Proceedings of the Geologists' Association 135 (2024) 260–281

Contents lists available at ScienceDirect

Proceedings of the Geologists' Association

journal homepage: www.elsevier.com/locate/pgeola

A thin-skinned thrust model for ice-marginal glacitectonic detachment and emplacement of Carboniferous bedrock rafts at Kilcummin Head, NW Ireland

David P. Vaughan [a], Emrys Phillips [b,*], Jonathan R. Lee [c], Jane K. Hart [d]

[a] Cathie, 2-4 Hanover Square, Newcastle upon Tyne NE1 3NP, UK
[b] British Geological Survey, Murchison House, Edinburgh EH9 3LA, UK
[c] British Geological Survey, Keyworth, Nottingham NG12 5GG, UK
[d] School of Geography and Environmental Sciences, University of Southampton, Southampton SO17 1BJ, UK

ARTICLE INFO

Article history:
Received 16 December 2023
Received in revised form 4 April 2024
Accepted 5 April 2024
Available online 2 May 2024

Keywords:
Glacitectonic deformation
Thin-skinned tectonism
Micromorphology

ABSTRACT

This paper presents the results of a detailed macro- and microscale structural study of the glacitectonised sequence at Kilcummin Head on the western side of Killala Bay, County Mayo, northwest Ireland. The sequence comprises two laterally extensive, thrust-stacked rafts of Carboniferous limestone and mudstone emplaced upon the *in situ* bedrock of the Ballina Limestone Formation. Restored cross-sections reveal that the glacitectonised sequence has undergone extensive deformation and shortening of 61 %. This accompanied the formation of a prominent thrust-moraine associated with a northward ice advance across Killala Bay during the Midlandian (Devensian). A five-stage model is proposed to describe the deformation. Stage 1 comprises detachment of the rafts, and the majority of the sequence shortening. North-directed transport of the rafts occurred on a major décollement surface located at the base of the rafted sequence, marked by a mudstone-rich glacitectonite. Stage 2 accommodated further shortening *via* a series of imbricate thrusts leading to the stacking of the bedrock rafts (Stages 3 and 4). Stage 5 saw final stacking of rafts within a prominent thrust-block moraine, followed by the deposition of a sequence of coarse-grained, ice-marginal glacigenic deposits.

1. Introduction

Deformation structures found within subglacially (*e.g.*, Berthelsen, 1979; Hart and Boulton, 1991a, 1991b; Boulton et al., 1996; Hart and Rose, 2001; Evans et al., 2006; Phillips et al., 2007, 2008; Lee and Phillips, 2008) and ice-marginal to proglacially (*e.g.*, Berthelsen, 1979; Hart, 1990; Phillips et al., 2002; Phillips et al., 2008; Benediktsson et al., 2008; Gehrmann et al., 2017) deformed sedimentary sequences typically include evidence of folding and thrusting. The architecture of these often complex glacitectonised sequences is comparable to foreland fold-and-thrust belts formed as a result of crustal shortening and mountain building in response to plate tectonic convergence. This has invariably led to the application of a thin-skinned thrust tectonic model to deformed glacial sequences (*e.g.*, Pedersen, 1987, 2005, 2014; Aber et al., 1989; Harris et al., 1997; Andersen et al., 2005; Phillips et al., 2008, 2017a; Lee et al., 2013) which has provided valuable insights into the evolution of these glacitectonic complexes, and therefore our understanding of the ice sheet dynamics responsible for their development (*e.g.*, van Gijssel, 1987; van der Wateren et al., 2000; Phillips et al., 2002, 2008; Lee et al., 2013). Understanding how glacitectonic fold and thrust belts develop and their relationships to ice sheet dynamics has become increasingly important over the past decade as large scale glacitectonic complexes are being increasingly recognised offshore (*e.g.*, Vaughan and Phillips, 2016; Phillips et al., 2017b, 2022; Mellett et al., 2019). These complexes can have a profound impact upon the structural architecture and properties of the shallow subsurface and can in turn influence ground conditions for both onshore infrastructure and offshore infrastructure (*e.g.*, Dudgeon windfarm — Mellett et al., 2019; Dogger Bank windfarm — Phillips et al., 2017b, 2022).

Locally included within these glacitectonic complexes are detached blocks or ‘rafts’ of bedrock and/or unconsolidated sedimentary strata which have been transported from their original position by glacial action (Stalker and Mac, 1976; Christiansen and Whitaker, 1976; Aber, 1985, 1988; Ruszczynska-Szenajch, 1987; Broster and Seaman, 1991; Aber and Ber, 2007; Burke et al., 2009; Vaughan-Hirsch et al., 2011; Sigfusdottir et al., 2018, 2019; Evans et al., 2021). Examples in the geological record include: the Interior Plains of North Dakota where rafts of shale and sandstone are thrust into younger sediments (Bluemle and Clayton, 1984); rafts of penecontemporaneous glaciofluvial deposits

* Corresponding author.
E-mail addresses: David.vaughan@cathiegroup.com (D.P. Vaughan), erp@bgs.ac.uk (E. Phillips).

https://doi.org/10.1016/j.pgeola.2024.04.001
0016-7878/

thrust into a predominantly clay-rich diamicton in central Poland (Ruszczynska-Szenajch, 1988); siltstone rafts within till in southwest Ireland (Hiemstra et al., 2007); thrust-staked blocks of chalk within a highly glacitectonised sequence in East Anglia (Reade, 1882; Slater, 1926, 1927; Peake and Hancock, 1961; Banham, 1975, 1977, 1988; Phillips et al., 2008; Burke et al., 2009; Vaughan-Hirsch et al., 2013) and Denmark (Jakobsen, 1996; Pedersen, 2005); and unconsolidated marine sediments within a glacitectonised sequence in Banffshire and Ayrshire, Scotland (Peacock and Merritt, 1997; Phillips and Merritt, 2008; Merritt et al., 2014). These glacitectonic rafts, also referred to as 'floes' or 'megablocks', are typically very thin (up to a few tens of metres) in comparison to their aerial extent (up to several 100 km^2). They may also have been transported for several hundred kilometres or just a few tens of metres (Bluemle and Clayton, 1984; Aber and Ber, 2007; Evans et al., 2021). Rafts can occur as single, horizontal slab-like features, or form several stacked fault-bound bodies located within ice-pushed landforms (moraines) of various types (Banham, 1975; Aber, 1988, 1989; Krüger, 1996; Aber and Ber, 2007; Benn and Evans, 2010; Evans et al., 2021). Internally they can be relatively undeformed preserving the original lithological character of the bedrock or unconsolidated sediment. In other examples, however, the rafted material may show evidence of folding and faulting, or ductile shearing (*e.g.*, Burke et al., 2009; Vaughan-Hirsch et al., 2011; Evans et al., 2021).

Early models argued that glacitectonic rafts were detached and transported frozen to the base of cold-based ice sheets and glaciers with deposition (or accretion) occurring as a result of melt-out from the decaying stagnant ice mass (Banham, 1975; Aber, 1988). Other studies, however, suggest that failure of the bedrock and/or sediment, leading to initial detachment of the raft is associated with elevated pore-water pressures within the substrate with subsequent transport occurring along water-rich décollement surfaces within a subglacial shear zone (Moran et al., 1980; Aber, 1985; Hart, 1990; Broster and Seaman, 1991; Phillips and Merritt, 2008; Benn and Evans, 2010; Evans et al., 2021), at the base of this deforming layer (Kjær et al., 2006), or as a consequence of subglacial hydrofracturing by forceful upward dewatering (Boulton and Caban, 1995; Rijsdijk et al., 1999). Alternative rafting models, however, consider that rafts are generated as a result of thrusting associated with proglacial to ice marginal deformation, leading to the development of an imbricate thrust stack (thrust moraine) in front of the advancing glacier or ice sheet (Banham, 1975; Christiansen and Whitaker, 1976; Moran et al., 1980; Bluemle and Clayton, 1984; Ruszczynska-Szenajch, 1987; Burke et al., 2009; Evans et al., 2021). It is not clear from any of these published models whether the detachment of rafts occurs at an active ice margin, with subsequent transport occurring as the detached block is overridden and entrained subglacially, or whether all the stages of the rafting process can occur entirely within a single glacial setting. Furthermore, processes occurring during detachment, transport and emplacement of the rafts remain poorly understood.

This paper contributes to our understanding of the evolution of large-scale glacitectonic fold and thrust belts, and presents the results of a detailed macro- and microscale structural study of the glacitectonic features associated with laterally extensive, thrust-stacked rafts of Carboniferous limestone and shale exposed on the eastern side of Kilcummin Head (National Grid Reference: [TG 181 432]), Killala Bay, County Mayo, northwest Ireland (Fig. 1). The occurrence of large-scale glacitectonic disruption at this locality has been previously recognised (McCabe, 2008; Philcox, 2013). However, this study is the first to propose a model of glacier-induced deformation at Kilcummin Head, and the associated glacigenic sediments (diamicton, glacitectonite). Micromorphology is used to examine the range of microstructures present within a shale-rich glacitectonite which marks the main detachments responsible for the transport and emplacement of the rafts. The results of the detailed microstructural study establish the transport direction along these thrusts and elucidate the processes occurring during glacitectonite formation and their relationship to raft emplacement. The macroscale structural study builds a detailed history of deformation recorded by the glacitectonised sequence at Kilcummin Head. Restored cross-sections constructed across the study area demonstrate that the bedrock has undergone extensive deformation and shortening which accompanied the formation of a prominent thrust-moraine associated with northward ice advance across Killala Bay during the Midlandian (Devensian). A five stage thin-skinned glacitectonic model is proposed to explain the evolution of this thrust stack. This glacitectonic framework is placed into the context of published regional ice sheet models for this part of the British and Irish Ice Sheet (Knight, 2006; Greenwood and Clark, 2008, 2009).

2. Regional Quaternary glacial history

The glaciation of County Mayo in the northwest of Ireland has left a well-developed geomorphological record comprising drumlin fields, striae and ribbed moraine (Charlesworth, 1924; Colhoun, 1973; Smith et al., 2008; Greenwood and Clark, 2009), as well as an accompanying

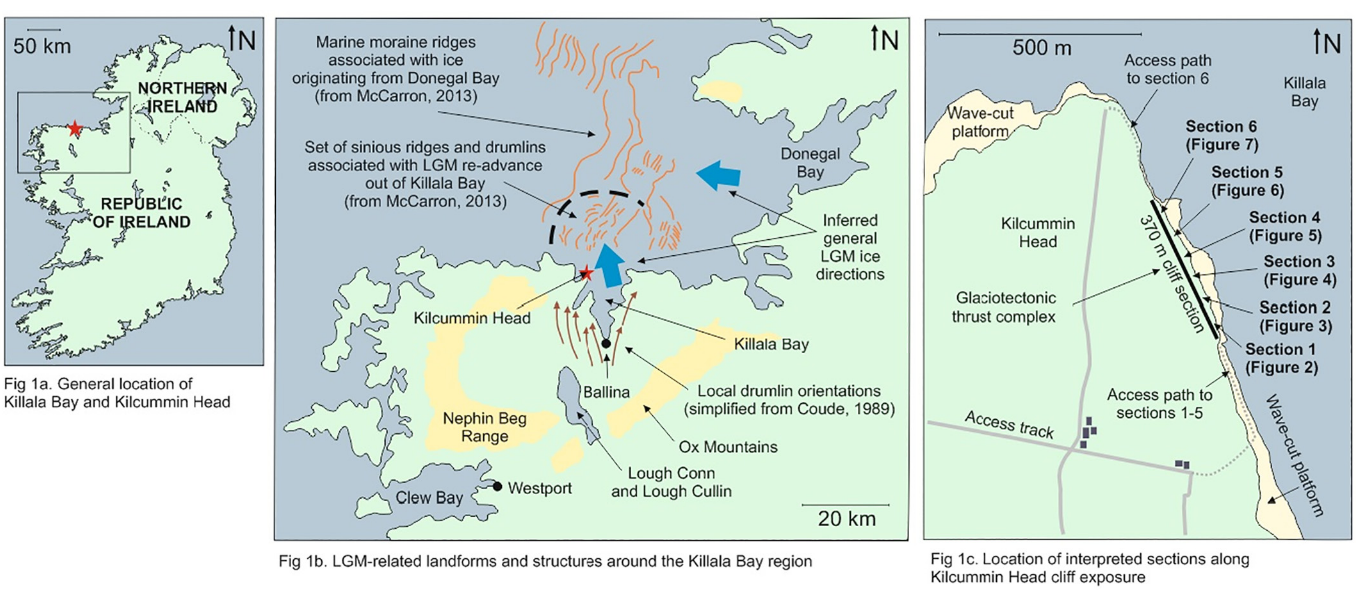


Fig. 1. Map showing (a) the location of Killala Bay and Kilcummin Head, (b) a summary of Midlandian ice-related landforms within previously published work, (c) and the specific locations of Sections 1–6 (Figs. 2–7).

sequence of tills and outwash sands and gravels (Symes and Baily, 1845; Symes, 1876, 1877; Charlesworth, 1924, 1928; Synge, 1963; McCabe, 1987; Coxon, 1991; McCabe et al., 2007). Based upon the orientation of the subglacial landforms and striae, the source of this ice is generally considered to have been the lowlands situated between the Ox Mountains of County Sligo, and the Nephin Beg range, in north County Mayo (Fig. 1) (Herries-Davies, 1978; Kenyon, 1986; Coude, 1989; Coxon and Browne, 1991a). Regionally, ice flowing from these highlands not only advanced northwards across the study area in Killala Bay, but also eastwards towards Clew Bay, and south through Lough Mask and Lough Corrib (Coxon and Browne, 1991b; Coxon and Hannon, 1991). A second ice lobe is thought to have existed inland of Donegal Bay (Colhoun, 1973; Knight et al., 2004; Ballantyne et al., 2007), with ice flowing westwards, to the north of the County Mayo/County Sligo coastline (Knight et al., 2004; Smith et al., 2006; Ballantyne et al., 2007). This second ice lobe resulted in localised glacitectonism with rafting of the bedrock and glacigenic sediment pile, and associated thrusting in the southern Sperrin Mountains of north central Ireland (Knight, 2002).

The glacial geomorphological record extends offshore of Donegal Bay and Killala Bay (Benetti et al., 2010; Ó Cofaigh et al., 2010a; McCarron, 2013), as well as Clew Bay (Glynn et al., 2008). At its maximum known extent, ice reached the outer continental shelf (Dunlop et al., 2010) leading to the formation of large-scale, nested arcuate moraines (Stoker and Holmes, 1991; Sejrup et al., 2005; O'Reilly et al., 2007; Ó Cofaigh et al., 2010b). These moraines are interpreted by Benetti et al. (2010) as representing the maximum known extent of the last British and Irish Ice Sheet during the Midlandian. At several coastal locations, in particular Clew Bay and Killala Bay, the subglacial landform record has been interpreted as recording fast ice flow, or ice streaming offshore (Greenwood and Clark, 2009; Knight, 2009). Off the north coastline of County Mayo and County Sligo, receding ice has left a sequence of transverse moraine ridges and drumlinised topography, interpreted to indicate a sequence of ice retreat and local re-advances (McCarron, 2013). These transverse moraine systems continue onshore as a series of ridges (Knight and McCabe, 1997; Clark and Meehan, 2001; Greenwood and Clark, 2008, 2009). These ridges commonly comprise thrusted, polydeformed glacigenic sediments, leading Knight and McCabe (1997) to propose that they were formed in response to several discrete phases of re-advance during the overall active retreat of the ice-margin.

3. Location of the study area and bedrock geology

The steep sea cliffs on the eastern side of Kilcummin Head [TG 181 432] on the western side of Killala Bay (Fig. 1) are approximately 1 km long and range from <5 m high, in the south, up to >20 m high at its northern-end (see Figs. 2 to 7). Killala Bay is a large (10 km long, 8 km wide), north–south oriented, north-facing bay within the northwest coast of County Mayo.

The bedrock geology in the study area is dominated by a Carboniferous (Mississippian) sedimentary succession (Symes, 1876, 1877; Stone, 1991; Long et al., 1992; Graham, 2010) which records an overall transgressive sequence from fluvial terrestrial and coastal plain deposits (Minnaun Formation), through a complex sequence of late Tournaisian to early Viséan non-marine and marine sedimentary rocks (Downpatrick and Moyny Limestone formations), which are in turn overlain by a mixed fluvial/marine sequence of the Mullaghmore Sandstone Formation (Graham, 2010). At Kilcummin Head, the Mullaghmore Sandstone Formation is directly overlain by the Ballina Limestone Formation which comprises a sequence of gently (1–10°) southerly dipping, interbedded marine limestones and mudstones. On both the east and west sides of Killala Bay, the Mullaghmore Sandstone and Ballina Limestone formations are intruded by a number of thin to relatively thick (several centimetres, to several metres in width), WNW–ESE-trending dolerite dykes (Cooper and Johnston, 2004a and b).

