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Sedimentological reconstruction of Glan-y-môr Isaf, North Wales: A model for the formation of stratified subglacial till assemblages from glaciolacustrine deposits

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ABSTRACT

Reconstruction of an understudied region of North Wales, north of the Llŷn Peninsula, redefines the dynamics and interaction of the Welsh Ice Cap and Irish Sea Ice Stream during the deglaciation of the last British-Irish Ice Sheet. Sedimentological research highlights the role of topography in creating distinct glacial environments as the Irish Sea Ice Stream retreated northwards from North Wales. Insights are gained into the production of stratified tills from previously deposited glaciolacustrine sediments and outwash sandur in a region where an ice-margin advanced over the site. Sedimentary analyses, including data on clast form, fabric, and diamicton particle size, are used to produce lithofacies profiles from which interpretations can be made into the styles of deposition and environmental change. Multiphase deposition, initially from Welsh ice flowing northwest, details a transition from a subglacial traction till to a distal, ice-marginal glaciolacustrine setting with laminated varves marking retreat. Above, sands and gravels formed by gravity flow, turbidity currents, and outwash document ice advance, then are capped by another subglacial traction till composed of Irish Sea deposits.

Sediments capture one of many oscillations of the Irish Sea Ice Stream along the North Wales coast while the ice remained anchored on Anglesey. Sedimentological analysis fortifies evidence that the last ice sheet, especially its ice stream outlets, was highly dynamic and oscillatory, responded heavily to topography, and created various ice-marginal environments during deglaciation.

This study presents a four-stage model for the formation of stratified tills at Glan-y-môr Isaf, beginning with initial glaciolacustrine sedimentation, ice then advanced towards the site, and finally overrode the pre-existing sediments. Processes forming stratified tills began with the contemporaneous deposition of outwash and deformation via glaciotectonism. Till stratification occurred from the cannibalisation of pre-existing laminated material into a subglacially deforming till layer, which laterally homogenised sediments over short transport distances and continued to occur well after ice had readvanced into the area. Crucially, sediments portray the complex behaviour of ice sheets in forming glacial sediments and provide knowledge that must be taken into consideration when modelling contemporary ice sheets.

1. Introduction

Large uncertainty exists surrounding ice-marine interactions on ice sheet scales and the impacts these will have on potential sea level rise and the climate system (e.g., Pollard et al., 2015; DeConto and Pollard, 2016; Edwards et al., 2019; Armstrong-McKay et al., 2022; Naughten et al., 2023) – important information if effective policy choices are to be made for the future stability of the Greenland and Antarctic ice sheets (e.g., Joughin et al., 2014; Golledge et al., 2015; Scambos et al., 2017; IPCC et al., 2019; King et al., 2020; IPCC et al., 2021). However, the observational record is hindered: ice sheets respond to forcings over millennia (Barry et al., 2009), hence affirming the need for accurate, space- and time-constrained reconstructions at different spatial scales (e.g., Benn, 1995; Evans & Ó Cofaigh, 2008; Roberts et al., 2013; Chiverrell et al., 2018; Callard et al., 2020; Benetti et al., 2021; Scourse et al., 2021; Clark et al., 2022).

The British-Irish Ice Sheet (BIIS) has been fundamental in developing understandings of ice sheet dynamics and providing a comprehensive dataset to test ice sheet models; recently amplified by BRITICE-CHRONO (Clark et al., 2021). The main aim of this project was to update the

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deglacial record of the BIIS's marine sectors using landform, sedimentological, and geochronological evidence (Patton et al., 2013a; Bradwell et al., 2019, 2021; Callard et al., 2020; Van Landeghem and Chiverrell, 2020; Evans et al., 2021; Simms et al., 2022). The BIIS was drained by asynchronous, transient ice streams which fluctuated in extent and intensity, with characteristic binge-purge cycles recorded by Ice Rafted Detritus (IRD) deposits and diagnostic geomorphic differences between the operation of cold and warm based ice (Hubbard et al., 2009). Bennett (2003) demonstrates the significance of basal conditions beneath ice streams for their flow speed and stability. Marine-based ice streams often have ice shelves which provide buttressing force to the ice upstream, loss of which could cause major ice sheet collapse (e.g. De Angelis and Skvarca, 2003; Pritchard et al., 2009; Joughin et al., 2014; Mengel and Levermann, 2014; Fürst et al., 2016; Scambos et al., 2017), a process which likely contributed to the demise of the last BIIS (Bradwell et al., 2019; Ó Cofaigh et al., 2019; Benetti et al., 2021; Clark et al., 2021). Across the BIIS, reconstruction denotes similar scenarios of retreat, initially driven by local ice loading which increased water depths and stimulated ice shelves as opposed to ocean or atmosphere temperature forcings. This is consistent with the nature of retreat recorded by Ó Cofaigh et al. (2019) on the Atlantic shelf northwest of Ireland where early deglaciation was driven by glacioisostatic depression and high relative sea level. Bathymetry is also noted as a major control over the pace of ice stream retreat: pinning points slowing retreat and retrograde slopes causing speed-up, very similar to other examples both palaeo and contemporary (Thomas et al., 2004; Stokes et al., 2007; Joughin et al., 2014; Jones et al., 2015; Arndt et al., 2018; Small et al., 2018; Bradwell et al., 2019, 2021; Hogan et al., 2020). Retreat is often marked by oscillations, evidenced by bathymetric data, retreat moraines, grounding-zone wedges and tectonised sediment (Evans & Ó Cofaigh, 2003; Thomas and Chiverrell, 2007; Smedley et al., 2017; Chiverrell et al., 2018; Callard et al., 2020; Evans et al., 2021).

Within BIIS reconstruction, building and developing sedimentological process-form relationships are key (Lukas et al., 2013; Evans and Benn, 2021). North Wales is one such location where recent studies are limited. The coastline here was impinged by the Irish Sea Ice Stream (ISIS) which flowed down the Irish Sea Basin (ISB) and characterised similar oscillatory and dynamic processes to other ice streams of the BIIS (e.g., Chiverrell et al., 2018; Callard et al., 2020). Recent work on the ISIS (e.g., Edge et al., 1990; Harris et al., 1997; Thomas and Chiverrell, 2007; Van Landeghem et al., 2009; Smedley et al., 2017; Chiverrell et al., 2018) demonstrates changing ice flow patterns, formation of ice-marginal lakes, and an ice stream profoundly impacted by the adjacent topography. Sediments deposited should reflect these conditions and adding updated knowledge surrounding both the ISIS and the genesis of sediments will help assemble a better picture of ice dynamism and more broadly the behaviour of major ice streams.

2. Ice sheet history

2.1. Irish Sea basin

The ISB (Fig. 1) extends 300 km from southern Scotland down to the Celtic Sea and can be split into three regions: St George's Channel in the south, the North Channel and the central trough connecting them. Clark et al. (2022) discuss that by 31 ka, ice had started to build on topographic high points including central Scotland, Northern Ireland, and Shetland. Ice that would have fed the oncoming ISIS from these centres coalesced around 30 ka and began to flow down the northern end of the ISB. Peninsulas such as Pembroke in southwest Wales and Llŷn and Anglesey in northwest Wales, would have constricted ice flow in this region. Chronological and sedimentological evidence from Ó Cofaigh and Evans (2007) alongside modelling in both Clark et al. (2022) and Hughes et al. (2014) detail that ice advance in the ISB likely occurred before the advance of ice terrestrially into southern areas of Britain and Ireland. It is debated when ice from the Welsh Ice Cap (WIC) and Lake

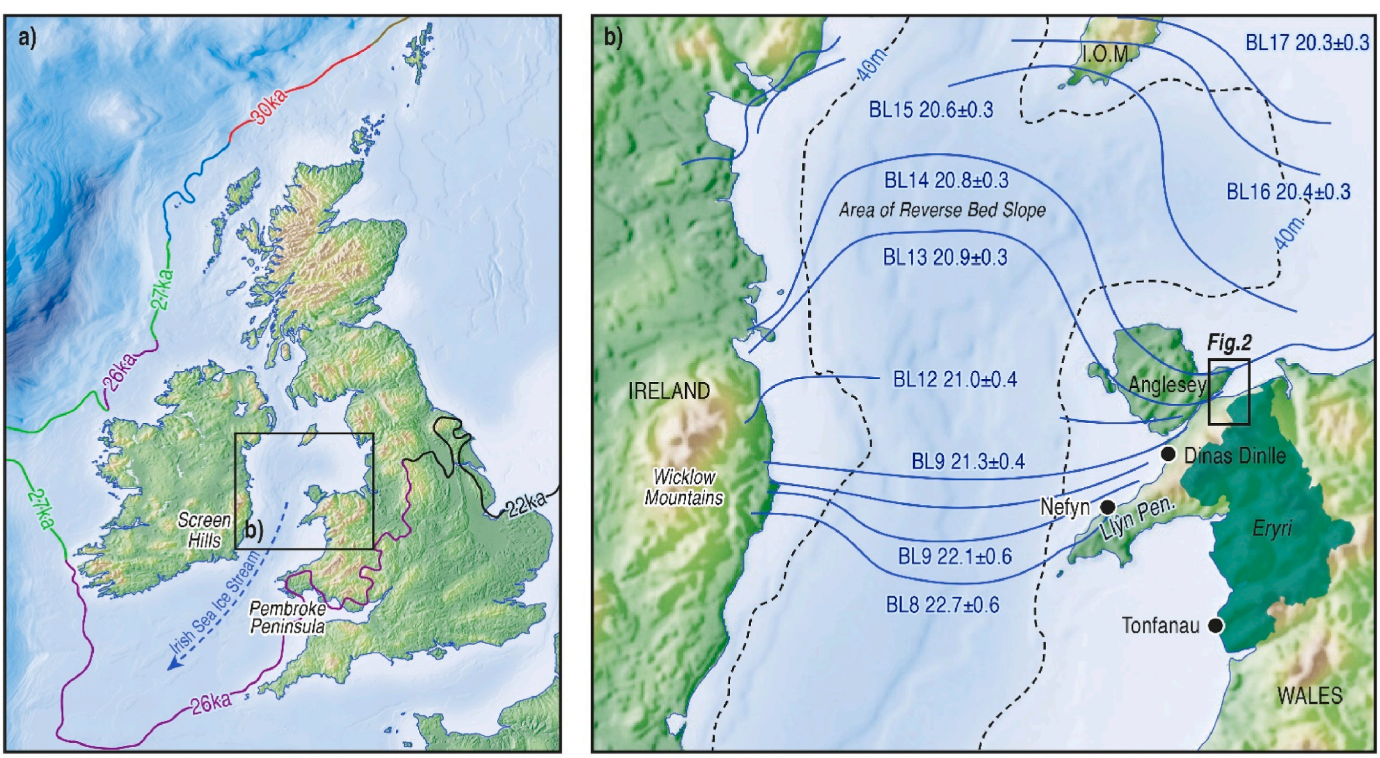

Fig. 1. (a) Map detailing the maximum extent of the BIIS with the timing of retreat for each sector highlighted (dates taken from Clark et al., 2022). The path taken by the ISIS is shown. (b) Deglacial reconstruction of the ISIS around North Wales, illustrating the ice-marginal Boundary Limits (BL) from Scourse et al. (2021) with ages given in cal ka BP ±1 σ, and the −40 m contour given to mark historic relative sea level (Bradley et al., 2011). Specific locations mentioned throughout the text are labelled with black points. An inset box in (b) shows the study area, shown in more detail in Fig. 2.

