A critical review and re-investigation of the Pleistocene deposits between Cranfield Point and Kilkeel, Northern Ireland: implications for regional sea-level models and glacial reconstructions of the northern Irish Sea basin.

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Abstract

The coastline of County Down includes sites that are pivotal to understanding the history of the last glaciation of the northern Irish Sea Basin in relation to relative sea level and regional glacial readvances. The cliff sections display evidence that has been used to underpin controversial models of glaciomarine sedimentation in isostatically-depressed basins followed by emergent marine and littoral environments. They also provide crucial evidence claimed to constrain millennial-scale ice sheet oscillations associated with uniquely large and rapid sea-level fluctuations. This paper reviews previous work and reports new findings that generally supports the 'terresrrial' model of glaciation, involving subglacial accretion and deformation of sediment beneath grounded ice. Deep troughs were incised into the till sheet during a post Late Glacial Maximum draw-down of ice into the Irish Sea

Basin. Ice retreat was accompanied by glaciomarine accretion of mud in the troughs during a period of high relative sea level. The trough-fills were over-ridden, compacted, deformed and truncated during a glacial re-advance that is correlated with the Clogher Head Readvance. Grounding-line retreat accompanied by rapid subaqueous ice-proximal sedimentation preserved a widespread subglacial stone pavement. Raised beach gravels cap the sequence. The evidence supports an uninterrupted fall in relative sea level from c. 30 m that is consistent with sea level curves predicted by current glacio-isostatic adjustment modelling. Critical evidence previously cited in support of subaerial dissection of the troughs, and hence rapid fall and rise in relative sea level prior to the deposition of the glaciomarine muds, is not justified.

Keywords: Irish Sea ice, glaciomarine, Northern Ireland glacial history, stone pavement, sea level change, Clogher Head Readvance.

1. Introduction

During the last major glaciation (Middle to Late Midlandian/Devensian) a dynamic ice sheet developed over the central lowlands of Ireland sourced from ice centres positioned over the peripheral mountain massifs (McCabe, 1987; McCabe, 2008; Greenwood and Clark, 2009; Roberson et al., 2016). The onset of glaciation is debated (Bowen et al., 2002; Barth et al., 2016), but judging from radiocarbon-dated organic material beneath till obtained from the Isle of Man, the Irish Sea Basin (ISB) was not glaciated until after 36 ka (Roberts et al., 2007). All of Ireland was covered by ice at the Last Glacial Maximum (LGM) when an ice divide stretched across the northern ISB between Northern Ireland and south-west Scotland (Finlayson et al., 2010, 2014; Ballantyne and Small, 2018) and a vast ice stream flowed through the ISB to reach the Isles of Scilly (Scourse and Furze, 2001: Roberts et al., 2007; Ó

Cofaigh and Evans, 2007; Scourse et al., 2009; Chiverrell and Thomas, 2010; Ó Cofaigh et al., 2012; Hughes et al., 2016; Smedley et al., 2017a) and beyond to the continental shelf break beneath the Celtic Sea (Praeg et al., 2015) (Fig. 1). Ice also expanded to the shelf break to the west of Ireland (Peters et al., 2015). There are different interpretations of the timing of the LGM globally, regionally and locally (Clark et al. 2009; Hughes et al. 2013; Lambeck et al. 2014; Hughes & Gibbard 2015) and different sectors of the last British and Irish Ice Sheet (BIIS) probably reached their maximum extent asynchronously (Clark et al., 2012: Hughes et al., 2016). A recent estimate of c. 30-27 ka for the Atlantic Shelf (Ballantyne and Small, 2018) is earlier than previous estimates of 24.3-23.1 ka (Clark J. et al., 2012; Lambeck et al., 2014), but is in line with the time-slice reconstruction of 27-26 ka for the Atlantic sector of the BIIS proposed by Hughes et al. (2016). The Irish Sea Ice Stream (ISIS) began to retreat slowly from the Isles of Scilly between 26 and 25 ka (Small et al., 2018). There followed a rapid (c. 5 ka), stepped retreat, triggered by climatic warming, sea-level rise, reactivation of meridional circulation in the North Atlantic and possible mega-tidal amplitudes (Chiverrell et al., 2013; Smedley et al., 2017b; Small et al., 2018). The margin of the ISIS had probably retreated into the northern ISB by 21.3-19.8 ka where it oscillated before a significant readvance occurred during the Killard Point Stadial, peaking at c. 16.5 ka (Thomas et al., 2004; McCabe et al., 2007b; Clark C et al., 2012; Chiverrell et al., 2013) (Table 1).

The coast of County Down studied here lies between the ISB and the Mourne Mountains, which reach 853 m above Ordnance Datum Belfast (OD) in elevation at Slieve Donard (Figs. 2 and 3). These mountains formed of granite presented a major topographic obstruction to regional ice flow, as revealed by the long-axes of streamlined subglacial bedforms that arc around the northern and southern margins of the Mournes towards the ISB (McCabe, 2008). The episode of circumventing flow that formed these streamlined bedforms followed the creation of a broad belt of ribbed moraine that extends eastwards from the central lowlands to the northern foothills the Mournes (McCabe et al., 1999) (Fig. 2). The ribbed moraine has been subsequently eroded and remoulded subglacially to create the iconic 'basket of eggs' drumlin topography of County Down (McCabe et al., 1998; Knight et al., 1999; McCabe, 2008). In the south-eastern lee of the mountains the gently shelving Mourne Plain widens southwards from Annalong towards Carlingford Lough (Fig. 4). This coastal plain, which lies at up to 60 m OD, is underlain by a thick sequence of glacigenic deposits underlain by Silurian wacke sandstones and mudstones and a small outlier of Carboniferous limestone at Cranfield Point (GSNI, 1997; Mitchell, 2004; Cooper, 2016). The seaward margin of the plain is stepped locally where late-glacial raised shoreline features are fronted by raised beach deposits (Stephens and McCabe, 1977) (Fig. 3).

The glacigenic deposits exposed along the actively retreating cliffs of the coastal plain, and within aggregate quarries immediately inland, have been studied extensively in the past, together with many other coastal exposures occurring around Dundalk Bay (Fig. 2), in the Republic of Ireland (see McCabe, 2008 for extensive description, discussion and references). The coastline includes several sites that are pivotal to understanding the complex pattern of glaciation and deglaciation of the region in relation to Relative Sea Level (RSL), none more so than between Kilkeel and Derryoge (McCabe, 1986; McCabe and Hirons, 1986; McCarron, 2008). These sites display critical components of the evidence-base that has been used to deduce models of glaciomarine sedimentation in isostatically depressed marine basins (McCabe, 1986; Eyles and McCabe, 1989; McCabe, 2008). Also millennial-scale ice sheet oscillations claimed to be associated with large-magnitude sea-level fluctuations of circum- North Atlantic, if not global significance (McCabe, 1996; McCabe and Clark, 1998; McCabe et al., 1998; Clark P et al., 2004; McCabe et al., 2005, 2007a, 2007b; Clark P et al., 2009; Clark J et al., 2012).

Traditionally the deglaciation of the ISB was thought to have involved a general stepwise northerly retreat of a vast, grounded ice-sheet lobe that was nourished from ice dispersion centres positioned over the Lough Neagh basin and the north-central lowlands of Ireland, the Southern Uplands of Scotland and Cumbrian Mountains of England (Charlesworth, 1939, 1973; Stephens et al., 1975; Stephens and McCabe, 1977; McCabe, 1980). This scenario was replaced by a model of relatively early collapse of a marine-terminating ice stream followed by widespread glaciomarine sedimentation in an isostatically-depressed ISB, into which flowed climatically-forced, oscillating tidewater glaciers (McCabe, 1986; Eyles and McCabe, 1989; McCabe and Dunlop, 2006; McCabe, 2008).

Here we review the literature and present the results of targeted fieldwork undertaken between Kilkeel and Cranfield Point (Fig. 4), where cliff sections reveal critical evidence pertinent to the lively debate that has ensued. Whilst the ‘terrestrial’ hypothesis involving subglacial processes and deposition in lakes ponded at the grounded lateral margin of the ISIS has been largely substantiated by subsequent investigations around the ISB (Thomas and Summers, 1983, 1984; Thomas and Kerr, 1987; Ó Cofaigh and Evans, 2001a,b; Evans and Ó Cofaigh, 2003; Rijsdijk et al., 2010; Thomas and Chiverrell, 2011; van der Meer et al., 2011; Clerc et al., 2014), and is now generally accepted, the possibility remains that tidewater glaciomarine sediments were deposited in the north-east of Ireland during deglaciation in a locally isostatically-depressed basin (McCarroll, 2001). We concentrate on scrutinising the evidence at Kilkeel and Derryoge that crucially underpins those published relative sea-level curves that indicate uniquely large and rapid local sea-level fluctuations (McCabe et al., 2005; McCabe and Dunlop, 2006; McCabe et al., 2007c; McCabe, 2008) that are at odds with curves for the region predicted by glacio-isostatic adjustment modelling (GIA) (Brooks et al., 2008, Bradley et al., 2011) (Fig. 5).

The aim of this paper is to describe, clarify and interpret the complex Pleistocene sequence exposed between Kilkeel and Derryoge in respect to both past and present investigations in order to establish the most likely sequence of events that have occurred during the last glaciation. The resulting knowledge then will be tested against published glacial and sea-level reconstructions for the northern ISB.

2. Background

The aerial distribution of subglacial and ice-marginal landforms on the coastal plain and south-eastern flanks of the Mournes, together with clast-provenance analyses of tills at natural exposures, suggests that the area has been crossed by ice from three distinct sources (McCabe, 1986, 2008). At the LGM ice flowed southwards from the northern ISB, conjoined by ice flowing over the Mournes and through the Carlingford Lough basin (Charlesworth, 1939, 1973; Stephens et al., 1975; Stephens and McCabe, 1977; Greenwood and Clark, 2009). The position of the mountains heavily influenced local flow patterns, causing ice-flow separation and determining patterns of retreat.

Published stratigraphical evidence supports an early incursion of Irish Sea ice on the flanks of the Mournes up to about 500 m OD, the *'Annalong Phase'* of McCabe (1980) (Table 2). In addition to ubiquitous clasts of Silurian wacke sandstone and siltstone, the silt-rich till associated with this event contains a characteristic suite of 'Irish Sea Drift' erratics (Wright, 1937), including shell fragments, flint and microgranite from the island of Ailsa Craig, off the south-western coast of the Southern Uplands of Scotland (Fig. 1). During the succeeding *'Moneydorragh Phase'*, granite-rich till was laid down in the vicinity of Ballymartin (Fig. 3) following a local expansion of ice from the Mournes. Irish Sea ice subsequently reinvaded the coast reaching about 120 m OD on the mountain flanks during the *'Ballymartin Phase'* (Hannon, 1974; McCabe, 1980). It laid down silt-rich diamict indistinguishable from the lower, 'Annalong Till'. Irish Sea ice deposited similar tills during the succeeding *'Mourne Phase'*, when well-defined drift limits, lateral moraines and ice-marginal glacial drainage channels were formed whilst ice still encircled the mountains.

The following *'Derryoge Phase'* of McCabe (1980) is of particular interest here as it covers the period during which a suite of channel-like features (troughs) were eroded deeply into the glacigenic sequence between Derryoge Bay and Kilkeel (Fig. 6). The troughs were subsequently filled mainly with laminated silt, clay and sand containing glaciomarine foraminifera and ostracods. These glaciomarine deposits were disturbed as a result of a subsequent eastward ice advance from the Carlingford Lough basin during the subsequent *'Ballykeel Phase'*, when ice readvanced contemporaneously around the northern rim of the Mournes, terminating at the 'Dunmore Head Moraine' (McCabe, 1980) (Fig. 3). Raised late-glacial marine shorelines at 28-30 m OD formed at the margin of an ice-free enclave between Annalong and Dunmore Head (Stephens and McCabe, 1977). There followed a 'phased retreat' of ice flowing from the Carlingford Lough basin, the *'Cranfield Phase'*, when ice stabilized to form the 'Cranfield Moraine Complex', a series of arcuate ridges (Stephens et al., 1975; McCabe, 1980) (Fig. 3). Raised shorelines formed at between 18 and 19 m OD without this glacial limit.

Considerable progress has been achieved in the past 35 years regarding the dating and correlation of deglacial events during the ‘Last Glacial Termination’ (LGT) (McCabe, 1996; McCabe et al., 2005, 2007b; McCabe and Dunlop, 2006; McCabe, 2008; Clark J et al., 2012). The LGT is generally acknowledged to have occurred between c. 21 ka and 11.7 ka (Lowe and Walker, 2015). Based mainly on the results of Accelerator Mass Spectrometer (AMS) radiocarbon dating of hand-picked, unabraded (*in situ*), low-species diversity, marine foraminiferids, the resulting chronostratigraphy and geochronology is summarized in Table 1. The Ballymartin and Mourne phases of McCabe (1980), if not the Annalong and Moneydorragh phases too, may now be assigned to the LGM. The channel-infills of the Derryoge Phase have been assigned to the Cooley Point Interstadial (c. 20.1-18.2 ka). The glacial readvances through the Carlingford Loch basin towards Kilkeel and Cranfield Point have been assigned to the Clogher Head Stadial (c.18.2-17.1 ka) and the following Killard Point Stadial (17.1-16.0 ka).

3. Lithostratigraphy

McCabe (1986) recognised four Lithofacies Associations (LA 1-4) that may be correlated with the eight informal phases of glaciation that he established earlier (McCabe, 1980) (Table 2). LA 1 consists of lensoidal masses and spreads of mud, sand and gravel that crop out sporadically at the base of the cliffs and on the foreshore. This unit correlates with the Annalong Phase. LA 2 is composed predominantly of diamict that forms tabular, 200-300 m wide, mesa-shaped units in cross section, some 12.5 m in height. It correlates with the Ballymartin Phase. LA 3

(Derryoge Phase) consists mainly of mud deposited within the six, 300-600 m-wide troughs interspersed with the mesas of diamict. LA 4 comprises a tabular unit, up to 5 m thick, of well stratified sand and gravel that rests on a laterally extensive planar unconformity cutting across the mesas and troughs of LA 2 and 3 respectively, underlain by a prominent line of boulders. Lithofacies LA 4 formed during the Cranfield and Dunnaval phases.

The deposits associated with the Annalong and Ballymartin phases of McCabe (1980) were subsequently regarded as interdigitating facies of one lithostratigraphical unit, the *Ballymartin Member (BMM)* of the *Mourne Formation* (McCabe, 1999). The trough-fills were assigned to the *Derryoge Member (DEM)* of the formation, whereas the ice-contact and glaciofluvial deposits associated with the Cranfield Moraine Complex were assigned to the *Cranfield Member (CRM)*. The late-glacial raised beach deposits became the *Dunnaval Member (DVM)*. This formal lithostratigraphy is adopted here with minor modification for continuity and to help determine the superimposition of units following sound geological principles (Table 2). The *Annalong Member (ALM)* (LA 1) is re-established as it underlies and does not interdigitate laterally with the BMM. The *Kilkeel Member (KLM)* has been introduced here to represent the deposits of a glaciofluvial fan that cuts out both the Dunnaval and Cranfield members towards Kilkeel; McCabe (1986) assigned all these units to LA 4 (Fig. 6). The absence of bedrock exposures along the foreshore indicates that the full Pleistocene sequence is not known.

4. Methods and locations of targeted fieldwork

This paper investigates the predominantly glacigenic sequence exposed in the cliffs between Kilkeel Steps and Crawford Point, particularly those backing Derryoge Bay

(Derryoge Harbour) (Fig. 6). These cliff sections lie at the margin of the Cranfield Moraine Complex, which is formed of nested arcuate ridges of gravel and sandy diamict, up to 30 m high and 300 m wide, that swing around from Cranfield Point towards the foot of Knockchree over a distance of 12 km (Fig. 3). The features link westwards with kettled ice-marginal terraces, benches and ridges along the slopes of Formal Mountain and Knockshee, up to an elevation of 120 m OD (McCabe, 2008). A stepped series of steep, ice-proximal slopes face westwards and decline in elevation towards Carlingford Lough. The prominent moraine ridge forming Cranfield Point (Cranfield Point Moraine) passes eastwards into a flattish outwash plain between 12 and 18 m OD that has been quarried extensively, as for example, at Sandpiper Pit (Fig. 3 and 7). The plain is dissected by a well-defined, 3 km-long, late-glacial shoreline feature at 18-19 m OD that stretches from Cranfield Point towards Derryoge (McCabe, 2008) (Fig. 3). This shoreline has been dissected by the glaciofluvial fan towards Kilkeel.

Although many of the cliffs are too high and dangerous to be safely cleaned and examined at close hand, the entire, almost continuous cliff line between Cranfield Point and Kilkeel has been examined, recorded and photographed by the authors on several occasions during the past 30 years. Eleven cliff sections (L1 to L11) have been examined closely in this investigation (Fig. 7): summary logs are given in Supplementary Information. The sections have been located on the generalized transect (Fig. 6) first published by McCabe (1986) (see also McCabe and Hirons, 1986) for purposes of continuity and comparison. Although parts of the cliff line have since retreated by coastal erosion the main elements observed by McCabe (1986) remain intact. A new interpretation of the cliff section backing Derryoge Bay is provided in Fig. 6. Graphic logs of representative sections are given in Fig. 8. Lithofacies codes follow Evans and Benn (2004) unless stated otherwise.

Four block samples of deformed laminated clay of the ALM were collected from the foreshore in Derryoge Bay using 10 cm cubed, aluminium Kubiena tins. Large format thin sections were cut from the resin impregnated blocks, which took over two years to cure. They were examined using a standard Zeiss petrological microscope and interpreted using the procedures and terminology adopted by Phillips et al. (2011).

5. Annalong Member (ALM; LA 1)

5.1. Fine-grained facies

In the cliffs backing Derryoge Bay the ALM generally consists of diamictic mud (Fmd) that is locally interbedded with very poorly sorted sand and gravel (Gm, Sh, Sm) (McCabe, 1986). The unit is at least 4.5 m thick and is exposed on the foreshore at low tide, where box samples were collected for micromorphological analysis in 2013 (Fig. 9A). The predominant lithology is pale olive grey, planar, coarsely interlaminated clayey silt and very fine-grained sand (Fl, Sh). Laminae are typically 1-3 mm thick and contained within discrete, cyclic units 30 to 60 mm thick (F-cpl). Syn-depositional, soft-sediment deformation structures are commonly displayed at both macroscopic (Fig. 9B) and microscopic scale (Fig. 10). There are sparse dropstones (Fl-d) and laterally discontinuous laminae of normally graded, fine to medium-grained sand up to 10 mm in thickness. The unit is generally fissile, firm to stiff, becomes stiffer upwards and includes sub-vertical fissures with ochreous sandy fills. Also included are irregular-shaped bodies of silty fine- to coarse-grained sand containing granules and fine pebbles. The gravel is composed mainly of pink granite with subordinate clasts of hornfelsed wacke sandstone and siltstone, and sparse flint. The quartzo-feldspathic sandy matrix is mainly derived from granite. Lenses (<1.5 x 0.5 m) of moderate brown clayey diamict are more common towards the base of the unit. Diamict that probably correlates with the ALM is exposed occasionally at the base of the cliff line near Kilkeel (Fig. 6, L1-2), where it comprises intensively sheared laminated clay.

The fine-grained laminae within the diamictic mud are locally crinkled and display poorly-developed cleavage, especially towards the top of the ALM at locality 10 (Fig. 9D). A thin section cut perpendicularly to the crinkling observed in the mud sampled on the foreshore is shown in Fig. 11. It reveals three distinct sediment units, the basal 3 cm-thick one comprising thin (1 – 2 mm) laminae, each fining upwards from silt into clay with sharp upper contacts. The middle 5 cm-thick unit comprises massive clay with thin partings (2 mm) of coarse silt fining upwards in clay. The upper 5 cm-thick unit, like the lowermost, comprises laminae of silt fining upwards into clay with sharp upper contacts, but the lamination is a little thicker and more diffuse. This unit is affected by small scale (1 mm amplitude) buckle folds that are truncated by centimetre-scale shear planes indicating overall sinistral sense of displacement. Shear planes of similar orientation also cut the units below, but are less common. The orientation of the thin section indicates that shear occurred in a roughly east to west direction. Syn-depositional, soft-sediment deformation structures affect some of the thicker laminae, as is apparent in the thin section shown in Fig. 10, but larger-scale vertical and horizontal structures clearly disrupt the lamination.

5.2. Coarse-grained facies

Bodies of sand and gravel have been recorded within the ALM at two localities along the coastline, at Ballymartin (Fig. 3), to the north of Kilkeel, and at the southern end of Kilkeel Bay (McCabe, 1986). At the latter site (Fig. 6; L4) over 4.4 m of poorly-sorted gravel crops out beneath stratified diamict of the BMM. The gravel occurs in two units separated by a 0.9 x 20 m lens of cross-laminated, fine to coarse-grained shelly sand and granule gravel (Fig. 9E). The upper 1.9 m thick unit comprises dense, clast-supported gravel with a relatively large proportion of tabular to bladed pebbles, but no obvious shell fragments. The unit occupies a channel with the lens of sand and granule gravel occurring at its erosional base. The upper gravel unit has been locally folded and sheared towards the south together with upper parts of the lens with its silt drape (Fig. 9F). The underlying unit of dense, well-packed, fine to cobble grade gravel is mainly clast-supported and partially openwork (Go). It is generally massive, but grades both laterally and vertically into sandy granule gravel. It is locally imbricated, with elongate clasts dipping southwards. The sand and granule gravel lens, and the underlying gravel, both contain abundant marine shells including *Turritella* and *Arctica islandica*, the former commonly being little abraded and packed within discrete thin beds, whereas the latter occur as broken valves.

McCabe (2008) reports that infinite radiocarbon dates of >40 ka BP were obtained from shells collected at Ballymartin, concluding that they were derived and older than the deposits in which they occur. Amino Acid Racemisation (AAR) determinations on *Arctica* shells yielded mixed ages, with the youngest assigned to Marine Isotope Stage (MIS) 3 (McCabe, 2008). Shells were collected during the present investigation from the sand and granule gravel lens and lower unit of gravel for additional radiocarbon dating. The new dates range upwards from 48.9 to 39.2 ka (Table 3), which is consistent with the previous age determinations.

5.3. Interpretation

The fine-grained facies of the ALM has been interpreted to be glaciomarine in origin (McCabe, 1986) and indeed the rhythmic silt and clay couplets with sharp transitions from clay to silt and graded transitions from silt to clay are broadly similar to cyclopels deposited from overflow and interflow plumes in glaciomarine environments (Mackiewicz et al., 1984), if not marine varves (Ó Cofaigh and Dowdeswell, 2001). Micro palaeontological analyses of laminated sediments that almost certainly occur within the ALM have yielded mixed assemblages in which the tests of abraded temperate foraminiferid species occur together with much better preserved Arctic species (McCabe, 2008).The size and condition of tests show clear evidence of transport and recycling (McCabe, 2008).