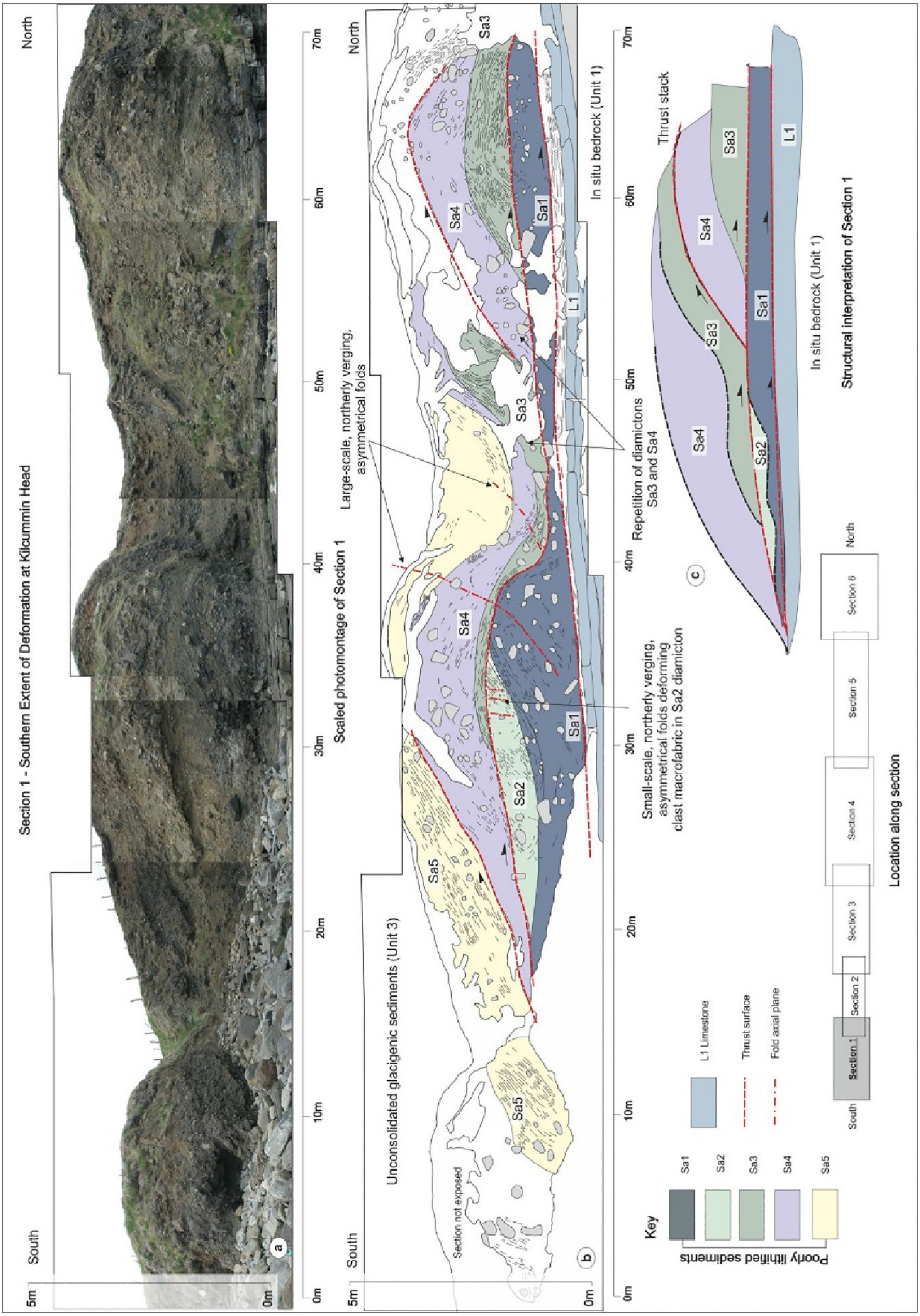
At Kilcummin Head the Ballina Limestone Formation has undergone extensive glacitectonic deformation which led to thrusting (Figs. 2 to 7), normal and reverse faulting (Figs. 4 and 5), as well as folding (Fig. 6) of the interbedded limestones and mudstones. In addition, the mudstones are locally brecciated forming a highly disrupted glacitectonite. This glacitectonised sequence overlies *in situ* bedrock (see Figs. 2 to 7) and occurs within a 370 m long, and 5 to 20 m high, N–S-trending topographic ridge which gradually increases in height from south to north (Fig. 8a). The eastern-side of this topographic high has subsequently undergone coastal erosion, exposing a cross-section through the long axis of this glacitectonic landform. Previous work at the site recognised the deformed bedrock sequence as a product of glacitectonism (McCabe, 2008), and describes the abundance and general architecture of large-scale structures (Philcox, 2013). This study builds upon this previous work by integrating a macro- and microscale structural analysis to develop a detailed model of glacier-induced deformation at Kilcummin Head.

4. Methods

The glacitectonised bedrock and associated glacigenic sediments exposed at Kilcummin Head were logged, photographed and described in detail with particular emphasis placed on recording the type of bedding, sediment type, bed geometry and structure (both sedimentary and glacitectonic). A sequence of overlapping photographs taken of the cliffs has allowed the analysis of the larger-scale structures. Due to changes in perspective between some of the photographs, the interpretive section is divided into six overlapping sections (Figs. 2 to 7). The orientation of bedding, joints, folds, foliations and faults present within the lower 1–2 m of the cliff face was recorded from a number of points along the length of the section. These data are displayed on a series of lower hemisphere stereographic projections (dip and dip-direction/azimuth) and rose diagrams (strike/trend) (Fig. 9). The sense of asymmetry of the folds and movement on the faults, and inter-relationships between the various generations of structures were established. Successive generations of structures (*e.g.*, folds F1, F2…Fn) are distinguished using the nomenclature normally used in structural geological studies (F1 earliest folds to Fn latest). However, this nomenclature does not necessarily imply that these structures were developed in response to separate deformation events (D1, D2…Dn). Clast macrofabric data (A axis dip and dip direction) obtained for the two diamictons exposed at this locality are shown graphically on a lower hemisphere stereographic projection (Fig. 10).

Two orientated samples (KH01, KH02) of the mudstone-rich glacitectonite were collected for detailed microstructural analysis using 10 × 7 cm oblong aluminium Kubiena tins. The tins were cut into the face in order to limit sample disturbance. The position of the sample relative to the base of the raft and its orientation relative to magnetic north and "way-up" were marked on the outside of the tin during collection. The samples were collected at different locations from below the raft to provide detailed information on the changes in the style and intensity of deformation within the glacitectonite. Sample preparation (total time *c.*, 4 months) was carried out at the Centre for Micromorphology at Royal Holloway University of London. Preparation of the samples involved the initial air drying followed by acetone replacement to remove all of the pore-water. The sample was then placed in a vacuum chamber and the acetone progressively replaced by a resin and allowed to cure (Carr and Lee, 1998). Large format orientated thin sections were taken from the centre of each of the prepared samples to avoid artefacts formed during sample collection. The thin sections

Fig. 2. Macroscale photomontage (a) and structural interpretation (b) of Section 1 (0 to 70 m) at the southern-end of Kilcummin Head. Figure (c) is a simplified structural cross section through this part of the glacitectonised sequence. The Sa1 to Sa5 are individual units of cobble to boulder sandy glacigenic sediment affected by large-scale thrusting and folding.


Section 1 - Southern Extent of Deformation at Kilcummin Head
South
North
a
5m
0m
0m
10m
20m
30m
40m
50m
60m
70m
Scaled photomontage of Section 1
b
Section not exposed
Unconsolidated glacigenic sediments (Unit 3)
Large-scale, northerly verging, asymmetrical folds
Sa5
Sa4
Sa3
Sa2
Sa1
L1
In situ bedrock (Unit 1)
Small-scale, northerly verging, asymmetrical folds deforming clast macrofabric in Sa2 diamicton
Repetition of diamictons Sa3 and Sa4
c
Thrust stack
Structural interpretation of Section 1
Key
Poorly lithified sediments
L1 Limestone
Thrust surface
Fold axial plane
Location along section
Section 1
Section 2
Section 3
Section 4
Section 5
Section 6

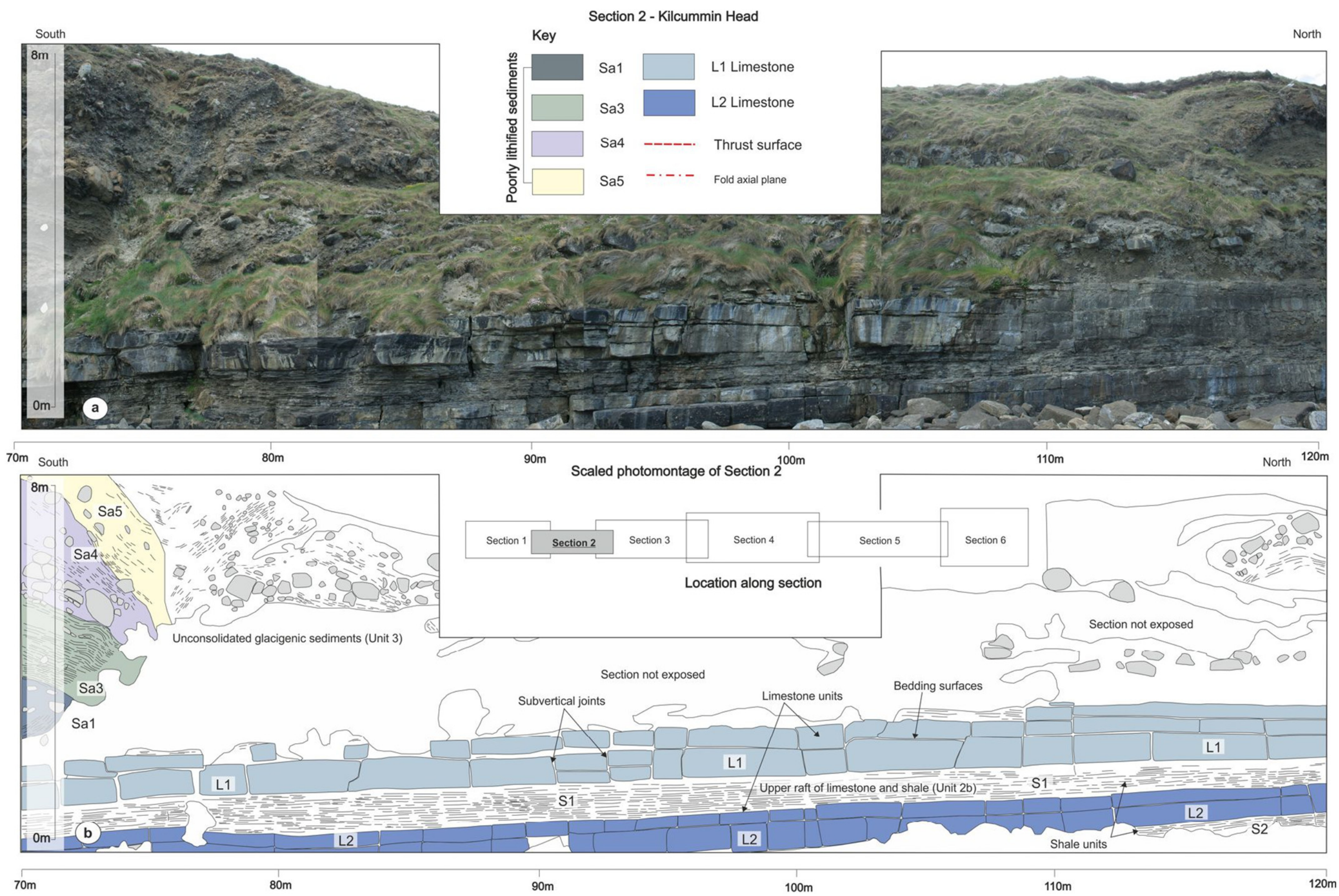


Fig. 3. Macroscale photomontage (a) and structural interpretation (b) of Section 2 (70 to 120 m) at Kilcummin Head. The Sa1 to Sa5 are individual units of cobble to boulder sandy glacigenic sediment affected by large-scale thrusting and folding. The lower part of the cliff section is dominated by a large (*c.*, 4 m thick), laterally extensive (*c.*, 300–400 m long) bedrock raft comprising two prominent limestone beds (L1 and L2) separated by mudstone (<1 m thick; S1 and S2).

were examined using a standard Zeiss petrological microscope and Zeiss projector, the latter allowing detailed study of the range of microstructures at very low magnification. The terminology used to describe the various micro-textures developed within these sediments in general follows that proposed by van der Meer (1987, 1993) and Menzies (2000). High-resolution scans of the thin sections were also analysed using a commercial graphics package (CorelDraw®) following the methodology of Phillips et al. (2011) and the resultant microstructural maps are shown in Figures 12 and 13.

5. Glacial tectonostratigraphy at the Kilcummin Head site

Kilcummin Head represents one of a number of sites around Killala Bay where the Carboniferous bedrock has been subjected to glacitectonic deformation resulting in the detachment, transport and subsequent accretion (stacking) of elongate, slab-like rafts comprising both limestone and mudstone. For ease of description the sequence has been divided into three principle tectonostratigraphical units (Figs. 2 to 7): Unit 1 (structurally lowest) — the underlying *in situ* limestone and mudstone of the Ballina Limestone Formation; Unit 2 — a structurally overlying 5–15 m thick unit of thrust-repeated, laterally extensive (up to 300–400 m in length) bedrock rafts separated by units of mudstone-rich glacitectonite; and Unit 3 (highest) — a locally exposed thin (<1 m thick) carapace of sandy, clast-rich diamicton.

The *in situ* bedrock (Unit 1) is mainly exposed at the central and northern parts of the section where it comprises four prominent, 1–2 m thick, limestone units (labelled L5 and L8 in Figs. 2 to 7) separated by 4–6 m thick units of mudstone (labelled S6 and S7 in Figs. 2 to 7). The mudstones are dark grey, thinly-bedded (centimetre-scale) to finely-laminated (millimetre-scale) rocks which possess a well-developed bedding-parallel fissility. These mudrocks locally contain tabular, elongate (3–6 cm in length) carbonate concretions which are aligned parallel to bedding. The dark to light grey limestones are massive to thickly-bedded (bed thickness 10–50 cm), fine-grained rocks which locally contain well-preserved fossils including corals. Bedding within Unit 1 is typically sub-horizontal to very gently south-easterly dipping (Figs. 7 and 9) and, in the lower part of the cliffs, shows very little evidence (if any) of tilting due to glacitectonic disturbance. Bedding surfaces within the limestones are locally marked by very thin (<1 cm thick) mudstone partings. Vertical, closed, widely spaced (1–2 m) joints within the limestones in this part of the section predate glacitectonism. At the northern-end of Kilcummin Head (Section 6 between 350 and 390 m; Fig. 7), however, the mudstones and limestones immediately below Unit 2 show increasing evidence of glacitectonic disturbance, including steeply inclined to subvertical, northerly directed, reverse faults within the mudstones (*e.g.*, S6 in Figs. 7 and 8b) and disruption/brecciation of the limestones (*e.g.*, L5 in Fig. 7). Fragmentation of the limestones occurred as a result of the opening of pre-existing joint and bedding surfaces, with the detached blocks becoming incorporated into the overlying glacitectonised sequence (see between 355 and 375 m, Section 6; Fig. 7).

The overlying highly glacitectonised sequence of Unit 2 (5–15 m thick) is principally composed of two thrust-repeated, laterally extensive (up to 300 m) rafts of limestone and mudstone separated by mudstone-rich glacitectonite marking the thrusts (Figs. 4 to 6). Both rafts show varying degrees of internal deformation (folding, fracturing, faulting and brecciation; see below) with both the limestones and

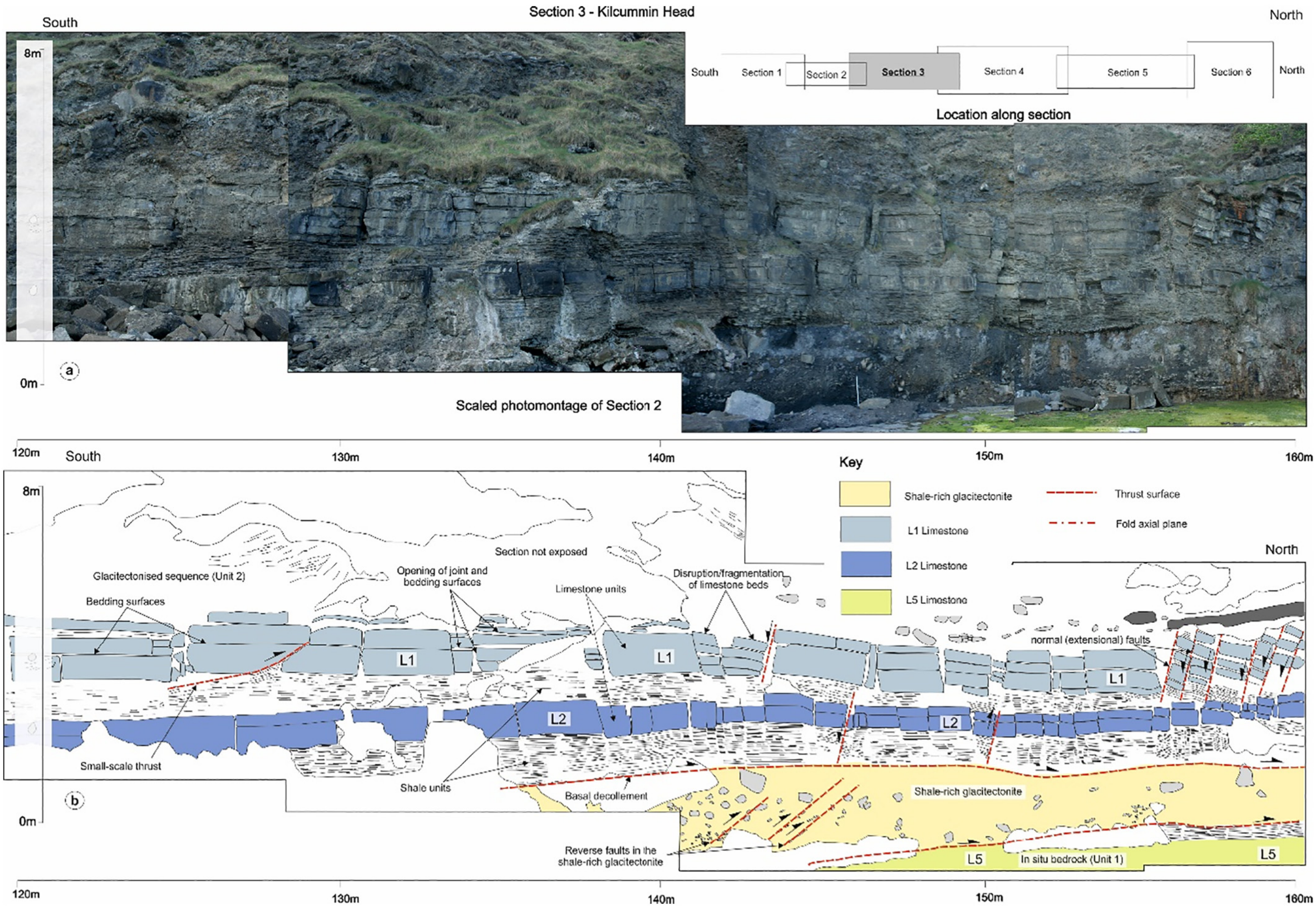


Fig. 4. Macroscale photomontage (a) and structural interpretation (b) of Section 3 (120 to 160 m) at Kilcummin Head. The central part of the section is dominated by a *c.*, 4 m thick, laterally extensive (*c.*, 300–400 m long) bedrock raft comprising two prominent limestone beds (L1 and L2) separated by mudstone (<1 m thick; S1 and S2). In this part of the section the raft is structurally underlain by a clay/mudstone-rich glacitectonite overlying a second structurally lower limestone unit (L5).

intervening mudstones becoming increasingly deformed and disrupted (fragmented) towards the north (see Figs. 3 to 7). The structurally lower raft (Unit 2a — comprising limestones L3 and L4) shows a greater degree of internal disruption with the limestone beds having been broken into a series of bedding- and joint-bound tabular blocks (see Fig. 6). This lower raft is cut out in Section 4 at approximately 220 m (Fig. 5), so that in the southern part of Kilcummin Head the structurally upper raft (Unit 2b — composed of limestones L1 and L2) rests directly upon the *in situ* bedrock (Figs. 5 to 7). Units 1 and 2 are separated by a sharp, gently southerly-dipping décollement surface (thrust) located at top of thick *in situ* limestone (L5). This bedding-parallel detachment is marked by a either a 20–30 cm thick zone of highly-brecciated mudstone and/or a 0–5 cm thick layer of wet (saturated) clay; the latter being interpreted as having been derived from highly comminuted mudrock. Towards the southern-end of Kilcummin Head (Sections 3 and 4; Figs. 4 and 5, respectively), this basal detachment is marked by a 1–3 m thick clay-rich glacitectonite.