District started to flow out into the basin (Livingstone et al., 2012; Patton et al., 2013b; Clark et al., 2022), but Clark et al. (2022) model their growth around 29–28 ka. By 27 ka, the ice centres had completely merged, and evidence builds for the formation of a fast-flowing ice stream (Van Landeghem et al., 2009) based on the diagnostic morphologies of fast-flowing ice in

contemporary ice streams (e.g. Blankenship et al., 1986; King et al., 2009). These include mega-scale glacial lineations and highly-attenuated bedforms as a product of convergent flow, sharply delineated shear margins, and Boothia-type dispersal trains on soft deformable sediments (Stokes and Clark, 1999). Evidence for these features in the ISB has been provided by previous studies (e.g., Roberts et al., 2007; Van Landeghem et al., 2009; Van Landeghem and Chiverrell, 2020). Although long debated, the ice stream reached its short-lived maxima at the continental shelf in the Celtic Sea, as indicated by bathymetry data, ocean coring and chronology, and geomorphic evidence on the Isles of Scilly (Ó Cofaigh and Evans, 2007; Praeg et al., 2015; Scourse et al., 2019; Scourse et al., 2021).

The deglaciation of the ISIS has been physically described by site-specific studies alongside larger Bayesian modelling papers (e.g. Chiverrell et al., 2018; Small et al., 2018; Clark et al., 2021; Scourse et al., 2021; Clark et al., 2022). Deglaciation began around 25.6 ± 0.5 ka and ice rapidly retreated into the confines of the basin. Both advance to the continental shelf and retreat throughout deglaciation up the ISB were conditioned by ocean bathymetry, adjacent terrestrial topography and dynamic thinning during its final rapid retreat (e.g. Small et al., 2018; Scourse et al., 2021; Clark et al., 2022) contrasting with the ISIS's terrestrial cousin which is governed by ocean-climate forcings (Chiverrell et al., 2021). Pinning points along the basin include the Pembroke and Llŷn peninsulas, and islands such as Anglesey and Isle of Man, and caused the deceleration of the ice margin as revealed in Fig. 1b showing results from Scourse et al. (2021). Pembroke became ice free around 24 ka, Llŷn and Anglesey at 21 ka, and the Isle of Man by 19 ka, however, these Bayesian results contrast to the individual in situ data points for each location which do not show deglaciation until much later; Chiverrell et al. (2018) highlight how the role of topography in decelerating the ISIS and modulating ice flow has often been underappreciated in ice flow models. Local scale studies in places such as the Screen Hills (Ireland), Llŷn Peninsula, and Isle of Man reveal areas of thick coastal till sequences, discussed later, which have been used to exhibit the oscillatory nature of the ice margin (Evans & Ó Cofaigh, 2003; Thomas et al., 2004; Thomas and Chiverrell, 2007; Small et al., 2018). Smedley et al. (2017) demonstrate from a chronological framework, using Optically Stimulated Luminescence (OSL) dates reconstructed from the Llŷn Peninsula, that ISIS retreat during 24–20 ka showed centennial-scale oscillatory behaviour despite stable climatic and sea level mechanisms. Oscillations were instead caused by internal ice dynamics and topographic forcings, as ice transitioned into an area of reverse bed slope and a widening calving margin north of Anglesey. Behaviour modulated by topography, rising relative sea levels and oscillations likens the ISIS to other ice streams on the BIIS and the contemporary ice streams of Antarctica and Greenland (Chiverrell et al., 2018; Clark et al., 2022; Van Landeghem and Chiverrell, 2022).

Sedimentary records in the ISB comprise Quaternary muds to over-consolidated tills interbedded with sand and gravel, typically under 20 m in thickness, but can increase to over 100 m in relict glacial valleys (Mellett et al., 2015). Large parts of the basin are covered in flutings, drumlins, ribbed moraines, and eskers which reveal ice streaming (Van Landeghem et al., 2009). Moving on-shore, sediment-landform distributions suggest convergence of the WIC and ISIS, a sharply delineated shear margin and ice-marginal glaciotectonism (Thomas and Chiverrell, 2007). The ice stream impinged the coastline depositing subglacial tills, proglacial sandur and lacustrine deltas. Studies by Thomas et al. (2004) on the Isle of Man, Thomas and Chiverrell (2007) on the Llŷn Peninsula, and Patton and Hambrey (2009) at Tonfanau, mid-west Wales, all detail stacked glaciotectonised sequences of two distinct diamictons and outwash (relating to Irish Sea and Welsh ice) demarcating numerous ice-marginal limits.

2.2. *Glaciomarine debate*

A long-standing debate exists surrounding the glaciomarine vs terrestrial origin of sediments deposited along the margins of the ISB. Eyles and McCabe (1989) argued that previously classified terrestrial deposits, the 'Irish Sea Drifts' (McCabe, 1987), are in situ glaciomarine deposits, not displaced marine muds or glaciolacustrine sediments containing reworked marine fauna, an interpretation supported by other studies (Campbell and Bowen, 1989; McCabe & Ó Cofaigh, 1996; McCabe, 1997). In addition, they suggest that marine limits occurred up to 140 m OD (Ordnance Datum) due to glacio-isostatic depression. On the other side, theories reside with the original terrestrial hypothesis, suggesting that deposits would have been delivered by the ice stream onshore from the ISB bed (McCarroll and Harris, 1992; Hart, 1995; Lambeck, 1996; Benn and Evans, 1998; Thomas et al., 1998; Scourse and Furze, 2001). The glaciomarine theory was firmly refuted by McCarroll (2001) who gave alternative explanations for the sediments recorded, and radiocarbon ages of cold-water foraminifera demonstrate that they have been reworked from the Irish Sea floor below present sea level and record sea level rise (Austin and McCarroll, 1992). Reconstructions of sea level and isostatic adjustment in the region (Bradley et al., 2011; Shennan et al., 2018) indicate sea level lower than present by around 40 m during the time of retreat (21–20 ka). The ISIS was still a marine based ice stream, especially when it extended beyond the British Isles, however, in the ISB the marine sector was confined to the central deepest part of the basin as detailed by the - 40 m contour in Fig. 1b. The ice actively calved throughout this period, a process which increased in rate when the reverse bedrock slope was reached and the North Wales pinning point was lost.

2.3. *Formation of stratified diamicton*

Diamictons, defined here as poorly sorted, terrigenous, unlithified sediment masses (Ó Cofaigh et al., 2011), can occasionally be stratified. Typically, stratification occurs from incremental deposition, but genesis in diamictons has been contested with early ideas revolving around subaqueous processes (Lamplugh, 1879; Carruthers, 1953; Charlesworth, 1957; Gibbard, 1980; Shaw, 1982; Eyles and McCabe, 1989). With the identification of a subglacial deforming layer (Boulton and Hindmarsh, 1987), the idea emerged that glaciotectonic processes could produce thick, stratified sediment stacks (Hart and Roberts, 1994; Benn and Evans, 1996; Roberts and Hart, 2005; Hiemstra et al., 2007). The concept of overriding is well-engrained in glacial sedimentology (Ó Cofaigh et al., 2011); hence it can be predicted that where ice is known to have advanced into ice-contact subaqueous settings, there will be resultant glaciotectonic deformation of stratified sediments (Benn, 1996; Phillips et al., 2002).

Ó Cofaigh et al. (2011) tested the subglacial versus subaqueous/glaciotectonite origin of the diamictons at Feohanagh, southwest Ireland. Described are stratified diamictons detailing anastomosing partings, discontinuous sand to gravel laminae, and sand lenses which preserve original structures separating diamicton beds. They arrived at a two-part model beginning with initial ice-marginal, subaqueous sedimentation via processes of gravity flow, ice rafting and suspension settling. Localised thickening occurs from glaciotectonic thrusting by ice-marginal oscillations. In phase two, overriding occurs, reworking the sediments from the glaciotectonites into stratified diamictons. Short transport distances and low strain rates prevent complete homogenisation. Such processes are common in coastal locations where topography acts to pin ice and form dammed lakes in which deposition rates are already higher.

2.4. Study area: Glan-y-môr Isaf and surrounding region

The glacial history of the Llŷn Peninsula (Fig. 1a), as discussed above, has been critical in developing an understanding of the behaviour of the ISIS, such as its terrestrial oscillatory nature during deglaciation. Ice flow maps built on initial models present ice emanating from Eryri (also known as Snowdonia) then coalescing with the ISIS moving southwards (e.g. Saunders, 1968; Whittow and Ball, 1970; Young et al., 2002). The ISIS impinged the coastline depositing sandur and deltas across the Llŷn Peninsula (Saunders, 1968; Addison et al., 1990; McCarroll, 2005). To the north, Anglesey acted as a major pinning point from which many oscillations are recorded along the coast – some of the most renowned sites include sequences at Dinas Dinlle (Harris et al., 1997) or Nefyn (Thomas and Chiverrell, 2007). Thomas and Chiverrell (2007) detail the associated landform assemblage – drumlins to the north (indicative of fast ice flow from the ISIS) (Fig. 2), and glaciotectonised morainal banks to the south indicating at least eleven different readvance phases (note, however, that one morainal bank exists to the north of Glan-y-môr Isaf (Fig. 2)). In extension, Thomas and Chiverrell (2007) suggest southern stratigraphies display a 'normal' sequence of lower Irish Sea till capped by Welsh till as a result of a retreating ISIS and expanding Welsh ice cap. The two tills are distinct in colour and composition, the Irish till red to brown, clay-rich, and

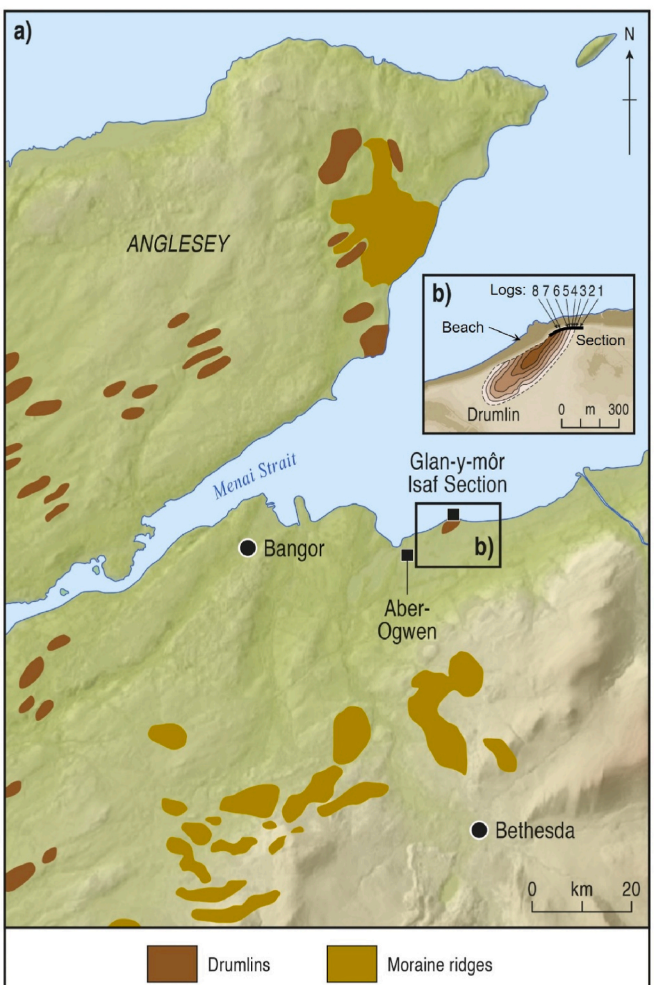

Fig. 2. (a) Geomorphological LiDAR map of the region surrounding Glan-y-môr Isaf. Depicted are moraine ridges and drumlin assemblages recorded by Thomas and Chiverrell (2007) and BRITICE mapping (Clark et al., 2018). (b) Inset map of the coastal bluff, or section, detailing the locations from east to west of the eight logs.

containing shell fragments, compared to the brown to grey, non-calcareous, clast-rich Welsh till. The two are occasionally separated by an intermediary sand and gravel series (McCarroll, 2005; Thomas and Chiverrell, 2007). Notably in a few locations, the stratigraphic order of the till sequences are flipped indicating how the two ice flows met and interfingered in this region, depositing different tills before the other in different regions.