Bedding is gently undulating with open folding into plunging domes and troughs of 0.5 to 1 m amplitude. These structures may simply result from compaction and settlement, but the crinkles that deform the laminated muds were originally interpreted as of glacitectonic origin, related to eastward, subglacial emplacement of the overlying till (BMM) (McCabe, 1980). However, in McCabe (1986), and subsequent publications by this author, the overlying till is re-interpreted as glaciomarine diamict and the crinkles, described as 'wavy lamination', are interpreted as belonging to the set of soft-sediment deformation phenomena. McCabe's former interpretation is supported by evidence of sinistral strain in the thin sections, particularly buckle folds dislocated by shears (Fig. 11), the poorly-developed cleavage associated with the crinkles and the degree of compaction of the whole member, which increases upwards towards the gradational base of the overlying diamict of the BMM. Some soft sediment deformation within laminae is most likely to have occurred syn-depositionally (Fig. 10), so too the larger structures cutting across laminae that result from water escape (Fig. 11). The latter are unlikely to be related directly to the deformation event (glacial over-riding) that created the shear features because they are not oriented perpendicularly to them.

The coarse-grained facies contain a mixed assemblage of shells and McCabe (2008) concludes that they were deposited sub aqueously by subglacial meltwater (efflux) erosion of ‘shell banks’ previously deposited on the seabed up-glacier of a tidewater glacial margin. Indeed, the sedimentology is broadly similar to that of the Killard Point Moraine (Fig. 2) described and interpreted by McCabe et al. (1984) as subaqueous outwash forming a glaciomarine morainal bank. Shared attributes include stacked, multi-storey channels with coarsening upward fills, rapid vertical and textural changes with variable grading patterns (massive to graded) and thin mud drapes (McCabe, 2008, fig. 9.7).

The locally over-folded and micro-faulted upper contact of the shelly sand and granule gravel lens, together with the compactness and poorly developed, sub-horizontal stratification observed within the overlying gravel, suggests that the deposits have been over-ridden by ice flowing southwards. This probably pulverised shells in the upper gravel unit.

The origin of the gravels remains unclear. They could have been deposited within subglacial cavities or ‘canals’ as has been proposed for lenses of sand and gravel occurring within ‘Irish Sea Drift’ sequences at Killiney Bay (Clerc et al., 2014) and Ballyhorsey (Ravier et al., 2014), 15 and 28 km south of Dublin respectively. In this hypothesis the shells would have been scavenged from over-ridden deposits. Another possibility is that the gravels form, or originally formed part of a beach, which would most likely have been created during a period of lowered sea level in the Middle Devensian. This suggestion is supported by the clusters of relatively unabraded shells, the sequence of age determinations that are mainly in stratigraphical order (Table 3) and the imbrication of clasts observed in the lower gravel unit. In the subaqueous efflux model proposed by McCabe (2008) the shells would have been scavenged from sub glacially over-ridden palimpsest shell lags (cf. Powell, 1984) or coquinas (Eyles and Lagoe, 1990). Further work is required to establish the origin of these gravels, which are only exposed occasionally.

6. Ballymartin Member (BMM; LA 2)

The BMM is formed of up to 14 m of flat lying, extremely compact beds of pale yellowish brown muddy sandy diamict (Dmm) (Fig. 12A). At Crawfords Point several tabular boulders dip into the cliff, towards the north-west, many with bevelled top surfaces bearing striae of similar orientation (Fig. 12B). Most beds are sharply defined and include moderately well dispersed, angular to sub-rounded clasts (< 1.2 m). Stone lines and boulder clusters are common, so too gently undulating concavo-convex discontinuities locally truncating cuspate, deformed gravel-filled lenses (Fig. 12C). The massive beds typically grade both vertically and laterally into more clast-rich, stratified varieties (Dcm, Dml-p, Dml-s). The matrix-rich diamict beds are generally calcareous, extremely stiff and fissile (Fig. 12D).

The lower boundary of the member in the headland south of Derryoge Bay reveals clasts that have been pressed downwards into silts of the ALM below (Fig. 12E). This basal 0.5 m or so of the member commonly includes a relatively large proportion of far-travelled clasts, including well-rounded pebbles probably derived from Devonian conglomerate, red sandstone, flint, chalk, shell fragments and microgranite probably derived from Ailsa Craig (Fig. 1). The upper boundary of the member is formed by the sharp, planar to very gently undulating unconformity that truncates the 'mesa-shaped' sections of the BMM between Cranfield Point and Kilkeel (Fig. 6); it is lined by a prominent line of boulders (Fig. 12A).

Most clasts in the BMM comprise Silurian wacke mudstone and sandstone, commonly hornfelsed, with pinkish Mourne granite. McCabe (1980) reports that Carboniferous limestone clasts become common towards Cranfield Point, carried from outcrops to the west, but sparse limestone was observed during the present investigations. Unless stones include diagnostic fossils, some baked, slightly calcareous wacke mudstones can easily be mistaken for limestone. Boulders are mainly composed of granite up to 1 m in diameter, many of them probably being former regolith corestones carried from the mountains inland. The diamicts typically have a gritty, quartzo-feldspathic matrix likely to have been mainly derived from crushed granite.

At Crawfords Point (Fig. 6; L10) the BMM includes folded inclusions of clayey silt and gravelly diamict together with some horizontally truncated, concave-upward, channel-like structures (1 m across, 0.5 m deep) lined by cobbles pressed into underlying diamict. The channels are filled with extremely compact, jointed, laminated silt displaying micro-folding and micro-thrusts with southward displacement (see Supplementary Information). A boulder in the diamict was observed to have been rotated southwards with a sediment prow to the north (Fig. 13A). In the cliffs backing Derryoge Bay (Fig. 6; L9) gritty, matrix-to clast supported diamict of the BMM includes open, decimetre-scale folding of sand lenses plunging at 20/285^{o}. The sequence includes 25 to 50 cm thick units of stiff, olive grey, laminated silt with compressional micro-folding and disturbance of laminae. The units pinch and swell, have erosional bases and horizontally sheared tops.

On the southern margin of the deep trough backing Derryoge Bay (Fig. 6; L8) diamict of the BMM is intercalated with very stiff clayey silt (Fmd) containing with very well dispersed, ice-scratched lonestones (<35 cm diameter) together with cuspate lenses (4 m wide, 0.3 m deep) of compact, silty, poorly sorted, matrix-rich sand and gravel. One lens included a 35 cm diameter boulder of hornfelsed wacke with a tapering wedge of unconsolidated gravelly sand to the south (Fig. 13B). The silty units are typically truncated by discontinuities that dip northwards parallel with the base of the overlying trough (Fig. 6; T2), beneath which thick lamination has been disrupted by shearing and overprinted by a poorly developed, tectonic lamination. This direction of strain is also apparent at L1, north of Kilkeel Steps, where a prominent boulder is associated with an irregularly-shaped, downward tapering structure filled with sand and gravel (Fig. 13C and D).

6.1. Interpretation.

The BMM is typical of 'Irish Sea Drift' in that it has been interpreted in terms of either the 'glaciomarine paradigm' (McCabe, 1986; Eyles and McCabe, 1989; McCabe, 2008), or a 'terrestrial' model of glaciation with widespread preservation of subglacial facies and deformation that support the 'deforming-bed paradigm' (Boulton, 1986; Hart et al., 1990; Hooke and Iverson, 1995; Benn and Evans, 1996; Eyles and Boyce, 1998). As the latter interpretation is now generally accepted, it is not considered necessary to provide a comprehensive review and discussion here of the opposing views, which have been considered elsewhere (Hart and Roberts, 1994; McCarroll, 2001; Knight, 2001; Ó Cofaigh and Dowdeswell, 2001; Ó Cofaigh and Evans, 2001a,b; Evans and Ó Cofaigh, 2003; Rijsdijk et al., 2010). However, the evidence for subglacial deposition and deformation in the BMM is overwhelming, including the considerable consolidation of the sediments, tabular geometry with sharp contacts expressed by sub-horizontal, planar to gently undulating discontinuities, boulder lines and pavements of striated clasts, concavo-convex discontinuities that possibly include ice-bed separation surfaces (cf. Piotrowski et al., 2001, 2006), tension fractures and minor thrust faults together with attenuated and folded laminae (cf. Benn and Evans, 2010).

The downward tapering structure recorded at L1 (Fig. 13 C & D) probably formed as a hydrofracture (cf. Rijsdijk et al., 1999), and the southward tapering wedge at L8 (Fig.13 C) in the 'down-glacier' pressure shadow of the boulder (cf. Benn and Evans, 2010). Some sheared and convoluted beds of sand and irregular-shaped masses of fine sediment are probably glacial rafts, but their boundaries and geometry could not be examined at close hand.

In common with most recent investigations into the origin of 'Irish Sea Drift' sequences we interpret most of the massive, matrix-supported diamict units of the BMM as 'subglacial traction till' or 'glacitectonite' *sensu* Evans et al. (2006) (Ó Cofaigh and Dowdeswell, 2001; Ó Cofaigh and Evans, 2001a,b; Evans and Ó Cofaigh, 2003). Some lenticular beds of clast-poor, silty diamict may have originated as low-viscosity cohesive debris flows, but subsequent glacial loading has generally resulted in over-consolidation and both ductile and brittle deformation overprint. Most non-graded sandy wisp structures (Dmm-c) that are interpreted by McCabe (1986) and Eyles and McCabe (1989) as resulting from glaciomarine bottom-current reworking are interpreted to be either glacitectonic laminae formed during intergranular shear (Type 1 laminae of Roberts and Hart, 2005), or to be attenuated remnants of sedimentary bedding (Type 2 laminae), both resulting from high strain conditions during subglacial shear deformation (cf. Hart and Roberts, 1996). However, some cuspate lenses of sand and with sharp, planar upper contacts possibly originated as subglacial canal-fills (cf. Evans et al., 1995; Clerc et al., 2014; Ravier et al., 2014) during periods of ice-bed decoupling (cf. Piotrowski et al., 2001, 2006). The origin of the stone lines capping the mesa-shaped sections is discussed below.

7. Derryoge Member (DEM; LA 3)

The DEM is confined to the six troughs that divide the flat-topped sections formed by the BMM (Fig. 6). Towards Kilkeel, the DEM comprises up to 10 m of stiff, olive grey to pale olive grey, coarsely-laminated calcareous mud (Fl, Fl-cpl) with subordinate laminae of fine to medium-grained sand, massive silt and sparse lonestones (Fl-d) (Fig. 14 B). The lamination generally takes the form of sand and mud couplets, each consisting of a sand lamina (<2 mm) overlain by, or grading up into a thicker lamina of mud (5 mm), as reported by McCabe and Dunlop (2006). Contacts between couplets are generally sharp. At Kilkeel Steps the couplets generally thicken upwards to about 15 mm with an increase in the relative thickness of sand relative to mud (Fig. 14C). The muds exhibit a range of loading structures including wavy to convolute bedding, flames, ball-and-pillows (Fig. 14E) and overturned bundles of lamina. At Kilkeel (Fig. 6; L1) the laminated muds are overlain by up to 2.5 m of compact silty fine-grained sand with discontinuous laminae of medium to coarse-grained sand and sparse lonestone pebbles. The top of the unit includes some flat-topped cuspate lenses of silty diamict that become increasingly folded and sheared upwards, truncated by sheared, tectonically-laminated silty sand. Nodules are common towards the base of the troughs. The trough-fills become more complex and deformed towards Derryoge.

The base of the DEM is rarely seen as most of the troughs descend below the level of the modern beach. Where observed it has a sharp, draped contact, either with an underlying stone pavement lining the trough, or a gravel lag at its base (Fig. 15 A and B). The upper bounding surface of the member is a planar to very gently undulating unconformity that is associated with a discontinuous stone pavement (see below) (Fig. 14A). Lenses of silty fine-grained sand occur sporadically beneath the unconformity, especially towards Kilkeel (Fig. 14G), suggesting the DEM originally coarsened upwards before the sequence was truncated.

Sparse marine microfossils have been identified, both at Derryoge (T2) (McCabe, 1980) and at Kilkeel Steps (T5) (Haynes et al., 1995; McCabe and Clark, 1998; Clark P et al, 2004; McCabe et al., 2005). McCabe (2008) reports that the microfauna is dominated by the foraminiferid *Elphidium clavatum*, with a good range of size and preservation of tests, and the ostracod *Roundstonia globulifera*, together with its intact instars. Accessory forms include miliolids, polymorphininids, *Lagena sp.*, *Quinqueloculina seminulum* and distinctly cold to very cold water forms including *Cytheropteron dimlingtonense and C. montrosiense*. Fragile foraminiferids (*Pseudopolymorphina novangliae*, *Lagena clavata*, Oolina/Fissurina spp.) are present together with articulate valves of *Cytheropteron* sp. with a range of juveniles. Radiocarbon age determinations undertaken on hand-picked tests of *Elphidium clavatum* sieved from samples taken from five consecutive horizons up the cliff section exposing the DEM at Kilkeel Steps have yielded dates ranging from 17.0 to 16.5 ^{14}C ka BP (20.1 to 19.7 cal ka BP IntCal 04) (McCabe et al., 2005: Clark P et al., 2004).

7.1 Interpretation of the depositional environment

The laminated muds of the DEM have been interpreted to be glaciomarine in origin (McCabe, 1986) and the rhythmic silt and clay couplets with sharp transitions from clay to silt and graded transitions from silt to clay (Fig. 14C) are comparable with cyclopels deposited from overflow and interflow plumes in glaciomarine environments (Mackiewicz et al., 1984; Benn and Evans, 2010, fig. 10.77a), if not marine varves (Ó Cofaigh and Dowdeswell, 2001).

The presence of *Elphidium clavatum* and the ostracod *Roundstonia globulifera*, together with its intact instars, suggested to Haynes et al. (1995) and McCabe (2008) that the microfauna represents an opportunistic biocoenose (living assemblage). This interpretation is supported by the reported absence of reworked temperate species, the good range of size and preservation of tests, the presence of fragile foraminiferids and articulate valves of ostracod with a range of juveniles. McCabe (2008) reports that the assemblage occurs in shallow (<30 m) contemporary Arctic to sub-Arctic waters recently vacated by tidewater glaciers (cf. Hald et al., 1994). However, the modern distribution of *Elphidium clavatum* is apparently not restricted to glaciomarine environments and the species is as much an indicator of low salinity as of temperature (Hald and Vorren, 1987; McCarroll, 2001). The dates are considered to be reliable as they are generally mutually supportive and because the dated fauna are exclusively *Elphidium clavatum* tests that are glassy, well-preserved and show no signs of reworking from older deposits (McCarroll, 2001). The ages therefore probably reflect the true age of the sediment, which was likely to have been deposited when RSL stood at up to about 30 m OD considering the palaeo-environmental interpretations of Haynes et al. (1995).

7.2 Interpretation of contact relationships and architecture of the troughs

In consideration of the wider significance of the age and depositional setting of the dated sequence at Kilkeel Steps in relation to claimed regional changes in RSL, it is particularly important to determine contact relationships at the margins and tops of the troughs and to interpret evidence of associated deformation. As no large-scale thrusting, decollement planes and folding have been recorded along the coastal sections examined here, there is little doubt that the troughs result from erosion, not glacitectonic stacking. The cut-and-fill architecture of the troughs requires that erosion was followed by the depositional phase. McCabe (1986) argues against both subglacial and subaqueous erosion mainly on the assumption that the underlying BMM is a glaciomarine deposit, rather than one formed sub-glacially. He maintains that the troughs were cut sub-aerially by meltwaters draining the Mourne Mountains, but this requires sea level to have dropped significantly to -10 m OD or less before rising back very quickly indeed (McCabe and Dunlop, 2006; McCabe et al., 2007c; McCabe, 2008) (Fig. 5). Subaqueous erosion is dismissed by McCabe (1986) because of the apparent absence of associated deltaic deposits in the vicinity and because there is no *a priori* reason why subaqueous processes should switch instantaneously from erosional to depositional.

The flanks of the six troughs are generally sharply defined and dip at angles up to 20^{o}. The laminated muds typically drape on-lapping contacts. The troughs contain beds of diamict, gravel, sand and silt that both dip and taper towards the trough axes (Fig. 6). This relationship is particular well-displayed on the southern flank of the trough backing Derryoge Bay (T2). McCabe (1986) concluded that the position, composition and geometry of the tapering units resulted from deposition by subaqueous mass flows and slumps down the flanks. Indeed, the sharp, steeply inclined and locally undercut wall towards the base of this trough (L8 and L9) is overlain and abutted by compact, extremely poorly sorted, chaotically-bedded gravel (Gm) that possibly formed as a cohesionless debris flow. However, most of the trough-fill is demonstrably more complex than reported and illustrated by McCabe (1986).

A re-interpretation of the architecture of the trough-fill (T2) exposed in Derryoge Bay is given in Fig.6, which also shows the original interpretation of McCabe (1986) for comparison. The section is largely inaccessible, but the trough clearly includes stacked, concave bounding surfaces within the main trough (Fig. 14A). The sequence includes several units of extremely compact diamict (Dmm, Dmm-c) with well-developed fissility parallel with the gently concave discontinuities. These units include coarse-grained, quartzo-feldspathic sand, both in the matrix and in non-graded, wispy laminae. The massive diamicts are re-interpreted here as subglacial traction till, whereas the sandy wisps are considered to be glacitectonic laminae and stringers formed under high strain conditions within units of glacitectonite (cf. Evans et al. 2006; Roberts and Hart 2005; Lee and Phillips 2008). The diamicts are intercalated with discrete units of laminated mud (Fl, Fl-d) that drape concave discontinuities lined by stones (L8 and L9).

Crucial evidence of the basal infill and contact relationships of four of the six troughs is obscured beneath the modern beach. However, on the southern flank of the trough backing Derryoge Bay (T2) a basal bed of gravel rests unconformably on very compact diamict of the BMM, at the top of which planar to shallow concave discontinuities are associated with very disturbed, sheared primary coarse lamination interpreted here as Type A2 glacitectonite (cf. Evans and Benn, 2004). The discontinuities dip northwards parallel to the flank of the trough. On the northern flank of the trough (T2), boulders forming a stone line are firmly planted into the underlying diamict (BMM), in which fissility and compactness becomes more pronounced upwards towards the bounding unconformity (Fig. 15A). Some of the embedded boulders rest on smaller clasts that have been crushed (Fig. 15B) suggesting that this part of the trough, at least, formed subglacially.

The genesis of the troughs has been puzzling, but on balance a subaerial origin is very unlikely. Firstly because no unequivocal subaerial slope deposits such as gelifluctate and gelifractate have been identified on the trough margins. Deposits such as these should abutt the trough walls, especially were they are locally undercut, considering the likely contemporaneous periglacial regime. Secondly, it is difficult to explain how the troughs are largely unscathed following the rapid marine transgression envisaged by McCabe (Fig. 5). We conclude that a subglacial origin for the troughs is most likely, probably involving initial erosion by channelized subglacial meltwater followed by modification by ice, much as envisaged for the creation of tunnel valleys (Kehew et al., 2012) (Fig. 16). The presence of truncated units of laminated mud draping concave, stone-lined discontinuities within the trough backing Derryoge Bay (Fig. 14A) suggests that the ice periodically lifted of its bed during the infilling of the trough (cf. Boyce and Eyles, 2000; Piotrowski et al., 2001, 2006).

7.3. Interpretation of the deformation within the trough-fills.

The complexity of the sedimentary architecture and the amount of compaction, fissility, homogenisation and deformation of the trough-fills increase southwards towards Crawfords Point. For example, the trough backing Derryoge Bay (T2) is truncated by a gently concave, stone-lined unconformity that cuts across some channelized units of stratified diamict (Dms-r) and very compact, fissile diamictic silt (Fmd) (Fig. 6; L8-9; Fig. 15C). McCabe (1980) reported that these channels contained over-consolidated and contorted bodies of diamict mixed with laminated muds, originally concluding that the deposits had been sheared by over-riding ice. The underlying laminated silts with sparse lonestones are extremely stiff and heavily jointed. Joints intercept to form rhomboid slabs, 10-40 mm thick, that are locally splayed around tight (sheath?) folds plunging gently into cliff-face (Fig. 6; L7; Fig. 14H). Less intense, open folding is developed at the base of the cliffs nearby (Fig. 6; L7; Fig. 17), where laminated clays have been subjected to simple shear towards the south-west, as indicated by the fold asymmetry and associated crenulation of poorly-developed, axial-plane cleavage.

The trough-fills at Kilkeel (T5 and 6) are less deformed than at Derryoge Bay. Shallow-plunging isoclinal folds exposed at beach level, just to the south of Kilkeel Steps (Fig. 14F), together with large-scale load casts, tear drops and ball-and-pillows (Fig. 14E), have been interpreted as vertical deformation structures resulting from settlement and slumping of rapidly deposited muds (McCabe, 1986). However, the muds become progressively more massive and blocky-fractured upwards (Fig. 14B), and the isoclinal folds are associated with poorly developed cleavage (Fig. 14D), both likely to result from glacial over-riding. Furthermore, on the southern flank of the trough (T5) the uppermost muds lying beneath the bounding, stone-lined unconformity are very consolidated, fissile and include diffuse, ungraded laminae of sand with sparse lonestones, characteristic of a Type A glacitectonite (cf. Evans and Benn, 2004). Similarly, the upper bounding unconformity of the next trough to the north (T6) is underlain by a 0.3 m-thick unit of very stiff, laminated silty sand that is interpreted as Type A glacitectonite grading down into Type B glacitectonite (Fig. 14G).

The troughs appear only to occur between Crawfords Point and Kilkeel, which suggests that their occurrence is related in some way to their location in the lee of the Mourne Mountains and close to the mouth of the Carlingford Lough basin, which was an important conduit for ice flowing from the main dispersion centre of the last ice sheet centred over the Loch Neagh basin (Charlesworth, 1939, 1973; Stephens et al., 1975; Stephens and McCabe, 1977; Greenwood and Clark, 2009). It is therefore likely that the troughs formed at about the location where ice flowing south-eastwards from the Mournes abutted a more vigorous flow out of the Carlingford Lough basin. Subglacial erosion is likely to have been focussed beneath this contact (shear margin), where subglacial drainage is also likely to have been focussed. The complexity of the sedimentary architecture and the amount of compaction, homogenisation and deformation of the trough-fills increases southwards towards Cranfield Point, suggesting that there was an increasing influence of Carlingford Lough ice in that direction.

Taken together, the pinch-and-swell architecture observed within the DEM at Derryoge, the gently concave, discontinuous, stone-lined discontinuities associated with glacitectonite and the draped inter-bed elements of laminated mud and stratified clastic sediment (Fig. 14A), suggest that subglacial deformation was punctuated by phases of ice-bed separation during the infilling of the troughs (cf. Boyce and Eyles, 2000; Benn and Evans, 2010 fig. 10.25) (Fig. 16). The troughs at Kilkeel were probably only partially infilled before glacial retreat occurred and open-water glaciomarine sedimentation began. However, depending on the palaeo-environmental interpretation of the muds at Kilkeel Steps (T5), specifically that of the modern distribution of *Elphidium clavatum* (see above), it is speculated that most of the DEM could have been laid down beneath an oscillating ice shelf, beneath which there was low-salinity sea water with periodic inflow of saltier water.