Unit 3 at the top of the sequence at Kilcummin Head comprises a loose, unconsolidated, brown sandy diamicton containing rounded pebbles of locally-derived limestone. Towards the northern-end of the section, this diamicton is over 5 m thick and rests directly upon *in situ* bedrock.

6. Macroscale glacitectonic deformation structures

It is clear from Figures 2 to 7 that the relative intensity and complexity of deformation within the glacitectonised sequence of Unit 2 increase dramatically from south to north. For ease of description this locally highly-disrupted sequence has been divided into six overlapping sections; Section 1, to south, through to Section 6, at the northern-end of Kilcummin Head (see inset at bottom of Figs. 2 to 7).

6.1. Section 1: southern-end of Kilcummin Head between 0 m and 70 m

Section 1 is dominated by a *c.*, 4 m thick sequence of deformed coarse (cobble to boulder) glacigenic sediments (diamictons Sa1 to Sa5; Fig. 2) which structurally overlie the L1 limestone of the uppermost raft (Unit 2b) and form a *c.*, 5 m high, N–S-trending linear ridge (Fig. 8a). At this end of Kilcummin Head the very gently dipping (2–5° towards the south–southeast; Fig. 9a) L1 limestone shows very little evidence of glacitectonic disturbance. Steeply inclined to subvertical (85°S/270°), widely spaced joints within the limestone are closed (tight) dividing the individual beds into 2–10 m long tabular blocks.

The overlying sequence comprises a number of elongate to crudely lenticular units of poorly-sorted, massive to weakly-bedded sandy diamictons (Sa1 to Sa5 in Figs. 2 and 8c) separated by a series of south to south-easterly dipping (Fig. 9a) thrusts. However, due to the coarse- to very coarse-grained nature of these deposits the actual thrust planes are locally difficult to identify. These thrust-repeated glacigenic deposits only occur at the southern-end of Kilcummin Head and are truncated between Sections 1 and 2 at *c.*, 75 m (see Fig. 3). The structurally lowest unit is a dark to moderate grey, clast-rich, sandy diamicton

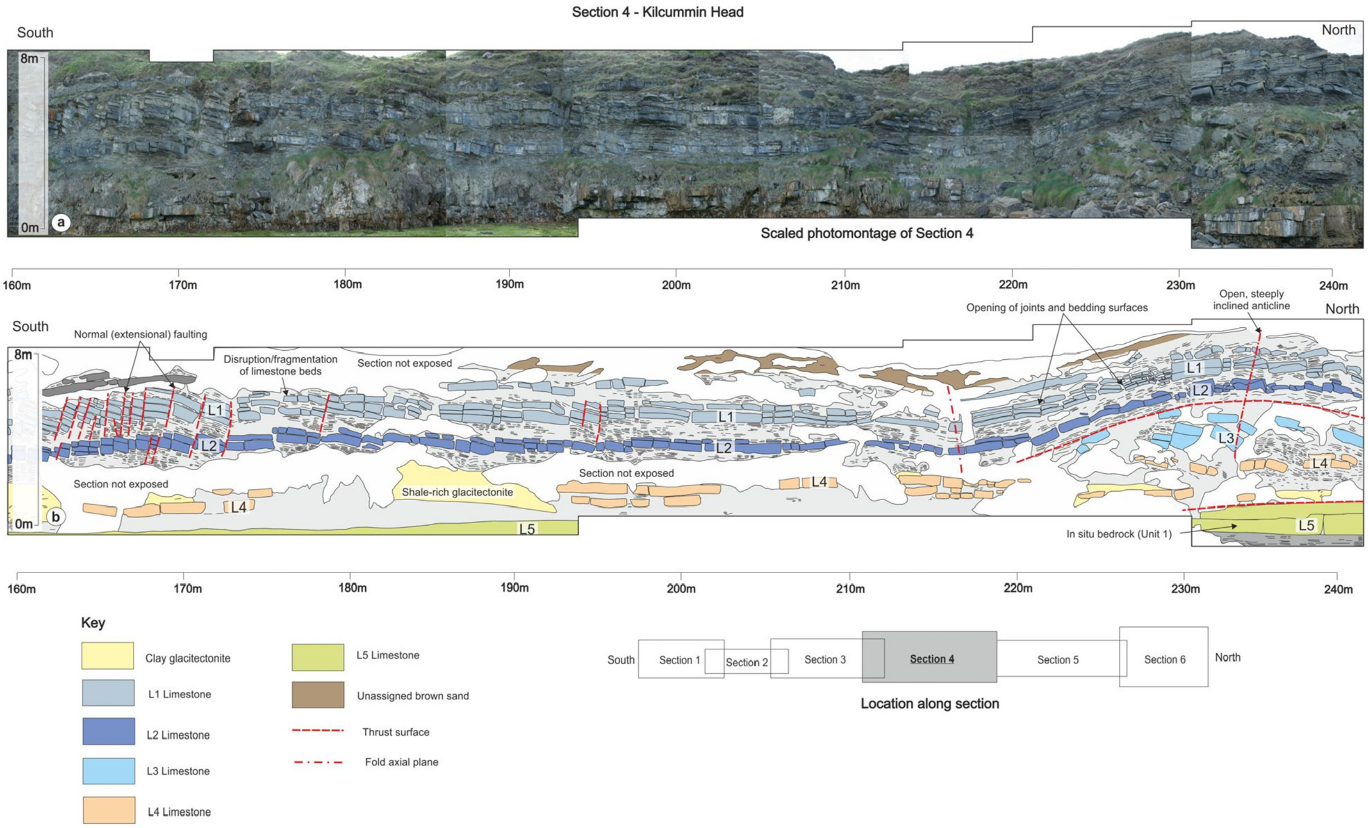


Fig. 5. Macroscale photomontage (a) and structural interpretation (b) of Section 4 (160 to 240 m) at Kilcummin Head. The middle to upper part of the cliff section is dominated by large (*c.*, 4 m thick), laterally extensive (*c.*, 300–400 m long) bedrock rafts comprising two prominent limestone beds (L1 and L2) separated by mudstones (<1 m thick; S1 and S2). This raft is structurally underlain by complex sequence of fragmented limestone beds within a matrix of highly disrupted mudstone. At the southern-end of the section (160 to 180 m) the limestone beds L1 and L2 are offset by a number of steeply inclined normal faults, downthrown towards the south.

(Sa1) (0.5–2.5 m thick; Fig. 2) which rests directly upon the mudstone at the top of Unit 2. This mudstone thickens towards the north and is highly-brecciated suggesting that this contact is tectonic (probably a thrust). Between 20 and 35 m (Fig. 2) diamicton Sa1 is overlain by a lens of matrix-rich, brown to orange, weakly bedded (*c.*, 30° towards the south), very sandy diamicton (Sa2). Sa2 locally possesses a well-developed bedding-parallel fabric defined by aligned tabular limestone pebbles, which is folded by tight, upright (80–85°), asymmetrical folds (F1) (Fig. 8c) which record a north-directed sense of shear. These folds do not affect the underlying diamicton (Sa1) and are clearly truncated at the thrust separating this unit from the overlying unit Sa3 (see Fig. 8c).

Between 20 and 55 m the diamictons Sa3 and Sa4, and to a lesser extent the underlying Sa1 are deformed by a large-scale, northerly verging, steeply to moderately inclined antiform and synform fold pair (Fig. 2). These large-scale folds also deform the thrust separating units Sa3 and Sa4, from the underling Sa1 and Sa2 diamictons (Fig. 2b), indicating that large-scale folding post-dated thrusting and stacking of this glacigenic sedimentary sequence (see Fig. 2c), and is therefore F2 in age. The upper part of the glacigenic sequence in Section 1 is dominated by a typically pale orange, massive to weakly bedded, matrix-supported sandy diamicton (Sa5) (Fig. 2). This diamicton also occurs within the core of the large-scale synform (40 to 60 m in Fig. 2b) indicating that deposition of Sa5 pre-dated folding.

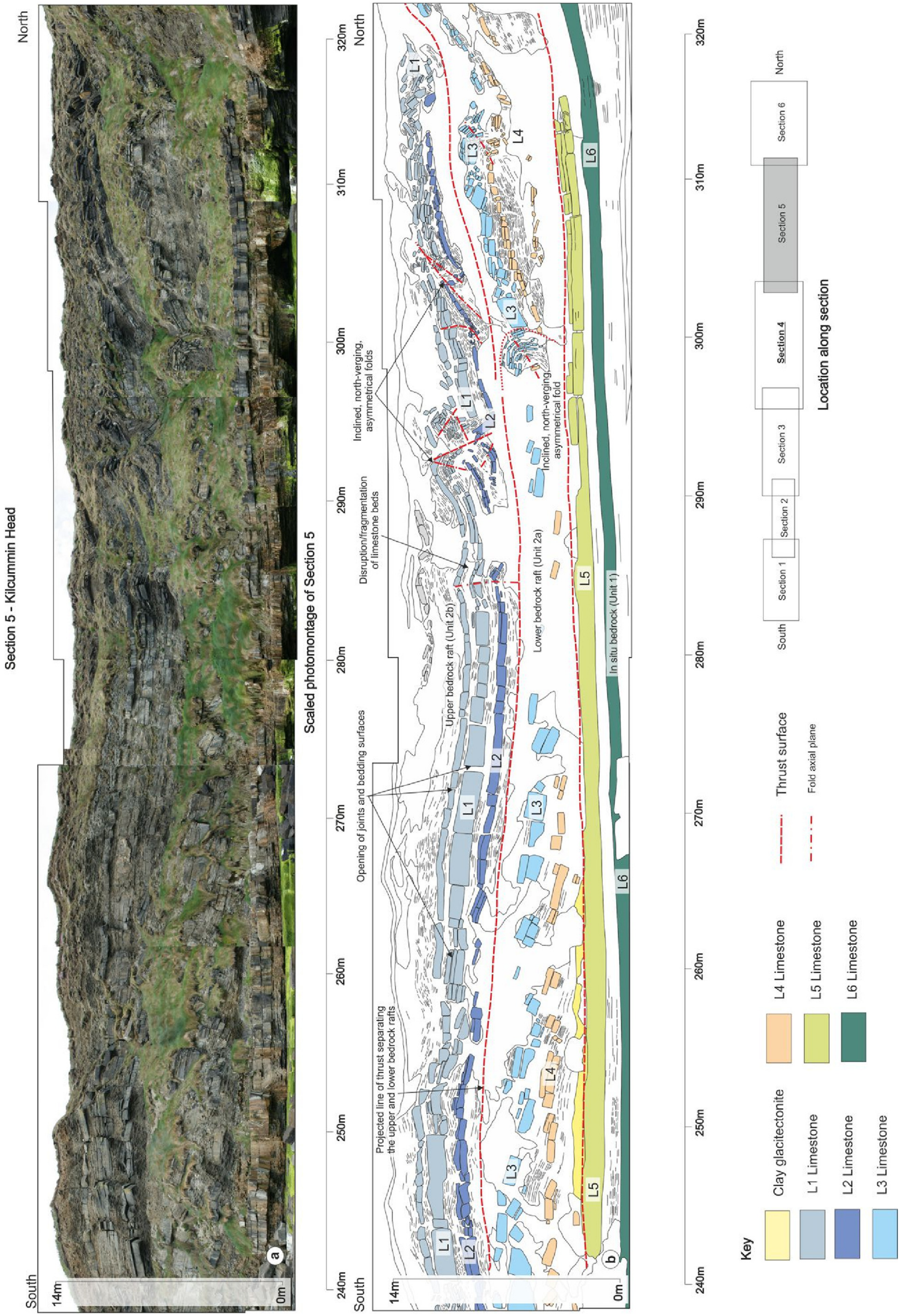
6.2. Section 2: between 70 m and 120 m

Section 2 (Fig. 3) is dominated by the upper part of two bedrock rafts (Unit 2b) which characterise the remainder of the glacitectonised sequence at Kilcummin Head. Bedding within the raft dips at a low angle towards the south (8°S/270°; Fig. 9b) with the limestones (L1 and L2) and mudstones (S1 and S2) showing very little evidence of deformation (Fig. 3). Steeply-inclined to subvertical joints within the limestones range from closed (tight) to open; the latter resulting from localised extension (boudinage) parallel to bedding which resulted in the separation of the individual limestone beds into 1–5 m long tabular blocks.

6.3. Section 3: between 120 m and 160 m

Section 3 is once again dominated by Unit 2b which structurally overlies a 2.5 m thick unit of mudstone-rich glacitectonite (Fig. 4). Bedding within the raft is sub-horizontal to very gently undulating and occurs parallel to the thrust at the base of this detached bedrock slab. Variations in the dip of bedding may be preserving an original bedrock feature, or alternatively may indicate the onset of very gentle folding (warping) of the limestones and mudstones. Both L1 and, to a lesser extent, L2 limestones become increasingly fragmented towards the north due to the reactivation and opening of pre-existing joints which locally

Fig. 6. Macroscale photomontage (a) and structural interpretation (b) of Section 5 (240 to 320 m) at Kilcummin Head. The middle to upper part of the cliff section is dominated by large (*c.*, 4 m thick), laterally extensive (*c.*, 300–400 m long) bedrock rafts comprising two prominent limestone beds (L1 and L2) separated by mudstones (<1 m thick; S1 and S2). This raft is structurally underlain by complex sequence of fragmented limestone beds within a matrix of highly disrupted mudstone. Both the upper and lower rafts show evidence of northerly verging, upright to inclined asymmetrical folding and associated faulting. The lower part of the cliff section comprises *in situ* Carboniferous bedrock which is composed of two prominent limestone beds (L5 and L6) separated by mudstone.


Section 5 - Kilcummin Head
South
North
14m
0m
a
240m
250m
260m
270m
280m
290m
300m
310m
320m
Scaled photomontage of Section 5
b
L1
L2
L3
L4
L5
L6
Projected line of thrust separating the upper and lower bedrock rafts
Opening of joints and bedding surfaces
Upper bedrock raft (Unit 2b)
Lower bedrock raft (Unit 2a)
In situ bedrock (Unit 1)
Disruption/fragmentation of limestone beds
Inclined, north-verging, asymmetrical folds
Inclined, north-verging asymmetrical fold
Key
Clay glacitectonite
L1 Limestone
L2 Limestone
L3 Limestone
L4 Limestone
L5 Limestone
L6 Limestone
Thrust surface
Fold axial plane
South
Section 1
Section 2
Section 3
Section 4
Section 5
Section 6
Location along section

form steeply south-dipping extensional faults (Figs. 4, 8d and 9c). These normal faults (offset on individual faults of *c*., 30–40 cm) are most common between 35 and 40 m at the northern-end of Section 3 (Fig. 4). Faulting in this part of the section resulted in the tilting of bedding, which dips at a low angle to the northeast (Fig. 9c), and dextral (top to the North) rotation of the fault-bound limestone blocks (Fig. 8d). Accompanying deformation of the thinly-bedded mudstones between the limestones led to normal faulting, tilting of bedding, brecciation and localised thrusting with associated small-scale drag folding within the hanging-walls of the thrusts.

The highly-deformed (brecciated) mudstone-rich glacitectonite (Figs. 4 and 11) underlying Unit 2b rests directly upon the *in situ* bedrock. In detail this glacitectonite can be subdivided into a lower unit (*c*., 1.5 m thick) of matrix-supported, apparently reverse-graded dark grey breccia, overlain by a very compact (overconsolidated), *c*., 1 m thick, clay-rich diamicton (Fig. 11). The boundary between the two units dips towards the southeast (Fig. 9c), coplanar to bedding within the adjacent limestones (see Fig. 11). A locally well-developed clast macrofabric (Fig. 10) defined by shape-aligned tabular mudstone fragments is present within both the upper and lower units of the glacitectonite. This fabric preserves the original bedding within the mudstone protolith (compare Figs. 9 and 10) and is deformed by a series of northward verging asymmetrical folds with steeply-inclined, southerly dipping axial surfaces (Fig. 9c). Folding may have resulted in the observed variation in the pitch of the A-axes of pebble to cobble sized clasts within the glacitectonite (Fig. 10). The folds are offset by a number of later, moderately to steeply-inclined, southerly dipping, north-directed reverse faults (Figs. 4 and 11). The sense of asymmetry of the folds and displacement on the faults is consistent with a northward-directed sense of shear during deformation. The upper boundary of the glacitectonite with the mudstone at the base of the overlying raft is sharp and marked by a thin (*c*., 2 cm thick), laterally extensive (traced laterally for c., 20–25 m) layer of pale brown sand which dips at a low-angle to the south–southeast (Figs. 9c and 11).

6.4. Section 4: between 160 m and 240 m

Section 4 is characterised by a marked increase in the complexity of deformation and number of limestone–mudstone rafts within Unit 2 (Fig. 5). The upper raft (Unit 2b), which dominates much of the cliff section, is an extension of the bedrock slab exposed in Sections 2 and 3. At the southern-end of Section 4 (between 160 and 215 m; Fig. 5) the typically sub-horizontal to gently-undulating bedding (Fig. 9d) within the raft is locally tilted to the north by a number of steeply-inclined, southerly-dipping extensional faults. These faults divide the individual limestone beds into tabular blocks of between <1 m and up to 3 m in length. At the northern-end of the section (between 215 and 240 m; Fig. 5), the limestones and mudstones are folded by an open, upright, weakly symmetrical antiform (Figs. 5 and 8e). This fold is developed immediately above the southern termination of the structurally lower raft (Unit 2a) with the boundary between the two rafts being formed by a prominent detachment or thrust (Fig. 5). This thrust plane is marked by a thin zone of highly-brecciated mudstone. Bedding within the lower raft is highly disrupted with the L3 and L4 limestones being broken-up into a number of variably rotated, 1–2 m long, joint- to fault-bound blocks (see Figs. 5 and 8e). The tilting of bedding within these blocks records an overall sense of rotation towards the north.

