seen in the more competent tuffaceous sandstones (Fig. 49a, b). These boudins indicate both along strike and vertical extension, indicating that the strong compression that produced the cleavage was accompanied by extension in the other two dimensions (Fig. 49c).

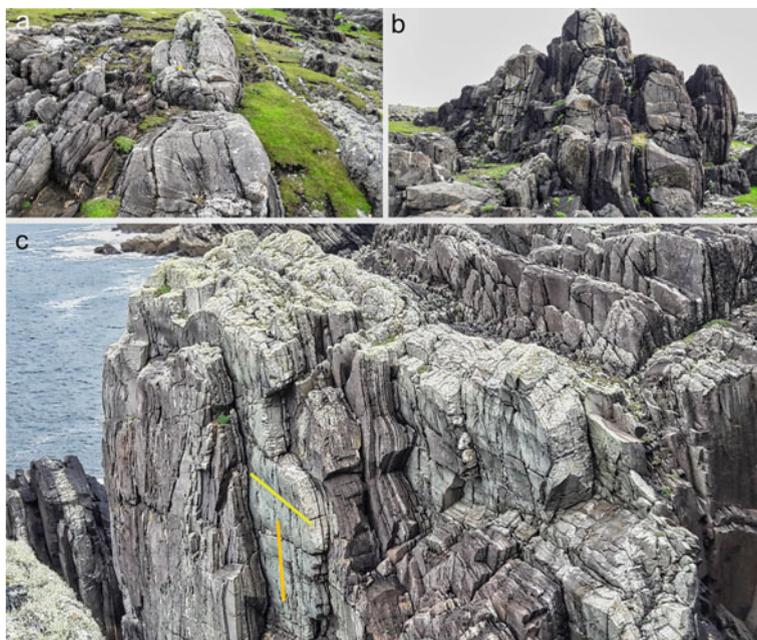


Fig. 49 a Boudins in sandstones of Strake Banded Formation showing along strike extension b Boudins in sandstones of the Strake Banded Formation showing vertical extension c Boudinage in sandstones of Strake Banded Formation, Brockal. Yellow line indicates the direction of along-strike extension; orange line indicates vertical extension

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