8. The Main Stone Pavement (MSP)

The line of cobbles occurring towards the top of the cliff line between Cranfield Point and Derryoge is referred hitherto as the 'Main Stone Pavement' (MSP) (Fig. 6). It is most prominent across the mesa-shaped sections at the planar to very gently undulating top of the BMM (Fig. 12A), but it also extends across the troughs. This relationship can be seen on the southern flank of the trough backing Derryoge Bay (Fig. 6, T2), where the pavement over-steps the DEM (Fig. 15C), peters out across the centre of the trough (L7), but reappears where the underlying unconformity dips gently into the next deep trough to the north (Fig. 6; T3). There it comprises a discontinuous lag of bevelled, striated pebbles and small cobbles that are firmly lodged into the top of the underlying 40 cm thick unit of silt. The latter is very compact, extensively sheared and includes a lens (1 x 0.3 m) of cross-bedded sand, probably a glacial raft. The pavement caps till of the BMM along most of the coastline between Spa Well and Manse Road (Fig. 6). It is discontinuous at the centre of the trough at Kilkeel Steps (T5) and, where it was possible to examine the pavement at close hand, the muds immediately underlying it displayed wavy to convolute lamination that was locally overprinted by poorly-developed, sub-horizontal, secondary (tectonic) lamination.

The MSP is mainly inaccessible, but it was accessed at three sites to measure the azimuths of any striae preserved on the upper, bevelled surfaces of cobbles. The measurements mainly fall within the south-east to east-south-east quadrants (Fig. 8 and 18) and elongate stones in the pavement generally dip north-westwards (Fig. 15C). Exceptionally, subtle sediment prows were observed on the south-eastern sides of some clasts forming the poorly-developed pavement that truncates the trough near Kilkeel (Fig. 6; L1, T6). Here the stones are relatively small (<120 cm) and the underlying sediment relatively soft.

8.1. Interpretation

McCabe (1980) reported that although some of the boulders in the MSP were ice-scratched there was no preferred orientation suggestive of emplacement by subglacial processes. McCabe (1986) interpreted the pavement as a subaqueous glaciofluvial or glaciomarine lag that resulted from winnowing of the underlying diamict by currents or storm waves (cf. Eyles, 1988), but in later publications the pavement is also attributed to marine transgression (McCabe, 2008). Stone lines and pavements are subject to variable interpretation (eg. Powell, 1984; Eyles, 1988; Hicock, 1991; Clark, 1991; Boulton, 1996; van der Wateren et al., 2000; Benn and Evans, 2010), but the firm lodgement of most cobbles and boulders into the underlying diamict of the BMM, together with the compaction, fissility, deformation and pervasive shearing observed immediately below the pavement, notably at the top of the troughs, strongly suggests that it formed subglacially. South-eastward flow of ice is indicated by the imbrication of many clasts towards the north-west together with the sediment prows observed at L1. Prows on the down-flow side of a clast and grooves trailing the clast on its up-flow end suggest ploughing of clasts through the substrate by active ice (Lesemann et al., 2010, Fig. 8a, b).

The striae measurements made in this investigation reveal two subordinate preferred azimuth orientations, one north-south and the other west-east (Fig. 18). One explanation of the two preferred orientations could be that scratched elongate clasts either swung around parallel to ice flow, or rolled at right angles to it, at the base of the over-riding ice. This observation has been reported in tills, where the fabric orientation of boulders is much more tightly constrained than smaller clasts (Evans et al., 2016). Another explanation, preferred here, is that pavement and striae evolved in relation to changing subglacial conditions and regional ice flow direction (cf. Davies et al., 2009). The north-south orientated striae were probably formed first, but further work is required to determine the relative age of crossing striae. It is interesting that McCabe and Haynes (1996) also found that about 50 per cent of the clasts forming well-developed boulder pavements around Dundalk Bay bear two or more orientation sets of striae, but cited this as evidence for riving by seasonal pack ice.

The MSP has been compared with broadly similar cobble lines within diamicts exposed between Clogher Head and Dunany Point, to the south of Dundalk Bay (McCabe and Dunlop, 2006, plate 24; Knight, 2016a) (Fig. 2). Another well-developed boulder pavement exposed at Cooley Point, to the north of that bay, has been interpreted as a raised late-glacial intertidal boulder pavement (McCabe and Haynes, 1996; McCabe and Dunlop, 2006, plate 21a and b; Knight, 2016b) and cited as pivotal evidence of a sea-level low-stand (c. 1-3 m OD) following the Clogher Head Readvance (McCabe et al., 2005, 2007b) (Fig. 5).

It is concluded that the MSP occurring between Derryoge and Kilkeel formed subglacially and that the matrix of the partly enclosing and underlying till was removed by the combined effects of subglacial meltwater flushing and glacier sliding, which isolated the larger clasts (cf. Boyce and Eyles, 2000). A significant glacial, short-lived readvance may be inferred that probably correlates with the Clogher Head Readvance identified by McCabe et al. (2007b).

9. Cranfield Member (CRM; LA 4, in part)

The CRM overlies the Main Stone Pavement along the entire cliff line (Fig. 6). At its base, a laterally-discontinuous lag deposit of very poorly sorted gravel (Gm, Gms) drapes over, and around, boulders of the pavement that are firmly anchored in the underlying diamict (BMM) (Fig. 19A and B). The lag is overlain conformably by up to 4.5 m of mainly fine-grained sand with silty seams and laminae formed of medium to coarse grains and sparse granules (Sh, St). The sand is disposed in south-east-trending, shallow, multi-storey channels within a stacked architecture. Shallow-dipping, tangential bedding parallel to the floor of channels is common, but northward and southward cross bedding is displayed locally at localities L10 and L3 respectively. The unit generally coarsens upwards and includes some minor soft-sediment deformation structures. The member is generally more fine-grained at Kilkeel Steps (L2), comprising silty fine-grained sand with 10-15 cm-thick seams of silt and sparse lonestone cobbles (Fig. 19C). Wavy to convolute lamination is developed locally and individual beds thicken towards the centre of channels. At

Manse Road Steps (L3) a channel at the top of the unit contains massive silt into which pebbles of an overlying lag deposit have sunk (Fig. 20B). The CRM is truncated by a minor planar, horizontal unconformity along most of the cliff line.

The cliff-top exposures of the CRM are generally inaccessible, but quarry faces in comparable sediments have been examined inland. For example, at Sandpiper Pit (Fig. 3 and 7), now mainly in-filled, poorly consolidated, trough cross-stratified pebble gravel, several metres thick, was interbedded with lenses of planar or ripple-laminated sand (McCabe, 2008). Lonestones up to a metre or more in diameter lay within the sequence (Fig. 19D). The sand and gravel at Sandpiper Pit was capped by an extensive tabular unit of stiff, crudely laminated diamict (McCabe, 2008). A similar sequence has been examined recently at the neighbouring Balnahatten Pit, 200 m to the north of Sandpiper, where the diamict included ice-scratched clasts lodged at its base (Merritt, 2016).

9.1 Interpretation

McCabe (1980, 1986) concluded that the major unconformity underlying the CRM (LA 4) was created by both glaciofluvial and glaciomarine processes and that the granular deposits overlying it were deposited as ice-proximal subaqueous (glaciomarine) outwash. Indeed, the sedimentology is broadly similar to that of the Killard Point Moraine (Fig. 2) described and interpreted by McCabe et al. (1984) as subaqueous outwash forming a glaciomarine morainal bank. More specifically, the CRM shares attributes with grounding line fans, including the stacked, multi-storey channels with coarsening upward fills, sigmoidal to tangential cross-stratification, rapid vertical and textural changes with variable grading patterns (massive to graded), evidence of syn-depositional mass flows and thin mud drapes (Powell and Alley, 1997; Thomas and Chiverrell, 2006; McCabe, 2008, fig. 9.7).

McCabe (2008) interprets the whole sequence exposed at Sandpiper Pit to be glaciomarine in origin, including the capping of diamict, which includes some vertically orientated clasts that he interprets as dropstones (McCabe and Dunlop, 2006, photograph 17b). However, the over-consolidated condition of the diamict (now seen at the adjacent Ballynahatten Pit) coupled with its extensive, planar basal contact, pronounced horizontal fissility and inclusion of ice-scratched clasts lodged at its base, all suggest subglacial deposition related to a glacial readvance (Merritt, 2016, fig. 9.2).

The preservation of some delicate, imbricated, striated cobbles forming the MSP, and the poorly sorted and consolidated condition of the sand and gravel draping them, suggests that rapid lift-off, carving or grounding-line retreat of ice occurred followed by rapid deposition of proximal subaqueous outwash. If subjected to terrestrial glaciofluvial, periglacial, littoral or shallow submarine processes the pavement should be more eroded and fragmentary than it is. The contemporary RSL is not known, but is suggested by the maximum altitude (c. 25 m OD) of eastward dipping gravelly foresets in a ridge situated inland of Sandpiper Pit (McCabe, 2008, p.180). The CRM and underlying pavement could be considered to provide a 'snap-shot' of rapid disintegration of ice at a receding grounding line, illustrating how pristine subglacial and ice-marginal landforms have been so widely preserved on the sea bed of the ISB and around the British Isles (eg. van Landeghem et al., 2009).

10. Dunnaval Member (DVM; LA 4, in part)

The DVM comprises up to 3 m of horizontally stratified gravel and pebbly sand (Gh, Sh, Go, Gmi) that is locally well size- and shape-sorted (Fig. 20A). Clasts are generally well rounded with bladed pebbles generally lying sub-horizontally. The basal contact of the unit with underlying sand and gravel of the CRM is generally horizontal, sharp and unconformable. The gravels locally display festooning, contain erect pebbles and include vertical, downward tapering, sand and gravel-filled cracks descending from the land surface.

10.1. Interpretation

A late-glacial raised shoreline has been identified behind the cliff line between Cranfield Point and Spa Well (Fig. 3 and 7), backed by notches at 18-19 m OD that tilt gently southwards (Stephens and McCabe, 1977; McCabe, 1980; McCabe and Hirons, 1986; McCabe and Dunlop, 2006). The sub-horizontal stratification, together with the good rounding, size and shape sorting of pebbles, is fully compatible with a littoral origin (cf. Bourgeois and Leithold, 1984). The festooning, erect pebbles and downward tapering cracks are interpreted to be ice wedge pseudomorphs (cf. Ballantyne and Harris, 1994) and demonstrate that the raised beach deposits have been affected by periglacial processes following a drop in relative sea level. McCabe and Clark (1998) report that the raised shoreline extends south-westwards towards Carlingford Lough, where it is cut out by a glaciofluvial terrace adjacent to, and associated with the ‘Cranfield Point Moraine’ (Fig. 3). A date of 15.6-14.7 ^{14}C ka BP (18.8-17.8 cal ka IntCal 04) obtained from mud underlying coarse gravel and diamict forming the terrace is reported to provide an estimate for the maximum age of the raised shoreline (McCabe et al., 2005; McCabe and Dunlop, 2006).

11. Kilkeel Member [KLM; LA 4, in part].

The raised marine shoreline and associated beach deposits of the DVM have been cut-out by a fan-shaped spread of sand and gravel (Kilkeel Fan) that extends inland from the coast between Spa Well and Kilkeel (Fig. 3 and 7). The fan deposit, named here as the *Kilkeel Member*, is underlain by very poorly sorted, clast-supported gravel (Gm, Gt) that is mainly disposed in stacked shallow channels, the lowermost eroded into the underlying sand and gravel of the CRM. Some channels are lined with silt (Fm) (L1) and others have near vertical sides (L3). The deposits locally coarsen upwards into loose, very poorly sorted gravel (Go) or gravel with thinly developed horizontal bedding (Fig. 20B). The channelized deposits display soft-sediment deformation structures and include isolated pellets (rip-ups) of clayey silt. Shallow tangential bedding parallel to the channel floors is commonly developed together with mainly northward-dipping, trough cross-bedding. To the north of Kilkeel Steps (Fig. 6; L2), a 0.9 by 0.2 m sized rip-up megaclast of laminated sand was observed towards the base of a 2.5 m deep channel eroded into silty fine-grained sand of the CRM (Fig. 20 C and D). The subangular to subrounded clasts are composed mainly of wacke-sandstone and siltstone with some pink granite and sparse flint and white quartzite.

11.1. Interpretation

The KLM lies at a slightly lower elevation than the DVM, from which it has not been distinguished hitherto. The sedimentology of the KLM is similar in many respects to the CRM, both members comprising sand and gravel disposed in shallow, multi-storey channels within a stacked architecture and displaying tangential cross bedding. The channels in the KLM, however, are generally shallower, steeper-sided, more asymmetric in cross profile, and some have been eroded much deeper into underlying sediments. The presence of large megaclasts of unconsolidated sand at the base of the unit suggests very rapid accumulation.

The lateral extent of the Kilkeel Fan suggests that it was formed by meltwaters that mainly flowed from the north, via the valley of the Kilkeel River, joined by meltwater flowing along the lower Aughrim Valley, from the west (Fig. 3 and 7). Nested sets of post-LGM, pre-Younger Dryas recessional moraines have been identified in both valleys, indicating retreat of outlet glaciers into the main south-eastern valleys of the Mournes (Barr et al., 2017, fig.1). The Aughrim Valley takes a 90° turn towards Kilkeel where it meets the Cranfield Moraine Complex (Fig. 3), suggesting that ice was probably forming this feature during the creation of the Kilkeel Fan. The thin, horizontal bedding typical of beach gravel (Bourgeois and Leithold, 1984) that occurs locally towards the top of the KLM (Fig. 20B), at c. 17 m OD, suggests that the glaciofluvial fan was modified by littoral processes during its accumulation when RSL stood at about this level.

12. Summary event stratigraphy.

The most likely depositional environments and passage of events that occurred during the last glaciation at the coast between Cranfield Point and Kilkeel are summarised below and illustrated in Fig. 21. This event stratigraphy, which is based on a parsimonious interpretation of the field evidence presented above, is related to the regional chronostratigraphy outlined in Table 1, phases of glaciation originally deduced by McCabe (1980) (Table 2) and wider events that affected the northern ISB.

12.1. Annalong Phase (pre-LGM). Subaqueous deposition of laminated mud in a probable glaciomarine setting, although reported mixed assemblages of foraminiferids in the muds suggest at least partial reworking by glacial processes. The origin of the shelly gravel bodies within the ALM is uncertain. They were possibly deposited by efflux jets at the front of the advancing ISIS, which scavenged palimpsest shell lags that had been over-ridden, but they could be glacial rafts of beach shingle. Evidence of folding and simple shear within both fine and coarse-facies of the ALM indicate subsequent over-riding by ice flowing west-south-westwards onshore. [Build-up of ice within the northern ISB; Fig. 21A].

12.2. Ballymartin Phase (LGM). Deposition of a stack of generally planar, horizontally-stratified units of subglacial traction till, including glacitectonite, folded rafts of subglacially scavenged materials and flat-topped cuspate lenses of sand, gravel and diamict likely to have been deposited within subglacial cavities. Consistent evidence of strain within the BMM, including minor thrusting and pressure shadows, indicate south to south-eastward flow offshore from the Mournes. [Extensive glaciation of ISB and surrounding land; Fig. 21B]

12.3. Mourne Phase (late LGM). An increasing dominance of ice flowing from the Carlingford Lough basin and the Mournes resulted in south-eastward flow across the Mourne Plain and the subglacial erosion of the seven deep troughs, partially lined by stone pavements. The troughs were possibly initially cut by subglacial drainage followed by subglacial modification by ice. [Regional ice sheet thinning accompanied with draw-down into the southern ISB; Fig. 21C]

12.4. Derryoge Phase (Cooley Point Interstadial). The architecture of the sediments filling the troughs (Fig. 16) suggests that phases of ice-bed separation and subglacial, subaqueous accumulation of mud were punctuated by subglacial deformation, most noticeably towards Crawfords Point. The troughs at Kilkeel were probably only partially infilled before glacial retreat occurred. Arctic to sub-Arctic distal glaciomarine sedimentation of the DEM followed, possibly beneath an ice shelf. Five reported radiocarbon dates on sieved foraminiferids (*Elphidium clavatum*) indicate deposition occurred at Kilkeel between 17.0 and 16.5 ^{14}C ka BP (20.1 and 19.7 cal ka IntCal 04) when geomorphological and palaeoenvironmental evidence suggests RSL stood at c. 30 m OD (McCabe and Clark, 1998; Clark P et al., 2004). [Glaciomarine conditions within the northern ISB following retreat of the ISIS; Fig.21D]

12.5. Ballykeel Phase (Clogher Head Stadial). Glacial readvance across the Mourne Plain resulted in the truncation of the entire glacigenic sequence and fashioning of the Main Stone Pavement. The deduced south-eastward flow direction suggests that the ice was sourced in the Mournes and well as issuing from the Carlingford Lough basin. [Clogher Head Readvance of McCabe et al. (2007b); Fig. 21E]

12.6. Cranfield Phase (Linns Interstadial). Rapid grounding line retreat of the ice occurred whilst RSL fell from at least c. 25 m OD, accompanied by rapid subaqueous glaciofluvial deposition of the CRM. The Main Stone Pavement was left largely in pristine condition. The subsequent 'active' retreat of ice toward the Carlingford Lough basin formed the Cranfield Moraine Complex, where at Sandpiper and Ballynahatten pits ice locally over-rode subaqueous glaciofluvial outwash correlated with the CRM, depositing a thin spread of till. [Phased retreat of ice back into the Carlingford Lough basin whilst RSL falls; Fig. 21F]

12.7. Dunnaval Phase (Linns Interstadial). Erosion of shoreline notches at 18-19 m OD between Cranfield Point and Spa Well associated with accretion of raised beach deposits of the DVM. A maximum age of 15.6-14.7 ^{14}C ka BP (18.8-17.8 cal ka IntCal 04) has been suggested for the raised beach where it abuts the Cranfield

Point Moraine (McCabe and Clark, 1998; McCabe et al., 2005). [Marine regression and creation of late-glacial raised beaches; Fig. 21G]

12.8. Kilkeel Phase (Linns Interstadial). Meltwaters issuing from retreating outlet glaciers in the Mournes, circumventing the Cranfield Moraine Complex, formed a glaciofluvial fan to the south-east of Kilkeel when RSL stood at c. 17 m OD. [Shortly before the Killard Point Readvance; Fig. 21H]

13. Discussion

13.1 Glacial limits during the Clogher Head and Killard Point readvances

The imbrication of cobbles in the MSP indicates that the final flow of ice in the area was from the north-west. Grounding line retreat was accompanied by rapid subaqueous glaciofluvial sedimentation across coastal parts of the Mourne Plain, where few unambiguous ice-marginal features have been identified (Fig. 3), either because they are buried beneath sand and gravel, or they have been subsequently eroded away. In comparison, the nested series of arcuate ridges of the Cranfield Moraine Complex are relatively well preserved and unmodified (Fig. 3). This suggests that they are younger and result from 'active' retreat of ice back into the Carlingford Lough basin after RSL had dropped below c. 25 m OD, otherwise they would have been destroyed by marine processes. Locally-sourced ice probably retreated into the eastern valleys of the Mournes following the Clogher Head Readvance, where poorly-developed recessional moraines have been identified (McCabe and Dunlop, 2006, fig. 16; Barr et al., 2016), but the age of these features is currently unknown. McCabe (2008) attributes the recessional moraines to the later Killard Point Readvance, which, he claims, formed the innermost ridge of the Cranfield Moraine Complex at Cranfield Point (Fig. 2).

The outer, northern limit of ice emanating from the Carlingford Lough basin during the Clogher Head Readvance was established in Ballykeel Bay, 3.5 km north-east of Kilkeel (Fig. 3), where a structurally-complex package of over-consolidated sediments, including laminated silts and sands are overlain, and intruded by, sandy diamict including clasts of granite (Stephens and McCabe, 1977; McCabe, 1980). There is no clear geomorphological evidence inland to corroborate this glacial limit, but a more convincing one occurs some 10 km to the north, at Dunmore Head (Fig. 3). This limit was thought to have formed contemporaneously by ice flowing from the north (McCabe, 1980, McCabe and Hirons, 1986), although in later publications it has also been correlated with the Killard Point Readvance (eg. McCabe and Dunlop, 2006, fig. 16 and 22; Clark J et al., 2012). The Dunmore Head Moraine links with well-developed, lateral ice-marginal features that rise gently northwards around the northern rim of the Mournes from c. 35 m OD to c. 150 m OD near Newcastle, some 7 km farther to the north (McCabe, 2008).

The highest raised marine shoreline feature etched into the Mourne Plain at c. 28 m OD extends from behind the village of Annalong northwards to Dunmore Head (Fig. 3), where it is thought to have been trimmed by ice during the creation of the Dunmore Head Moraine (McCabe and Hirons, 1986; McCabe, 2008). It is generally accepted that the Mourne Plain was largely ice-free between Dunmore Head and the limit of the mainly Carlingford Lough-derived ice established at Ballykeel (McCabe and Dunlop, 2006; McCabe 2008) (Fig. 2). However, the interpretation of the high (28 m) shoreline feature is controversial for it was considered earlier to more likely represent the innermost edge of a very gently sloping spread of glaciofluvial outwash that descends from Dunmore Head towards Mullartown and Annalong (Stephens and McCabe, 1977, Fig. 8) (Fig. 3).

The Dunmore Head and Ballykeel limits are correlated with the Clogher Head Readvance, which was established by McCabe et al. (2007b, fig. 1b) mainly from evidence at the Port and Cooley Point sites backing Dundalk Bay (Fig. 2). These authors deduce that the event occurred between 18.7 and 18.2 ka, linking it with global climatic cooling into the Oldest Dryas recorded in sea-surface temperature proxies obtained from other sites around Ireland (Clark J et al., 2012). We conclude that the dated glaciomarine mud of the DEM at Kilkeel Steps was over-ridden during this event, after 19.8 ka, the youngest of the five readjusted age determinations reported by Clark J et al. (2012). Further work is required to identify glacial limits inland once better resolution digital terrain models become available.

13.2 Correlations across the northern Irish Sea basin

There have been many attempts to correlate limits of glacial readvances across the northern ISB (Thomas, 1985, fig. 8.6). This is no longer just an esoteric exercise as knowledge of the extent of ice during former retreat stages is necessary in GIA and related modelling, which is becoming more temporally resolved and sophisticated (Bradley et al., 2011). For example, in palaeotidal modelling of regions in which isostatic loading was greater than the global reduction in sea level, ice limits like those of the Clogher Head Readvance are required to mask out areas that would otherwise be simulated to have been flooded (Ward et al., 2016).