One such location is Glan-y-môr Isaf (National Grid Reference SH 621 727), a coastal drumlin exposure to the northeast of Bangor. Here Quaternary deposits overlie an Ordovician siltstone bedrock beneath beach level. Eryri, from which the WIC emanated, lies southeast of the site occupying sedimentary siltstones and sandstones, igneous microgranite, microgabbro and tuff, and metamorphic slates. The drumlin feature sits prominently in the landscape and coastal erosion has revealed a section, or coastal bluff, around 300 m in length, of which only 200 m is accessible extending from the most northeastern point. At its central high point, the section reaches 8 m in height, dropping down to merge with the beach towards its tails. The

section likely continues below the beach height and provides much of the sediment for the adjacent sand flats. Glan-y-môr Isaf was last discussed by Edge et al. (1990). Sedimentology described records a sequence starting with Welsh tills, grey in colour transitioning from homogenous at the base (basal till) grading upwards to more gravel-rich which Hart, in Edge et al. (1990), interprets as a 'supraglacial till' representative of a deglacial signature. Above, laterally continuous diamicton lows or synforms represent small push moraines between which silts, sand and gravel sediments were deposited. Conclusions drawn by Hart (1995), from sediments deposited on Anglesey, indicate the presence of an ice-dammed lake, Llŷn Greenly, before Irish and Welsh ice coalesced. Edge et al. (1990) present similar interpretations at Glan-y-môr Isaf: the silts, sand and gravel sediments are varves, formed from a low-energy fluvial environment and redden upwards as a result of an advancing ISIS. The capping Irish Sea till illustrates advance from the north, deforming underlying deposits in the process, and with it producing stratified diamicton. OSL dates from the sands at the base of the Irish till in nearby Aberogwen date this transition to 20.3 ± 0.6 ka (Smedley et al., 2017). At the south-western end of the section, an interpretation by Pointon (in Edge et al. (1990)) notes that the Irish till interfingers the Welsh till, interpreted as a waxing and waning of the two ice sheets. Two interpretations are discussed by Hart and Pointon, in Edge et al. (1990). Hart (in Edge et al. (1990)), signifies the importance of ice coalescence to produce an ice-marginal lake which was then overridden. On the other hand, Pointon (in Edge et al. (1990)) discusses assimilation later on after WIC retreat, exposing the area to weathering and fluvial processes.

Sedimentologies at Glan-y-môr Isaf are partly contested and frame the processes occurring north of the Llŷn Peninsula where the WIC and ISIS converged. Prior work predates modern developments in glacial landsystems and models of the BIIS, which this project seeks to address. Ice-marginal lake deposits are fundamental for testing the formation of stratified diamicton, based on the conceptual model presented by Ó Cofaigh et al. (2011). The research here on the sedimentology of Glan-y-môr Isaf updates our understanding of the ice-marginal setting of the ISIS, contributing to broader scale models (e.g., Chiverrell et al., 2018; Scourse et al., 2021; Clark et al., 2022), and reframes the interpretation of subglacial, ice-marginal, and glaciotectonic deposition in the region. Additionally, this research evaluates the role of subaqueous sedimentation in determining whether the depositional environment was glaciolacustrine, glaciomarine, or glacioterrestrial, and how these findings align with the stratified till model proposed by Ó Cofaigh et al. (2011).

3. Methods

The coastal bluff exposed at Glan-y-môr Isaf was divided into eight key vertical sections (Fig. 2b), running from the most northeastern of the site along the coast to the southwest. Similar to other sedimentological studies (e.g., Evans & Ó Cofaigh, 2003, 2008; Davies et al., 2009; Roberts et al., 2013), complexities of equifinality and inheritance in glacial environments highlight the importance of good observation ahead of interpretation (Eyles and Lazorek, 2007; Evans and Benn, 2021). In accordance with techniques outlined in Evans and Benn (2021), sections were cleaned, photographs taken, and vertical lithofacies profiles produced, recording: colour, thickness, bedding, clast size and sorting, and deformation structures – all described with lithofacies codes modified from Eyles et al. (1983) and Reading (1986).

Samples of 50 clasts, or 30 where sparse, were taken from each appropriate matrix. A-axis orientation and dip measured using compass clinometer, long (a), intermediate (b) and short (c) axis lengths of each clast recorded (Sneed and Folk, 1958), and then categorised with reference to the Powers-Roundness Scale (1953). Large boulders were avoided to remove the impact of their stress signatures in the diamicton matrix (Catto, 1990). Such data on clast form and fabric illustrates the imparted stress signature and development along the debris cascade at the time of deposition (Catto, 1990; Benn and Ballantyne, 1994; Benn, 1995; Bennett et al., 1999; Iverson et al., 2008; Lukas et al., 2013; Evans and Benn, 2021). Macrofabric data is presented on Schmidt equal area stereonets produced in RockWare, and the returned eigenvalue (S_1, S_2 and S_3) ratios reveal the relative strengths of clustering, compared to other clast fabric ternary diagrams based on modern analogues (Woodcock, 1977; Benn, 1994, 1995; Thomason and Iverson, 2006; Iverson et al., 2008; Evans, 2018). Clast data from each appropriate diamicton matrix are used to calculate a C_{40} index and angularity roundness measurement which can be used to interpret the nature of clast deposition (Lukas et al., 2013). C_{40} index refers to the percentage of samples with a c:a (short:long) axis ratio of ≤ 0.4, therefore lower C_{40} values indicate a high c:a ratio and diamictons dominated by 'blocky' clasts rather than 'platy' or 'elongate' ones (Lukas et al., 2013). For angularity roundness, both RA and RWR are calculated, referring to the percentage of clasts that are angular or very angular for RA or rounded or well-rounded for RWR in each matrix (Powers, 1953; Lukas et al., 2013). Subsequent co-variance plotting of the $C_{40,}$ RA and RWR values enable interpretation of the nature of clast deposition against the 'type I' catchment types presented in Lukas et al. (2013) for low-anisotropic lithologies in lesser mountain ranges with significant reworking processes (Evans and Benn, 2021). Particle size analysis (PSA) was undertaken on samples of diamicton matrix via laser diffraction following methods outlined in Switzer and Pile (2015). A total of 39 samples were taken, up to 20g, large enough to characterise the properties of the full diamicton, and then aliquoted into samples with masses 1–3 g and diameters <2 mm. Samples were left to digest in H_2O_2 (20% v/v) until all organic material had decayed, then decanted, centrifuged at 4000 rpm for 4 min and decanted with deionised water, adding 2 ml of sodium hexametaphosphate (3.3% w/v, containing sodium carbonate to raise the pH) to deflocculate any clay particles before adding the sediment to the laser diffractor. PSA results are compared to the statistical parameters set out by Folk and Ward (1957).

4. Results: Observations and descriptions

Fig. 3, looking south towards the exposure, details a lateral section sketch for the site in which several distinct units are shown. The majority of these units are laterally continuous, increasing in height towards the centre of the drumlin. Log 1, at the northeastern end, runs to the southwestern-most log 8, the tallest coastal section observable. Each log, drawn in Fig. 4 and accompanied by photo mosaics, is described in turn using a lithofacies approach, before being grouped into lithofacies associations (LFAs).

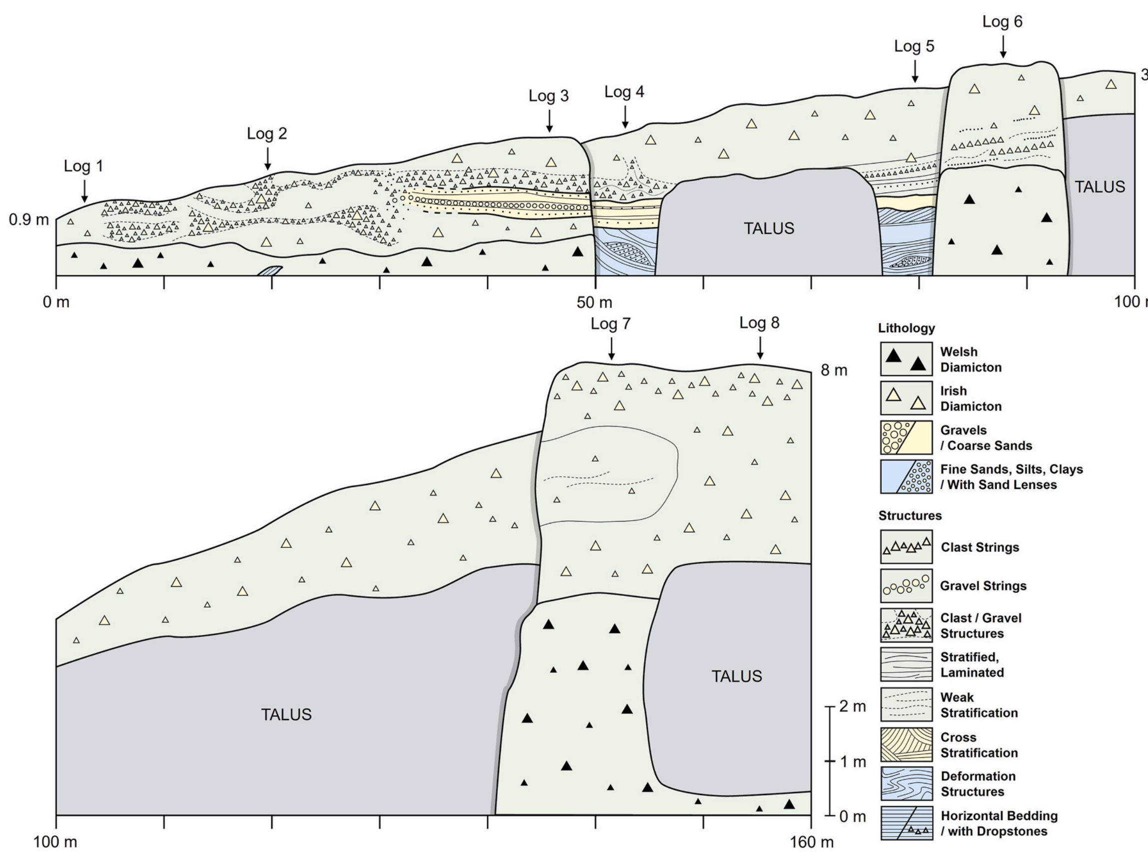

Fig. 3. Lateral section sketch looking south. Log numbers begin at the northeastern end of the section, with logs 4 and 5 shown inset to the rest of the cliff face. Facies are coloured accordingly. Laminae and stratification shown by full and dashed thin lines respectively.