6.5. Section 5: between 240 m and 320 m

Section 5 (Fig. 6) shows an overall increase in the relative intensity of deformation within both Units 2a and 2b. Unit 2b dominates the upper part of the cliff and is deformed by an open, warp-like anticline (between 240 and 280 m; Fig. 6). In the hinge of this fold both the L1 and L2 limestones are disrupted, possibly due to extension occurring across the hinge-zone during folding. Between 285 and 320 m the intensity of deformation within Unit 2b increases dramatically with both the L1 and L2 limestones becoming increasingly fragmented and folded by initially open, upright, symmetrical folds (*c*., 285 m; Fig. 6) which progressively tighten and become more asymmetrical towards the north (between 290 and 305 m, Fig. 6). The mesoscale (wavelength *c*., 5 m) steeply- to moderately-inclined (Fig. 9e), northward-verging anticlines present between 290 and 310 m are cut by a number of later, steeply-to moderately-dipping faults, with faulting having occurred in response to brittle failure of the limestone beds as the folds continued to tighten. The sense of asymmetry of the folds and displacement on reverse faults are consistent with an overall northward-directed sense of shear during glacitectonism.

The thrust separating Unit 2b from the underlying and relatively more internally disrupted lower raft (Unit 2a) is poorly exposed. However, the glacitectonic nature of this contact can be inferred by the marked angular discordance in bedding within the two rafts (Fig. 6), with this contact representing a lateral extension of the thrust identified in Section 4. At the northern-end of Section 5, between 295 and 320 m (Fig. 6), the L3 and L4 limestones become increasingly fragmented with bedding in the raft being traced laterally by the preferred alignment of isolated, slab-like blocks of limestone. This preserved bedding is deformed by a number of mesoscale (wavelength *c*., 10 m), asymmetrical, close to tight, northerly verging folds (Figs. 6 and 8f). The geometry of these folds once again records an overall northward directed sense of shear during glacitectonism.

The décollement surface at the base of the glacitectonised sequence is locally marked by a *c*., 40 cm thick lens of mudstone-rich glacitectonite (between 240 and 267 m; Fig. 6).

6.6. Section 6: northern-end of Kilcummin Head between 320 m and 390 m

Section 6 at the northern-end of Kilcummin Head (see inset Fig. 7) is characterised by a thicker exposed sequence of *in situ* bedrock (Unit 1) which, unlike in the previous sections, shows some evidence of glacitectonic deformation (faulting in the mudstones and disruption of the L5 limestone; Fig. 8b). The overlying glacitectonised limestones and mudstones form a prominent topographic feature which is up to 20 m high (Figs. 7 and 8a). The more coherent upper raft (Unit 2b) which dominated Sections 2 to 5 (Figs. 3 to 6) is absent within Section 6, with the glacitectonised sequence being composed of thrust-repeated slices of Unit 2a (Fig. 7). Bedding with these thrust-bound slices is variably disrupted but can be traced laterally by the preferred alignment of isolated, slab-like blocks of L3 and L4 limestone (Figs. 7 and 8g). The mudstones are locally deformed by a set of steeply inclined (Fig. 9f), open to close, north-verging folds (Fig. 8g). At the northern-end of the section, between 360 and 385 m, the lowermost L4 limestone bed is deformed by a series of steeply inclined to vertical, open, symmetrical to asymmetrical, northward verging folds (Figs. 7 and 9f). These folds also deform a relatively thin (2–3 m thick) carapace of orange–brown, matrix-rich sandy diamicton which mantles the landform at this northern-end of Kilcummin Head.

7. Micromorphology of the shale-rich glacitectonite

Two orientated thin sections (KH01, KH03) of the mudstone-rich glacitectonite (Fig. 11) exposed between 135 and 190 m in Section 3 were examined to establish the range of microstructures developed during the formation of this glacitectonite and the sense of displacement accommodated by the décollement at the base of the glacitectonised sequence. Sample KH01 was collected from the hinge zone of a northerly verging fold which deforms a clast fabric present within the glacitectonite (Fig. 11b, c, d). Sample KH03 was taken from a structurally higher position at the top of the glacitectonite and includes a laterally extensive sand layer marking the contact between the glacitectonite and the structurally overlying raft (Unit 2b) (Fig. 11a, b).

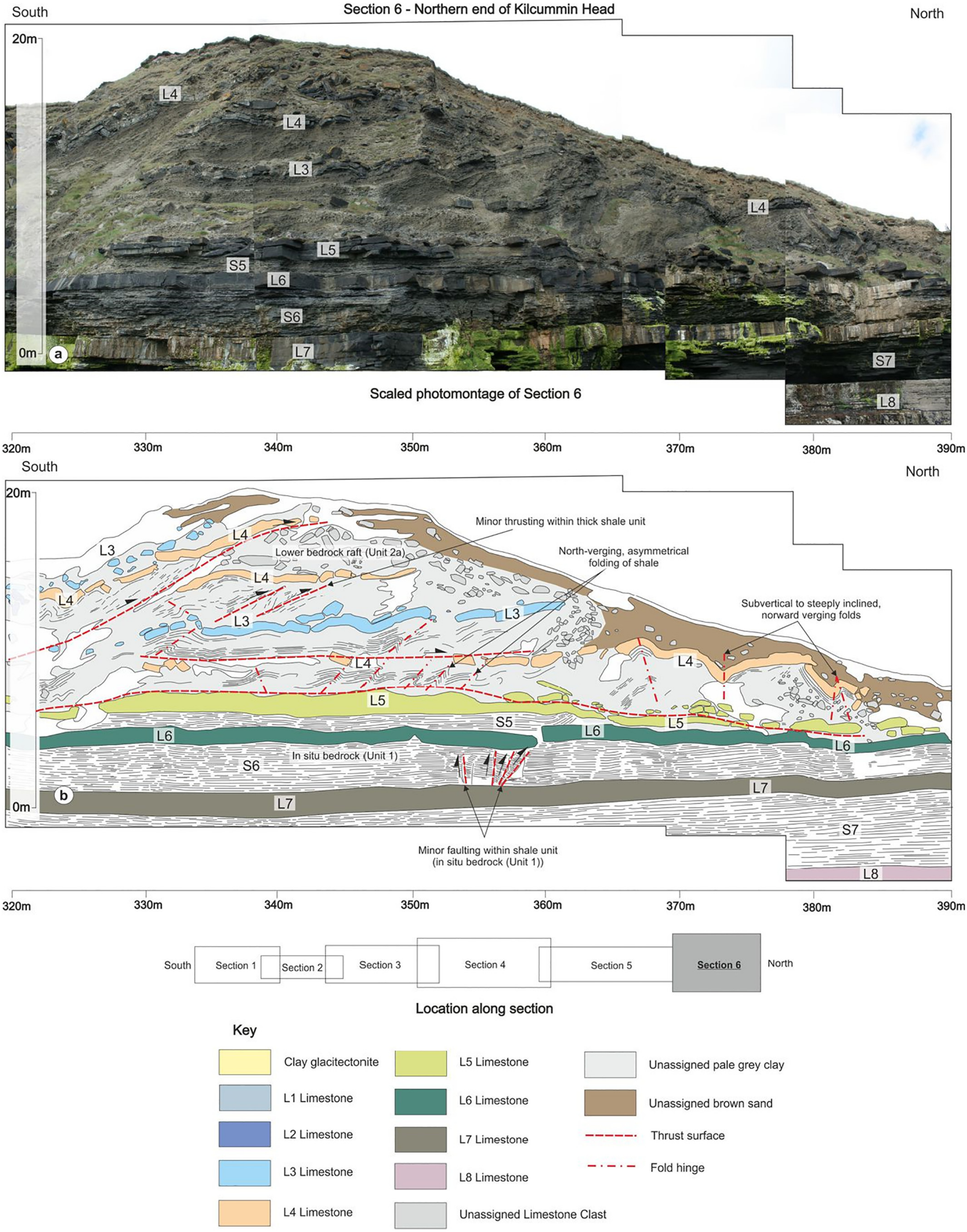


Fig. 7. Macroscale photomontage (a) and structural interpretation (b) of Section 6 (320 to 390 m) at Kilcummin Head. The upper part of the cliff is dominated by a complex sequence of fragmented limestone beds within a matrix of highly disrupted mudstone. This disrupted sequence is repeated by subhorizontal to moderately inclined, southerly dipping thrusts. The lower part of the cliff comprises *in situ* Carboniferous bedrock which is composed of two prominent limestone beds (L5 to L8) separated by mudstone (S5 to S7).

7.1. Sample KH01

Sample KH01 (Fig. 11a, b) is of a pale to dark grey to brown, very poorly-sorted, fine- (fine sand) to very coarse-grained (pebble), bedrock-rich, clayey diamicton. The thin section is composed of large (up to 7 cm in length) calcareous mudstone fragments in a silty clay matrix (Fig. 12) which is compositionally/lithologically similar to the mudstone. This combined with a high modal proportion of mudstone clasts (*c*., 45 modal % of the total sediment) indicates that the diamicton was almost entirely derived from the shale bedrock with very little (if any) 'exotic' material having been introduced into the glacitectonite. The elongate shape of the typically angular to subangular (rarely subrounded), low-sphericity bedrock fragments is controlled by bedding and/or lamination within the mudstone (*e.g.*, large clast in the centre of Fig. 12). Graded silt to clay laminae within the mudstone show that the majority of the clasts are the "right-way-up", indicating that very little or no significant rotation occurred which may have led to overturning of the clasts during brecciation and subsequent deformation. Fractures within some of the clasts are partially filled by the silty clay matrix; consistent with the matrix of the diamicton having been 'squeezed' or 'injected' into the fractures during brittle deformation suggesting that the matrix was relatively 'mobile' during the formation of the glacitectonite.

Although at a macroscale sample KH01 was clearly taken from the faulted hinge zone of a northerly verging fold (Fig. 11d), in thin section this fold hinge is less apparent (Fig. 12). In the upper part of the thin section (top left Fig. 12) the preferred shape alignment of fine sand- to granule-sized mudstone fragments defines a well-developed S-shaped to sigmoidal clast microfabric. This microfabric dips at *c*., 46° towards the south (in this plane of section) (Area A rose diagram, Fig. 12). The geometry of this foliation is similar to S-C-type fabrics described from both brittle and ductile shear zones (Passchier and Trouw, 1996) and yields an overall northerly directed sense of shear; consistent with the sense of asymmetry of the larger, mesoscale folds which deform the glacitectonite (see Fig. 11b, c). A fine asymmetrical foliation is locally developed within the silty clay matrix defining a number of anastomosing shears (Fig. 12) which also record a sense of displacement towards the north. In the lower part of the thin section (bottom right Fig. 12) the clast microfabric relationships are more complex with marked changes in the orientation of this foliation (Area B rose diagram, Fig. 12) indicating that the diamicton in this area is cut by brittle faults and shears. The clast microfabric associated with these shears dips at *c*., 35° towards the south. However, the sense of displacement on these structures cannot be established due to the lack of distinct marker horizons and/or shear fabric developed along the diffuse, poorly defined shear/fault planes.

7.2. Sample KH03

Sample KH03 includes the boundary zone between the mudstone-rich glacitectonite and the structurally overlying limestone and shale raft (Fig. 11a, b). This boundary dips at *c*., 10° towards the south and is marked by a thin layer of sand (Figs. 9c and 11b). In thin section (Fig. 13) the boundary between the raft and underlying glacitectonite is marked by a sand-rich diamicton containing subangular to occasionally well-rounded, angular clasts of calcareous mudstone. The lower part of the thin section is composed of a mudstone-rich diamicton composed of angular to subangular, sand to pebble-sized (up to 4 cm long) fragments of mudstone and calcareous mudstone within a fine-grained silty clay matrix. The diamicton possesses two distinct clast microfabrics: the dominant fabric dips at *c*., 34° towards the north; and the second, relatively weaker, steeply inclined foliation dips at *c*., 65° towards the south (Area B rose diagram, Fig. 13). As in sample KH01, the matrix in sample KH03 is compositionally/lithologically similar to the mudstone fragments, consistent with this diamicton having been derived from the mudstone bedrock. The greater degree of rounding and overall finer grain size of the diamicton, coupled with an increase in the modal proportion of matrix indicates that the diamicton within sample KH03 records a higher degree of comminution (grain size reduction) when compared to the structurally lower sample KH01 (compare Figs. 12 and 13). This is consistent with an overall increase in the relative intensity of deformation/brecciation towards the detachment marking the base of the overriding raft.

The contact between the mudstone-rich diamicton and overlying sandy diamicton is sharp, but irregular in form with no obvious gradation or mixing of the matrix across this boundary (Fig. 13). The sandy matrix within the upper layer in sample KH03 is compositionally distinct and possesses two distinct clast microfabrics: the dominant fabric dips at *c*., 15° towards the north; and the second, relatively weaker, steeply-inclined foliation dips at *c*., 58° towards the south (Area A rose diagram, Fig. 13). The geometry of these two clast microfabrics is similar to that observed in the underlying mudstone-rich diamicton indicating that they developed in response to the same overall stress regime. The slight changes in the angle of dip may be due to differences in the lithology of the matrix resulting in the refraction of these glacitectonic fabrics (*cf*., cleavage refraction in metamorphic rocks). Importantly, no obvious sand layers have been identified within the glacitectonised sequence or underlying *in situ* Carboniferous bedrock which is dominated by the interbedded limestones and shales of the Ballina Limestone Formation (see Figs. 2 to 7). This has led to the conclusion that the sandy matrix to this diamicton is 'exotic', probably glacigenic in origin, and introduced into the deforming sequence during glacitectonism. As a result, the sandy layer separating the base of the raft (Unit 2b) from the underlying shale-rich glacitectonite is interpreted as a hydrofracture which exploited this prominent lithological/glacitectonic boundary (see below).

8. Thin-skinned thrust tectonic model for rafting at Kilcummin Head

It is clear from the above description of the glacitectonised sequence exposed at Kilcummin Head that it is essentially composed of two thin (5–10 m thick), laterally extensive (up to 300 to 400 m in length) bedrock rafts composed of variably-deformed limestone and mudstone, emplaced upon the *in situ* bedrock of the Ballina Limestone Formation (Figs. 2 to 7). These rafts are bounded by a number of gently southerly-dipping brittle thrusts and rest upon a major décollement surface which separates the glacitectonised sequence (Unit 2) from the underlying *in situ* bedrock (Unit 1). This décollement is thought to have accommodated the bulk of the displacement (transport) during the rafting process and is locally marked by a thick zone of mudstone-rich glacitectonite.

Detailed analysis of this glacitectonised sequence has revealed that the relative intensity of deformation increases from south to north, and is characterised by an increase internal disruption (faulting, boudinage) of the rafts, as well as a marked decrease in the length and increase in the number of these stacked thrust-bound slices of limestone and shale bedrock (see Figs. 4 to 7). High-angle faulting of the limestones within the rafts which led to this disruption resulted from the reactivation of pre-existing joints within these sedimentary rocks. Furthermore, the opening of the joints and bedding surfaces, as well as the normal sense of displacement on the majority of the faults, indicates that internally the rafts were undergoing extension/boudinage (*i.e.*, they were being pulled apart) during transport and emplacement.

Meso- and small-scale kinematic indicators such as the asymmetrical folds (Figs. 2, 4, 5 and 8b, f, g), displacement on thrust and reverse faults, as well as folding and microscale S-C-like fabric geometries present within the shale-rich glacitectonite (Figs. 11, 12 and 13) all record a consistent northward-directed sense of shear. This indicates that glacitectonic rafting of the Carboniferous bedrock at Kilcummin Head occurred during the same progressive, northerly-directed deformation event. Importantly, the direction of tectonic transport accommodated

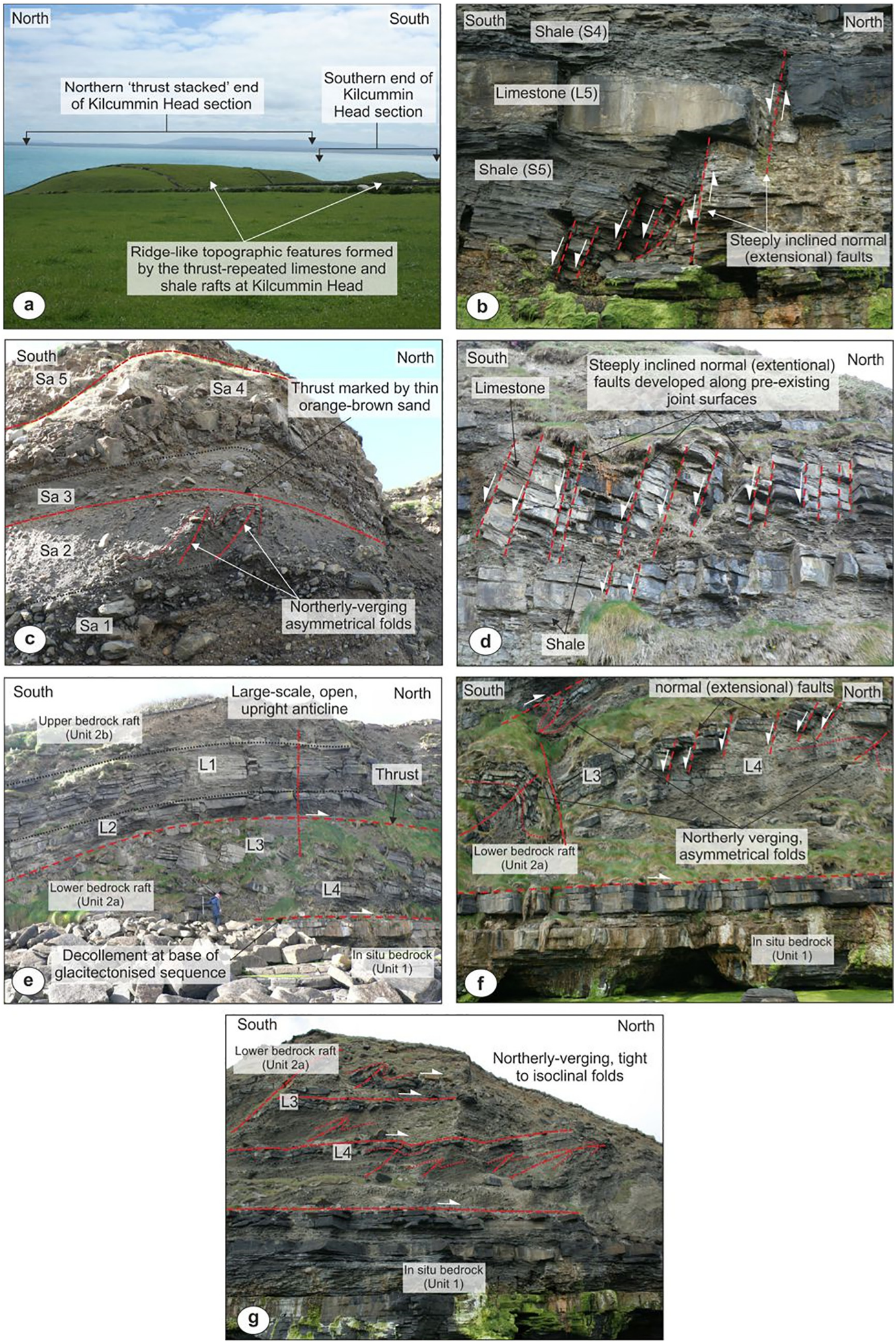


Fig. 8. (a) Ridge-like topographic features formed by the thrust-repeated limestones and shales in at Kilcummin Head. Note that this linear, N–S-trending landform is restricted to the area close to the sea cliffs; (b) photograph showing steeply inclined to subvertical reverse faults within *in situ* shale bedrock exposed within Section 6 (350 to 360 m; Fig. 7); (c) photograph showing the relationships between the diamicton units Sa1, Sa2, Sa3, Sa4 and Sa5 in Section 1 at Kilcummin Head between 25 to 35 m (Fig. 2); (d) well-developed, steeply inclined normal (extensional) faults developed along pre-existing joints within a thick unit of limestone at the northern-end of Section 3 (Fig. 4); (e) large-scale open folding of upper bedrock rafts exposed in Section 4 (Fig. 5) (see text for details). Also shown is the marked angular discordance in bedding within the upper and lower rafts exposed in this part of the Kilcummin Head section; (f) mesoscale folding and normal (extensional) faulting of limestone beds within the lower bedrock raft exposed in Section 5 (Fig. 6); and (g) highly glacitectonised limestone and mudstone overlying relatively undeformed *in situ* Carboniferous bedrock at the northern-end of Kilcummin Head (Section 6; Fig. 7).

during this event is consistent with the northerly directed pattern of ice flow across Killala Bay (see Fig. 1) established from the landform record of the region (Coude, 1989; Coxon, 1991; Coxon and Browne, 1991a; Knight, 2002; Greenwood and Clark, 2008, 2009).