In many recent reconstructions the northern ISB had become ice free by c. 21.3 ka (eg. Clark C et al., 2012; Chiverrell et al., 2013), based on evidence from an off-shore sampling site positioned midway between Killard Point and the Isle of Man (Fig. 1), where cold-stage ice-proximal marine deposits overlie glacigenic material (Kershaw, 1986). Calibrated radiocarbon ages of c. 23.3 ka from this site have been used to constrain initial deglaciation of the northern ISB (eg. Eyles and McCabe, 1989; Clark J et al., 2012), but they should be regarded as maximal age estimates as they were obtained from bulk samples of marine carbonate simply for establishing post-glacial sedimentation rates, not supported by detailed palaeontological or palaeo-environmental analyses. Furthermore, there are uncertainties regarding the marine reservoir correction for this period of time. Bayesian modelling control for the retreat of the ISIS northwards suggests that a younger age of c. 21.9 - 20.7 ka is more likely (Chiverrell et al., 2013), especially as a cluster of four Cosmogenic Nuclide (CN) ages of c. 19.2 ka have been obtained from glacially scoured bedrock in western Anglesey, off North Wales (McCarroll et al., 2010; Phillips et al., 2009).

The evacuation of ice from the northern ISB was associated with a phase of ice-stream drawdown around the Isle of Man (Roberts et al., 2007), which we suggest probably also formed the troughs between Derryoge and Kilkeel (Fig. 22B). It is likely that the margin of the ISIS retreated farther, more rapidly, more actively and was more unstable in the deeper, western ISB that is was in the shallower, eastern ISB (Chiverrell et al., 2013, 2016). How far the ice margin retreated to the north is not known, nor is its position across the northern ISB during the subsequent Clogher Head Readvance (Roberts et al., 2006). For the latter it is tempting to resurrect the glacial reconstruction of ice in the northern ISB offered by Thomas (1985), in which an ice shelf extends from Dundalk Bay across to the western coast of the Isle of Man (Fig. 22C). If correct, the glaciomarine muds at Kilkeel may correlate with the Dog Mills Member of the Orrisdale Formation on the Isle of Man (cf. Thomas et al., 2004, fig. 8b). These muds were also subsequently over-ridden by ice during a substantial glacial readvance from the north, but the event is correlated with the Killard Point Readvance by Thomas et al. (2004), who also conclude that the foraminiferal assemblages in the Orrisdale Formation are derived and cannot be used to confirm the existence of raised, fully glaciomarine deposits on the Isle of Man. Roberts et al. (2006), however, suggest that reduced salinity conditions in a shallow water, ice-proximal marine embayment may have occurred.

Low-salinity, proglacial glaciomarine muds similar to the Dog Mills Member underlie the Vannin Sound, some 20 km to the south-east of the island, which possibly then linked to open water in the southern ISB (Thomas, 1985; Pantin, 1978) (Fig. 22C). The Vannin Muds contain dropstones and ice-berg dump structures that were interpreted by Pantin (1978) to have accumulated sub-tidally by sediment-laden meltwater plumes adjacent to a floating ice shelf. These coarsely laminated muds, up to 35 m thick, could perhaps have been deposited from low-velocity hyperpycnal flows, a style of sedimentation that was apparently characteristic of conditions in the North Atlantic during Heinrich Event 1 (H1), particularly between 16.7 and 15.1 ka BP (Stanford et al., 2011). The Vannin muds are truncated by an unconformity of regional extent that has been traced across the eastern ISB from geophysical records and correlated tentatively with a significant readvance (Blackhall Wood-Gosforth Oscillation) that affected the Solway Lowlands and the west Cumbrian coast (Livingstone et al., 2012) (Fig. 22C).

The limit of the Killard Point Readvance at c. 16.5 ka (Table 1) is generally accepted to have stretched between Killard Point (Fig. 1) and the Bride Moraine, on the northern tip of the Isle of Man (Thomas et al., 2004; Roberts et al., 2007), and thence either with the Kirkham Moraine in Lancashire (Chiverrell et al., 2013, 2016), or a limit off the west Cumbrian coast (Livingstone et al., 2012) (Fig. 22D). However, these publications all generally either ignore, or play down the regional significance of the earlier Clogher Head Readvance, which is more firmly established here.

13.3. Sea-level change

Clark P et al. (2004) proclaimed the international importance of the sequence exposed between Derryoge and Kilkeel, stating that it contains unique evidence of rapid fall in RSL during the Last Glacial Termination from about +30 m to -10 m OD (or lower) followed by even more rapid (<500 years) rise back to +20 m OD at about 19 ka BP (Fig. 5). They correlated the rise with Global Meltwater Pulse 1A (Peltier, 2005) and subsequently reinforced their story through the acquisition of new AMS radiocarbon dates on foraminifera collected from raised marine muds at other sites in the north and west of Ireland (McCabe et al., 2005; McCabe and Dunlop, 2006; McCabe et al., 2007b; McCabe 2008; Clark J et al., 2012). However, although this substantial sea-level fluctuation is 'new to the construction of sea level curves in the British Isles….and truly remarkable' (Whitehouse et al., 2008), it was not included in a review of sea level change in Ireland (Roe, 2008) and has not been accommodated in subsequent glacio-isostatic adjustment (GIA) modelling (Brooks et al., 2008; Bradley et al., 2011). This circumspection by the GIA community was challenged by McCabe in his formal reply to Brooks et al. (2008) and in McCabe (2008).

The dates and palaeoenvironmental interpretation of the glaciomarine muds of the DEM at Kilkeel Steps reported by Clark P et al. (2004) and McCabe et al. (2005) were generally accepted by Roberts et al. (2006) in a review of Holocene sea levels, LGM glaciomarine environments and geophysical models for the northern ISB. However, the Kilkeel data were categorised as 'secondary' sea-level index points in a database developed by Brooks and Edwards (2006) in which observations of RSL were screened and classified according to established protocol for the analysis of sea-level data. Secondary points such as these were derived from sites where the environment of deposition was unclear or contested. No evidence was reported that clearly contradicted the interpretation of Clark P et al. (2004) and McCabe et al. (2005) that the Kilkeel dates indicate RSL to have stood at up to about +30 m OD at c. 19 ka BP, but this level was up to 20 m higher than predicted by the GIA models of Lambeck (1996), Lambeck and Purcell (2001), Peltier et al. (2002) and Shennan et al. (2006). Some of these models were questioned by McCabe (1997) and McCabe (2008).

The GIA modelling for the region has been improved firstly by Brooks et al. (2008) and then Bradley et al. (2011), primarily by accepting an earlier and more extensive, thicker ice sheet (700 m) over north and central Ireland at the LGM, together with substantial thinning after 19 ka BP. These models incorporate a modest increase in ice thickness during the Killard Point Stadial, but still predict RSL at Kilkeel at 19 ka BP to be some 6 m lower than suggested by the evidence presented here (Fig. 5). This small discrepancy may result from continued underestimation in the modelling of ice thickness at the LGM (cf. Kuchar et al., 2012) together with the time-span of the LGM that has was adopted in the calculations. For example, Bradley et al. (2012) assume that deglaciation began at 21 ka BP, whereas there is now a convergence of evidence that the ISIS began to retreat some 2000 years or more earlier (Smedley et al., 2017) (Fig. 1). The models of Brooks et al. (2008) and Bradley et al. (2011) also do not factor in any build-up of ice during the Clogher Head Stadial, although regional glacio-isostatic loading seems to control the isostatic component of the local RSL record, rather than short term perturbations in the ice thickness and residence time (Roberts et al., 2006).

The results of this investigation clearly indicate that crucial evidence cited by McCabe (1986) and thereafter in support of subaerial dissection of the troughs occurring between Derryoge and Kilkeel, and hence rapid fall and rise in RSL prior to the deposition of the glaciomarine muds dated at Kilkeel, is not justified. We find evidence only for falling RSL during deglaciation that is compatible with published sea-level curves in the region (Carter, 1982, 1983) and current GIA modelling.

14. Conclusions

- This review and targeted reinvestigation of the Pleistocene sequence exposed between Derryoge and Kilkeel broadly supports traditional interpretations of the last glaciation of the region, involving subglacial accretion and deformation of till beneath grounded ice during the LGM, followed by local glacial readvances.
- A series of deep troughs were eroded subglacially into the till sheet during a post-LGM drawdown of ice into the northern ISB. The architecture of the sediments filling the troughs suggests that phases of ice-bed separation and subglacial, subaqueous accumulation of mud were initially punctuated by episodes of subglacial erosion and deformation.
- Glaciomarine muds were deposited in the troughs at Kilkeel following retreat of ice from the coast and whilst RSL stood at up to about 30 m OD. The five published age determinations on hand-picked foraminiferids of between 17.0 and 16.5 ^{14}C ka BP (20.1 - 19.7 cal ka IntCal 04) reported by Clark P et al. (2004) and McCabe et al. (2005), are accepted.
- The trough-fills were over-ridden, compacted, deformed and truncated during a re-advance of ice from inland. A widespread subglacial stone pavement was formed during this event, which is correlated with the Clogher Head Readvance established by McCabe et al. (2007b).

- Grounding line retreat was accompanied by rapid accretion of ice-proximal, subaqueous glaciofluvial sand and gravel. Ice emanating from the Carlingford Lough basin subsequently stabilized and retreated to form the nested arcuate moraine ridges of the Cranfield Moraine Complex situated inland of Derryoge. Ice locally over-rode outwash deposits to lay down till.
- The coastal sequence was truncated during marine regression, which created a raised shoreline at 18-19 m OD. The beach gravels were subsequently dissected by meltwater flowing towards Kilkeel from inland whilst RSL stood at c. 17 m OD.
- There was an apparently uninterrupted fall in RSL from c. 30 m OD that is consistent with the pattern of RSL curves for the region predicted by current GIA modelling.
- Crucial evidence cited by McCabe (1986) in support of subaerial dissection of the troughs and large-magnitude sea-level fluctuations of supposed circum-North Atlantic significance (McCabe, 1996; McCabe and Clark, 1998; McCabe et al., 1998; Clark P et al., 2004; McCabe et al., 2005, 2007a, 2007b; Clark P et al., 2009; Clark J et al., 2012), is not justified.
- Despite laborious efforts during the past 35 years, much of the research reviewed here has focussed on gathering bits of evidence from many sites to support and refine hypotheses, rather than testing them critically against all the evidence available at specific sites. This inductive approach to science is inherently weak, has led to a polarisation of views and unfortunately has resulted in confusion.
- Further work is now required to review and firmly establish the stratigraphical, sedimentological and geomorphological context of all the published dates on

raised marine muds that underpin the generally-accepted chronostratigraphy of the region (Clark J et al., 2012; Table 1), and to correlate ice limits across the northern ISB.

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Supplementary Information

Generalised logs of cliff sections between Kilkeel and Crawfords Point.

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Full Figure and Table captions

Figures

1. Median deglacial ice sheet limits around the Irish Sea Basin (after Hughes et al., 2016). Inset: maximum limits of the BIIS at the LGM.

2. Bedforms, flowlines and glacial readvance limits in north-eastern Ireland (based on McCabe et al., 2005 and McCabe and Dunlop, 2006).

3. Digital surface model of the Mournes and Mourne Plain showing key geomorphological features. CMC, Cranfield Moraine Complex; CPM, Cranfield Point Moraine; DHM, Dunmore Head Moraine; F, Formal Mountain; K, Knockchree; KF, Kilkeel Fan; KS, Knockshee; SP, Sandpiper Pit. Digital surface model reproduced with the permission of Land & Property Services under delegated authority from the

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4. The Mourne Plain looking northwards towards Kilkeel and the Mountains of Mourne. Photograph reproduced with permission of NIEA.

5. Sea level curves for north-eastern Ireland. Grey line and associated data points after McCabe (2008). Red line is derived from the new ice model of Bradley et al. (2011), based on the optimum earth model inferred in Bradley et al. (2009). 1) Raised beach notches bordering the Mourne Plain near Annalong (McCabe, 1986); 2) Low-stand recorded by supposed subaerial channels (troughs) between Derryoge and Kilkeel (Clark et al., 2004); 3) Dated glaciomarine muds at Kilkeel Steps (Clark et al., 2004); 4) Dated marine muds at Cooley Point and Port (McCabe and Haynes, 1996; McCabe et al., 2007b); 5) Readvance to Clogher Head (McCabe et al., 2007b); 6) Dated marine mud at Cranfield Point and reported intertidal boulder pavement at Cooley Point (McCabe et al., 2005); 7) Readvance to Killard Point limits; 8) Drapes of dated red marine mud on subglacial bedforms and formation of late-glacial raised shoreline on Rough Island, Strandford Lough (McCabe et al., 2005); 9) Creation of gravel barrier on Rathin Island (Carter, 1993); 10) Submerged beach and intertidal sands, Belfast Lough (Kelley et al., 2006).

6. Generalized section between Kilkeel and Crawfords Point (modified after McCabe and Dunlop, 2006) with new interpretation of the section backing Derryoge Bay. Localities 1-11 are sited in next figure.

7. Localities L1 to 11 critically re-examined in this study. Generalised logs are given in Supplementary Information. Digital surface model © Crown copyright and database right MOU577.3 (2018).

8. Graphic logs at selected localities, showing new radiocarbon dates on shells and pie diagrams of striae measurements on stone pavements that are enlarged in a following figure.

9. Images of the Annalong Member (ALM): A) laminated silt on foreshore, Derryoge Bay [L9], from where sediment blocks were taken for thin sectioning; B) intraformational deformation within laminated mud [L9]; C) diamict of BMM resting on deformed laminated mud of ALM (L9); D) crinkly deformation on bedding planes (arrowed) within open-folded laminated mud [L7]; E) cross-stratified gravel with shell fragments beneath the BMM [L4]; F) folded and sheared bed of gastropod shells within cross-stratified gravel [L4].

10. Thin section of laminated silt of the ALM at L9, showing coarsely interlaminated clayey silt and very fine-grained sand with evidence of syn-depositional soft-sediment deformation (1) and micro-thrusting (2).

11. Annotated thin section of crinkled laminated silt of the ALM at L9 with close-up of buckle folding.

12. Images of the Ballymartin Member (BMM): A) typical sequence at Crawfords Point [L11] with diamict including stone lines and clusters truncated by the Main Stone Pavement, overlain by sand (CRM) and capped by raised beach gravel (DVM); B) bevelled boulder of granite with striae on upper surface orientated NW-SE [L11]; C) gravel lens within diamict interpreted as subglacial nye-channel fill, Kilkeel [L1]; D) fissile muddy diamict towards base of the BMM at Manse Road steps, Kilkeel [L3]; E) diamict at base of the BMM with relatively far-travelled pebbles pressed down into mud of the ALM [L9]; F)) intensely sheared laminated mud of the ALM beneath the BMM at L1-2 (white helmet for scale).

13. Structures within the BMM: A) sketch of a rotated boulder [L10]; B) boulder with tapering lens of sandy gravel (above the trowel) on down-glacier side (left) [L8]; C) gravel-filled structure beneath boulder [L1]; D) annotated sketch of the structure shown in the previous image interpreted as a hydrofracture.

14. Images of the Derryoge Member (DEM): A) sequence of muds and diamict filling the trough (T2) backing Derryoge Bay with arrow showing a draped contact; B) blocky-fractured massive mud passing down into relatively undisturbed laminated mud [L2]; D) rhythmically laminated mud interpreted as glaciomarine cyclopels [L2] (pound coin for scale); D) compact laminated mud towards base of trough (L2), displaying steep-angled fissility (to right of the scale) and shearing; E) ball-and-pillow structure [L2]; F) folded laminated mud towards base of trough [L2]; G) poorly-developed stone pavement (MSP) capping sheared mud (glacitectonite) including lens (raft) of sand (above hammer) towards top of the trough [L1]; H) folded and heavily jointed, fissile muds within the trough [T2] backing Derryoge Bay [L7-6]. Sub-horizontal joints intercept incipient axial-plane cleavage (top left to bottom right) to form rhomboid slabs that are diffracted around the tight (sheath?) fold that plunges into the cliff-face (arrowed).

15. Images of stone pavements: A) mud of the DEM resting on a stone pavement that lines the base of the northern limb of the trough [T2] backing Derryoge Bay [L6]; B) crushed pebbles beneath a boulder in the pavement shown in the adjoining image; C) the Main Stone Pavement, beneath sands of the CRM, truncating a minor silt and diamict-filled channel structure lined by another stone pavement (arrowed) atop the main trough backing Derryoge Bay [L8-9]. Note that boulders of both pavements dip into the cliff face towards the WNW; D) bevelled stones of a delicate stone pavement capping the trough at Kilkeel [L1], with striae (arrowed) dipping gently into the cliff-face (towards handle of hammer).

16. Conceptual model for the formation, in-filling and deformation of the troughs backing Derryoge Bay: A) subglacial erosion of the BMM caused by drawdown of ice into the ISB (towards viewer) with localized subglaciofluvial erosion and deposition at base of troughs. Glacitectonite and boulder pavements are formed beneath ice; B) subglacial accumulation of mud within troughs punctuated by episodes of subglacial erosion leading to local development of glacitectonite, subglacial traction bed till and

boulder pavements, open folding and soft-sediment deformation; C) continued subglacial accumulation of mud within troughs punctuated by episodes of subglacial erosion, with local subglaciofluvial sheet flow resulting in interbeds of very fine-grained sand; D) either continued subglacial accumulation of mud within troughs punctuated by episodes of subglacial erosion, or retreat of ice followed by open glaciomarine sedimentation of mud, as probably occurred towards Kilkeel; E) thickening and readvance of ice leads to severe compaction, folding and fissuring of muds within the troughs and truncation of the entire sequence together with creation of the Main Stone Pavement.

17. Image and annotated sketch of open-folded muds of the DEM at the base of the trough [T2] backing Derryoge Bay [L7], showing structural measurements.

18. Azithimuths of striae measured on bevelled clasts of the Main Stone Pavement.

19. Images of the Cranfield Member (CRM): A) boulder lodged firmly into top of the BMM, draped by poorly consolidated sand and gravel [L11]; B) recording azimuths of striae on the Main Stone Pavement atop the diamict and mud-filled trough [T2] backing Derryoge Bay [L8]; C) trough-cross stratified sand with a truncated channel filled with massive mud, overlain unconformably by horizontally stratified gravel (KLM) at top of section L3; D) sand, gravel and diamict formerly exposed at Sandpiper Pit. Reproduced from McCabe and Dunlop (2006) with thanks.

20. Images of gravel units capping the succession: A) horizontally stratified gravel of the DVM associated with a raised shoreline behind the section at 18 m OD, south of Crawfords Point [L11] (Reproduced from McCabe and Dunlop, 2006, with thanks); B) laminated silty sand (CRM) overlain by shallow trough-cross stratified sand and gravel and capped by horizontally stratified (beach?) gravel [L3], note cobbles sunk into top of the silty sand (arrowed); C) channelized glaciofluvial gravel (KLM) containing a rip-up body of the underlying sand (CRM) atop the trough at Kilkeel Steps [L2]; D) close-up of the rip-up body.

21. Cartoon figures illustrating the most likely sequence of events during the last glaciation of the Mourne Plain.

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Tables

1. Chronostratigraphy for the north-east of Ireland (modified after Clark J et al., 2012).

2. Lithostratigraphy for the Pleistocene deposits underlying the Mourne Plain. Lithofacies associations after McCabe (1986); informal phases after McCabe (1980).

3. New radiocarbon dates on shells collected from the Annalong Member.

Supplementary Information

Generalised logs of cliff sections between Kilkeel and Crawfords Point.

Table 1. Chronostratigraphy for the north-east of Ireland (modified after Clark J et al., 2012).

Stage	**^{14}C ka BP***	**Calib ^{14}C ka BP**	**Palaeoenvironment**	**References**
Last Glacial Maximum		30 27	Full glaciation of Ireland and Irish Sea Basin	Small and Ballantyne, 2018
[Greenland Interstadial 2]		23.3 22.9	Stepped retreat of ISIS from the Isles of Scilly from 26-25 ka	Small et al., 2018; Rasmussen et al., 2014
Cooley Point Interstadial (CPS)	≥17 ≤15.0	≥20.1 ≤ 18.2	Deposition of raised massive to laminated glaciomarine muds along coast of South Down.	McCabe, 1997; McCabe and Clark, 1998; McCabe et al., 2005
Clogher Head Stadial (CHS)	≤ 15.0 ≥ 14.2	≤18.2 ≥17.1	Glacial readvances into Dundalk Bay, Carlingford Lough and northern ISB. Local subglacial deformation of glaciomarine mud.	McCabe and Clark, 2003; McCabe et al., 2005, 2007b
Linns Interstadial (LI)	≥14.2 ≥13.8	≥17.3 ≥17.0	Mud deposition in open marine embayments following limited glacial retreat.	McCabe et al., 2005
Killard Point Stadial (KPS)	≥ 14.2 ≥13	≥17.1 ≥16.0	Deposition of glaciomarine mud coeval with glacial readvance to limits within those of the CHS.	McCabe et al., 1984; McCabe and Clark, 1998
Rough Island Interstadial (RII)	c. 13.0	≥16.0 12.9	Drawdown of ice into marine calving bays followed by rapid Stagnation Zone Retreat inland.	McCabe and Haynes, 1986; McCabe and Clark, 1998; McCabe 2008

Mainly based on AMS radiocarbon dating of monospecific samples of *Elphidium clavatum*, corrected for 400 yr reservoir effect only.

Table 2. Lithostratigraphy for the Pleistocene deposits underlying the Mourne Plain. Lithofacies associations after McCabe (1986); informal phases modified after McCabe (1980).

Lithostratigraphy	**Depositional facies**	**Lithofacies Association**	**Phase**
Kilkeel Member (KLM)	Subaerial outwash/beach	LA 4 in part	Kilkeel
Dunnaval Member (DVM)	Beach	LA 4 in part	Cranfield>Dunnaval
Cranfield Member (CRM)	Subaqueous outwash	LA 4 in part	Ballykeel>Cranfield
Derryoge Member (DEM)	Distal glaciomarine?	LA 3	Derryoge
Ballymartin Member (BMM)	Subglacial traction till and glacitectonite	LA 2	Ballymartin>Mourne
Annalong Member (ALM)	Glaciomarine	LA 1	Annalong

Table 3. New radiocarbon dates on shells collected from the Annalong Member.