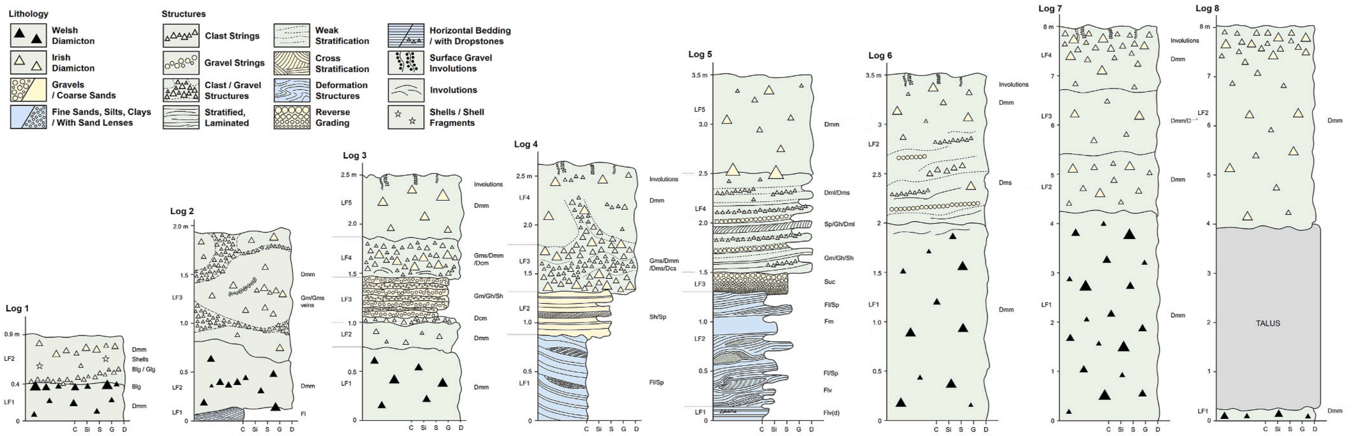

Fig. 4. Vertical section logs running from log 1 (northeast) to log 8 (southwest). Illustrations and lithofacies codes resemble those used by Evans et al. (2021) for consistency. Different diamictons are distinguished by different coloured triangles (black triangles for Welsh, and yellow triangles for Irish) and the density of triangles is representative of clast density in the diamictons. Laminae and stratification shown by full and dashed thin lines respectively and stars in log 1 represent shells. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4.1. Log 1 (northeast)

Two lithofacies are described, as shown in Fig. 4. The lowermost (LF1), 40 cm thick, is a grey-coloured, homogenous, massive, matrix-supported, silty diamicton (Dmm) with a wide range of clast lithologies. Notably, a small gravel-to-cobble boulder lag (Blg) separates the above unit. Very distinct, LF2 is a yellow-brown, homogenous, massive, matrix-supported, clayey diamicton (Dmm). In this exposure, the cobble-lag intrudes upwards into LF2, whereby the gravels become more visible. This upper section, as shown in Fig. 5, contains bivalve shell fragments scattered homogenously through the diamicton.

4.2. Log 2

At the base, a small, northeast-dipping, laminated clay lens (LF1), layers millimetres thick, intrudes into the lower diamicton. LF2, the lower diamicton, similar to LF1 in log 1, is massive, grey in colour, and clast-rich (Fig. 5). There are no obvious structures and macrofabric (Fig. 6) depicts orientation along a northwest-southeast lineation, and clasts that are rounded (RA = 6.67%) and blocky (C_{40} = 36.7%) in nature. PSA results (Fig. 5; Table 1), depict a matrix that is poorly-sorted, composed of very fine silt, and fine-skewed. Above a sharp contact (Fig. 5d), a 1.2 m thick, yellow-brown diamicton caps the section. Dissimilar to other sections, large laterally-discontinuous horizontal gravel structures (Gm to Gms veins and pockets) characterise the unit. These

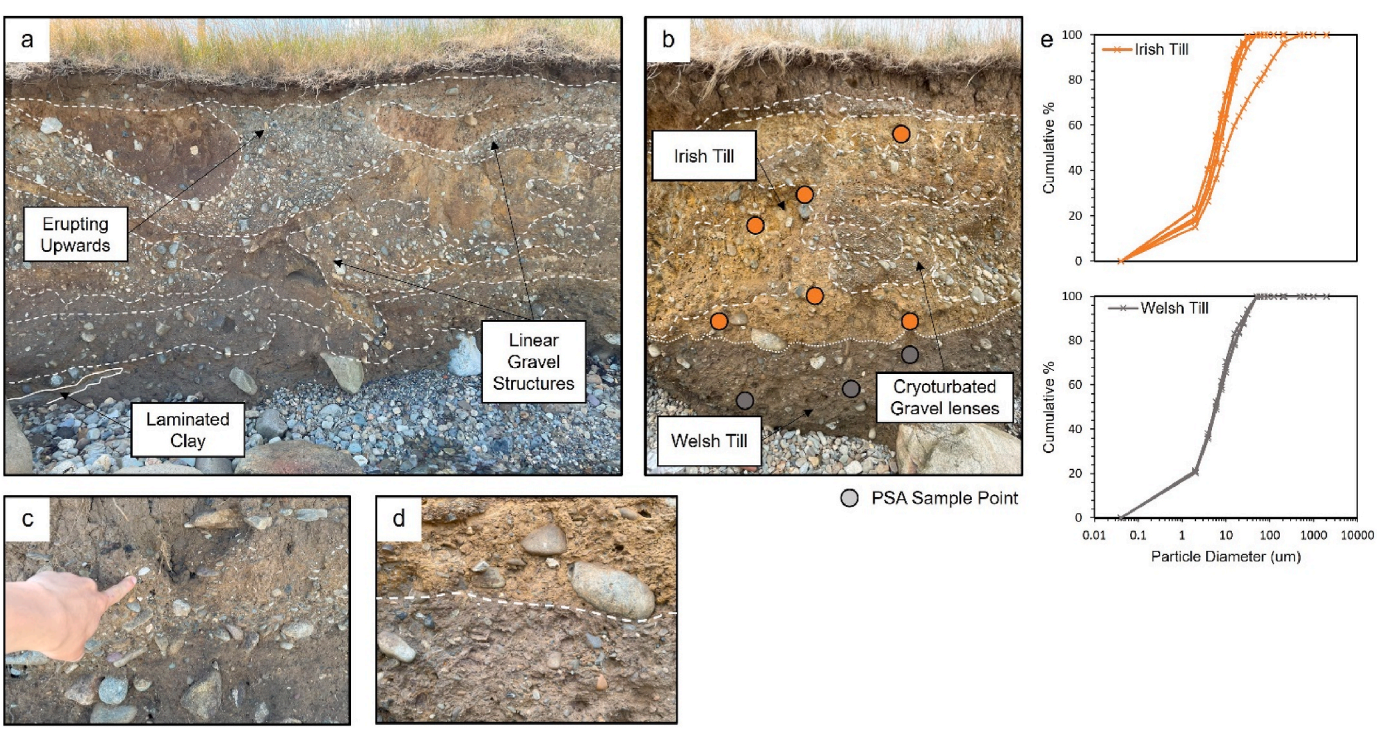

Fig. 5. Photo mosaic of the sediments exposed at log 1 and 2. (a) Log 2 disturbed clast strings running laterally and ‘trumpeting’ or erupting within the upper diamicton. (b) Log 2 clast pockets in the upper diamicton with syn- and anti-cline deformation, which are signs of cryoturbation-lensing. Locations of PSA samples are given, coloured accordingly to match the graphs. (c) Broken bivalve shell in the upper diamicton at log 1. (d) Log 2 contact between upper and lower diamicton. (e) PSA results for log 2 from the upper Irish and lower Welsh diamictons. Graphs display logarithmic, cumulative particle diameter (μm).

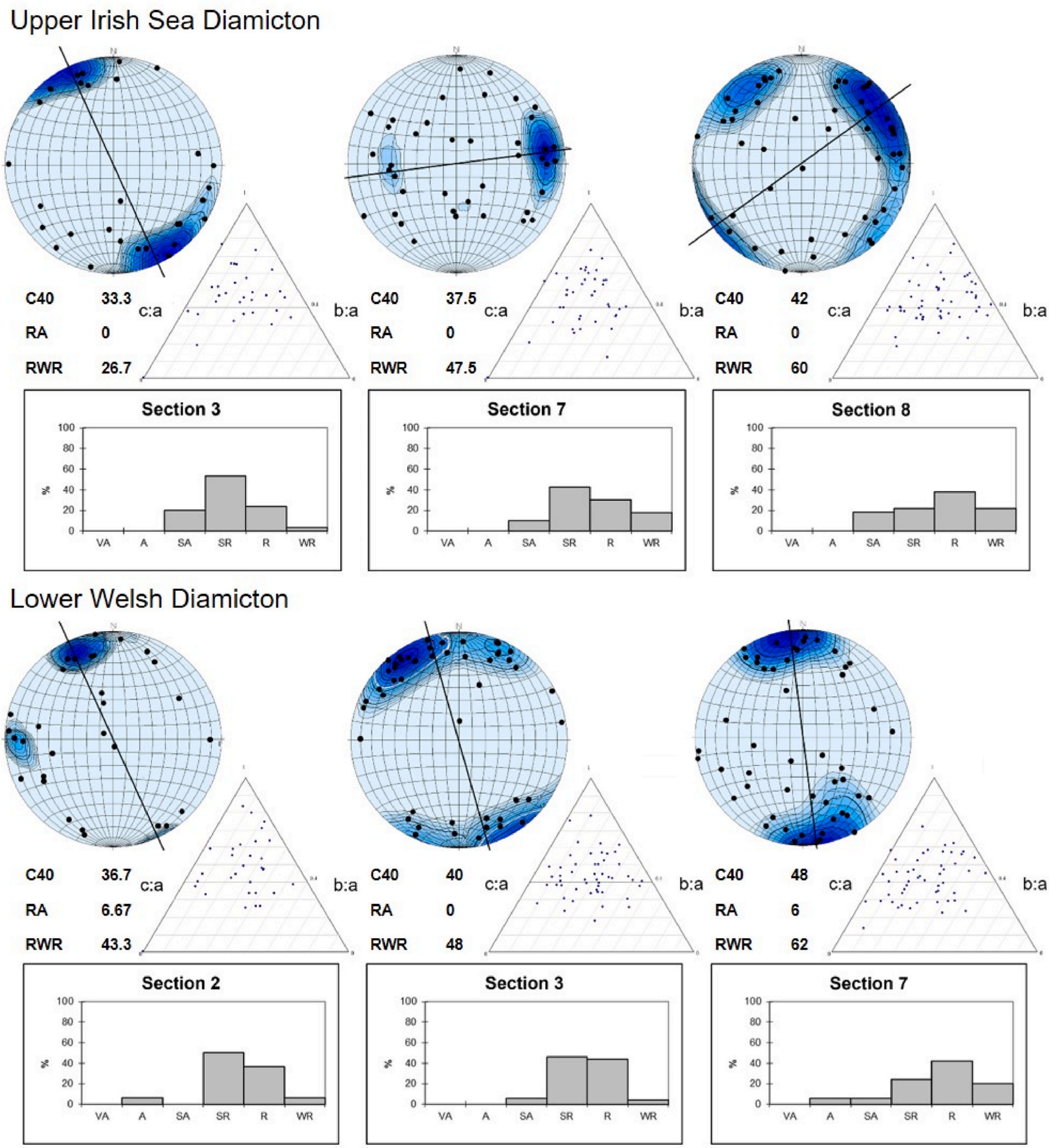

Fig. 6. Clast form and fabric data presented for the logs where data were collected (sections concurrent with the logs in Figs. 3 and 4). Equal area stereonets, clast form ternary diagrams and angularity roundness plots for the upper (Irish) and lower (Welsh) diamictons at Glan-y-môr Isaf. Upper Irish diamicton displays a general northeast-southwest trend, apart from the fabric collected at log 3 (inferred later as a result of cryoturbation), whereas the lower Welsh diamicton displays a north-northwest - south-southeast (NNW-SSE) lineation. Angularity roundness is broadly similar, the lower Welsh diamictons with slightly higher percentages of rounded clasts.

structures appear random, and string horizontally between larger 'blob-like' masses (Fig. 5). Structures continue depth-wise into the cliff face as marked by a small break in the section. Occasionally, these structures appear to rupture towards the surface, and lower down the lens structures composed of smaller gravels display syncline patterns (Fig. 5b).

PSA (Fig. 5; Table 1) shows a relatively homogenous diamicton, also fine-skewed and leptokurtic but larger in grain size than the lower diamicton.

Table 1
PSA results for log 2 from the upper Irish and lower Welsh diamictons. Statistical values categorised as per Folk and Ward (1957). Note that the Irish diamicton (till) is marginally larger in grain size, but other characteristics are very similar.