The detailed structural interpretations shown in Figures 2 to 7 were combined into a single cross-section which was then simplified using the tectonostratigraphy outlined above (Section 5). This was then restored placing the bedrock rafts in their approximate structural configuration prior to thrusting (Stage 1 in Fig. 14) indicating that the glacitectonised sequence at Kilcummin Head has accommodated in the order of *c.*, 61 % total shortening during thrusting and raft emplacement (Fig. 14). This would have resulted in the formation of a prominent thrust-block moraine at the margin of the ice as it advanced northwards across Killala Bay. A five-stage thin-skinned glacitectonic model is proposed to explain the evolution of this imbricate thrust stack (see below).

8.1. Stage 1: initial detachment of the Carboniferous bedrock rafts

Stage 1 was dominated by the detachment and subsequent initial transport of the bedrock rafts (Fig. 14). The basal décollement surface which separates the rafts (Unit 2) from the underlying *in situ* bedrock (Unit 1) was preferentially developed within one of the thicker mudstone units of the Ballina Limestone Formation. This mudstone features horizontally-laminated bedding, providing stress-parallel planes of weakness. It would therefore have been relatively weaker than the interbedded limestones, with the latter acting as relatively ridged bodies at this stage of the deformation history. During Stage 1 it is likely that the detached limestone and shale beds (L1 to L4 in Figs. 2 to 7) were undergoing very little internal deformation, and were probably being transported as single, laterally extensive (500 to 600 m long) slab-like rafts which were just a few beds thick (see Stage 1 in Fig. 14). By the end of Stage 1, shortening accommodated by movement along the basal décollement surface has been estimated as approximately 29 %, with the amount of displacement along this thrust being the order of 250 to 300 m (Fig. 14).

Deformation at this stage of the rafting process would have been focused within the weaker mudstones leading to the fragmentation of this thinly bedded/laminated mudrock and the formation of the glacitectonite which marks the basal décollement (Fig. 11). Although deformed by a series of northerly verging folds and northward-directed small-scale thrusts the original bedding within the mudstones is thought to be preserved by a locally well-developed clast macrofabric (Fig. 10). The preservation of this inherited clast macrofabric, defined by shape-aligned, tabular bedrock fragments set within a comminuted mudstone/clay matrix (Fig. 11), indicates that although highly fragmented, displacement associated with the initial transport of the raft was being focused along a number of discrete zones within the developing glacitectonite. Micromorphological evidence suggests that northerly directed shearing resulted in the development of an asymmetrical S-C-like fabric within the matrix of the glacitectonite (Fig. 12). The thin sections of the glacitectonite also show that there is a marked increase in the intensity of grain size reduction (comminution) towards the top of the glacitectonite (compare Figs. 12 and 13), consistent with an overall increase in the intensity of deformation towards the base of the overriding raft. This may also suggest that displacement, leading to transport of the raft, was largely focused along a single décollement surface.

In outcrop, the basal décollement is marked by a thin sand-rich layer (Figs. 11a, b and 13) which is lithologically similar to and probably derived from the overlying glacial sediments. This sand layer is considered to be an infill of a hydrofracture which exploited this prominent glacitectonic boundary and led to the introduction of glacially-derived sand along the décollement surface at the base of the deforming bedrock sequence. The relative age of hydrofracturing with respect to the evolution of the glacitectonised sequence at Kilcummin Head remains uncertain. However, the introduction of overpressurised meltwater into the Carboniferous bedrock during the early stages of glacitectonism (*i.e.*, Stage 1) would have provided a mechanism for the initial detachment of the raft, as well as facilitated its subsequent transport along a water–sediment–lubricated décollement surface (*cf.*, Moran et al., 1980; Aber, 1985; Mooers, 1990; Broster and Seaman, 1991; Kjær et al., 2006; Phillips and Merritt, 2008; Burke et al., 2009; Evans et al., 2021). Entry of the meltwater into the bedrock is most likely to have occurred along the pre-existing network of joints and bedding surfaces within the limestones and shales of the Ballina Limestone Formation. It is possible that the introduction of overpressurised meltwater into the glacier bed during the early stages of the rafting process may have led to the fragmentation of the mudstones thereby weakening these mudrocks and aiding propagation of the basal décollement through the bedrock. However, there is no evidence of hydrofracturing and/or water-escape on either a macro- (see Fig. 11) of microscale (see Figs. 12 and 13) within the glacitectonite. Furthermore, thin sections of the glacitectonite (samples KH01 and KH03) reveal an apparent lack of 'exotic' glacially derived detritus within the matrix of this bedrock-rich diamicton which is largely composed of comminuted shale.

Fragmentation of the mudstone to form the glacitectonite clearly occurred during the early stages of or possibly prior to rafting as the clast macrofabric within this diamicton is clearly deformed by northerly verging folds and northward-directed thrusts (Fig. 11) developed during rafting. Furthermore, this fragmentation appears to have occurred at a specific stratigraphical/structural level within the Carboniferous bedrock as the mudstones exposed elsewhere within the *in situ* bedrock (Unit 1) and also within the rafts (Unit 2) have remained largely 'intact', showing the same level of fragmentation/brecciation at the northern-end of the Kilcummin Head section and the leading edge of the rafts (-Section 6, Fig. 7). An alternative explanation for the locally intense fragmentation of the shale at a specific level within the bedrock is that these mudrocks were brecciated prior to glacitectonism possibly as a result of locally intense periglacial activity. In the literature, brecciation of mud-rich and chalk bedrock in permafrost areas has been attributed to three principle mechanisms:

(i) Frost shattering within the active layer above the permafrost due to seasonal freezing and expansion of water trapped in pores and fractures, followed by thawing (Higginbottom and Fookes, 1970; Hall, 1999; Hall et al., 2002);
(ii) Brecciation due to thermal contraction and the growth of needle ice in the upper layer of permafrost (Büdel, 1982), and;
(iii) The growth of segregation ice in permafrost associated with perennial freezing leading to the formation of an ice-rich layer within the bedrock (ice content of 40 to 60 % or more) just beneath the palaeo-permafrost table (French et al., 1986; Murton, 1996; Murton et al., 2006).

All of these processes lead to the formation of angular to subangular, pebble- to cobble-sized clasts that are tabular in shape. The first two mechanisms would have led to fragmentation of the mudstones at the surface with the resultant head deposit probably being reworked by the advancing ice to form the bedrock-rich diamictons exposed in Section 1 (see Figs. 2 and 8c). The third mechanism would have led to brecciation of the shales at depth within the Carboniferous bedrock. Growth of segregation ice along these pre-existing bedding and joint surfaces would have led to the progressive expansion and fragmentation of these mudrocks, and the formation of the bedrock-rich diamicton, whilst preserving the orientation of these features (*i.e.*, bedding) within the inherited clast macrofabric. During the subsequent early stages of glacitectonism, this periglacially disrupted shale horizon would have represented a significant weakness within the bedrock providing the focus of initial detachment and propagation of the basal décollement. The thickness of the resultant rafts would therefore have been governed by the thickness of the active layer of permafrost in the

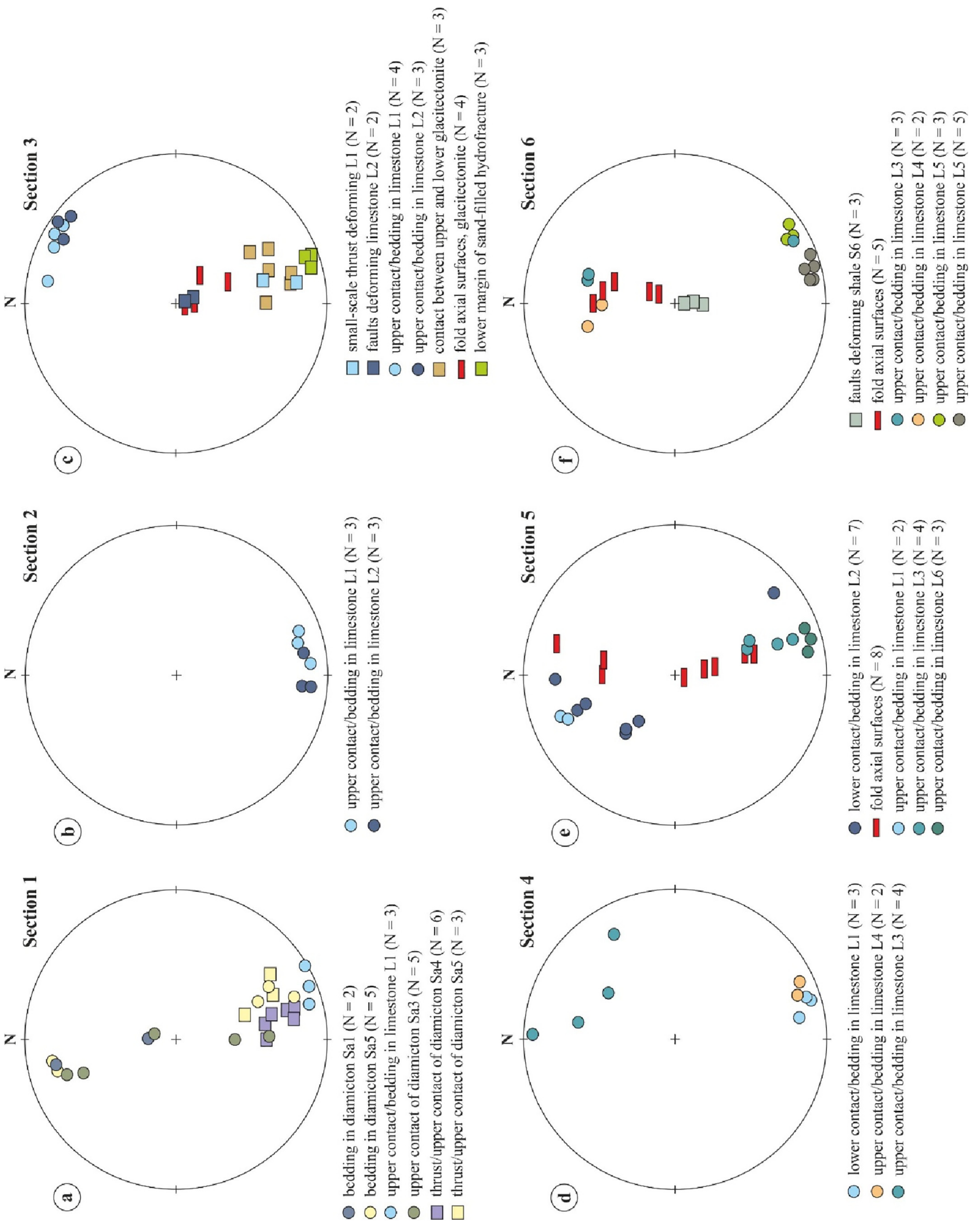


Fig. 9. Lower hemisphere stereographic projections of orientation data (plotted as dip and dip-direction) for bedding, thrusts, faults and fold axial surfaces within the glacitectonised sequence at Kilcummin Head. (a) Data collected from Section 1 (see Fig. 2); (b) data collected from Section 2 (see Fig. 3); (c) data collected from Section 3 (see Fig. 4); (d) data collected from Section 4 (see Fig. 5); (e) data collected from Section 5 (see Fig. 6); and (f) data collected from Section 6 (see Fig. 7).

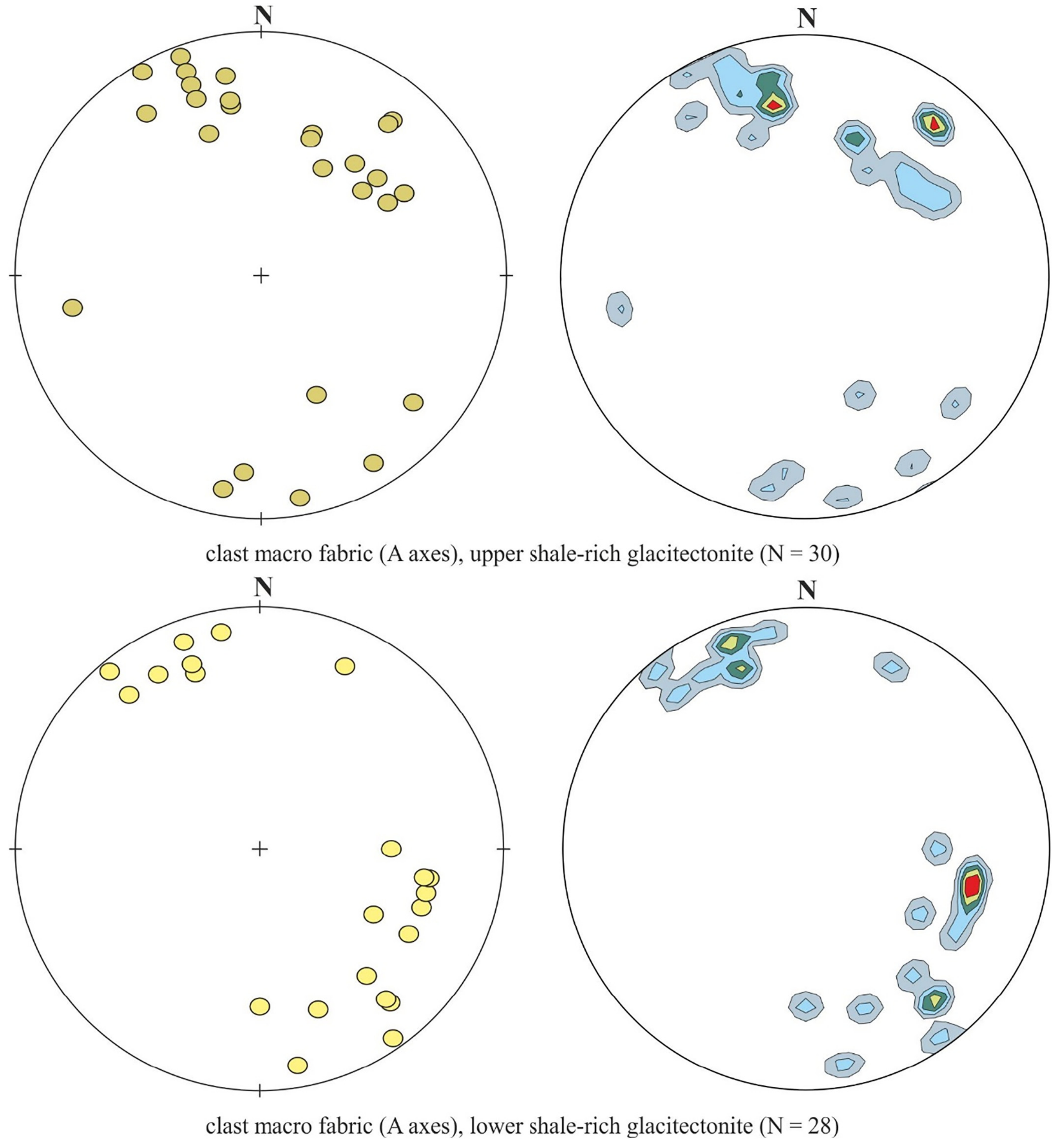


Fig. 10. Lower hemisphere stereographic projections of clast macrofabric data (A-axes) measured for pebble and cobble sized clasts within the glacitectonite exposed in Section 3 (Fig. 4) at Kilcummin Head. Plot of pitch and direction of clast long axis within the upper unit of mudstone-rich glacitectonite (see Fig. 12); contour plot of clast long axis within the upper unit of mudstone-rich glacitectonite; plot of pitch and direction of clast long axis within the lower unit of mudstone-rich glacitectonite (see Fig. 12); and contour plot of clast long axis within the upper unit of shale-rich glacitectonite.