UBA No	Sample ID	Material	^{14}C Age	±	$F^{14}C$	±
UBA-31643	SS0226	Turritella	39,176*	522	0.0076	0.0005
UBA-31644	SS0227	Turritella	39,938*	607	0.0069	0.0005
UBA-31645	SS0228	Turritella	44,429*	1014	0.0040	0.0005
UBA-31646	SS0229	Turritella	47,475	1774	0.0027	0.0005
UBA-31647	SS0230	Turritella	48,069	1671	0.0025	0.0005
UBA-31648	SS0231	Arctica	48,899	1803	0.0023	0.0005

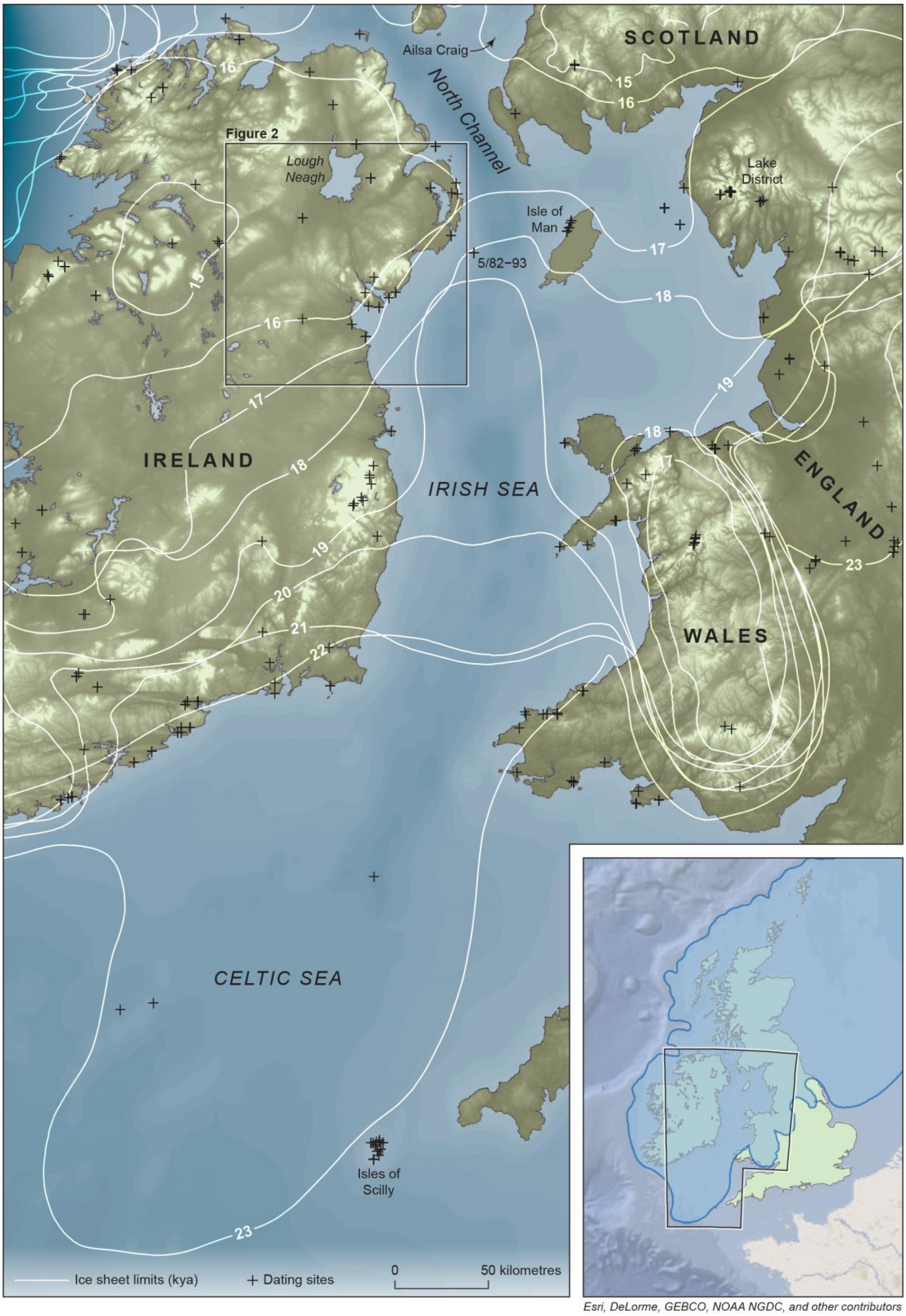


Figure 1. Median deglacial ice sheet limits around the Irish Sea Basin (after Hughes et al., 2016). Inset: maximum limits of the BIIS at the LGM.

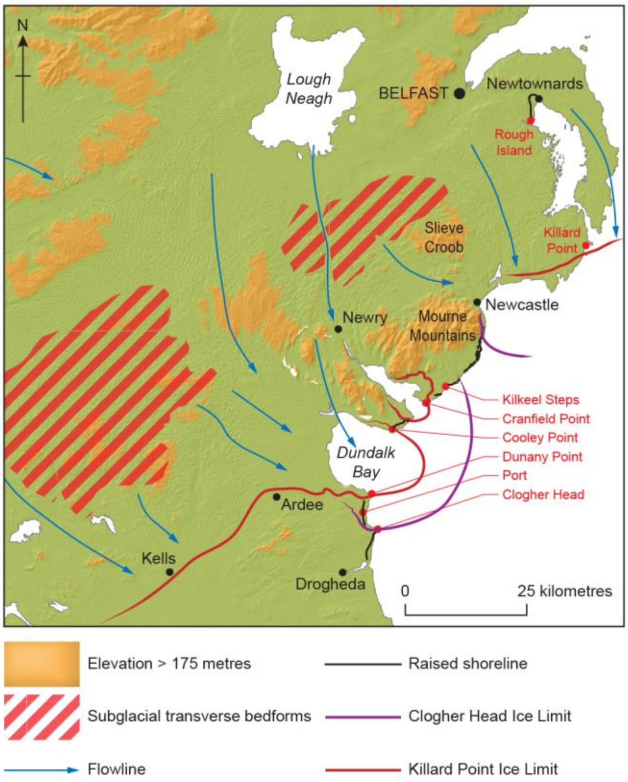


Figure 2. Bedforms, flowlines and glacial readvance limits in north-eastern Ireland (based on McCabe et al., 2005 and McCabe and Dunlop, 2006).

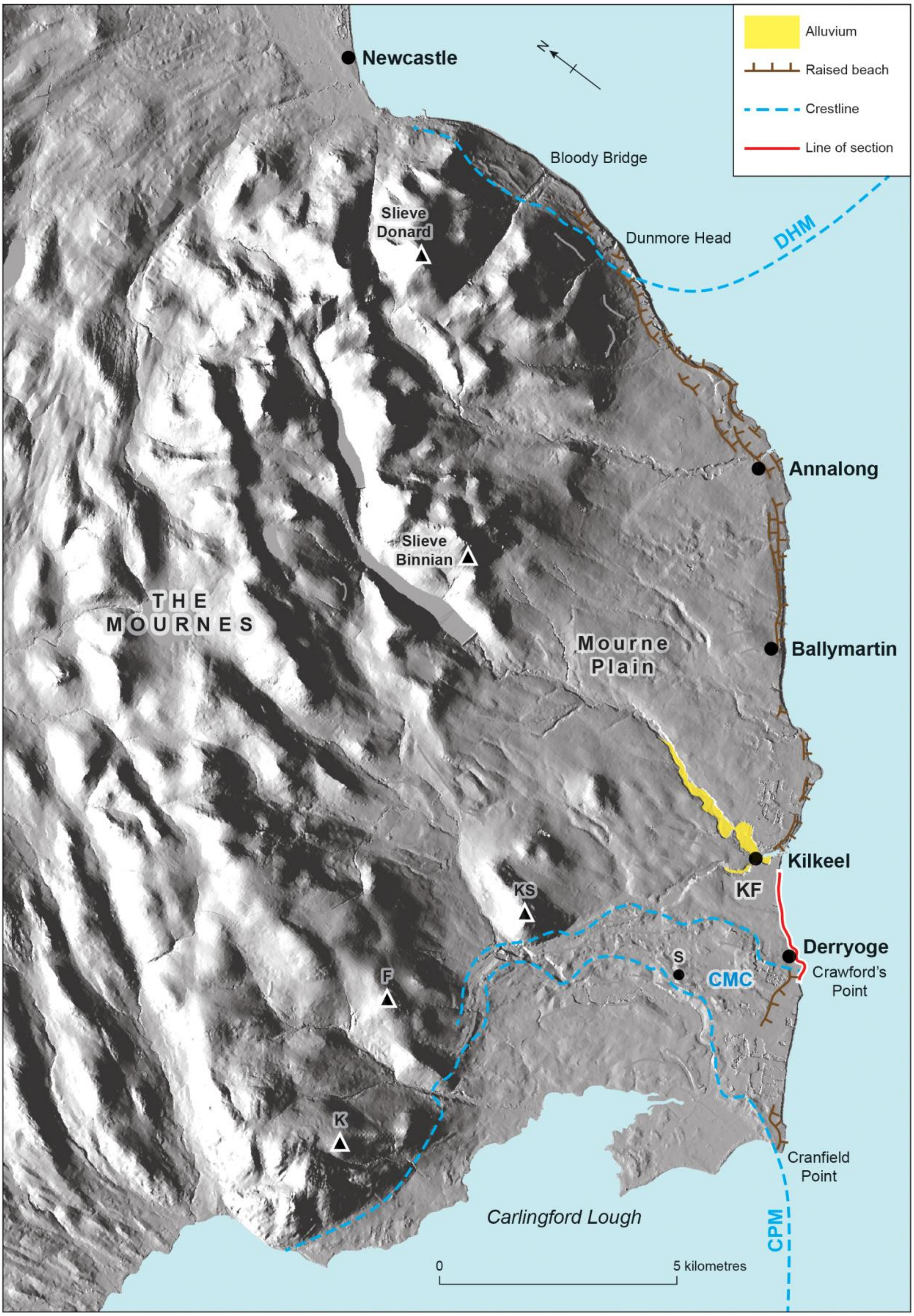


Figure 3. Digital surface model of the Mournes and Mourne Plain showing key geomorphological features. CMC, Cranfield Moraine Complex; CPM, Cranfield Point Moraine; DHM, Dunmore Head Moraine; F, Formal Mountain; K, Knockchree; KF, Kilkeel Fan; KS, Knockshee; SP, Sandpiper Pit. Digital surface model reproduced with the permission of Land & Property

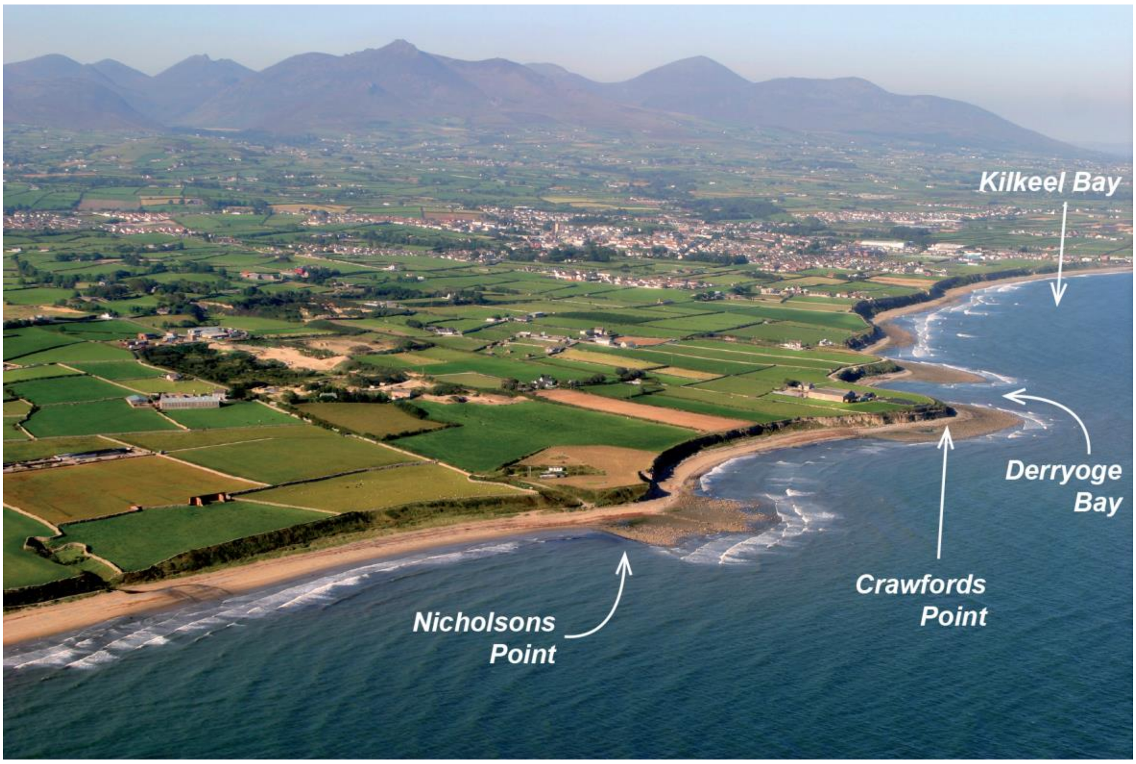


Figure 4. The Mourne Plain looking northwards towards Kilkeel and the Mountains of Mourne. Photograph reproduced with permission of NIEA.

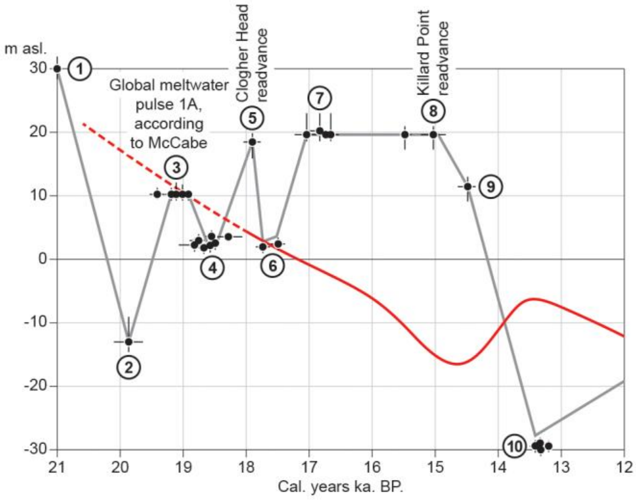


Figure 5. Sea level curves for north-eastern Ireland. Grey line and associated data points after McCabe (2008). Red line is derived from the new ice model of Bradley et al. (2011), based on the optimum earth model inferred in Bradley et al. (2009). 1) Raised beach notches bordering the Mourne Plain near Annalong (McCabe, 1986); 2) Low-stand recorded by supposed subaerial channels (troughs) between Derryoge and Kilkeel (Clark et al., 2004); 3) Dated glaciomarine muds at Kilkeel Steps (Clark et al., 2004); 4) Dated marine muds at Cooley Point and Port (McCabe and Haynes, 1996; McCabe et al., 2007b); 5) Readvance to Clogher Head (McCabe et al., 2007b); 6) Dated marine mud at Cranfield Point and reported intertidal boulder pavement at Cooley Point (McCabe et al., 2005); 7) Readvance to Killard Point limits; 8) Drapes of dated red marine mud on subglacial bedforms and formation of late-glacial raised shoreline on Rough Island, Strandford Lough (McCabe et al., 2005); 9) Creation of gravel barrier on Rathin Island (Carter, 1993); 10) Submerged beach and intertidal sands, Belfast Lough (Kelley et al., 2006).

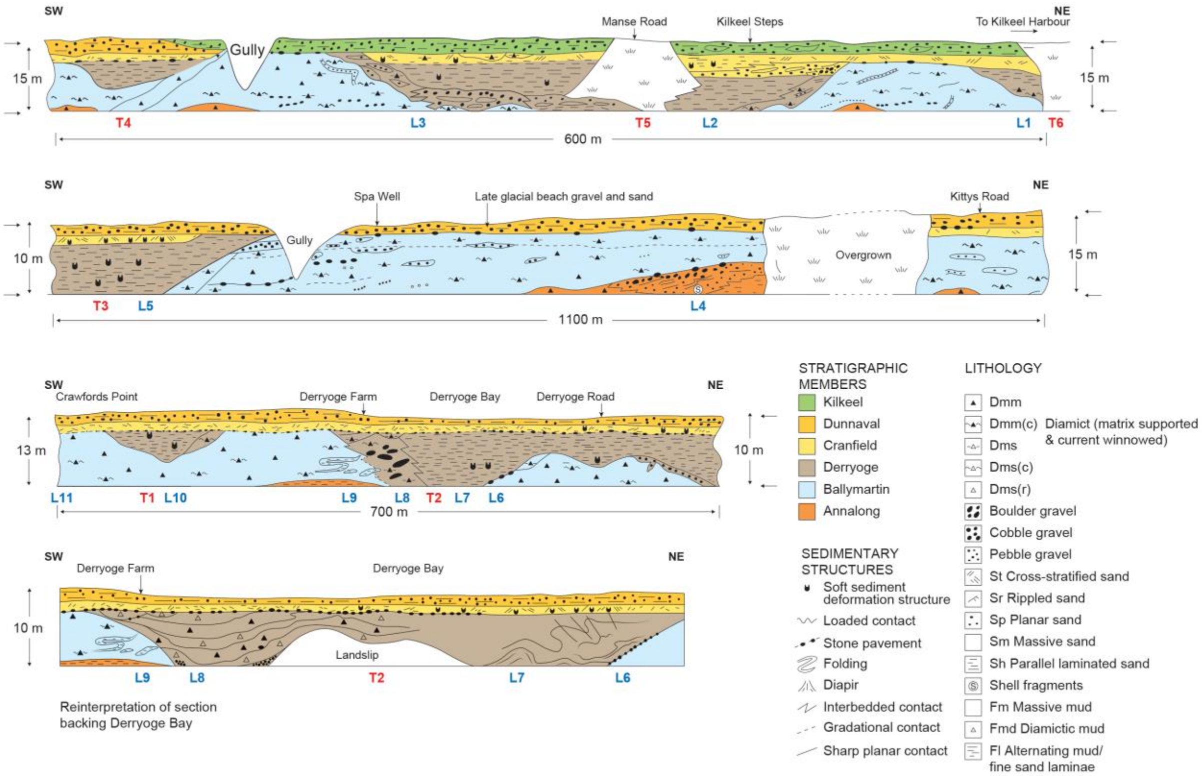


Figure 6. Generalized section between Kilkeel and Crawfords Point (modified after McCabe and Dunlop, 2006) with new interpretation of the section backing Derryoge Bay. Localities 1-11 are sited in next figure.

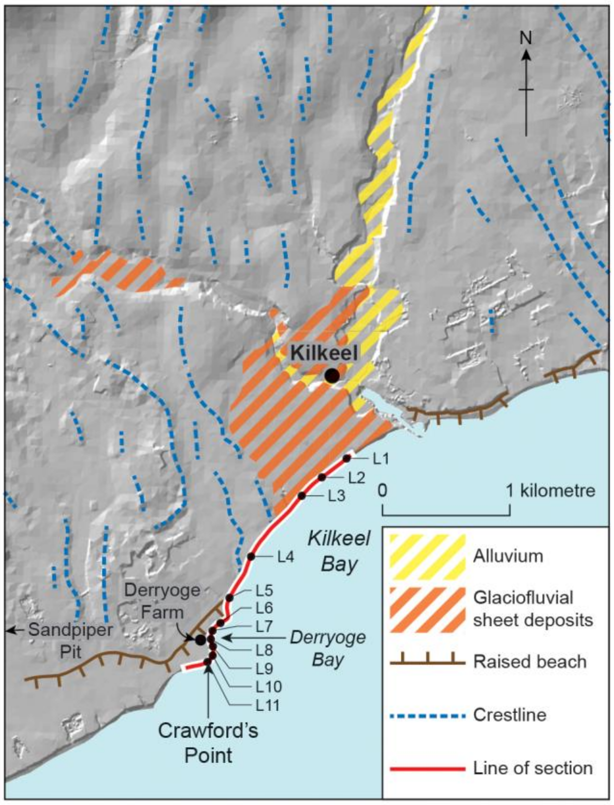


Figure 7. Localities L1 to 11 critically re-examined in this study. Generalised logs are given in Supplementary Information. Digital surface model © Crown copyright and database right MOU577.3 (2018).

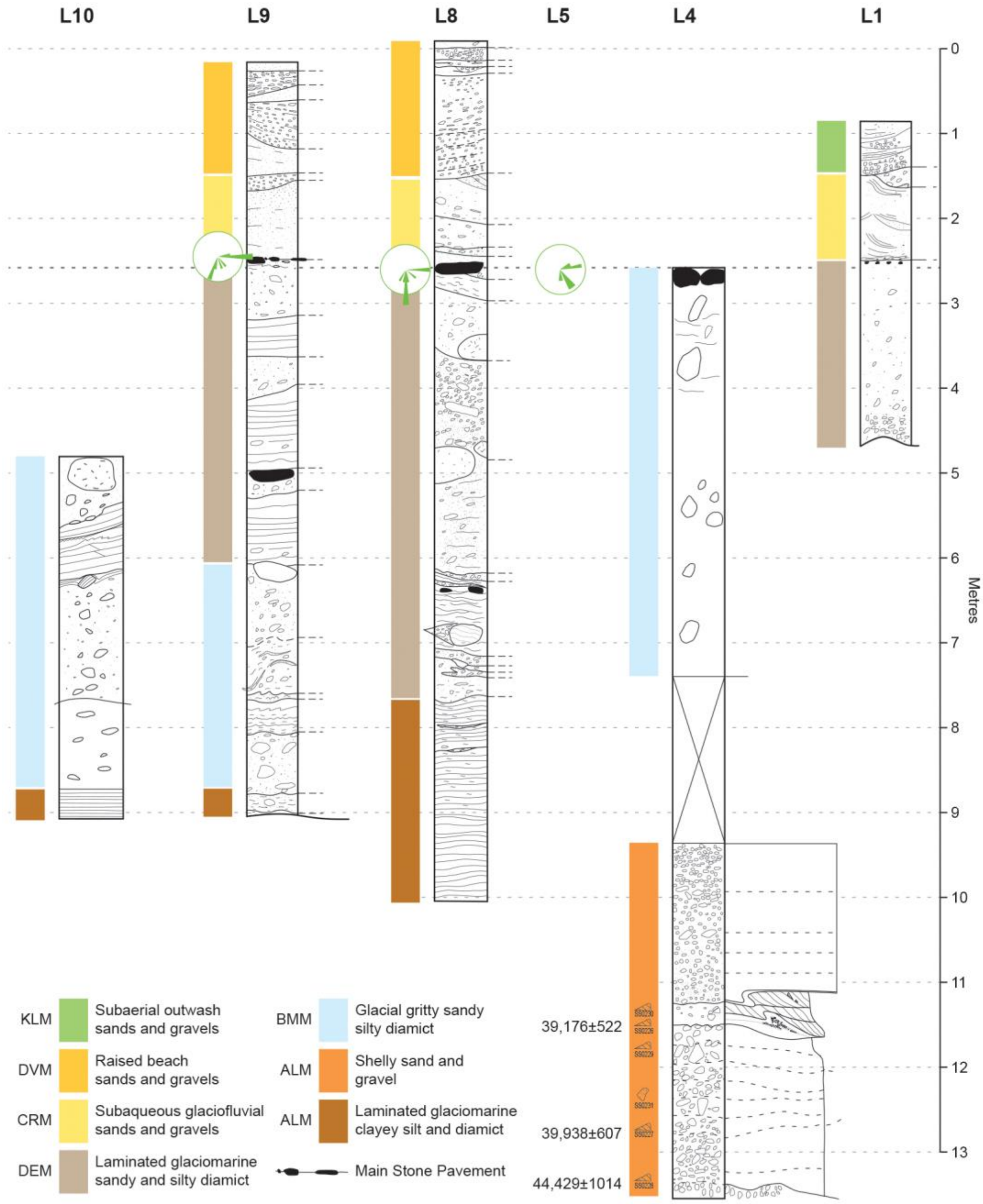


Figure 8. Graphic logs at selected localities, showing new radiocarbon dates on shells and pie diagrams of striae measurements on stone pavements that are enlarged in a following figure.