	Mean (um)	Mean (Phi Units)	Median (um)	Std. D. (Phi Units)	Skewness (Phi Units)	Kurtosis
Irish Till	13.29	7.382 *Fine silt*	6.77	1.831 *Poorly-sorted*	0.178 *Fine skewed*	2.337 *Very leptokurtic*
Welsh Till	9.81	7.504 *Very fine silt*	5.91	1.825 *Poorly-sorted*	0.118 *Fine skewed*	1.916 *Very leptokurtic*

4.3. Log 3

Five lithofacies are defined (Figs. 4 and 7). The lowermost, a grey, clast-rich, massive, matrix-supported, silty diamicton (LF1) the same as those above. Macrofabrics are strong ($S1 = 0.655$), clast form values (Fig. 6) agree with those from log 2, and PSA results (Fig. 7; Table 2) also display a fine-skewed, leptokurtic, silt matrix. Above, a thin unit of yellow-brown, matrix-supported diamicton (LF2) (outer layer discoloured by marine action), similar to that in log 2, separates the lower diamicton from an intermediary gravel unit (LF3) and is identical to the uppermost LF5. The central LF3 contains alternating horizontally bedded layers of sorted coarse sands and gravels. The unit dips southwest and PSA on the sands and limited matrix depicts a highly varied and mesokurtic grain size (Fig. 7). LF4 is a matrix-supported, poorly-sorted gravel (Gms) to clast-rich diamicton (Dmm/Dcm). The unit displays properties of both gravels and diamictons, hence both codes are used (Eyles et al., 1983). Matrix and clast compositions are similar to that of LF5 but clasts are more abundant and poorly sorted and displayed are some syn- and anti-cline patterns. Lastly, LF5 is a matrix-rich, light yellow-brown, homogenous diamicton with a northwest-southeast lineation in its macrofabric ($S1 = 0.601$), and subrounded ($RA = 0\%$) and blocky ($C_{40} = 33.3\%$) clasts. At the very top a few wedge structures appear. Matrix PSA results are very different for the clast-rich LF4 and matrix-rich LF5 diamicton. LF5 has a smaller grain size (av. 10.2 μm), is more homogenous, and mesokurtic, whereas the matrix in LF4 is much larger (av. 148 μm), more varied in size, and extremely leptokurtic.

4.4. Log 4

At the base of log 4, laminated clays, silts, and sands (LF1) dip around 20° southwest in a trough or syncline form such that the strata become more horizontal southwards along the section (Fig. 4), The layers are interjected by lenses or boudinaged structures within which sands retain original cross-stratification. LF2, composed of largely horizontally-bedded sand of different thickness (1–40 mm) and colours (Fig. 7d) caps the finer sediment. Above, a light yellow-brown, matrix-supported gravel (Gms) to clast-rich diamicton (Dmm/Dms/Dcs) (LF3) emerges after a sharp contact and contains occasional, weak stratification. A southwest-dipping ejection, with crude sorting and stratification of the same material ejects upwards into LF4 above. LF4, the remaining 80 cm, is the same light yellow-brown, massive, matrix-supported diamicton as previously described.

4.5. Log 5

Similar to log 4, the base is dominated by rhythmically bedded (varve-like), laminated clay, silt and sand layers (LF1) of different thicknesses, marked by the occasional lonestone strings. Beginning perfectly horizontal, the layers dip increasingly northeast up-unit. Fig. 8 illustrates examples of the deformation structures found here including boudinaged and cross-stratified sand lenses and flame structures. A typical sequence in this layer progresses from sands to laminated sands and silts, with an upper massive clay unit (Figs. 4 and 8). Above a sharp

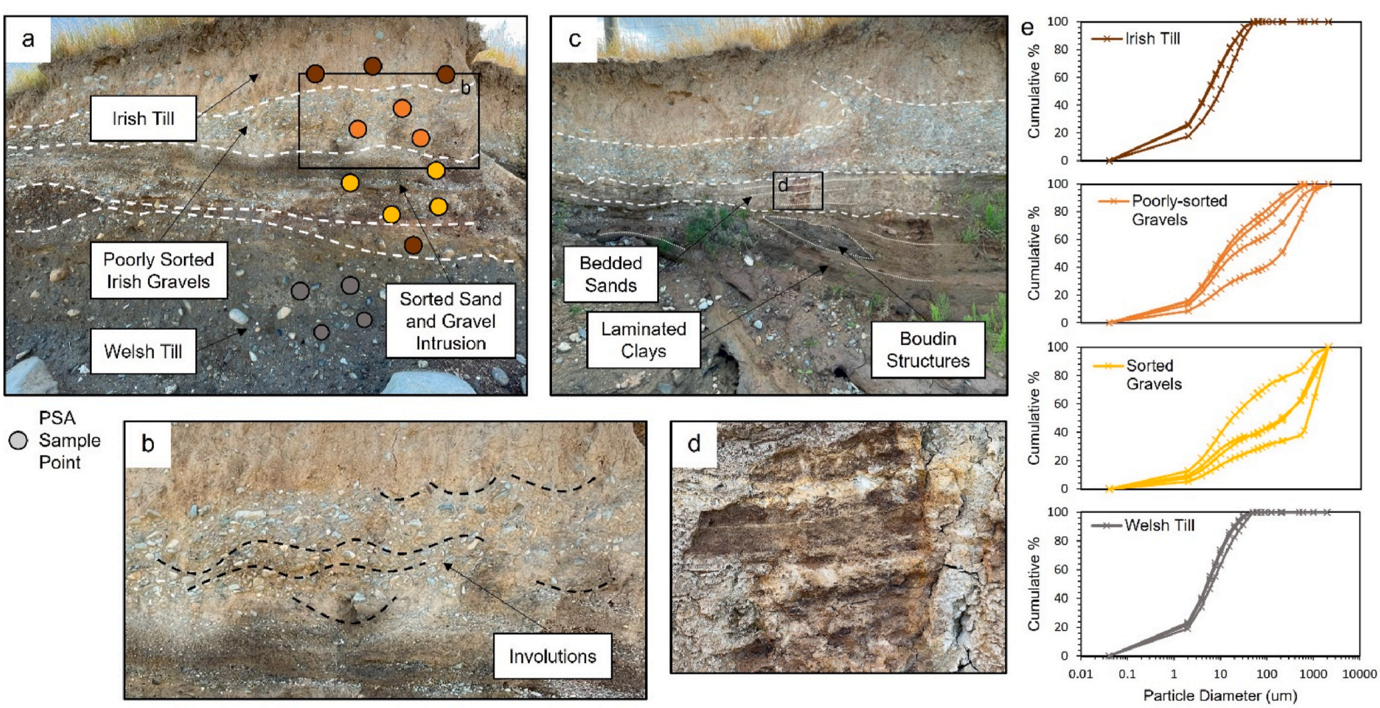

Fig. 7. Photo mosaic of the sediments exposed at log 3 and 4. (a) Log 3 showing the horizontally bedded sorted gravel to coarse sand unit (LF3), capped by poorly sorted larger pebble gravels (LF4) running within the upper diamicton. Locations of PSA samples are given, coloured accordingly to match the graphs. (b) Involutions marking cryoturbation lenses from the upper poorly sorted gravels of log 3. (c) Log 4 stratigraphy from laminated fines to sands, clast rich diamicton and matrix supported diamicton. Boxed is (d) detailing the horizontally bedded sands (LF2). (e) PSA results for log 3 from the upper Irish and lower Welsh diamictons, and gravels. Graphs display logarithmic, cumulative particle diameter (μm).

Table 2
PSA results for log 3 from the upper Irish and lower Welsh diamictons. Statistical values categorised as per Folk and Ward (1957). Sorted gravels have the largest grain size and are characteristically distinct to the other logs. The matrix surrounding the poorly sorted gravels is also larger, but not to the same extent.

	Mean (um)	Mean (Phi Units)	Median (um)	Std. D. (Phi Units)	Skewness (Phi Units)	Kurtosis
Irish Till	10.2	7.493 *Fine silt*	6.63	1.897 *Poorly-sorted*	0.183 *Fine skewed*	1.006 *Mesokurtic*
Poorly Sorted Gravels	148	5.226 *Coarse silt*	59.8	3.075 *V. poorly-sorted*	0.042 *Aprx. Symt.*	3.613 *Ext. leptokurtic*
Sorted Gravels	461	3.511 *Fine sand*	301	3.500 *V. poorly-sorted*	0.350 *Fine skewed*	0.825 *Mesokurtic*
Welsh Till	8.83	7.615 *Very fine silt*	5.67	1.774 *Poorly-sorted*	0.156 *Fine skewed*	2.113 *Very leptokurtic*

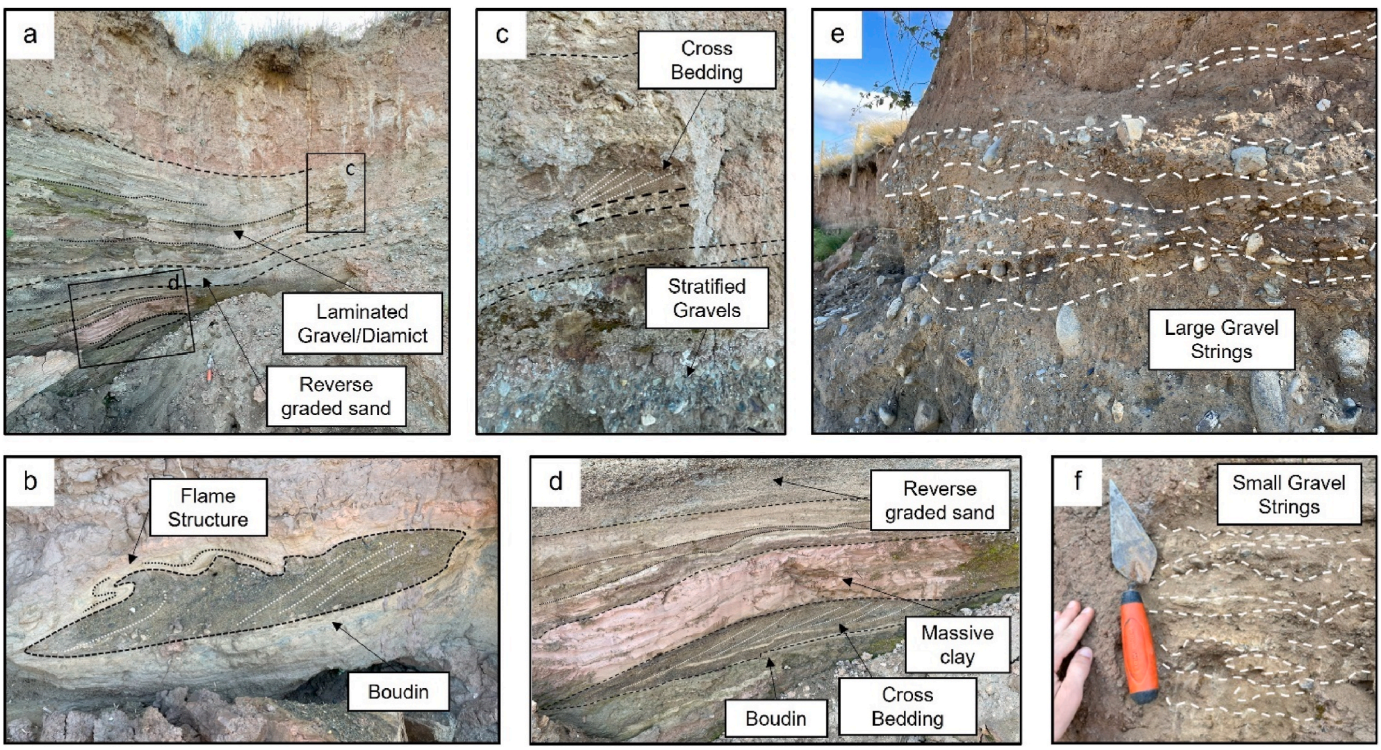

Fig. 8. Photo mosaic of the sediments exposed at log 5 and 6. (a) Log 5, as drawn in log, boxed are photos 'c' and 'd'. (b) Log 5, boudinaged coarse sand to gravel facies with some flame structures and cross-bedding inside. (c) Zoomed-in section detailing horizontal stratification of different sized sands and gravels, with some cross-bedding observed in one of the strata. (d) Zoomed-in section illustrating laminated layers, boudin structure with cross-bedding and a massive clay facies. (e)(f) Log 6, showing gravels running laterally through the sequence in semi-horizontal strings extending from the strata in log 5.

contact, a 20 cm thick reverse graded sand unit occurs (LF2). Coarse sands transition into stratified strings of massive and horizontally bedded layers of gravel and sand which transition upwards into stratified to laminated diamicton (LF3). Between, occasional planar cross-stratified sand and gravel layers occur (Figs. 4 and 8). LF4 is identical to the capping units of other logs, the light yellow-brown diamicton.