Killala Bay area. Another possibility is that raft thickness was controlled by frost susceptibility. Shale horizons throughout the section would likely generate relatively high cryostatic pressure *via* cryosuction (*i.e.*, Williams and Smith, 1989), compared to the adjacent limestone units. This would promote the growth of segregation ice and promote discrete delamination surfaces within the shale. The penecontemporaneous introduction of overpressurised groundwater into the bedrock as it is overridden by the northerly advancing ice, along with the associated hydrofracturing, may have further contributed to the northward propagation of the basal décollement through the bedrock.

8.2. Stage 2: continued shortening and initial overriding of the upper raft

Stage 2 led to the continued shortening of the rafted sequence and the dissection of the initial single, laterally extensive limestone and shale raft into two shorter segments (Fig. 14). By the end of Stage 2,

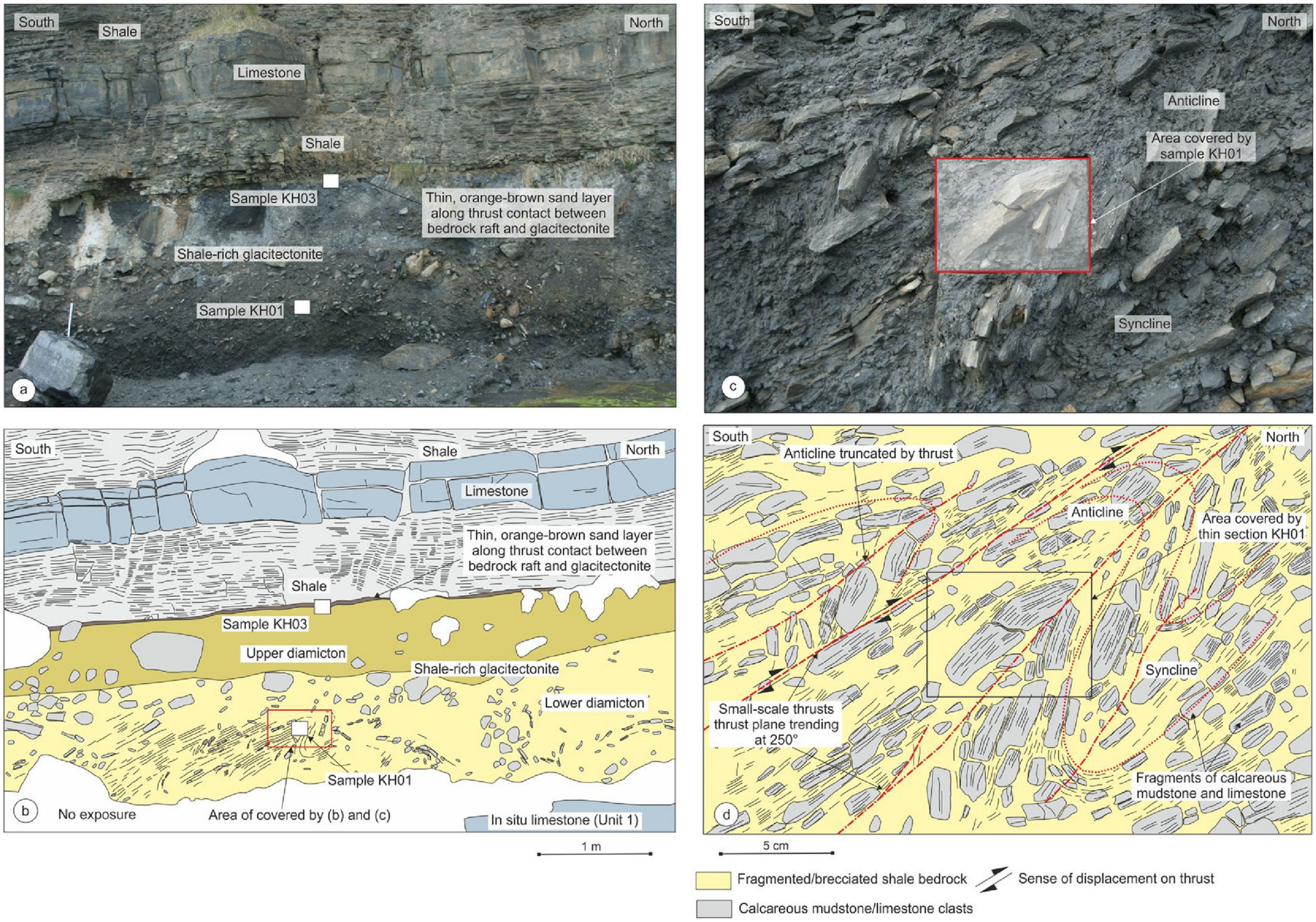


Fig. 11. (a) and (b) Thick unit of glacitectonite marking major detachment separating the *in situ* bedrock of Unit 1 from the glacially transported limestone and mudstone raft (Unit 2) in Section 3 (see Fig. 4). Shows the location of the two samples (KH01 and KH03) taken for micromorphological analysis; and (c) and (d) details of northerly verging asymmetrical folds developed within the lower unit of glacitectonite (diamicton).

this glacitectonised sequence had apparently shortened by a further 16 % with this additional shortening being accommodated by a combination of continued movement along the basal décollement and the upward propagation from this basal detachment of the first of a number of imbricate thrusts (Fig. 14). Growth of this imbricate thrust would have not only resulted in the dissection of the single, 'Stage 1' raft into two shorter sections (Units 2a and 2b), but also the initial overriding and stacking of these thrust-blocks during continued northerly directed transport; a process that eventually led to the development of the imbricate thrust stack and associated thrust-block moraine (landform) observed at Kilcummin Head.

The factor(s) leading to the development of this imbricate thrust stack remain unclear. Figures 2 to 7 show that the spacing and number of the pre-existing joints within the Carboniferous strata vary laterally, with the subsequent reactivation of these fractures leading to the observed increase in the internal disruption within the limestone and mudstone rafts towards the northern-end of Kilcummin Head. The presence of these pre-existing structures coupled with the overall geometry of the rafts detached during Stage 1 would have meant that this thin (a few beds thick) laterally extensive, slab-like body would have been inherently unstable during glacitectonic transport. The *in situ* Ballina Limestone Formation at Kilcummin Head dips gently (1–10°; limestones L5, L6 and L7 in Fig. 9e and f) towards the south/south–southeast. The regional dip of the Carboniferous strata would have meant that the detached bedrock raft would, in effect, have been driven up a dip-slope with the basal décollement also having to propagate up this inclined surface (see Fig. 14). Physical factors such as the intensity of brecciation within the mudstones forming the main décollement, the volume of meltwater entering into the bed along this low-angle detachment and the amount of shear being transmitted into the bed by the advancing ice are also likely to have varied temporally and spatially during rafting, directly affecting not only the rate of movement on the basal décollement but also the forward motion of the overriding bedrock raft. These factors combined with the regional dip of the Carboniferous strata are likely to have reduced the rate of forward propagation of the leading edge of the advancing thrust system, leading to compression of the raft within its hanging-wall, steepening of thrusting and the upward propagation of a series of imbricate thrusts through this bedrock slab.

8.3. Stages 3 and 4: continued shortening and transport of bedrock rafts and development of an imbricate thrust stack

Stages 3 and 4 are characterised by raft emplacement (accretion) and the progressive development of an imbricate thrust stack at the leading edge of the glacitectonised sequence (Fig. 14). The progressive stacking of the individual thrust slices of bedrock was accompanied by localised folding as well as increased faulting and disruption of the limestone beds within these rafts (see Figs. 6 and 7) in response to continued shortening. High-angle normal and reverse faults developed as a result of the reactivation of pre-existing joints within the bedrock. Movement along these brittle structures led to the northerly directed rotation of the individual fault-bound blocks of limestone (see Figs. 6, 7 and 8d).

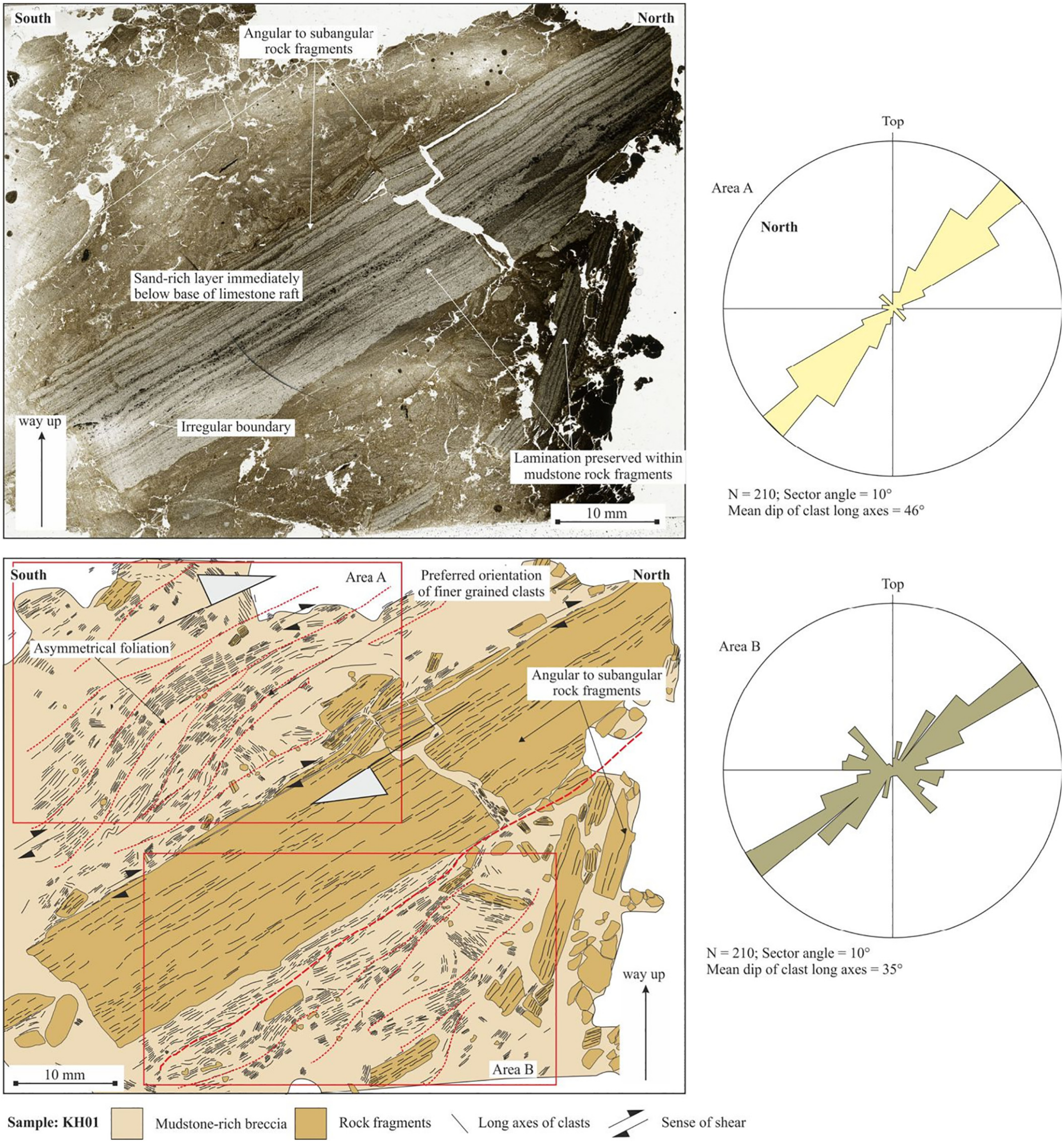
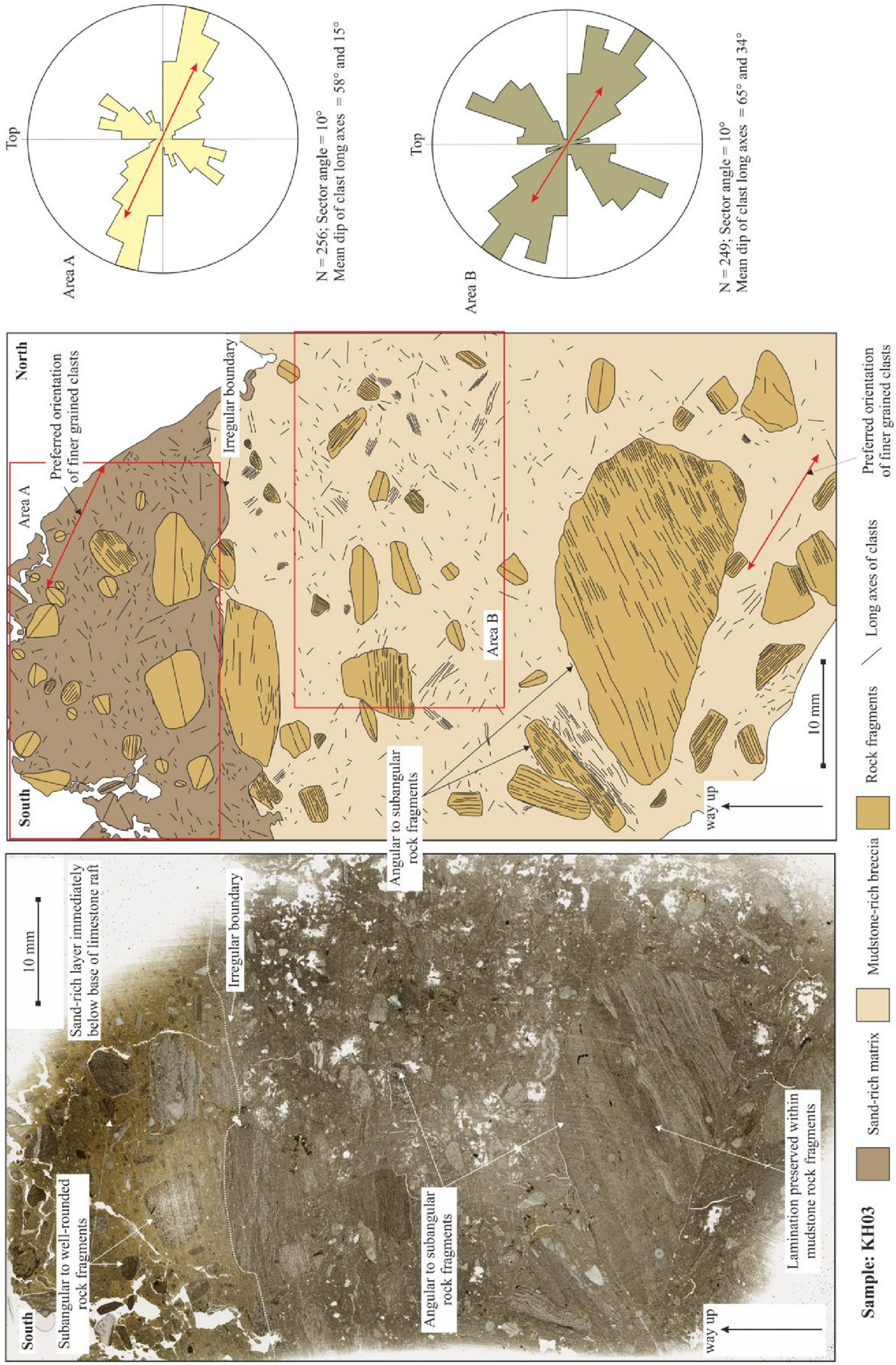


Fig. 12. High resolution scan and detailed microstructural map of thin section KH01 taken from the core of a tight, north-verging asymmetrical fold deforming a well-developed clast macrofabric present within the mudstone-rich glacitectonite. Clast microfabric data obtained for the long axes of the elongate sand to pebble sized clasts present within this thin section are displayed graphically on the rose diagrams.

The estimated amount of shortening accommodated during Stages 3 and 4 (7 % and 9 %, respectively) shows a marked decrease when compared with the main transport phase of the rafting process (Stage 1 = 29 % shortening and Stage 3 = 16 % shortening), consistent with a marked slowing down of the forward propagation of the leading edge of the advancing thrust system. This retardation in forward propagation would have resulted in further imbricate thrusting 'up-ice' of the thrust front, leading to the progressive development of a glacitectonic thrust-

Fig. 13. High resolution scan and detailed microstructural map of thin section KH03 taken from the boundary between the mudstone-rich glacitectonite (upper diamicton) and the overlying bedrock raft. The sample also includes the sand-rich layer which marks this tectonic boundary. Clast microfabric data obtained for the long axes of the elongate sand to pebble sized clasts present within this thin section are displayed graphically on the rose diagrams.


Area A
Top
N = 256; Sector angle = 10°
Mean dip of clast long axes = 58° and 15°
Area B
Top
N = 249; Sector angle = 10°
Mean dip of clast long axes = 65° and 34°
South
North
Area A
Preferred orientation of finer grained clasts
Irregular boundary
Area B
Angular to subangular rock fragments
Preferred orientation of finer grained clasts
10 mm
way up
South
Subangular to well-rounded rock fragments
Sand-rich layer immediately below base of limestone raft
10 mm
Irregular boundary
Angular to subangular rock fragments
Lamination preserved within mudstone rock fragments
way up
Sample: KH03
Sand-rich matrix
Mudstone-rich breccia
Rock fragments
Long axes of clasts

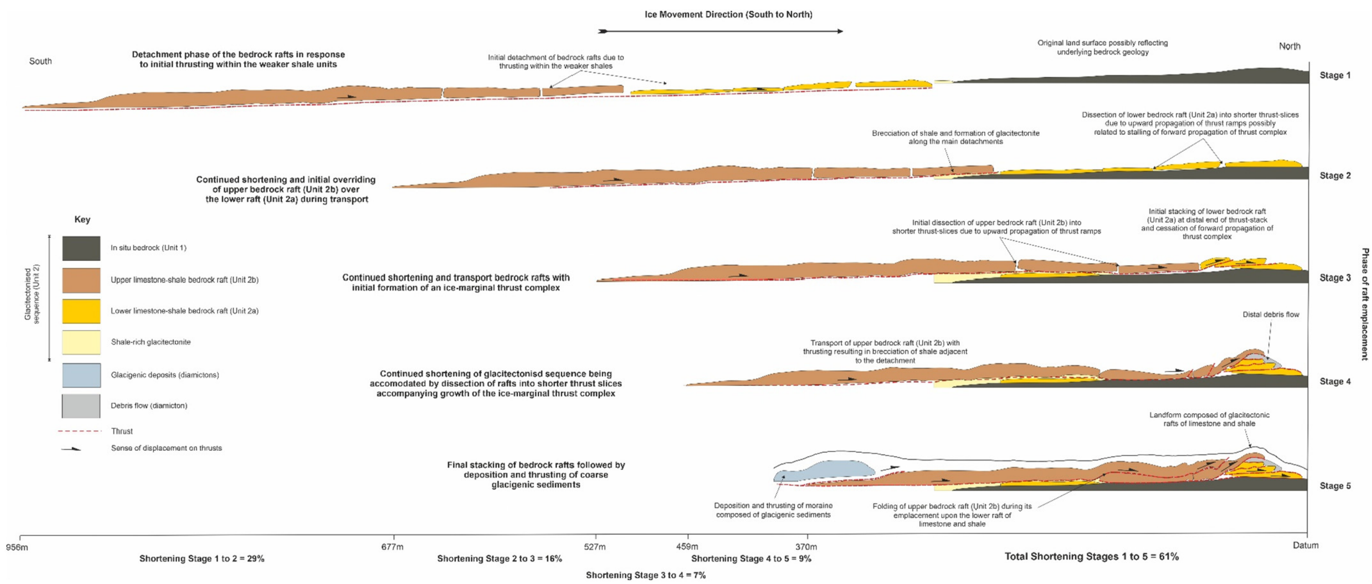


Fig. 14. Thin-skinned model for the evolution of the thrust stack at Kilcummin Head constructed using a restored cross-section through this glacitectonised sequence. The structural evolution of this glacially deformed bedrock sequence has been divided into five stages (see Section 8.1 to 8.4 for details). An estimate of the percentage shortening of the sequence at each of the five stages is also shown.

moraine composed of stacked thrust-bound blocks of limestone and mudstone (Fig. 14). The shape of the developing landform would have been partially controlled by the arched hanging-wall of the imbricate thrust stack. The steep face of the moraine is mantled by a very coarse, poorly sorted boulder diamicton comprising slab-like blocks of limestone within a mudstone-rich matrix (see Fig. 7). As noted above, the thrust-bound bedrock rafts were becoming increasingly disrupted with the limestone beds being broken into tabular slabs. During the growth of the thrust-block moraine the lee-face of this glacitectonic landform would have been unstable with rock falls and mass flows being sourced from the bedrock slices exposed on this steep slope. Importantly the resultant bedrock-rich diamicton is locally folded and/or partially overridden by the rafts (Fig. 7), supporting the conclusion that deposition of this chaotic deposit accompanied at least the later stages of the development of the thrust-block moraine.