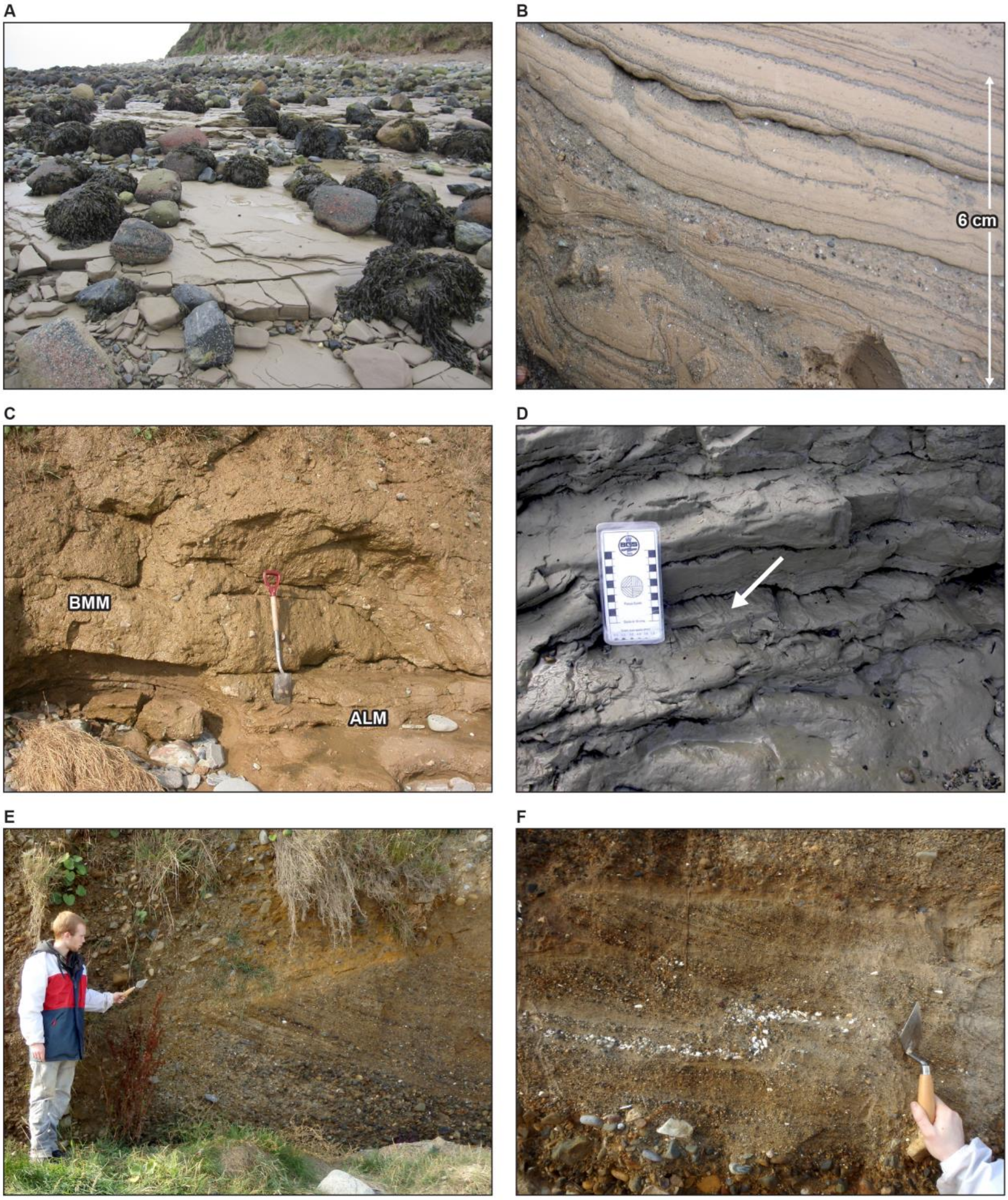


Figure 9. Images of the Annalong Member (ALM): A) laminated silt on foreshore, Derryoge Bay [L9], from where sediment blocks were taken for thin sectioning; B) intraformational deformation within laminated mud [L9]; C) diamict of BMM resting on deformed laminated mud of ALM (L9); D) crinkly deformation on bedding planes (arrowed) within open-folded laminated mud [L7]; E) cross-stratified gravel with shell fragments beneath the BMM [L4]; F) folded and sheared bed of gastropod shells within cross-stratified gravel [L4].

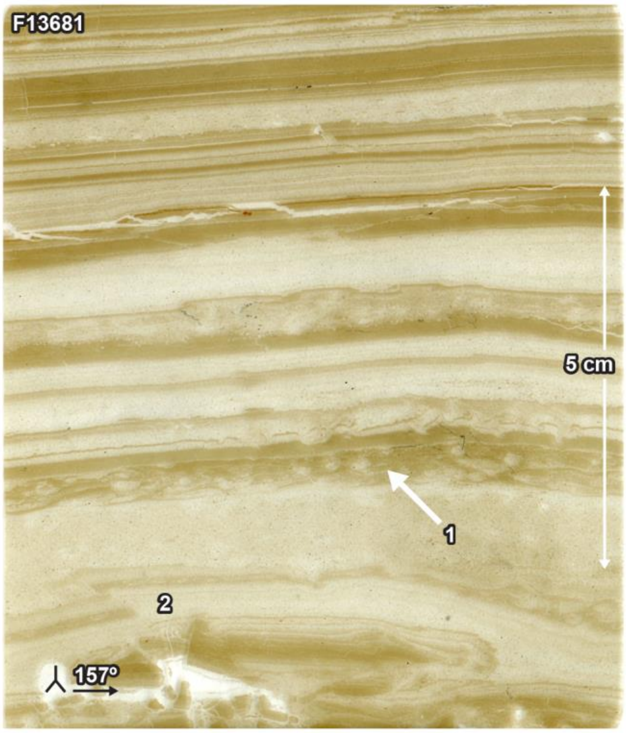


Figure 10. Thin section of laminated silt of the ALM at L9, showing coarsely interlaminated clayey silt and very fine-grained sand with evidence of syn-depositional soft-sediment deformation (1) and micro-thrusting (2).

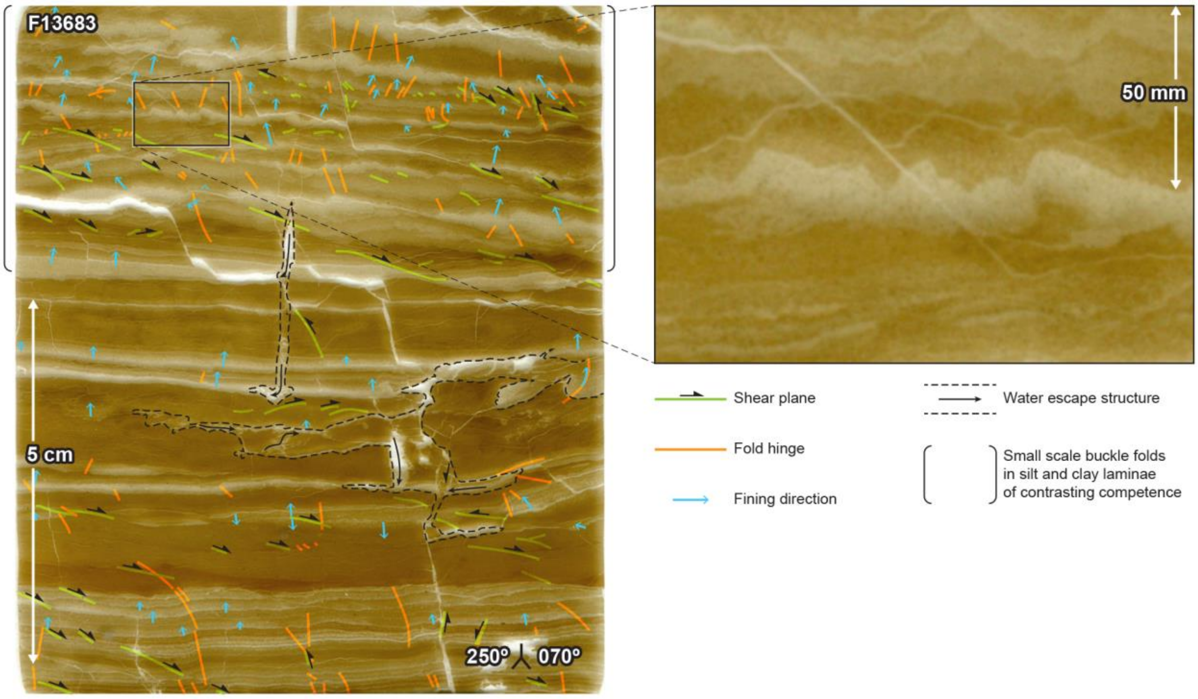
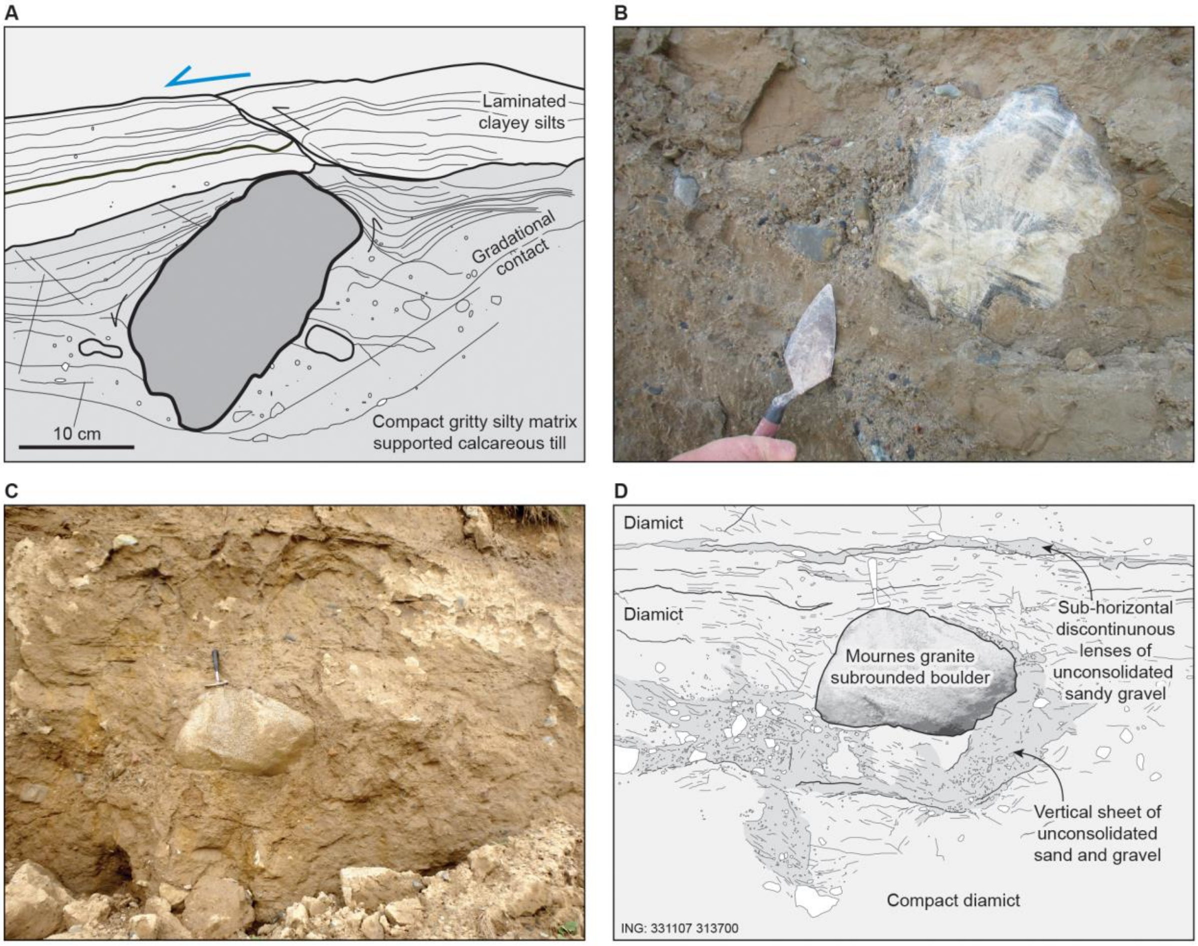
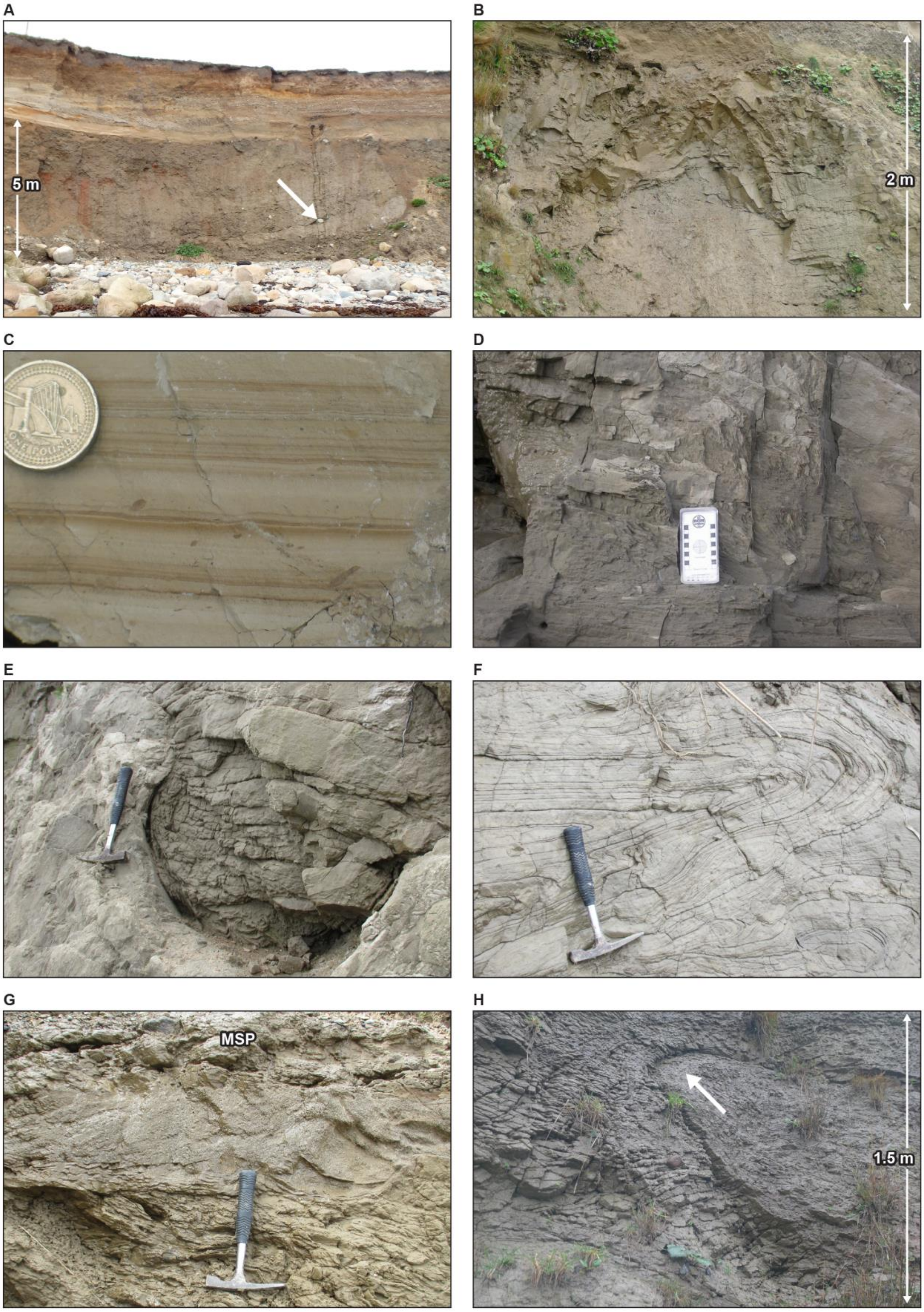
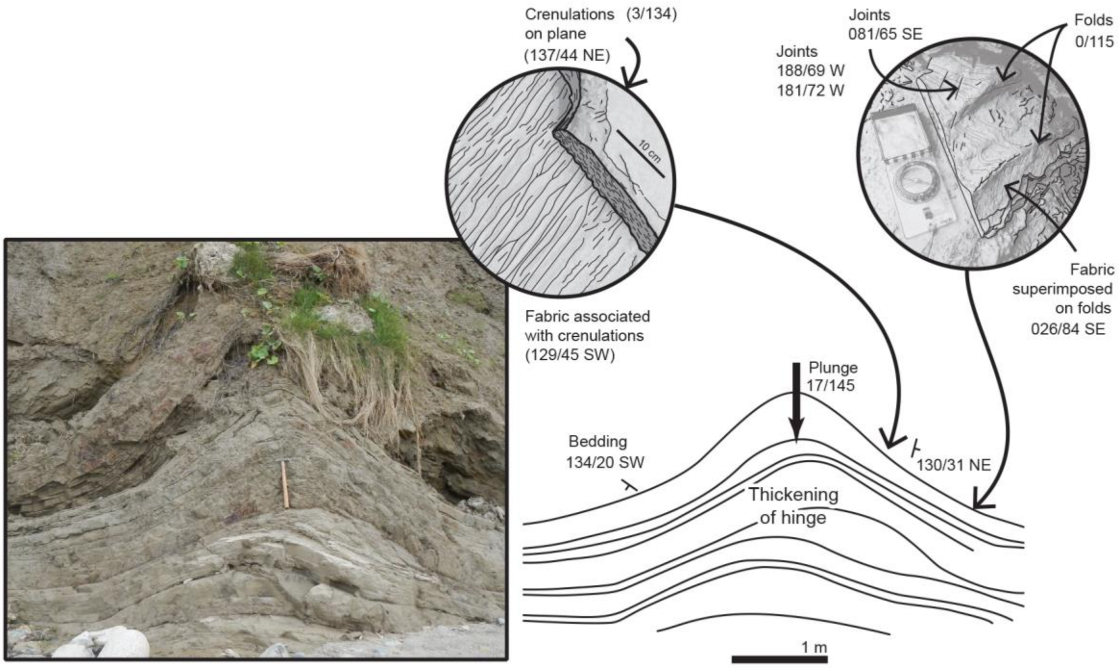


Figure 11. Annotated thin section of crinkled laminated silt of the ALM at L9 with close-up of buckle folding.


A
DVM
CRM
MSP
12 m
BMM
B
C
D
1 m
E
F


A
Laminated clayey silts
Gradational contact
10 cm
Compact gritty silty matrix supported calcareous till
B
C
D
Diamict
Diamict
Mournes granite subrounded boulder
Sub-horizontal discontinunous lenses of unconsolidated sandy gravel
Vertical sheet of unconsolidated sand and gravel
Compact diamict
ING: 331107 313700


A
5 m
B
2 m
C
D
E
F
G
MSP
H
1.5 m



Crenulations (3/134)
on plane
(137/44 NE)
10 cm
Fabric associated
with crenulations
(129/45 SW)
Joints
081/65 SE
Joints
188/69 W
181/72 W
Folds
0/115
Fabric
superimposed
on folds
026/84 SE
Plunge
17/145
Bedding
134/20 SW
130/31 NE
Thickening
of hinge
1 m

Figure 12. Images of the Ballymartin Member (BMM): A) typical sequence at Crawfords Point [L11] with diamict including stone lines and clusters truncated by the Main Stone Pavement, overlain by sand (CRM) and capped by raised beach gravel (DVM); B) bevelled boulder of granite with striae on upper surface orientated NW-SE [L11]; C) gravel lens within diamict interpreted as subglacial nye-channel fill, Kilkeel [L1]; D) fissile muddy diamict towards base of the BMM at Manse Road steps, Kilkeel [L3]; E) diamict at base of the BMM with relatively far-travelled pebbles pressed down into mud of the ALM [L9]; F)) intensely sheared laminated mud of the ALM beneath the BMM at L1-2 (white helmet for scale).

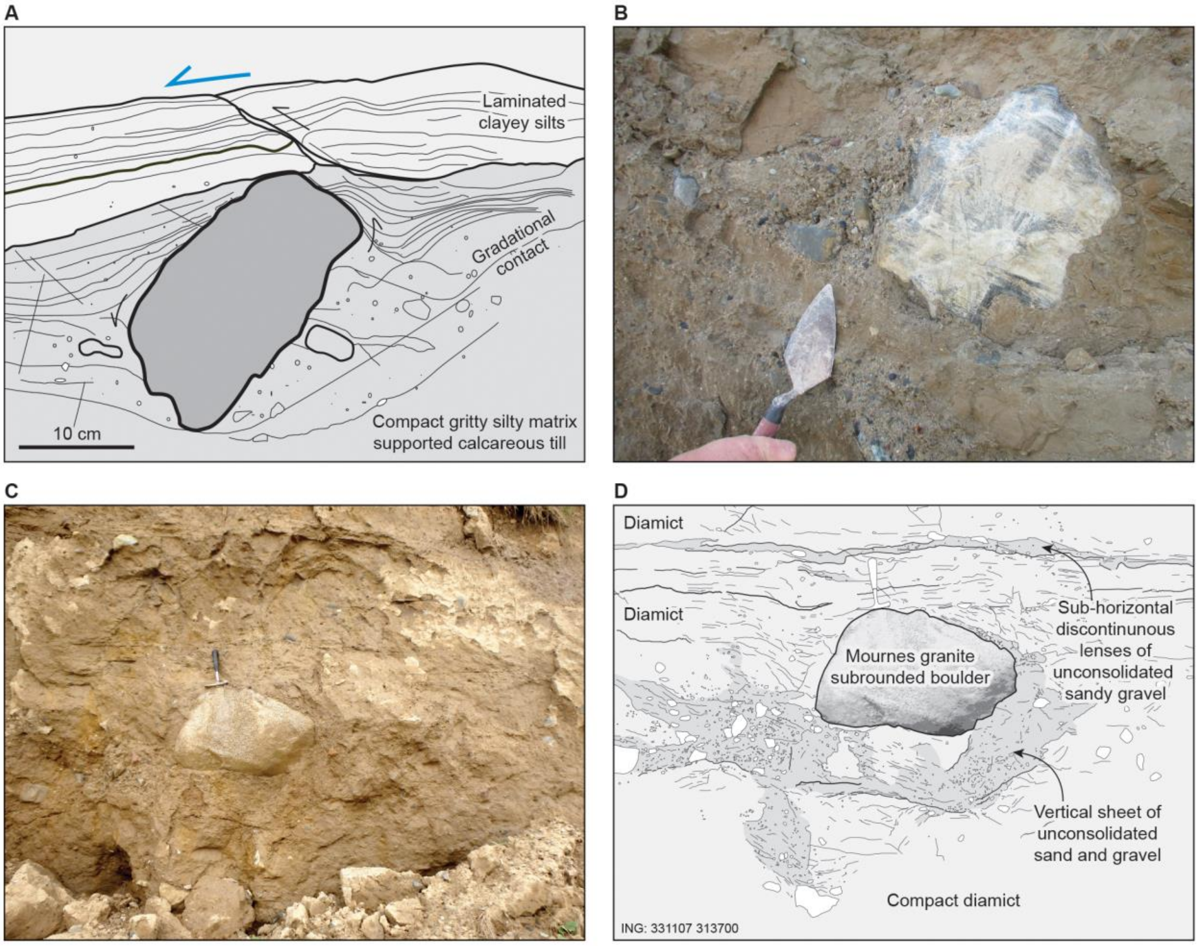


Figure 13. Structures within the BMM: A) sketch of a rotated boulder [L10]; B) boulder with tapering lens of sandy gravel (above the trowel) on down-glacier side (left) [L8]; C) gravel-filled structure beneath boulder [L1]; D) annotated sketch of the structure shown in the previous image interpreted as a hydrofracture.