4.6. Log 6

Less than a few meters away from log 5, log 6 depicts a lower grey, massive, matrix-supported diamicton at the base (LF1). Above, LF2 transitions from crudely stratified light yellow-brown diamicton with strings of gravel and sand running through (Dms) (Fig. 8) to homogenous, massive, matrix-supported diamicton (Dmm). The clast strings are geologically similar as those in LF3 of log 5 but show increasing homogeneity into the surrounding diamicton than in log 5. Like other capping units, visibly weak wedge and syncline structures are found near the surface.

4.7. Log 7

Four lithofacies are detailed (Figs. 4 and 9). The basal 4 m is composed of a grey, clast-rich, massive, matrix-supported diamicton (LF1) with macrofabric ($S_1 = 0.563$) aligned along a northwest-southeast lineation and rounded clasts (Fig. 6). PSA results (Fig. 9; Table 3) reveal a very fine silt matrix, fine-skewed and very leptokurtic in nature. Above, the light yellow-brown, massive diamicton with areas of anastomosing partings (LF2 and 4) is separated by a 1.5 m unit. This LF3 is redder in colour, clast-poor, and has crude stratification (Fig. 9). LF3 is not laterally continuous and becomes homogenous with the surrounding light yellow-brown diamicton towards log 8. Macrofabric and clast form from LF2 (Fig. 6) shows a northeast-southwest lineation, and subrounded (RA = 0%) and blocky (C_{40} = 37.5%) clasts. PSA results show a difference between LF2 and LF4, and LF3 (Fig. 9), firstly, that the matrix of LF3 is larger in grain size (av. 33.1 μm compared to 7.91 μm), and although also being very leptokurtic, the matrix of LF3 has not fine-skewed. LF2 contained a decomposed 'peat ball' and in the upper 0.5 m of LF4, the number of clasts increases, and weak wedge and syncline structures are visible.

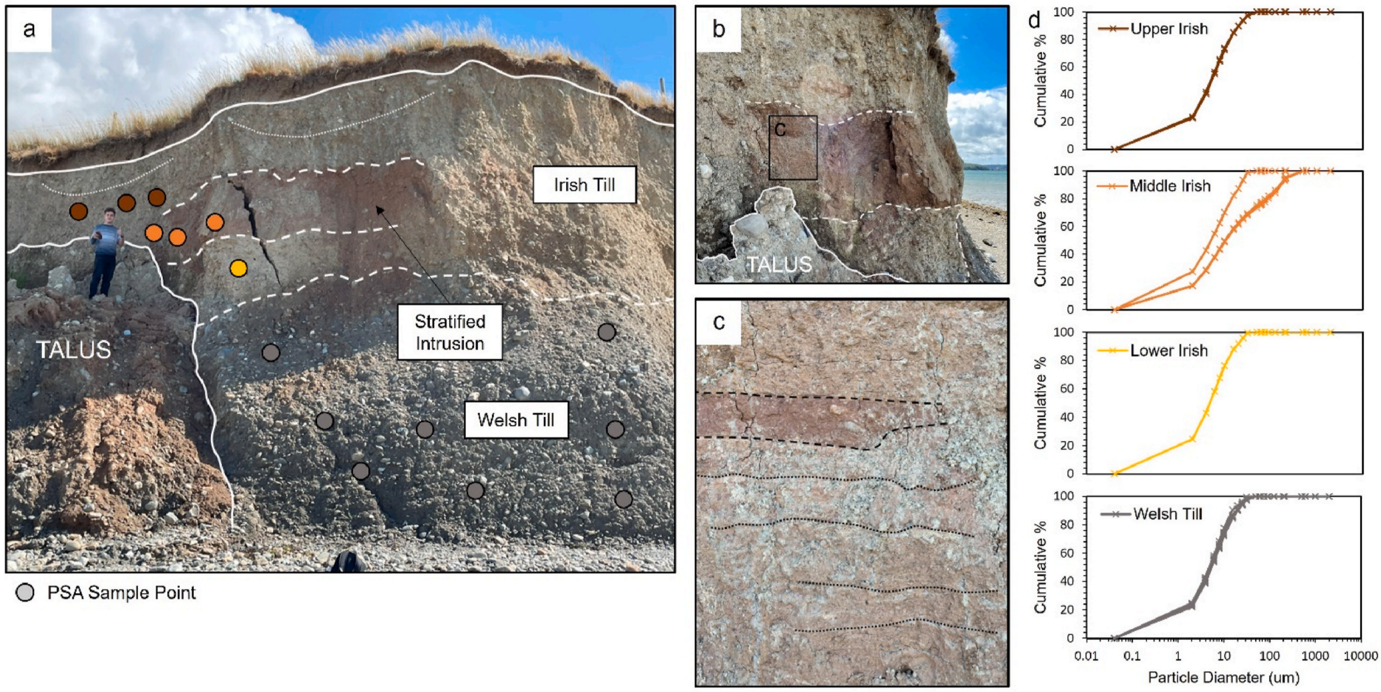

Fig. 9. Photo mosaic of the sediments exposed at log 7. (a) Full vertical section displaying the four lithofacies: the basal Welsh diamicton, and upper Irish diamictons in three facies-distinct parts (lower, pale diamicton; middle, clast-poor, red intrusion; upper, clast-rich, pale diamicton). Locations of PSA samples are given, coloured accordingly to match the graphs. (b) Close up of the Irish diamicton, taken from field assistants' position in '*a*', detailing the stratification observed in the diamicton, specifically the central 'red diamicton'. Boxed is (c) detailing the different coloured banding observed in LF3. (d) PSA results for log 7 from the upper Irish and lower Welsh diamictons. Graphs display logarithmic, cumulative particle diameter (μm). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
PSA results for log 7 from the upper Irish and lower Welsh diamictons. Statistical values categorised as per Folk and Ward (1957). The Irish and Welsh diamictons, outside of the red banded intrusion, are characteristically similar, however, the red, middle Irish, clast-poor intrusion reveals significantly larger grain sizes and symmetrical skewness.

	Mean (um)	Mean (Phi Units)	Median (um)	Std. D. (Phi Units)	Skewness (Phi Units)	Kurtosis
Upper Irish Till	7.91	7.755 *Very fine silt*	5.08	1.745 *Poorly-sorted*	0.140 *Fine-skewed*	2.328 *Very leptokurtic*
Middle Irish Till	33.1	6.791 *Fine silt*	8.58	2.486 *V. poorly-sorted*	−0.006 *Aprx. Symt.*	1.531 *Very leptokurtic*
Lower Irish Till	7.13	7.874 *Very fine silt*	4.79	1.695 *Poorly-sorted*	0.163 *Fine-skewed*	1.977 *Very leptokurtic*
Welsh Till	7.72	7.787 *Very fine silt*	5.12	1.747 *Poorly-sorted*	0.175 *Fine-skewed*	2.495 *Very leptokurtic*

4.8. *Log 8 (southwest)*

A thin exposure of grey, clast-rich, massive diamict is visible at the base (LF1), capped by slump talus. Above, a single homogenous, light yellow-brown, structureless and massive, matrix-supported diamicton forms LF2, similar to other upper units presented. Clast fabric and form analysis (Fig. 6) reveal a northeast-Southwest lineation and rounded (RA = 0%) and blocky (C_{40} = 42%) clasts, comparable to the upper lithofacies from log 7. The number of clasts also increases near the surface.

5. Interpretations

5.1. *Welsh till (Dmm)*

The lowermost, grey, homogenous, poorly-sorted, matrix-supported diamicton can be interpreted as a subglacial traction till (Evans et al., 2006; Evans, 2018). Fig. 10, presenting clast fabric ternary and clast form co-variance plots, would illustrate a fluvial signature as per Lukas et al. (2013), however, the preservation of anastomosing partings, strong macro-fabrics, and a poorly-sorted matrix argue that this material was being actively deformed underneath the base of the glacier. The fluvial signatures (Fig. 10) are likely due to the great thickness of the till causing a lack of fresh angular clasts to be eroded from the bed so the clasts within the matrix have time to erode, mature and become well-rounded. Despite Lukas et al. (2013) arguing that RWR is a better choice of comparison than RA to C_{40}, however, data here would suggest a reverse due to the erosion of aforementioned clasts. Clast fabric (Fig. 6) and lithology indicate ice flow from the southeast, from the WIC over Eryri, hence Welsh till. Interpretations of this LFA align with those presented by Edge et al. (1990) for their Llwyd Diamicton and are comparable to other subglacial tills found for the BIIS and WIC (McCarroll and Harris, 1992; Thomas et al., 2004; Thomas and Chiverrell, 2007; Patton and Hambrey, 2009; Scourse et al., 2021). PSA results portray a laterally consistent, fine-skewed clay/silt matrix that is very leptokurtic. As per Folk and Ward (1957) and Landim and Frakes (1968), high kurtosis illustrates a matrix far better sorted in the centre of the distribution than in the tails and is often representative of outwash deposits. Where deposits have high kurtosis and are skewed, as they are for the Welsh till, it can often allude to the influence of water sorting, hence demonstrating a till with high pore-water pressure and high volumes of water at the margin (Landim and Frakes, 1968). Lastly, the lack of Welsh till in the inset part of the cliff between log 4 and 5 corresponds to the interpretations made by Hart in Edge et al. (1990) where

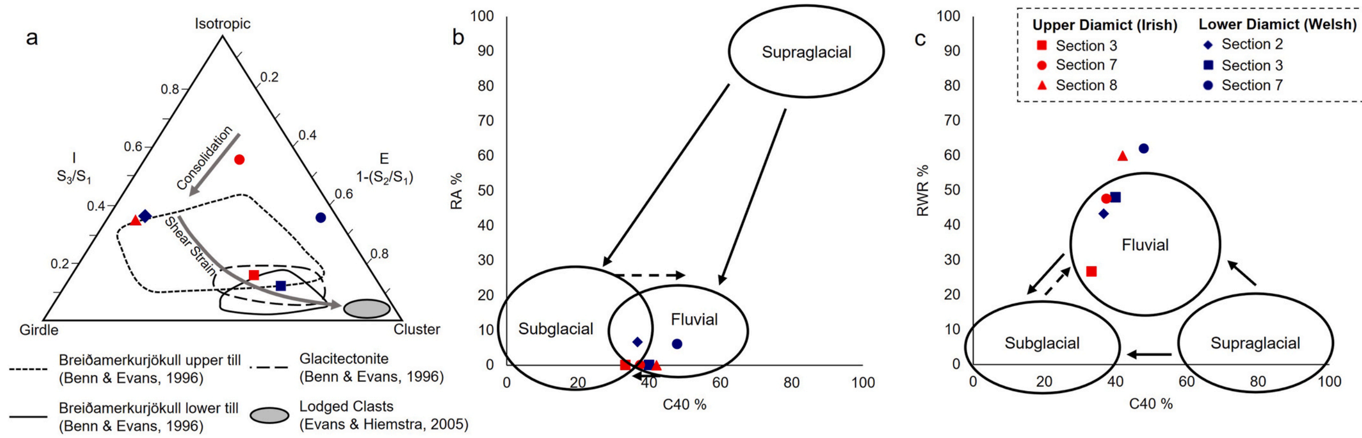

Fig. 10. (a) Fabric shape ternary diagram for upper Irish (red) and lower Welsh (blue) diamictons across Glan-y-môr Isaf overlaid onto envelopes of previous results from Benn and Evans (1996), Evans and Hiemstra (2005) and the shear strain development pathway proposed by Iverson et al. (2008) to portray the degree of clustering. (b) Clast co-variance plot of RA (%) against C_{40} (%) values for the same sections detailing low proportions of angular clasts, relatively high 'blockiness', and a subglacial to fluvial signature across both diamictons. (c) Clast co-variance plot of RWR (%) against C_{40} (%) values for the same sections presenting relatively high roundness values and an apparent fluvial signature for all samples. Envelopes for clast interpretation from Lukas et al. (2013) relate to 'type 1', low-anisotropic, and ice cap outlet lithologies. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the exposures of Welsh till are diamict synforms representing push moraines as there is no evidence for 'syndepositional overturning'. As discussed later, interpretations made suggest there are forms of glaciotectonism at the site, but exposures of Welsh till are coherent with the push moraine theory.