8.4. Stage 5: final stacking of bedrock rafts followed by deposition and thrusting of the coarse glacigenic sediments

During Stage 5 the emplacement (accretion) of the bedrock rafts was completed (Fig. 14) and the forward propagation of the imbricate thrust stack had ceased. The final deformation event recorded by the glacitectonised sequence at Kilcummin Head appears to have been the deposition and penecontemporaneous thrusting and folding of the coarse, poorly lithified diamictons observed in Section 1 (Fig. 2). The bedded to massive nature of these sediments suggests that they were deposited as a series of mass flows at the ice margin. There is no evidence of these glacigenic sediments having been included within the main part of the imbricate thrust stack which is almost entirely composed of bedrock rafts with minor intercalations of mudstone-rich glacitectonite. Field evidence suggests that this thrusted and folded sequence of diamictons rests upon the trailing edge of the imbricate thrust stack (Figs. 2, 3 and 14) where it forms a distinctly separate ridge-like landform (Fig. 8a). Consequently, it is concluded that these sediments were deposited at a very late stage in the evolution of the glacitectonised sequence at Kilcummin Head, possibly as the ice retreated from the advance position marked by the earlier formed thrust moraine (see below).

The whole of the glacitectonised sequence at Kilcummin Head is mantled by a thin (<1 m thick) carapace of sandy, clast-rich diamicton (Unit 3) which is apparently unaffected by the large scale folding and thrusts, leading to the conclusion that this deposit postdates glacitectonism.

9. Implications for the glacial evolution of the Killala Bay area

Although a thin-skinned model has been proposed for the evolution of the glacitectonised sequence at Kilcummin Head, the relationship of this imbricate thrust stack to the ice as it advanced across Killala Bay requires further discussion. It is clear from the above that the geometry of all the deformation structures records a northward directed sense of shear and that glacitectonic rafting of the Carboniferous bedrock occurred during the same progressive, northerly directed deformation event. The direction of tectonic transport of the rafts during this event is consistent with the pattern of ice flow established from the landform record of the region (see Fig. 1) (Coxon, 1991; Knight, 2002; Greenwood and Clark, 2008, 2009), linking glacitectonism to the northerly directed advance of ice across Killala Bay.

Several published glacitectonic models consider that rafting occurs as a result of proglacial to ice-marginal thrusting leading to the development of an imbricate thrust stack (thrust moraine) in front of the advancing glacier or ice sheet (Banham, 1975; Christiansen and Whitaker, 1976; Moran et al., 1980; Bluemle and Clayton, 1984; Ruszczynska-Szenajch, 1987; Burke et al., 2009). The overall geometry of the imbricate thrust stack observed at Kilcummin Head is consistent with rafting having occurred at the margin of the ice as it advanced across Killala Bay. The formation of a thrust-block moraine effectively rules out a subglacial setting as this positive topographic landform requires space to accommodate the stacking of the individual thrust-bound bedrock rafts. In a subglacial setting the formation of this type of glacitectonic landform is more unlikely as the developing thrust stack would also have to 'lift' an overlying, potentially thick layer of ice.

In many of the published rafting models the processes occurring during the detachment, transport and emplacement remain poorly understood. At Kilcummin Head it is possible that the initial detachment of the rafts occurred within a thick mudstone unit which had been periglacially deformed, with brecciation occurring at the base of the active permafrost layer. If correct, this has important implications for the glacial history of the Killala Bay area indicating that it was potentially ice-free for a prolonged period prior to being inundated by ice advancing from the south (Fig. 1) (Herries-Davies, 1978; Kenyon, 1986; Coxon and Browne, 1991a). The presence of a sand-filled hydrofracture locally marking the basal décollement between the structurally higher raft (Unit 2b) and the underlying glacitectonite (Fig. 11) may indicate that the major detachments were potentially water lubricated, with overpressurised meltwater penetrating the glacier bed not only helping to detach the bedrock rafts, but also transport these slab-like bodies (*cf.*, Vaughan and Phillips, 2016; Sigfusdottir et al., 2018, 2019). Furthermore, hydrofracturing within the Carboniferous bedrock at Kilcummin Head requires the existence of a pressurised subglacial drainage system beneath the advancing ice. Pressurised subglacial meltwater systems are thought to represent one of the main factors controlling fast ice flow within former and contemporary ice streams (Clark and Stokes, 2001; Bennett, 2003; Bamber et al., 2003). Greenwood and Clark (2009) interpret the subglacial landform record in the Clew Bay and Killala Bay areas as recording fast ice flow, or ice streaming offshore. However, the relative age of the glacitectonism to this postulated ice streaming event remains uncertain.

The glacitectonism responsible for the stacking of detached thrust-bound slice of pre-existing sediments and/or bedrock is likely to form linear, ridge-like ice-pushed landforms (moraines) of various types (Banham, 1975; Aber, 1988; Krüger, 1996; Aber and Ber, 2007; Benn and Evans, 2010). Importantly, these glacitectonic landforms are developed orthogonal to the direction of ice push. At Kilcummin Head, however, the topographic high formed by the thrusted and folded bedrock and coarse glacial sediments occurs parallel to the coast, trending approximately N–S (Fig. 8a); *i.e.*, parallel to the direction of ice-push responsible for the rafting. The glacitectonised sequence at Kilcummin Head is mantled by a thin layer of sandy diamicton (Unit 3) which post-dated glacitectonism at the site. The most likely interpretation of the geological and geomorphological record preserved at Kilcummin Head is that the thrust-block moraine was overridden as the ice continued to advance across Killala Bay and further offshore. As it was overridden, the originally more extensive moraine was dissected into N–S-trending, ice-flow parallel ridges with these relicts being draped by a layer of diamicton (Unit 3) deposited either at the margin of, or beneath the advancing ice sheet. Rafting of the Carboniferous bedrock and the construction of the associated ice-marginal thrust moraine clearly marked a change in conditions at the margin of the ice sheet as it advanced across Killala Bay.

The landform record in this part of County Mayo has previously been interpreted as recording fast ice flow, or ice streaming as the ice sheet advanced offshore (Greenwood and Clark, 2009). Fast ice flow is typically equated with the development of a pressurised subglacial drainage system leading to enhanced basal sliding and the decoupling of the ice from its bed. However, at some point as the ice mass advanced into Killala Bay it must have coupled with the bed allowing the transmission of shear into the underlying Carboniferous bedrock which led to the observed glacitectonism at Kilcummin Head. The rafting of the bedrock and construction of the associated thrust moraine probably mark a point at which the ice mass may have temporarily stalled in its northward advance. It is thought that initial detachment of the rafts may have occurred along a periglacially brecciated shale horizon at depth within the Carboniferous strata, coupled with hydrofracturing of the bedrock. The presence of periglacially disrupted strata would have locally increased the permeability of the bed, reduced the efficiency of the subglacial drainage system and thereby leading to the coupling of the ice to the bedrock substrate.

In summary, the evidence suggests that thin-skinned glacitectonism of the Carboniferous bedrock at Kilcummin Head occurred at the margin of the ice sheet as it advanced northwards across Killala Bay. Rafting of the bedrock occurred at an early stage of this advance with the thrust moraine subsequently being overridden and dissected as the ice continued to extend further offshore.

10. Conclusions

The glacitectonised sequence at Kilcummin Head on the western side of Killala Bay, County Mayo, northwest Ireland comprises two laterally extensive, thrust-stacked rafts of Carboniferous limestone and mudstone emplaced upon the *in situ* bedrock of the Ballina Limestone Formation. Deformation accompanied the formation of a prominent thrust-moraine associated with northward ice advance across Killala Bay during the Midlandian. The glacitectonised bedrock at Kilcummin Head has undergone extensive deformation and shortening, with large- and small-scale deformation structures (folds, thrusts, faults) recording a consistent northward directed sense of shear with the relative intensity of deformation increasing from south to north. A five-stage thin-skinned glacitectonic model has been erected to explain the evolution of this thrust stack. Stage 1 accommodated the bulk of the shortening of the sequence and led to the initial detachment of the Carboniferous bedrock rafts and their transport upon a major décollement surface as a single, laterally extensive slab-like raft which was just a few beds thick. During Stage 2 continued shortening resulted in the development of a series of imbricate thrusts and the stacking of the rafts, a process which continued during Stages 3 and 4 leading to construction of a thrust moraine at the leading edge of the thrust stack. Stage 5 saw the final stacking of bedrock rafts which was followed by the subsequent deposition and deformation of the coarse glacigenic sediments exposed at the southern end of the Kilcummin Head section. The thrust moraine constructed during glacitectonism is associated with the early stages of ice advance and was subsequently overridden and dissected into a series of N–S-trending, ice-flow parallel ridges as the ice sheet continued to extend across Killala Bay to reach its maximum limit further offshore during the Midlandian.

Credit authorship contribution statement

David P. Vaughan: Conceptualization, Investigation, Writing – original draft. **Emrys Phillips:** Supervision, Writing – review & editing. **Jonathan R. Lee:** Supervision, Writing – review & editing. **Jane K. Hart:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank Michael Philcox for his assistance during fieldwork, and Andrew Finlayson, Gareth Carter, and Jaap van der Meer for their comments on an earlier version of this paper. Thin sections were prepared under the guidance of Adrian Palmer (Royal Holloway). We thank the two anonymous reviewers for their constructive comments during the final stages of preparation. This research was supported by, and undertaken during, a NERC-BUFI studentship. This paper is published with permission of the Director of the British Geological Survey, Natural Environmental Research Council, and with the permission of the Engineering Manager at Cathie.

References

Aber, J.S., 1985. The character of glaciotectonism. Geologie en Mijnbouw 64, 389–395.

Aber, J.S., 1988. Ice-shoved hills of Saskatchewan compared with Mississippi Delta mud lumps: implications for glaciotectonic models. In: Croot, D.G. (Ed.), Glaciotectonic Forms and Processes. Balkema, Rotterdam, pp. 1–9.

Aber, J.S., 1989. Spectrum of constructional glaciotectonic landforms. In: Goldthwait, R.P., Matsch, C.L. (Eds.), Genetic Classification of Glacigenic Deposits. Balkema, Rotterdam, pp. 281–292.

Aber, J.S., Ber, A., 2007. Glaciotectonism. Developments in Quaternary Science, vol. 6. Elsevier, Amsterdam (246 pp.).