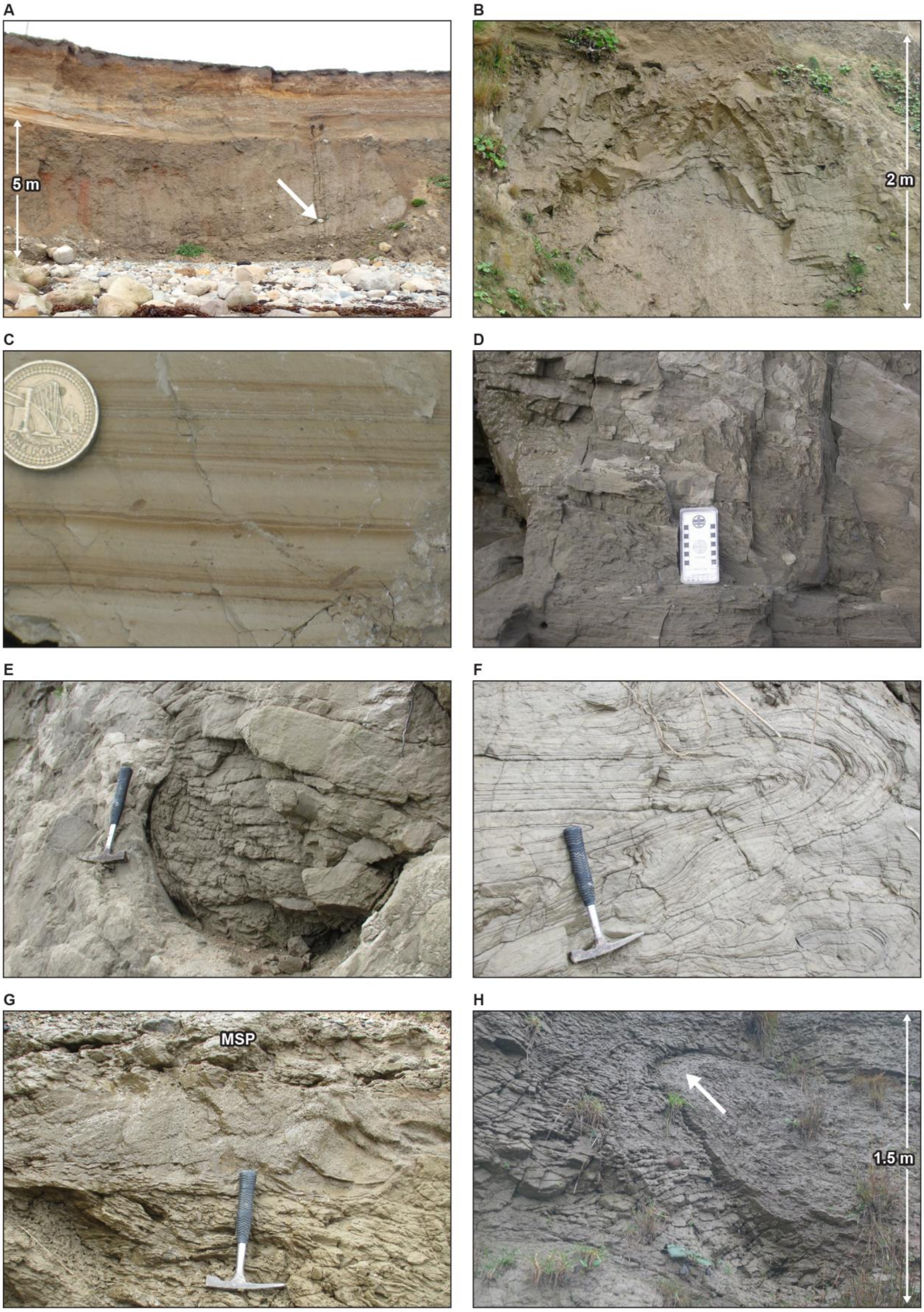
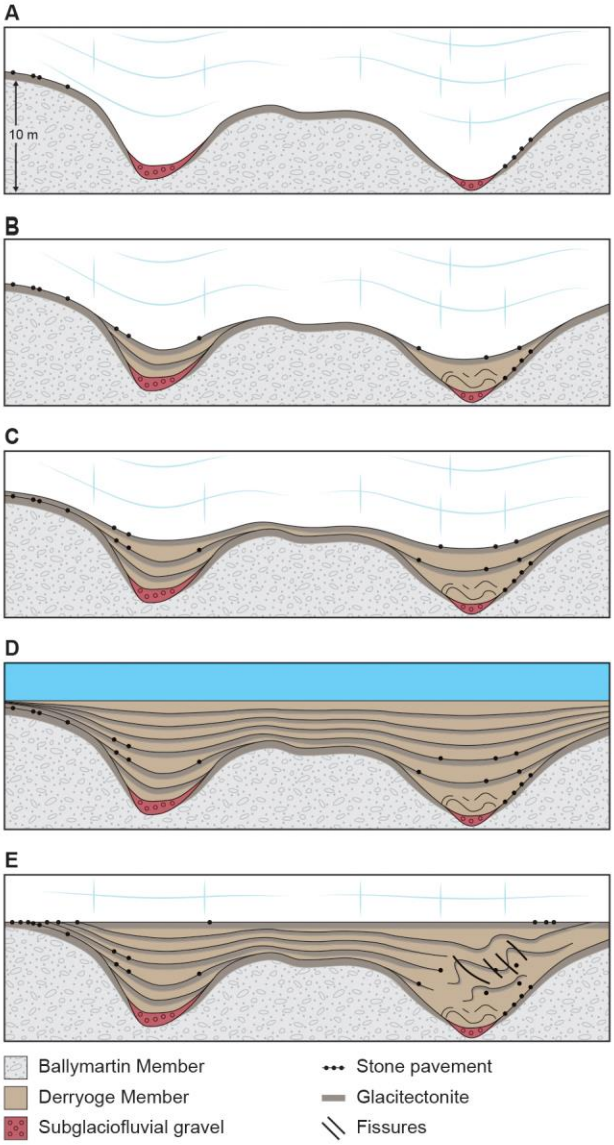


Figure 14. Images of the Derryoge Member (DEM): A) sequence of muds and diamict filling the trough (T2) backing Derryoge Bay with arrow showing a draped contact; B) blocky-fractured massive mud passing down into relatively undisturbed laminated mud [L2]; D) rhythmically laminated mud interpreted as glaciomarine cyclopels [L2] (pound coin for scale); D) compact laminated mud towards base of trough (L2), displaying steep-angled fissility (to right of the scale) and

shearing; E) ball-and-pillow structure [L2]; F) folded laminated mud towards base of trough [L2]; G) poorly-developed stone pavement (MSP) capping sheared mud (glacitectonite) including lens (raft) of sand (above hammer) towards top of the trough [L1]; H) folded and heavily jointed, fissile muds within the trough [T2] backing Derryoge Bay [L7-6]. Sub-horizontal joints intercept incipient axial-plane cleavage (top left to bottom right) to form rhomboid slabs that are diffracted around the tight (sheath?) fold that plunges into the cliff-face (arrowed).

Figure 15. Images of stone pavements: A) mud of the DEM resting on a stone pavement that lines the base of the northern limb of the trough [T2] backing Derryoge Bay [L6]; B) crushed pebbles beneath a boulder in the pavement shown in the adjoining image; C) the Main Stone Pavement, beneath sands of the CRM, truncating a minor silt and diamict-filled channel structure lined by another stone pavement (arrowed) atop the main trough backing Derryoge Bay [L8-9]. Note that boulders of both pavements dip into the cliff face towards the WNW; D) bevelled stones of a delicate stone pavement capping the trough at Kilkeel [L1], with striae (arrowed) dipping gently into the cliff-face (towards handle of hammer).



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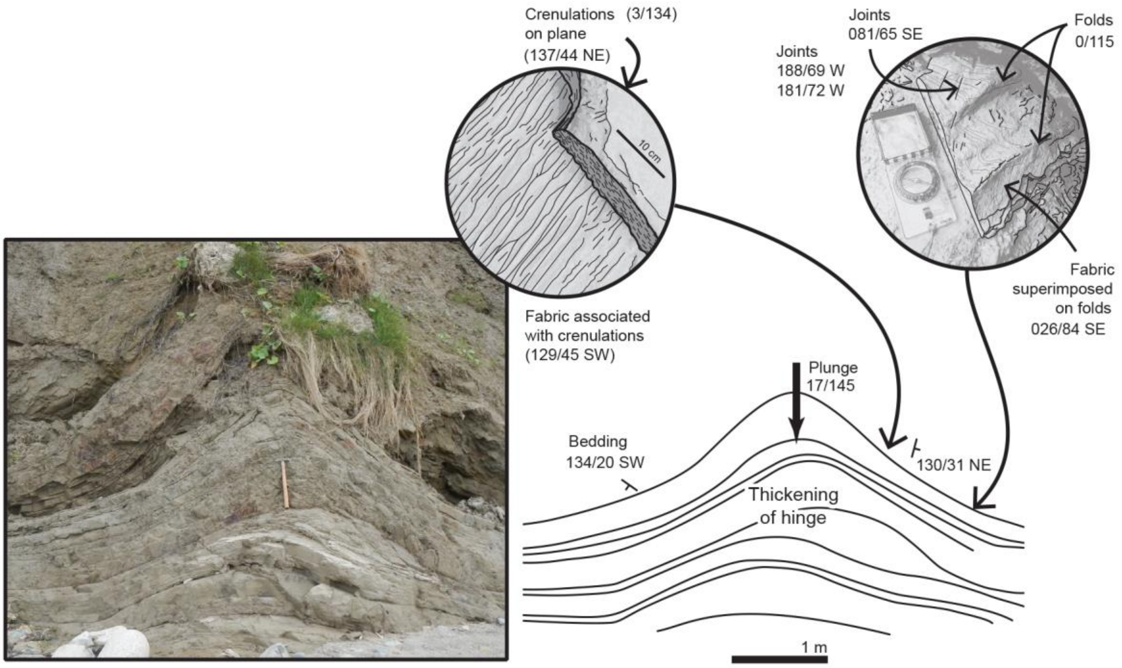

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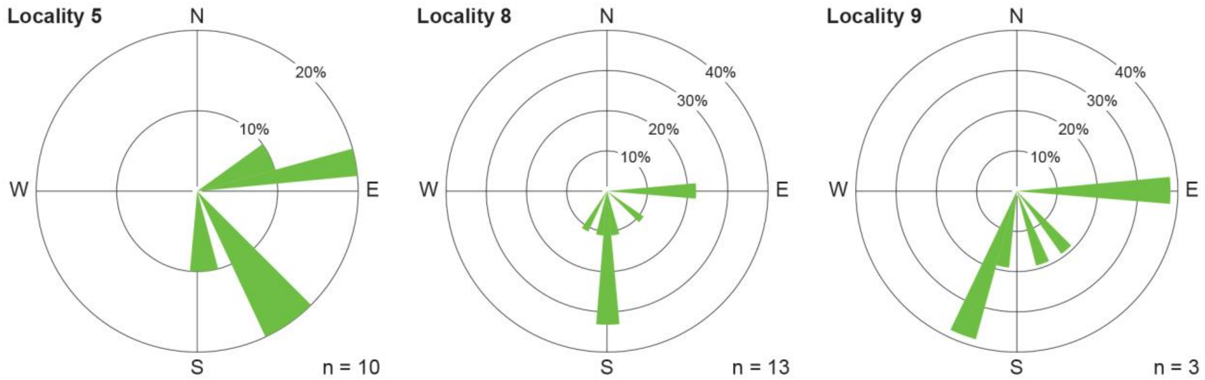

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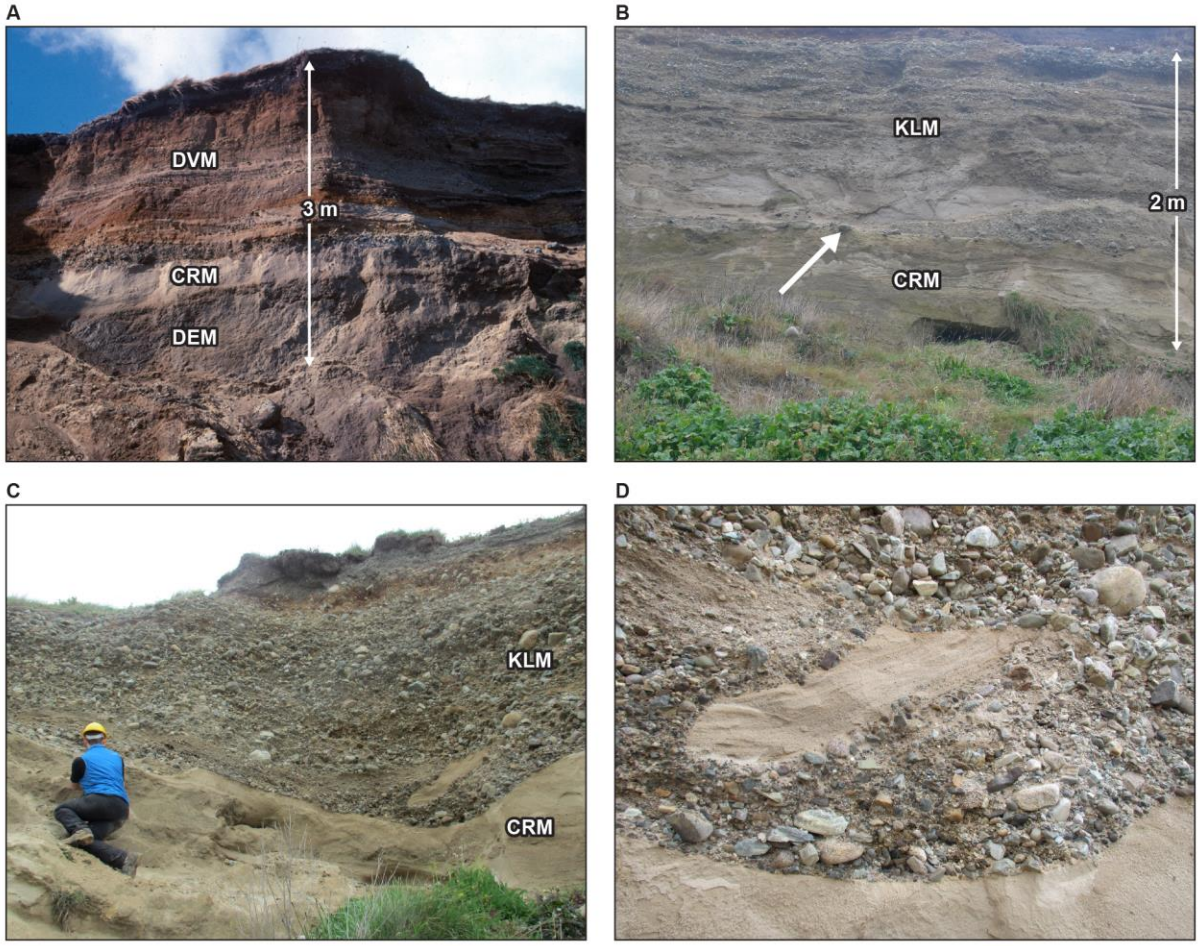

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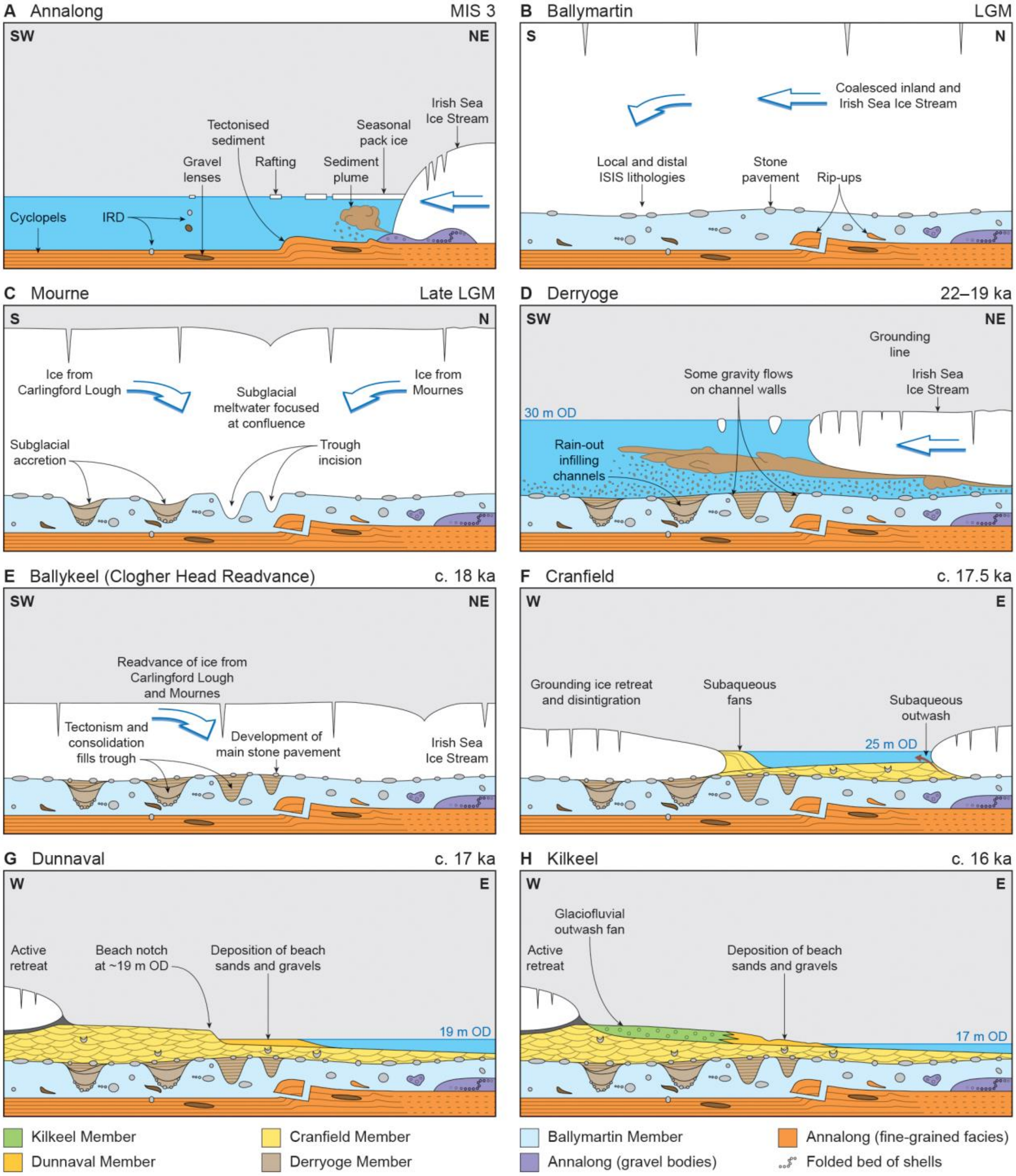

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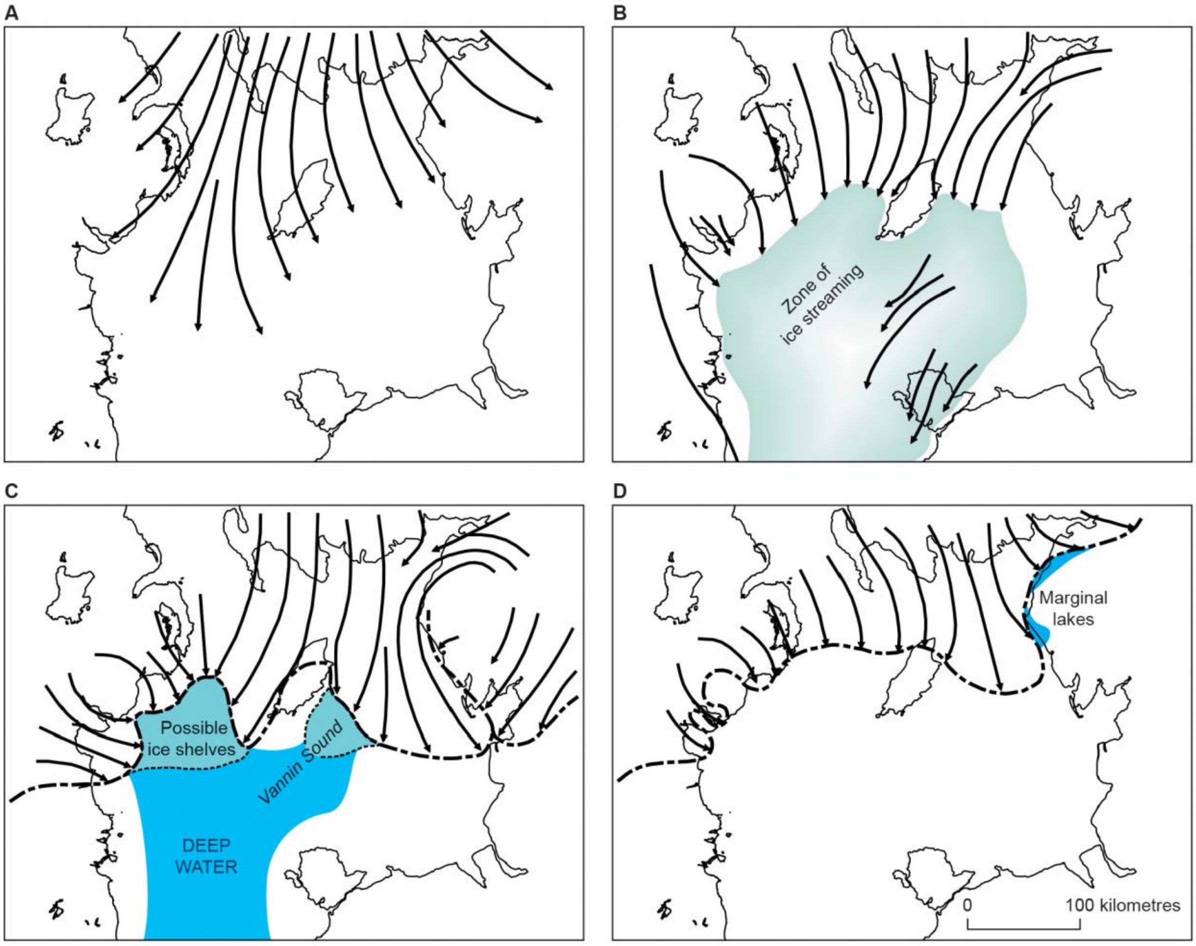

Figure 22. Speculative reconstructions for the last glaciation of the northern ISB: A) build-up of ice leading into the LGM (based partly on Greenwood and Clark, 2009; Roberts et al., 2007; Phillips et al., 2009; Finlayson et al., 2010); B) draw-down into ice-streams following the LGM (based partly on Roberts et al., 2007: van Landeghem et al., 2008; Phillips et al., 2009; Greenwood and Clark, 2009); C) Clogher Head Readvance (based partly on Thomas, 1985; Merritt and Auton, 2000; McCabe et al., 2007b; Livingstone et al., 2012); D) Killard Point Readvance (after McCabe and Dunlop, 2006; Roberts et al., 2007; Livingstone et al., 2012).