5.2. Irish till (Dmm)

Above the lower units, the light yellow-brown, homogenous, poorly-sorted, matrix-supported, massive diamicton can interpreted as another subglacial traction till with clast fabric pointing to an origin from the northeast Irish Sea Basin. The colour, geological composition, and presence of homogenised shells agrees with an ISB origin – the till representing the part of the ISIS that impinged North Wales (McCarroll and Harris, 1992; Harris et al., 1997; Thomas et al., 1998; Thomas and Chiverrell, 2007). Though deposited glacioterrestrially, the inclusion of shells broken homogenously through the till would imply an allochthonous source, that the deposits came from an area of the ISIS that flowed through marine sediments. The homogenous, massive, matrix-supported part of the till, described here, is interpreted as a subglacial traction till due to the preservation of some anastomosing partings, strong fabrics, and a poorly-sorted, massive diamicton with shells dragged from the seabed (Evans et al., 2006). Fluvial signatories (Fig. 10) can be explained as before – higher RWR values occur because of a lack of freshly eroded angular clasts being incorporated at the bed, and as described below the ISIS flows over glacial outwash and lacustrine deposits whereby this fluvial signature will be cannibalised into the clast record (higher C_{40} values for example). Particle size and matrix characteristics are similar to the Welsh till above, still leptokurtic but particles are typically slightly larger which is likely due to the range of different sediment pockets at the base of the ISB that the ISIS flowed over (Cronan, 1972; Mellett et al., 2015). At the top of the sequences, an increase in the number of clasts, wedge structures, and involutions all point to periglacial cryoturbation processes which would have occurred post-glaciation (Ó Cofaigh et al., 2008; Ballantyne, 2018).

5.3. Stratified Irish Diamicton (Dml/Dms)

A subsection of the homogenous, massive Irish till is its laminated to stratified counterpart, exemplified in logs 5 and 6. First occurring above laminated upwards-coarsening material, the base of the laminated diamicton (Dml, Log 5) incorporates massive and stratified gravels and cross-stratified sands, which become increasingly homogenous both up-section and further southwest (Dms, Log 6) losing their laminated property. Reflecting on other stratified tills and diamictons (e.g., Ó Cofaigh and Dowdeswell, 2001; Phillips et al., 2002; Roberts and Hart, 2005; Evans & Ó Cofaigh, 2008; Ó Cofaigh et al., 2008, 2011), this LFA begins as a result of the ISIS overriding the sequence and locally cannibalising and dragging sediment from underneath it into the deforming till base, as is described by Ó Cofaigh et al. (2011) and Evans (2018). The banding of the pseudo-laminated diamicton produced is composed of discontinuous stringers of the underlying sediment. At this stage, the sediment lacks the nomenclative quality of till (Evans, 2018), hence diamicton, but as the ISIS moves over the region, the overlying massive till incorporates these sediments into a stratified subglacial till that is actively deforming. Interpretations that the sediment has a fluvial genesis such as melt-out (Shaw, 1982; Eyles and McCabe, 1989) can be refuted because of the overwhelming evidence to suggest that the stratified diamicton was actively being homogenised and new laminated to stratified sediment being eroded underneath the till.

5.4. Poorly-sorted outwash gravel to clast-rich diamicton (Gms, Dmm, Dms, Dcm, Dcs)

This LFA is challenging to ascribe nomenclative definition. Poorly-sorted, pebble gravels underly the Irish till in log 3 (LF4), log 4 (LF3), and become deformed in log 5 (LF4). The LFA also exists in log 2 as pockets of cobble-to-gravel strings. As posited by Eyles et al. (1983), there is little distinction between matrix-supported gravels (Gms) and clast-rich diamictons (Dmm), and between massive gravels (Gm) and clast-supported diamictons (Dcm). As explained below, there is evidence that the deposits are outwash gravels subject to subglacial and periglacial modification, therefore both lithofacies codes are used.

The colour and clast composition of this unit, similar to the Irish till above, suggests an ISIS origin prior to the deposition of the Irish subglacial traction till. Genesis can be contested, but presented here is an interpretation that forms the structures observed. Firstly, the deposit, poorly-sorted and presenting minor crude stratification, could be part of a cobble-to-gravel outwash that would have existed in front of the ISIS. This is similar to outwash observed at modern analogues (Evans, 2000) or outwash deposits from the Screen Hills, Ireland, discussed in Evans and Ó Cofaigh (2003) as the ISIS advanced onshore. Situated above upwards-coarsening sands and glaciolacustrine sediments (discussed later), this interpretation would correspond to an advancing ISIS margin. PSA results (Fig. 7) also show a larger matrix grain size (ice-distal setting) than the subglacial Irish till above (transition to ice-proximal setting). The alternative explanation could be that the unit is a clastic dyke from hydrofracture infilling when large volumes of meltwater and sediment were under pressure at the ice sheet margin (Rijsdijk et al., 1999; Evans and Hiemstra, 2005). However, unlike the hydrofracture LFA6.5 described below, there is no sediment sorting or evidence of repeated injection to produce such a thick infill (Le Heron and Etienne, 2005).

Deformation structures observed can be explained by three possible scenarios: firstly, that the sediments have been cryoturbed; glaciotectonism and soft sediment deformation from glacier loading; or they are water burst-out structures. Initial deformation took place from the loading and thrusting of ice, and secondly by an active subglacial deforming till layer. This formed the deformed pockets and strings of cobble-to-gravel outwash closer to the surface. Thereafter, the ejection structures are likely from cryoturbation (similar to Harris and McCarroll, 1990) as opposed to hydrofracturing as there are no other signatures that the clast-rich diamicton actively channelled water or underwent burst out as is seen in Nichols et al. (1994), Rijsdijk et al. (1999) and Phillips and Hughes (2014). For example, the gravel ejection into the upper till in log 4: doesn't reach the surface, as a hydrofracture infill would; shows signs of sediment sorting; and dips the wrong way for it to be subglacially deformed. There are also other examples of periglacial activity in the exposure such as involutions (syncline features) (e.g., Figs. 5 and 7). Overall, this LFA is interpreted as a deformed outwash deposit (gravel nomenclature), initially deposited horizontally with crude stratification, and has since been deformed by ice-loading, active subglacial deformation, and cryoturbation post-deglaciation to present diamicton qualities.

5.5. Gravel hydrofracture

The finer, sorted gravels deposited in the sequence exist in stratified pockets (e.g., in LF3 in log 2) and as a channel or raft dipping southwest as appears in log 3 (Figs. 3 and 4). The gravels, stratified and sorted by size, point to a glaciofluvial origin, and the channel in log 3 gives the appearance they have been injected into the upper till; hence gravels are interpreted as downward infilled hydrofractures at the edge of an advancing ISIS where large volumes of water and sediment would have been under pressure (Rijsdijk et al., 1999; Phillips et al., 2013). During the deformation of the clast-rich outwash gravels above, the high porosity of this material would have allowed hydrofractures to develop in the Irish till, causing the downward gravel infills. This would have occurred in stages allowing gravels of different sizes to form and present their sorted nature, as shown in Le Heron and Etienne (2005). Sediments close to the surface have since deformed into gravel stings and pockets as a result of subglacial deformation and cryoturbation to form involute structures.

5.6. Glaciolacustrine clays, silts and sands

Laminated sediments at the base of log 4 and 5 are not found in other sections besides a small clay unit in log 2 suggesting they have only been preserved in the drumlin core. Clay and silt layers are interpreted as seasonal varves, different coloured strata corresponding to winter and summer deposition. They detail a low-energy fluvial environment, and upwards-coarsen into increasingly dominant sand strata and then into gravels. Being capped by subglacial traction till, inferred from the sediments' grain size is evidence for an advancing ice margin and increase in glaciofluvial energy (Ó Cofaigh and Dowdeswell, 2001). Sediments display evidence for soft-sediment deformation, synonymous with type 2 glaciotectonites classified in Roberts and Hart (2005) where laminae are the remnants of pre-existing bedding. Deformation is not as severe as is recorded in Phillips and Auton's (2000) four-stage deformation model, but there is indication of increased deformation up the sequence from two distinct mechanisms. As ice advanced over the area, it enacted two processes: tectonic deformation via the loading and thrusting of ice which squished the fine sediments causing dipping and boudinaged structures; and sediment reworking from erosion and incorporation into the overlying till forming stratified diamicton. Laminated clays, silts, and sands may be subglacial channel infills (as exemplified in Ó Cofaigh et al. (2008)), glaciomarine sediments or glaciolacustrine sediments (Evans & Ó Cofaigh, 2003).

Without being able to observe the basal contact of the fine sediments, interpretation becomes more challenging but there are numerous features which reject a channel infill origin. As is described by Benn and Evans (2010) and Miall (1977), channel infill facies often include ripple cross-laminated sands and cross-bedded sands and gravels for which there is minimal evidence at this site. Instead, varves with strings of dropstones represents an ice-distal fluvial setting which was still being fed by icebergs (Ó Cofaigh and Dowdeswell, 2001; Ó Cofaigh et al., 2008). Notwithstanding the fact that sea level was not high enough to form such an autochthonous deposit, there are other lines of evidence which suggest a glaciolacustrine environment as opposed to a glaciomarine one. Expanding on the evidence collected by Ó Cofaigh and Dowdeswell (2001) , the sediments at Glan-y-môr Isaf, despite being deformed post-deposition, display sharp boundaries between summer and winter couplets, and some strata have different grain sizes representing the interaction between underflows and interflows – more common in sediment-laden glaciolacustrine meltwaters. Compared to glaciomarine deposits, there is no evidence of normal grading on each strata or scouring, and minimal evidence of cross-stratification (especially in the lower ice-distal part of the sequence). A transition above the clays to laminated sands and silts illustrates an advancing ice margin, and sediments here typify deformed Bouma sequences (Kneller and Buckee, 2000) implying that turbidity currents dominated deposition during ice advance. Above, the sands and gravels document a transition to an ice-proximal lacustrine setting in which subaqueous, gravel, deltaic outwash was deposited instead.