Aber, J.S., Croot, D.G., Fenton, M.M., 1989. Glaciotectonic Landforms and Structures. Kluwer, Dortrecht.
Andersen, L.T., Hansen, D.L., Huuse, M., 2005. Numerical modelling of thrust structures in unconsolidated sediments: implications for glaciotectonic deformation. Journal of Structural Geology 27, 587–596.
Ballantyne, C.K., McCarroll, D., Stone, J.O., 2007. The Donegal ice dome, northwest Ireland: dimensions and chronology. Journal of Quaternary Science 22, 773–783.
Bamber, J.L., Baldwin, D.J., Gogineni, S.P., 2003. A new bed elevation data set for modelling the Greenland ice sheet. Annals of Glaciology 37, 351–356.
Banham, P.H., 1975. Glaciotectonic structures: a general discussion with particular reference to the contorted drift of Norfolk. In: Wright, A.E., Moseley, F. (Eds.), Ice Ages: Ancient and Modern. Seel House Press, Liverpool, pp. 69–94.
Banham, P.H., 1977. Glaciotectonites in till stratigraphy. Boreas 6, 101–105.
Banham, P.H., 1988. Polyphase glaciotectonic deformation in the Contorted Drift of Norfolk. In: Croot, D.G. (Ed.), Glaciotectonics: Forms and Processes. Balkema, Rotterdam, pp. 27–32.
Benediktsson, I.O., Möller, P., Ingólfsson, Ó., van der Meer, J.J.M., Kjær, K.H., Krüger, J., 2008. Instantaneous end moraine and sediment wedge formation during the 1890 glacier surge of Brúarjökull. Iceland Quaternary Science Reviews 27, 209–234.
Benetti, S., Dunlop, P., Ó Cofaigh, C., 2010. Glacial and glacially-related features on the continental margin of northwest Ireland mapped from marine geophysical data. Journal of Maps 14–29.
Benn, D., Evans, D.J.A., 2010. Glaciers and Glaciation.
Bennett, M.R., 2003. Ice streams as the arteries of an ice sheet: their mechanics, stability and significance. Earth-Science Reviews 61, 309–339.
Berthelsen, A., 1979. Recumbent folds and boudinage structures formed by subglacial shear: an example of gravity tectonics. Geologie en Mijnbouw 58, 253–260.
Bluemle, J.P., Clayton, L., 1984. Large-scale glacial thrusting and related processes in North Dakota. Boreas 13, 279–299.
Boulton, G.S., Caban, P., 1995. Groundwater flow beneath ice sheets, part II. It's impact on glacier tectonic structures and moraine formation. Quaternary Science Reviews 14, 563–587.
Boulton, G.S., van der Meer, J.J.M., Hart, J., Beets, D., Ruegg, G.H.J., van der Wateren, F.M., Jarvis, J., 1996. Till and moraine emplacement in a deforming bed surge — an example from a marine environment. Quaternary Science Reviews 15, 961–987.
Broster, B.E., Seaman, A.A., 1991. Glacigenic rafting of weathered granite: Charlie Lake, New Brunswick. Canadian Journal of Earth Sciences 28, 649–654.
Büdel, J., 1982. Climatic Geomorphology. Princeton University Press, Princeton.
Burke, H., Phillips, E., Lee, J.R., Wilkinson, I.P., 2009. Imbricate thrust stack model for the formation of glaciotectonic rafts: an example from the Middle Pleistocene of north Norfolk, UK. Boreas 38, 620–637.
Carr, S.J., Lee, J.A., 1998. Thin section production of diamicts; problems and solutions. Journal of Sedimentary Research 68, 218–220.
Charlesworth, J.K., 1924. The glacial geology of the north-west of Ireland. Proceedings of the Royal Irish Academy 36B, 174–314.
Charlesworth, J.K., 1928. The glacial geology of north Mayo and west Sligo. Proceedings of the Royal Irish Academy 38B, 100–115.
Christiansen, E.A., Whitaker, S.H., 1976. Glacial thrusting of drift and bedrock. Glacial till, an interdisciplinary study. Royal Society of Canada. Special Publication 12, 121–130.
Clark, C.D., Meehan, R.T., 2001. Subglacial bedform geomorphology of the Irish Sea Ice Sheet reveals major configuration changes during growth and decay. Journal of Quaternary Science 16, 483–496.
Clark, C.D., Stokes, C.R., 2001. Extent and basal characteristics of the M'Clintock Channel Ice Stream. Quaternary International 86, 81–101.
Colhoun, E.A., 1973. Two Pleistocene sections in south-western Donegal and their relation to the last glaciation of the Glengesh plateau. Irish Geography 6, 594–609.
Cooper, M.R., Johnston, T.P., 2004a. Late Palaeozoic intrusives. In: Mitchell, W.I. (Ed.), The Geology of Northern Ireland: Our Natural Foundation, 2nd Edition Geological Survey of Northern Ireland, Belfast, pp. 61–88.
Cooper, M.R., Johnston, T.P., 2004b. Palaeogene intrusive igneous rocks. In: Mitchell, W.I. (Ed.), The Geology of Northern Ireland: Our Natural Foundation, 2nd Edition Geological Survey of Northern Ireland, Belfast, pp. 179–198.
Coude, A., 1989. Comparative study of three drumlin fields in western Ireland: geomorphological data and genetic implications. Sedimentary Geology 62, 321–335.
Coxon, P., 1991. Field Guide to the Quaternary of North Mayo. Irish Association for Quaternary Studies (IQUA), Dublin.
Coxon, P., Browne, P., 1991a. The Nephin Beg range and the Late Glacial. In: Coxon, P. (Ed.), North Mayo. Field Guide No. 14. Irish Quaternary Association (IQUA), Dublin, pp. 41–49.
Coxon, P., Browne, P., 1991b. Glacial deposits and landforms of central and western Ireland. In: Ehlers, J., Gibbard, P.L., Rose, J. (Eds.), Glacial Deposits in Britain and Ireland. Balkema, Rotterdam, pp. 355–365 (1991).
Coxon, P., Hannon, G., 1991. The interglacial deposits at Derrynadivva and Burren Townland. In: Coxon, P. (Ed.), North Mayo. Field Guide No. 14. Irish Quaternary Association (IQUA), Dublin, pp. 24–36.
Dunlop, P., Shannon, R., McCabe, M., Quinn, R., Doyle, E., 2010. Marine geophysical evidence for ice sheet extension and recession on the Malin Shelf: new evidence for the western limits of the British Irish Ice Sheet. Marine Geology 276, 86–99.
Evans, D.J.A., Phillips, E.R., Hiemstra, J.F., Auton, C.A., 2006. Subglacial till: formation, sedimentary characteristics and classification. Earth Science Reviews 78, 115–176.
Evans, D.J.A., Phillips, E.R., Atkinson, N., 2021. Glacitectonic rafts and their role in the generation of Quaternary subglacial bedforms and deposits. Quaternary Research, 1–35 https://doi.org/10.1017/qua.2021.11.
French, H.M., Bennett, L., Hayley, D.W., 1986. Ground ice conditions near Rea Point and on Sabine Peninsula, eastern Melville Island. Canadian Journal of Earth Sciences 23, 1389–1400.
Gehrmann, A., Hüneke, H., Meschede, M., Phillips, E., 2017. 3D microstructural architecture of deformed glacigenic sediments associated with large-scale glacitectonism, Jasmund Peninsula (NE Rügen), Germany. Journal of Quaternary Science 32, 213–230.
Glynn, B., Brown, C., Rooney, S., 2008. Coincident swath acoustic backscatter and bathymetry for the interpretation of shallow-water sediment composition and processes. Journal of the Geological Society, London 165, 597–607.
Graham, J.R., 2010. The Carboniferous geology of North Mayo. Irish Journal of Earth Sciences 28, 25–45.
Greenwood, S., Clark, C.D., 2008. Subglacial bedforms of the Irish Ice Sheet. Journal of Maps 2008, 332–357.
Greenwood, S.L., Clark, C.D., 2009. Reconstructing the last Irish Ice Sheet 2: a geomorphologically-driven model of ice sheet growth, retreat and dynamics. Quaternary Science Reviews 28, 3101–3123.
Hall, K., 1999. The role of thermal stress fatigue in the breakdown of rock in cold regions. Geomorphology 31, 47–63.
Hall, K., Thorn, C.E., Matsuoka, N., Prick, A., 2002. Weathering in cold regions: some thoughts and perspectives. Progress in Physical Geography 26, 577–603.
Harris, C., Williams, G., Brabham, P., Eaton, G., McCarroll, D., 1997. Glaciotectonized Quaternary sediments as Dinas Dinlle, Gwynedd, North Wales, and the bearing on the style of deglaciation in the eastern Irish Sea. Quaternary Science Reviews 16, 109–127.
Hart, J.K., 1990. Proglacial glaciotectonic deformation and the origin of the Cromer Ridge push moraine complex, North Norfolk, England. Boreas 19, 165–180.
Hart, J.K., Boulton, G.S., 1991a. The glacial drifts of Norfolk. In: Ehlers, J., Gibbard, P.L., Rose, J. (Eds.), Glacial Deposits of Great Britain and Ireland. Balkema, Rotterdam, pp. 233–243.
Hart, J.K., Boulton, G.S., 1991b. The interrelation of glaciotectonic and glaciodepositional processes within the glacial environment. Quaternary Science Reviews 10, 335–350.
Hart, J.K., Rose, J., 2001. Approaches to the study of glacier bed deformation. Quaternary International 86, 45–58.
Herries-Davies, G.L., 1978. Ireland: The Geomorphology of the British Isles. Methuen, London 0-416-84640-8.
Hiemstra, J., Evans, D.J.A., Ó Cofaigh, C., 2007. The role of glaciotectonic rafting and comminution in the production of subglacial tills: examples from southwest Ireland and Antarctica. Boreas 36, 1–15.
Higginbottom, I.E., Fookes, P.G., 1970. Engineering aspects of periglacial features in Britain. Quarterly Journal of Engineering Geology and Hydrology 3, 85–117.
Jakobsen, P.R., 1996. Distribution and intensity of glaciotectonic deformation in Denmark. Bulletin of the Geological Society of Denmark 42, 175–185.
Kenyon, R., 1986. The glaciation of the Nephin Beg range, Co. Mayo, Eire. Quaternary Studies 2, 14–21.
Kjær, K.H., Larson, E., van der Meer, J.J.M., Ingólfsson, Ò., Krüger, J., Benediktsson, Ì.Ö., Knudsen, C.G., Schomacker, A., 2006. Subglacial decoupling at the sediment/bedrock interface: a new mechanism for rapid flowing ice. Quaternary Science Reviews 25, 2704–2712.
Knight, J., 2002. Glacial sedimentary evidence supporting stick-slip basal ice flow. Quaternary Science Reviews 21, 1–9.
Knight, J., 2006. Geomorphic evidence for active and inactive phases of Late Devensian ice in north-central Ireland. Geomorphology 75, 4–19.
Knight, J., 2009. Subglacial erosion forms in northwest Ireland. Boreas 38, 545–554.
Knight, J., McCabe, A.M., 1997. Drumlin evolution and ice sheet oscillations along the NE Atlantic margin, Donegal Bay, western Ireland. Sedimentary Geology 111, 57–72.
Knight, J., Coxon, P., McCabe, A.M., McCarron, S.G., 2004. Pleistocene glaciations in Ireland. In: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations — Extent and Chronology: Part 1: Europe. Elsevier, Amsterdam, pp. 183–191.
Krüger, J., 1996. Moraine ridges formed from subglacial frozen-on sediment slabs and their differentiation from push-moraines. Boreas 25, 57–63.
Lee, J.R., Phillips, E., 2008. Progressive soft sediment deformation within a subglacial shear zone — a hybrid mosaic-pervasive deformation model for Middle Pleistocene glaciotectonised sediments from Eastern England. Quaternary Science Reviews 27, 1350–1362.
Lee, J.R., Phillips, E., Booth, S.J., Rose, J., Jordan, H.M., Pawley, S.M., Warren, M., Lawley, R.S., 2013. A polyphase glacitectonic model for ice-marginal retreat and terminal moraine development: the Middle Pleistocene British Ice Sheet, northern Norfolk, UK. Proceedings of the Geologists Association 124, 753–777.
Long, C.B., et al., 1992. Geology of North Mayo. Dublin, Geological Survey of Ireland.
McCabe, A.M., 1987. Quaternary deposits and glacial stratigraphy in Ireland. Quaternary Science Reviews 6, 259–299.
McCabe, A.M., 2008. Glacial Geology and Geomorphology: The Landscapes of Ireland. Dunedin Press, Edinburgh (274 pp.).
McCabe, A.M., Clarke, P.U., Clarke, J., 2007. Radiocarbon constraints on the history of the western Irish ice sheet prior to the Last Glacial Maximum. Geology 35, 147–150.
McCarron, S., 2013. Offshore evidence. In: Warren, G.M., Davies, S. (Eds.), North Mayo, Field Guide No. 31. Irish Quaternary Association, Dublin, pp. 10–19.
Mellett, C.L., Phillips, E., Lee, J.R., Cotterill, C.J., Tjelta, T.I., James, L., Duffy, C., 2019. Elsterian ice sheet retreat in the southern North Sea: antecedent controls on large-scale glacitectonics and subglacial bed conditions. Boreas 49, 129–151.
Menzies, J., 2000. Micromorphological analyses of microfabric and microstructures indicative of deformation processes in glacial sediments. In: Maltman, A.J., Hubbard, B., Hambrey, M.J. (Eds.), Deformation of Glacial Materials, Geological Society Special Publications, vol. 176, pp. 245–258 (London).
Merritt, J.W., Akhurst, M.C., Wilkinson, I.P., Riding, J.B., Phillips, E.R., Smith, R.A., Finlayson, A., Dean, M.T., 2014. The Late Pleistocene Afton Lodge Clay Formation, Ayrshire, Scotland: evidence for Early to Middle Devensian climatic changes and Late Devensian onshore

ice flow and rafting from the Firth of Clyde. Proceedings of the Geologists' Association 125, 195–214.
Mooers, H.D., 1990. Ice-marginal thrusting of drift and bedrock: thermal regime, subglacial aquifers, and glacial surges. Canadian Journal of Earth Sciences 27, 849–862.
Moran, S.R., Clayton, L., Hooke, R.L., Fenton, M.M., Andriashek, L.D., 1980. Glacier-bed landforms of the prairie region of North America. Journal of Glaciology 25, 457–476.
Murton, J.B., 1996. Near-surface brecciation of chalk, Isle of Thanet, south-east England: a comparison with ice-rich brecciated bedrocks in Canada and Spitsbergen. Permafrost and Periglacial Processes 7, 153–164.
Murton, J.B., Peterson, R., Ozouf, J.-C., 2006. Bedrock fractured by ice segregation in cold regions. Science 314, 1127–1129.
Ó Cofaigh, C., Dunlop, P., Benetti, S., 2010a. Marine geophysical evidence for Late Pleistocene ice sheet extent and recession off north-west Ireland. Quaternary Science Reviews 44, 147–159.
Ó Cofaigh, C., Evans, D.J.A., Hiemstra, J.F., 2010b. Formation of a stratified 'till' assemblage by ice-marginal thrusting and glacier overriding. Boreas 40, 1–14.
O'Reilly, Shannon, P.M., Readman, P.W., 2007. Shelf to slope sedimentation processes and the impact of Plio-Pleistocene glaciations in the northeast Atlantic, west of Ireland. Marine Geology 238, 21–44.
Passchier, C.W., Trouw, R.A.J., 1996. Microtectonics. Springer-Verlag, Berlin (ISBN: 3540587136).
Peacock, J.D., Merritt, J.W., 1997. Glacigenic rafting at Castle Hill, Gardenstown, and its significance for the glacial history of northern Banffshire, Scotland. Journal of Quaternary Science 12, 283–294.
Peake, N.B., Hancock, J.M., 1961. The Upper Cretaceous of Norfolk. In: Larwood, G.P., Funnell, B.M. (Eds.), The Geology of Norfolk. Castle Museum, Norwich, pp. 293–339.
Pedersen, S.A.S., 1987. Comparative studies of gravity tectonics in Quaternary sediments and sedimentary rocks related to fold belts. In: Jones, M.E., Preston, R.M.F. (Eds.), Deformation of Sediments and Sedimentary Rocks, Geological Society Special Publication, vol. 29, pp. 165–180.
Pedersen, S.A.S., 2005. Structural analysis of the Rubjerg Knude Glaciotectonic Complex, Vendsyssel, northern Denmark. Geological Survey of Denmark and Greenland Bulletin 8 (192 pp.).
Pedersen, S.A.S., 2014. Architecture of glaciotectonic complexes. Geosciences 4, 269–296.
Philcox, M., 2013. Glacio-tectonics at Kilcummin Head, Co. Mayo. In: Warren, G.M., Davies, S. (Eds.), North Mayo, Field Guide No. 31. Irish Quaternary Association, Dublin, pp. 39–52.
Phillips, E., Merritt, J., 2008. Evidence for multiple water-escape during rafting of shelly marine sediments at Clava, Inverness-shire, NE Scotland. Quaternary Science Reviews 27, 988–1011.
Phillips, E.R., Evans, D.J.A., Auton, C.A., 2002. Polyphase deformation at an oscillating ice margin following the Loch Lomond Readvance, central Scotland, UK. Sedimentary Geology 149, 157–182.
Phillips, E., Merritt, J., Auton, C.A., Golledge, N., 2007. Microstructures in subglacial and proglacial sediments: understanding faults, folds and fabrics and the influence of water on the style of deformation. Quaternary Science Reviews 26, 1499–1528.
Phillips, E., Lee, J.R., Burke, H., 2008. Progressive proglacial to subglacial deformation and syntectonic sedimentation at the margins of the Mid-Pleistocene British Ice Sheet: evidence from north Norfolk, UK. Quaternary Science Reviews 27, 1848–1871.
Phillips, E., van der Meer, J.J.M., Ferguson, A., 2011. A new 'microstructural mapping' methodology for the identification, analysis and interpretation of polyphase deformation within subglacial sediments. Quaternary Science Reviews 30, 2570–2596.
Phillips, E., Evans, D.J.A., Atkinson, N., Kendall, A., 2017a. Structural architecture and glacitectonic evolution of the Mud Buttes cupola hill complex, southern Alberta, Canada. Quaternary Science Reviews 164, 110–139.
Phillips, E., Cotterill, C., Johnson, K., Crombie, K., James, L., Carr, S., Ruiter, A., 2017b. Large-scale glacitectonic deformation in response to active ice sheet retreat across Dogger Bank (southern central North Sea) during the Last Glacial Maximum. Quaternary Science Reviews 179, 24–47.
Phillips, E., Johnson, K., Ellen, R., Plenderleith, G., Dove, D., Carter, G., Dakin, N., Cotterill, C., 2022. Glacitectonic evidence of ice sheet interaction and retreat across the western part of Dogger Bank (North Sea) during the Last Glaciation. Proceedings of the Geologists' Association 133, 87–111.
Reade, T.M., 1882. On the chalk-masses or boulders included in the Contorted Drift of Cromer, their origin and mode of transport. Quarterly Journal of the Geological Society of London 28, 222–238.
Rijsdijk, K.F., Owen, G., Warren, W.P., McCarroll, D., van der Meer, J.J.M., 1999. Clastic dykes in over-consolidated tills: evidence for subglacial hydrofracturing at Killiney Bay, eastern Ireland. Sedimentary Geology 129, 111–126.
Ruszczynska-Szenajch, H., 1987. The origin of glacial rafts: detachment, transport, deposition. Boreas 16, 101–112.
Ruszczynska-Szenajch, H., 1988. Glaciotectonics and its relationship to other glaciogenic processes. In: Croot, D.G. (Ed.), Glaciotectonic Forms and Processes. A.A. Balkema, Rotterdam, pp. 191–193.
Sejrup, H.P., Hjelstuen, B.O., Torbjørn Dahlgren, K.I., Haflidason, H., Kuijpers, A., Nygård, A., Praeg, D., Stoker, M.S., Vorren, T.O., 2005. Pleistocene glacial history of the NW European continental margin. Marine and Petroleum Geology 22, 1111–1129.
Sigfusdottir, T., Benediktsson, I.O., Phillips, E., 2018. Active retreat of a Late Weichselian marine-terminating glacier: an example from Melasveit, western Iceland. Boreas 47, 813–836.
Sigfusdottir, T., Phillips, E., Benediktsson, I.O., 2019. The role of pressurised water in large-scale glaciotectonic thrusting: evidence from submarine, ice-marginal thrust-block moraines in Melasveit, W-Iceland. Quaternary Research 93, 88–109.
Slater, G., 1926. The structure and disturbed deposits of Moens Klint, Denmark. Transaction of the Royal Society of Edinburgh 55, 289–302.
Slater, G., 1927. Studies in the drift deposits of the south-west part of Suffolk: the structure of the disturbed deposits in the lower part of the Gipping Valley near Ipswich. Proceedings of the Geologists' Association 38, 157–216.
Smith, M.J., Dunlop, P., Clark, C.D., 2006. An overview of sub-glacial bedforms in Ireland, mapped from digital elevation data. In: Knight, P. (Ed.), Glacier Science and Environmental Change. Blackwell, London, pp. 384–386.
Smith, M.J., Knight, J., Field, K.S., 2008. Glacial striae observations for Ireland compiled from historic records. Journal of Maps 2008, 378–398.
Stalker, A., Mac, S., 1976. Megablocks, or the enormous erratic of the Albertan Prairies. Geological Survey of Canada Paper 76-1C, pp. 185–188.
Stoker, M.S., Holmes, R., 1991. Submarine end-moraines as indicators of Pleistocene ice limits off northwestern Britain. Journal of the Geological Society, London 148, 431–434.
Stone, J.J., 1991. North Mayo — regional geology. In: Coxon, P. (Ed.), Field Guide to the Quaternary of North Mayo. Irish Quaternary Association (IQUA), Dublin, pp. 4–11.
Symes, R.G., 1876. Killala map sheet 53, 1:63 360 series. Available online at:Geological Survey of Ireland http://www.geologicalmaps.net/irishhistmaps/.
Symes, R.G., 1877. Downpatrick Head map sheet 41, 1:63 360 series. Available online at: Geological Survey of Ireland http://www.geologicalmaps.net/irishhistmaps/.
Symes, R.G., Baily, W.H., 1845. Geological Survey of Ireland Memoir. p. 53.
Synge, F.M., 1963. The glaciation of the Nephin Beg range, County Mayo. Irish Geography 4, 397–403.
van der Meer, J.J.M., 1987. Tills and end moraines in The Netherlands and NW Germany. In: van der Meer, J.J.M. (Ed.), Tills and Glacitectonics. Balkema, Rotterdam, pp. 261–268.
van der Meer, J.J.M., 1993. Microscopic evidence of subglacial deformation. Quaternary Science Reviews 12, 553–587.
van der Wateren, F.M., Kluiving, S.J., Bartek, L.R., 2000. Kinematic indicators of subglacial shearing. In: Maltman, A., Hubbard, B., Hambrey, M.J. (Eds.), Deformation of Glacial Materials, Geological Society, London, Special Publication, vol. 176, pp. 259–278.
van Gijssel, K., 1987. A lithostratigraphic and glacitectonic reconstruction of the Lamstedt Moraine, Lower Saxony (FRG). In: van der Meer, J.J.M. (Ed.), Tills and Glaciotectonics. Balkema, Rotterdam, pp. 145–156.
Vaughan, D.P., Phillips, E.R., 2016. Mid-Pleistocene thin-skinned glaciotectonic thrusting of the Aberdeen Ground Formation, Central Graben region, central North Sea. Journal of Quaternary Science Special Issue: The Quaternary of the North Sea Basin 196–212.
Vaughan-Hirsch, D.P., Phillips, E.R., Lee, J.R., Burke, H.F., Hart, J.K., 2011. Glacitectonic rafting of chalk bedrock: overstrand. In: Phillips, E., Lee, J.R., Evans, H.M. (Eds.), Glacitectonics — Field Guide. Quaternary Research Association, Pontypool, pp. 198–217.
Vaughan-Hirsch, D.P., Phillips, E.R., Lee, J.R., Hart, J.K., 2013. Micromorphological analysis of poly-phase deformation associated with the transport and emplacement of glaciotectonic rafts at West Runton, north Norfolk, UK. Boreas 42, 376–394.
Williams, P.J., Smith, M.W., 1989. The frozen earth; fundamentals of geocryology. Studies in Polar Research Series, vol. 306. Cambridge University Press (ISBN: 0 521 36534 1).