A critical review and re-investigation of the Pleistocene deposits between Cranfield Point and Kilkeel, Northern Ireland: implications for regional sea-level models and glacial reconstructions of the northern Irish Sea basin. *Jon W Merritt, Sam Roberson and Mark Cooper.*

Supplementary Information: Generalised cliff section logs between Kilkeel and Crawfords Point

Logs are located on Figure 6 and 7 of the main paper. Original locality registration numbers in brackets. Lithofacies and terminology after Evans and Benn (2004)

Locality 1. Composite log of cliffs 50 to 150 m north of Kilkeel Steps; 1a (JWM303/ME673) within Trough 6; 1b (JWM304/ME674) to the south.

m	Facies	Notes	Interpretation	Member
<1	Gh	Gravel, clast-supported, sharp, gently undulating erosional base. Inaccessible.	Glaciofluvial fan interdigitating with beach	Kilkeel
<2	St, Gt	Loose, interbedded sand and gravel, pinching out southwards. Erosional base.		
<0.2	Dmm	Lens of diamict deforming underlying sand. Probable nose of a cohesive debris flow.	Subaqueous glaciofluvial	Cranfield
<2.5	St (Fm)	Silty coarse-grained sand, coarsening up overall, some troughs lined with silt, some graded beds and flame structures. Draped on sharp, erosional basal contact cutting out underlying units southwards onto till, lined by a laterally discontinuous pebble lag. This unit thins southwards to 1m, becoming more gravelly and resting on a discontinuous boulder pavement (BL). Most cross-bedding dips southwards.		
(<2.5)	Fl, Fl-d, (Dms, Sh)	Locally composed of compact silty fine sand with discontinuous laminae of medium to coarse sand and sparse lonestone pebbles. Some flat-topped cuspate lenses of silty diamict, becoming increasingly folded and sheared upwards (B2 glacitectonite) capped by 0.3 m unit of pseudohorizontally laminated silty sand (A2 glacitectonite).	Subglacially deformed glaciomarine deposit	Derryoge
<5		Firm to stiff, thickly laminated, dark yellowish brown to olive grey, calcareous silt with sparse lonestones, becoming very stiff and massive in uppermost 1.5 m, with hackly fracture.	Glaciomarine cyclopels	Derryoge
<12	Dmm (Dcm)	Very stiff diamict with moderate yellowish brown, sandy silty clayey matrix, clast-supported at base becoming less stony and	Subglacial traction till including sub-	Ballymartin

		siltier upwards. SA-SR clasts <25 cm mostly wacke mudstone with granite and sparse flint. This unit thickens southwards to about 12 m, being mostly massive with gently undulating concavo-convex discontinuities locally bounding small gravel-filled lenses (subglacial cavity-fills). One large boulder is associated with a sand and gravel-filled, downward tapering structure (hydrofracture).	glaciofluvial cavity fills.	
<1	Fmd, Fl (Dmm)	Extremely stiff, fissile, intensely-sheared, pale yellowish brown, sandy mud diamict with well dispersed SA-R clasts of wacke and granite. Traces of original coarse lamination. Laterally discontinuous seams (<30 mm) of moderate brown stony clayey diamict. Undulating, gradational contact with unit above.	Penetrative glacitectonite	Annalong

Locality 2. Log of cliffs at Kilkeel Steps within Trough 5 (JWM305/ME675).

m	Facies	Notes	Interpretation	Member
<0.3	Gh	Poorly exposed, locally disturbed periglacially.	Glaciofluvial fan interdigitating with beach	Kilkeel
<2.5	Gm, Gt (Go)	Gravel, clast-supported, loose, very poorly sorted, with mainly SA-SR clasts of wacke with pink granite and sparse flint and white quartzite. Sharp, erosional, channelized base. Rip-up megaclast of laminated sand observed towards base (0.9 x 0.2 m).		
<3	Sl, Sh, Sr(S), Fl-w, Fm	Silty fine sand with 10-15 cm-thick seams of silt and sparse lonestone cobbles, coarsening upwards. Wavy to convolute lamination developed locally. Sharp, draped, undulating basal contact. Individual beds thicken towards centre of swale, on-lapping onto the swale margins.	Subaqueous glaciofluvial	Cranfield
<6	Fl, F-cpl, Fl-w	Thickly laminated, dark yellowish brown to olive grey, firm to stiff, calcareous silt. Individual beds typically 10-15 mm thick, generally fining upwards, but with variable subordinate fine lamination. Spectacular shallow-plunging, isoclinal folds are exposed within this unit at beach level, associated with an incipient penetrative fabric. Fissures dip 4/258, 3/345, 12/160, 0/186, 7/212	Glaciomarine cyclopels, glacially compacted.	Derryoge

Locality 3. Log of southern margin of Trough 5, south of Manse Road steps; 3a (JWM96; 3b (JWM306/ME676).

m	Facies	Notes	Interpretation	Member
0.8	Gm, Gms	Gravel, locally matrix-rich, probably cryoturbated. Inaccessible.	Head	Kilkeel
<2.5	Gm, Gt (St)(Gh)	Gravel, very poorly sorted, in stacked shallow channels, the lowermost cut sharply into the underlying sand unit, locally with near vertical sides. Generally coarsening upwards. Local horizontal bedding in uppermost 1 m. Local northward dipping sigmoidal cross bedding towards base. Inaccessible.	Glaciofluvial fan interdigitating with beach	
2.5	Sh	Silty sand, mainly fine grained with laminae of medium to coarse, and sparse granules. General horizontal to gently undulating lamination. Locally siltier, more massive and with pebble lag set into the top. Some stacked shallow channels, including one filled with massive silt towards top. Draped on sharp, gently undulating basal contact. Unit pinches out southwards.	Subaqueous glaciofluvial	Cranfield
<1.5	Fl, Fm-d	Stiff, pale olive grey, laminated silt, locally folded and contorted, with diffuse laminae (possibly tectonic laminae) of medium to coarse sand and sparse lonestones towards top. Blocky fracture with ochreous staining. Top inaccessible. Draped on sharp, subhorizontal planar top of underlying unit.	Subglacially deformed glaciomarine cyclopels	Derryoge
<2	Dms, Gms (Gt)	Very compact, interstratified pale olive grey fine to coarse-grained silty sand, matrix-rich gravel and silty gravelly diamict, locally including flat-topped lenses (1 x 0.25 m) of poorly sorted gravel (subglacial channel infills). Sharp, gently undulating basal contact.	Subglacial traction till including sub-glaciofluvial cavity fills.	Ballymartin
<10	Dmm (Dms)	Very stiff, stony diamict with pale yellowish brown, sandy silty clayey matrix, including diffuse lenses (<1.5 x 0.3 m) of laminated silty fine to coarse-grained sand. Clasts mainly wacke mudstone and granite, some facetted and striated, mostly dispersed, but including some clusters.	Subglacial traction till including sheared sub-glaciofluvial cavity fills.	

Locality 4. Shell site midway between Kitty's Road and Spa Well.

m	Facies	Notes	Interpretation	Member
>2.5	Gt, St	Statified gravel and sand. Inaccessible.	Subaqueous glaciofluvial	Cranfield
0.2	BL	Stone pavement.	Ice-bed separation	Ballymartin
4.6	Dmm	Pale yellowish brown, very silty diamict, firm to very firm, with weak horizontal fissility in uppermost 1.2 m.	Subglacial traction till	
2		Poorly exposed transition from sheared gravel up into diamict.	Glacitectonite	
1.9	Gm	Dense, clast-supported gravel, fine to coarse with sparse cobbles, with silty coarse sand matrix, occupying channel structure. Relatively large proportion of tabular to bladed pebbles, which reveal local folding associated with southward displacement of underlying sand lens.	Subglacially tectonized gravel	Annalong
<0.9	St	Lens (< 30 cm thick) of fine to coarse-grained shelly sand and granule gravel, capped by a drape of clay that is locally folded over towards the south together with cross lamination within the unit. Erosional, channelled base.	Subglacially deformed sub-glaciofluvial channel fill?	
<0.25	Gm, Gms	Dense gravel, mainly clast-supported and locally openwork, becoming matrix-supported upwards. Fine to cobble grade, generally massive, but with local weak subhorizontal stratification. Local imbrication with elongate clasts dipping southwards.	Beach deposit?	
0.8	Gms	Dense gravel occupying channel structure, fine to coarse with sparse cobbles, matrix-supported, well packed. Numerous shell fragments.		
>0.6	Gm, Gms	Dense gravel, clast-supported, fine to cobble grade, well packed, normally graded with numerous shell fragments including little-abraded gastropods sitting within sub-horizontal laminae and large, broken bivalve shells. Locally shape-sorted with relatively large proportion of tabular and bladed pebbles displaying imbrication with elongate clasts dipping southwards.		

Locality 5. Log of cliffs north of Derryoge Bay within Trough 3 (JWM311/ME681)

m	Facies	Description	Interpretation	Member
c. 1.5	Gh	Gravel, horizontally bedded. Inaccessible.	Raised beach	Dunnaval
c. 2.5	Gt	Gravel and sandy gravel, tangentially bedded. Inaccessible.	Subaqueous glaciofluvial	Cranfield
0.1	BL	Gently concave unconformity lined with a discontinuous pavement of bevelled, striated pebbles and small cobbles firmly planted into the top of the underlying unit and aligned SE or E.	Ice-bed separation	Derryoge
> 2.5	Fmd, Fl-cpl	Very stiff, fissile, pale olive grey silt with folds, convolute lamination and ball-and-pillow structures. Detached balls of silty fine-grained sand. Becoming progressively more fissile and blocky-fractured upwards. Uppermost 40 cm is extensively sheared and includes a lens (1 x 0.3 m) of cross-bedded sand, possibly a glacial raft.	Subglacially deformed glaciomarine cyclopels	

Locality 6. Combined log of cliffs on northern margin Trough 2 (Derryoge Road); 6a (JWM309/ME679); 6b (JWM93); 6c (JWM308/ME678).

m	Facies	Notes	Interpretation	Member
<1.5	Gh, Sh, St	Sand and gravel exhibiting periglacial festooning and an ice wedge pseudomorph. Inaccessible.	Raised beach	Dunnaval
<1.5	St	Sand. Inaccessible.	Subaqueous glaciofluvial	Cranfield
<5	Fl	Stiff, fissile, thickly laminated, pale olive grey silt. Locally folded, contorted and heavily fissured. Draped upon underlying boulder pavement.	Subglacially deformed glaciomarine cyclopels	Derryoge
0.3	BL	Stone pavement on southward sloping unconformity. Some boulders are firmly planted into underlying diamict, others are wrapped within extremely poorly sorted gravel. Crushed clasts occur beneath some boulders.	Ice-bed separation	
<2	Dmm	Very stiff, sandy silty stony diamict, including lenses (shallow channel features) of very poorly sorted gravel. Sub-horizontal fissility becomes more pronounced upwards.	Subglacial traction till with sub-glaciofluvial cavity fills	Ballymartin

Locality 7. Log of cliffs at Derryoge Road within Trough 3 (JWM307/ME677)

m	Facies	Notes	Interpretation	Member
<1.5	Gh, Sh	Gravel overlying silty sand and gravel, locally exhibiting periglacial festooning. Inaccessible.	Raised beach	Dunnaval
<4.5	St, Gt	Sand, mainly fine grained with laminae of medium to coarse, and sparse granules. Locally gravelly at top. Mainly sigmoidal trough bedding. Base sharp and gently undulating.	Subaqueous glaciofluvial	Cranfield
>7	Fl, Fl-cpl	Very stiff, heavily jointed, pale olive grey silt with sparse lonestones. Joints intercept to form rhomboid slabs, 10-40 mm thick, that are locally defracted around tight (sheath?) folds plunging gently into cliff-face, displaying incipient axial-plane cleavage. General hackly fracture. Open folding at base.	Subglacially deformed glaciomarine cyclopels	Derryoge

Locality 8. Log of cliffs backing Derryoge Bay on southern margin of Trough 2 (JWM310/ME680)

m	Facies	Notes	Interpretation	Member
<2.5	Gh, Gt	Gravel, mostly horizontally to shallow tangentially bedded, coarsening upwards, locally with erect pebbles at top and festooned. Sharp, channelized erosional contact with sands below.	Raised beach	Dunnaval
2	Sh, St	Mainly coarse-grained sand with silty seams, occupying a stack of shallow channels, coarsening upwards overall, with soft-sediment deformation structures and isolated pellets of clayey silt. Shallow tangential bedding parallel to floor of channels and basal contact of unit. Bedding draped over and around boulders of pavement below. Local pockets of gravel at base between boulders.	Subaqueous glaciofluvial	Cranfield
1	BL	Stone pavement with bevelled, striated boulders (<1.2 m) firmly planted into underlying diamict or the silt-filled channel locally below. Elongate boulders commonly dip gently NW into cliff face with striae orientated between E and SSW.	Ice-bed separation	Derryoge
1	Fm, Fl	Very stiff, fissile, olive grey silt, occupying 5 x 1 m channel with sharp base lined by boulders dipping northwards. Locally overlain either by <	Subglacially deformed	

		0.3 m diamict, like that below, or capped directly by the boulder pavement. Local sheath fold dips into cliff-face beneath pavement.	subglacial channel fill mud	
<2.5	Dmm (Gm)	Extremely compact, dark yellowish brown, silty clayey sandy diamict with A-SR clasts (<1 m). Well developed, sub-horizontal fissility and much comminuted granite in matrix. Locally includes a sharply-defined channel structure filled with unconsolidated sandy gravel with scattered cobbles. Lower contact of diamict is sharp and even.	Subglacial traction till with sheared sub-glaciofluvial channel-fills	
<1.5	Fmd (Gm, Dmm)	Stiff, pale to dark yellowish brown, fissile clayey silt with very well dispersed, ice-scratched lonestones. Upper contact associated with thin lenses of gravelly sand intercalated with fissile silt. Lower contact sharp, draped on gravel below. Thickening northwards towards axis of swale.	Subglacially deformed subglacial channel fill mud	
<1	Gm	Compact, extremely poorly sorted sand and gravel, chaotically-bedded, with A-SR clasts <0.8 m diameter, lying on sharp, irregular, locally undercut surface of trough, dipping steeply to the north.	High-energy sub-glaciofluvial or cohesionless debris flow	
<1.5	Dmm, Dms	Very stiff, sandy clayey silty diamict with well dispersed SA-SR clasts (< 0.8 m). Grading upwards and southwards into more clast-rich diamict with stratification and planar discontinuities dipping tangentially northwards parallel to margin of the overlying trough.	Subglacial traction till	Ballymartin
<2.5	Fmd	Stiff, fissile, pale to dark yellowish brown clayey silt with sparse lonestones and cuspate lenses (<4 x 0.3 m) of compact, silty, poorly sorted, matrix-rich sand and gravel. Includes a 35 cm diameter boulder of hornfelsed wacke with a tapering wedge of unconsolidated gravelly sand to the south (in pressure shadow). Some very disturbed (sliced-up) primary thick lamination and poorly developed, tectonic lamination sloping to the north parallel to the base of the overlying diamict. Gravelly diamict at base grading down into underlying silts.	Subglacially deformed subglacial channel-fill mud and glacitectonite	
>0.5	Fl	Stiff, pale yellowish brown, coarsely laminated silt, as exposed on foreshore.	Glaciomarine cyclopels	Annalong

Locality 9. Combined log of foreshore (9a: JWM 87/ME 587; 9b: JWM90) and cliffs (9c: JWM88/ME586; 9d: Loc 002) backing centre of Derryoge Harbour (Trough 2).

m	Facies	Notes	Interpretation	Member
<4.5	Gt, St	Sand and gravel resting on planar, sub-horizontal unconformity.	Beach and subaqueous glaciofluvial	Dunnaval and Cranfield
1	BL	Stone pavement with boulders (<1.5 m) firmly planted into underlying diamict.	Ice-bed separation	Derryoge
4.2	Fmd, Fl, Dmm	Poorly-exposed, laterally and vertically variable package of stiff to extremely stiff, mainly olive grey (5 Y 4/1) diamictic clayey silt grading upwards and southwards into more clast-rich diamict. Heavily fissured with vivid orange staining. General hackly fracture. Package includes poorly-defined masses of very stiff to hard, massive silty clay-clayey silt that are probably glacial rafts. Sharp, uneven base.	Subglacially deformed subglacial channel-fill mud, rafts and glacitectonite	
0.7	Fl-d	Stiff, olive grey, laminated silt with sparse lonestones. Draped base.	Subglacially deformed channel-fill mud	
1.0	Dmm	Gritty matrix-to clast supported diamict with some large boulders.	Subglacial traction till	Ballymartin
<0.5	Dmm	Gritty matrix-to clast supported diamict with open, decimetre-scale folding of included sandy lenses. Plunges 20/285°. Uneven top gradational over 5 cm.	Glacitectonite	
<0.5	Fl	Stiff, olive grey, laminated silt with compressional micro-folding and disturbance of laminae on cm scale. Unit pinches and swells between 25 and 50 cm in thickness and has sharp undulating base and sheared top.	Subglacially deformed subglacial channel-fill mud	
0.8	Dmm (Dcm)	Diamict with a stiff matrix of coarse quartzo-feldspathic sand. Clasts up to boulder size of granite and hornfelsed wacke sandstone, with sparse WR pebbles derived from Devonian conglomerate, red sandstone, flint, chalk and shell fragments.	Subglacial traction till	
0.2	Dmm	Extremely stiff, fissile admixture of diamict and silt with uneven, sharp to gradational contacts (over 0.1 m). Stones (<0.5 m) are pressed into the underlying silts.	Glacitectonite	
>4.5	Fl	Pale olive grey (5Y 5/2), coarsely laminated silt and very fine-grained sand, exposed on extensive wave-cut platform. Firm to stiff, becoming very stiff upwards. Laminae typically 1-3 mm thick, normally graded with local intra-bed soft sediment deformation structures. Crinkly bedding/cleavage intersection lineations are commonly developed towards top, orientated NNW-SSE. The package includes	Glaciomarine cyclopels and rain-out	Annalong

		sparse laminae (<10 mm) of fine to medium-grained sand, irregular bodies of matrix-rich, quartzo-feldspathic granule gravel composed of SR-R clasts (<8 mm), and lensoidal beds (<30 mm) of A-SR gravel composed of mostly of pink granite with hornfelsed wacke siltstone and very sparse flint, locally cemented with iron pan. Irregular bodies (1 to 1.5 m across and 0.5 m thick) of gravelly diamict with clasts <0.4 m are common towards base.		

Locality 10. Composite log of cliff sections at headland immediately south of Derryoge Harbour (Trough 1). (Upper 6 m is 10a: JWM302/ME672 and 10b: Loc 001, some 20 m to the north of JWM301). Basal 6 m based on 10c: JWM301/ME671 and 10d: JWM 89/ME 588 8 m to south).

m	Facies	Notes	Interpretation	Member
c.2	Sh, Gh, Gt	Inaccessible. Cross-bedding locally northward-dipping.	Subaqueous glaciofluvial	Cranfield
0.3	BL	Stone pavement with boulders firmly planted into underlying diamict.	Ice-bed separation	
1.2	Fl	7 m-wide channel filled with stiff, coarsely laminated silt with laminae of fine to medium-grained sand. Heavily fissured. Laminae typically 10 mm thick, many graded. Sharp, draped basal contact.	Cyclopels within subglacial channel	Derryoge
6	Dmm (Dms)	Dark yellowish brown, calcareous diamict, generally matrix-supported, locally stratified, with folded inclusions of clayey silt and gravelly diamict, laterally and vertically variable clast content, including granite boulders <1.5m in diameter. Some channel-like structures and truncation surfaces(1 m across, 0.5 m deep) lined by cobbles pressed into underlying diamict and filled with extremely compact, jointed laminated silt with some microfolding and micro-thrusts showing southward displacement*. One clast clearly rotated southwards with a sediment prow to the north. Closely-spaced, gently undulating fissility and hackly fracture becoming more prominent upwards where unit comprises extremely compact pebbly silt**. Uneven, 10 cm-thick gradational basal contact.	Subglacial traction till, glacitectonite and sheared sub-glaciofluvial channel-fills	Ballymartin
1.2	Fl-d (Fcpl, Dm)	Stiff, fissile, clayey silt, thinly to coarsely laminated within discrete, cyclic, 3-6 cm thick beds. Sparse dropstones, laterally discontinuous laminae of sand and thin	Glaciomarine cyclopels	Annalong

		lenses of granule gravel. Ochreous staining on subvertical fissures, hackly fracture. Draped basal contact.		
>1.2	Gm (Gms,Fl,)	Densely-packed, very poorly sorted, SA-SR clasts < 80 cm, wacke and granite, some imbrication and silt draped reactivation surfaces.	Ice-proximal glaciomarine?	

*measurements on planar joints; 030/39NW, 044/35NW, 026/46NW, 145/52E, 141/46E, 143/45E. **Measurements on prominent fissures; 142/50 SW, 232/18 NW

Locality 11. Representative log of cliffs at Crawfords Point (JWM300/ME670).

m	Facies	Notes	Interpretation	Member
3	Gh (Go,Gmi)	Locally well size and shape sorted gravel. Sharp planar base.	Raised beach	Dunnaval
2	Sh/Gh (St)	Sand and gravel draped on stone pavement with lag of very poorly sorted gravel.	Subaqueous glaciofluvial	Cranfield
0.3	BL	Stoner pavement with boulders firmly planted into underlying diamict.	Ice-bed separation	Ballymartin
>7	Dmm (Dcm, Dml-p, Dml-s	Extremely compact, pale yellowish brown diamict with muddy sandy matrix, A-SR clasts including stone lines and clusters, becoming less stony and fissile towards base*. Boulders mostly granite, but smaller clasts dominated by hornfelsed wacke sandstone with some slaty wacke mudstone and vein-quartz, and sparse microgranite, basalt, mica schist and black chert. Many bevelled boulders dipping gently into the cliff-face with striae orientated NW-SE.	Subglacial traction till	

* measurements on prominent fissures; 180/40 E, 072/39 N, 144/68 W