5.7. Stratified till intrusion

A subset of the stratified Irish till presented above is a small, clast-poor, reddish, stratified intrusion seen in log 7 emerging from behind the talus (Figs. 3, 4 and 9). Notably, the colour, larger grain size, and differing PSA results demonstrate that the sediment was not formed with the surrounding Irish till (e.g., banded tills in Douglas, 1974), instead the sediment is a tectonic raft that has been dragged in the deforming till from the glaciolacustrine sediments beneath, similar to examples from Ireland and Antarctica (Hiemstra et al., 2007). This LFA, alongside others, implies that ISIS advance over the area was able to cannibalise and deform pre-deposited, ice-marginal glaciolacustrine sediments.

6. Discussion

Sediments presented at Glan-y-môr Isaf allow research questions to be answered relating to the different styles of deposition involved, the interaction of the Welsh and Irish ice, and the importance of subaqueous sedimentation in forming stratified assemblages, comparing results to the conceptual model proposed by Ó Cofaigh et al. (2011). Specifically, these deposits hold key insights into the nature of the ISIS, its retreat, and interaction with the WIC as summarised by Small et al. (2018), Scourse et al. (2021) and Clark et al. (2022).

Glan-y-môr Isaf is characterised by multi-phase deposition. The site is first covered by ice from the WIC, then from the ISIS with a deglacial glaciolacustrine period in between. This is a reversal of the 'normal' sequence in other areas along the Llŷn Peninsula, confirming ideas from Thomas and Chiverrell (2007) and implying that the two ice masses interfingered and interacted heavily in this region. There is no evidence at the site that the ISIS oscillation which covered the region reached its maximum point at Glan-y-môr Isaf as it did at other locations such as

Dinas Dinlle (Fig. 1) (Harris et al., 1997). Rather ice flow continued across the site terminating further south, allowing the drumlin to form as a product of fast ice flow and the localised stacking of sediment (Hart, 1995; Evans and Hiemstra, 2005; Thomas and Chiverrell, 2007; Clark, 2010; Evans and Orton, 2015; Jónsson et al., 2016). Both the Welsh and Irish tills interpreted are clast-rich with high proportions of rounded clasts. Relating sediments at Glan-y-môr Isaf to the 'erosional to depositional' model presented by Boulton (1996), typified are ice-marginal deposits of a predominantly depositional setting which would otherwise be characterised by angular material and supraglacial signatures (Lukas et al., 2013). Furthermore, illustrated is an ice margin characterised by high volumes of meltwater which allowed downward hydrofracture gravel infills to form whilst the site was overrun. Another supporting line of evidence that the ISIS oscillation did not reach its maximum point at this site is the lack of upward hydrofracture infills, composed of smaller grain sizes, which occur when pressure on the underlying sediment reduces at the ice margin (Rijsdijk et al., 1999; Phillips et al., 2013). Highly leptokurtic PSA results also signify the importance of water volumes at the margin, however, PSA is often not the most accurate technique and samples may not be fully representative – diamicton matrixes are, by nature, filled with pockets of different sized material (Evans, 2018). There is significant difference, however, in the grain size of the stratified intrusion into the Irish till after the glaciolacustrine sediments, verifying the observed processes of cannibalisation (at the base of the till forming gravel strings), but at a smaller particle scale.

Glaciolacustrine and glaciofluvial sediments detail a period of separation between the WIC and ISIS, and the upwards-coarsening nature of the sediments suggests that the WIC and ISIS retreated at similar times before the ISIS re-advanced over the area – conclusions of formation here are limited as the base of these deposits cannot be observed. Findings support the presence of Lake Greenly, presented by Hart in Edge et al. (1990) and Hart (1995), situated above a foreland marked by push moraines from the retreat of the WIC. Due to the subaqueous nature of the sediments above, it is possible to interpret the push moraines as De Geer moraines (Ottesen and Dowdeswell, 2006; Benn and Evans, 2010). However, given the inability to examine the moraine ridges below beach level and fully assess their relationship with the glaciolacustrine sediments, we retain their classification as push moraines, consistent with Edge et al. (1990).

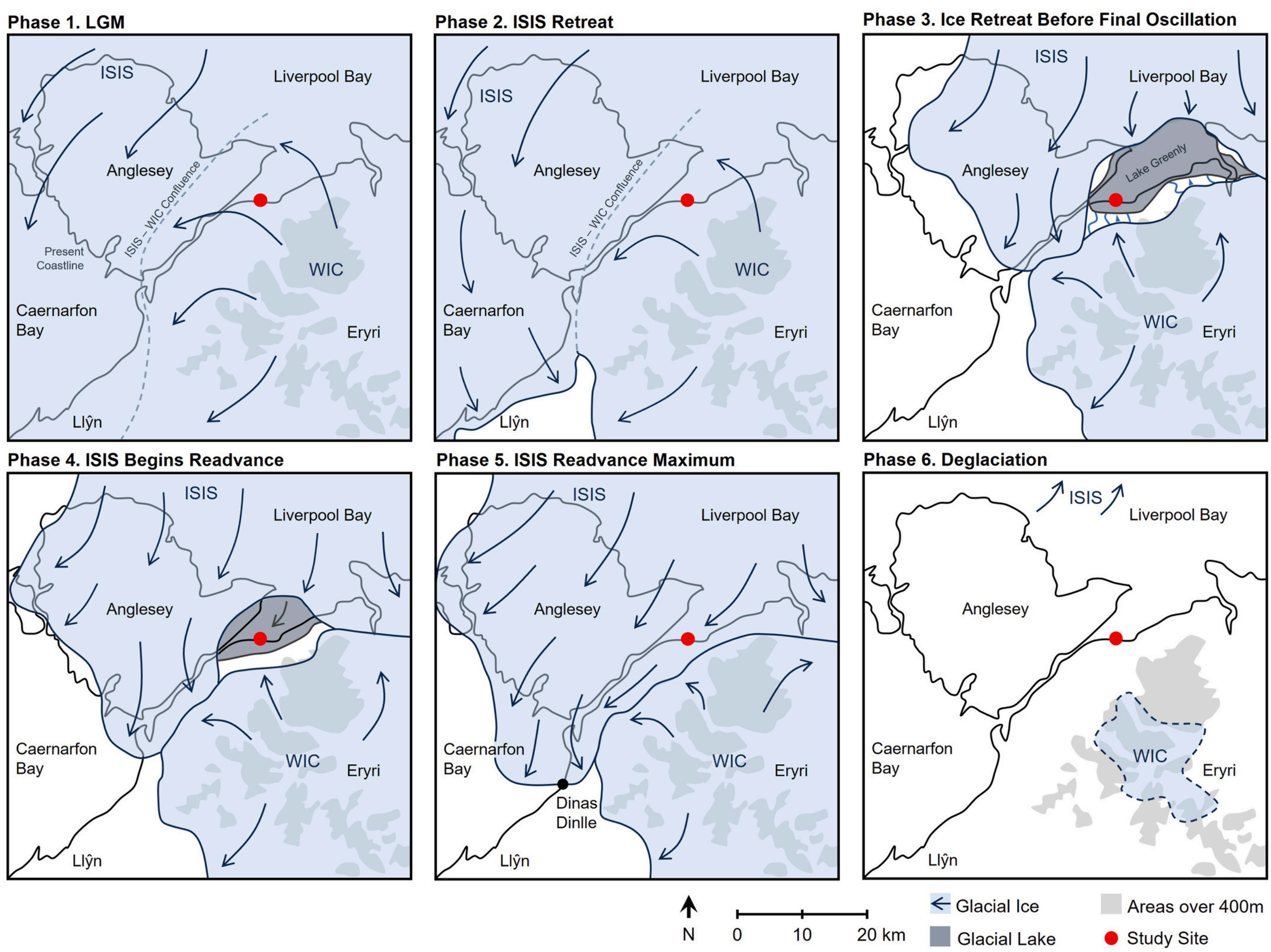

Fig. 11. Six-phase relative timestep schematic reconstructing the events that created the sediments exposed at Glan-y-môr Isaf. Ice margins and flow directions are adapted from the literature explored in text to match the interpretations and conclusions drawn at Glan-y-môr Isaf. At LGM (Phase 1), the confluence between the ISIS and WIC was west of the Menai Strait, contradicting the original position drawn by Thomas and Chiverrell (2007). In phase 2, well into deglaciation, the ISIS and WIC unzip from each other during retreat. Ice boundary margins are based on Thomas and Chiverrell (2007) and their mapping of the deposition of sediment across the Llŷn Peninsula. In phase 3, before final oscillation, the ISIS retreats and pins on Anglesey allowing for the formation of Lake Greenly, fed by icebergs from the ISIS. During oscillatory advance (Phase 4), the ISIS advances towards the site depositing coarser grained materials. The ice margin crosses the site and reaches its maxima in phase 5 (ice margins are estimates based on literature review, (e.g. Thomas and Chiverrell, 2007; Smedley et al., 2017)), this phase forms the stratified diamictons as is explained below. Post-retreat (Phase 6), the area is subject to periglacial activity. The WIC displayed in phase 6 are hypothetical, hence the dashed line.

Sediments show evidence of a transition from a low-to high-energy environment, the calm glaciolacustrine setting developed between the push moraines, which aided low-energy clay deposition, accompanied by either a distal ice margin or a quasi-stable, low-energy period in the ISIS's retreat. The former is more likely considering the evidence for dynamic behaviour with multiple oscillations (Thomas and Chiverrell, 2007; Clark et al., 2022). This ice-distal lake was bounded by ice (marked by iceberg dropstones) in the north pinned against Anglesey and by a terrestrially retreating WIC foreland to the south. Ice advanced, depositing turbidites and ice-proximal gravel outwash (similar to phase 1 in the model by Ó Cofaigh et al. (2011)) deforming and incorporating the sediments underneath (upper gravels first) into the till above to form stratified diamicton homogenising down ice (Evans & Ó Cofaigh, 2008; Ó Cofaigh et al., 2008, 2011; Ó Cofaigh and Dowdeswell, 2001; Phillips et al., 2002; Roberts and Hart, 2005). Downward infilled gravel hydrofractures present themselves on the stoss side of the drumlin as the water above the upper Irish till would have been under increased pressure (Phillips and Hughes, 2014). A glaciolacustrine outwash origin, similar to the sediments observed in the Screen Hills (Evans & Ó Cofaigh, 2003), supports the model presented by Ó Cofaigh et al. (2011).

6.1. Relative timestep reconstruction

Fig. 11 illustrates a schematic reconstruction sequence forming the stratigraphy at Glan-y-môr Isaf. At the last glacial maximum (LGM) around 26ka (Phase 1), the ISIS flowed into the Celtic Sea, impinging the Llŷn Peninsula, and ice from the WIC covered the site. The transition between Welsh and Irish ice is situated on the mainland side of the Menai Strait by Thomas et al. (1998), however, evidence from Glan-y-môr Isaf contradicts this. Instead, the ISIS was pinned by Anglesey (agreeing with Smedley et al. (2017)) and did not advance over Glan-y-môr Isaf until the WIC had retreated in one of its final oscillations. Hence the ISIS-WIC margin shown in Phase 1 in Fig. 11 is west of Glan-y-môr Isaf, which then tracks down the Llŷn Peninsula. Uncertainty arises when extrapolating from a single-site study, particularly given the constraints imposed by limited outcrop availability. Broader investigations along the Welsh coast could help address these limitations and provide a more robust understanding of the ISIS-WIC interaction. During initial deglaciation (Phase 2), the ISIS had retreated up the Irish sea, driven by topography and dynamic thinning. Impinged against the Llŷn Peninsula and Anglesey (Small et al., 2018; Scourse et al., 2021), the ISIS deposited significant outwash across North Wales (Thomas& Chiverrell, 2007) which provides information regarding the ice margin position during this period. Welsh ice, in this model however, still resided over Glan-y-môr Isaf as the glaciolacustrine deposits were deposited directly after WIC retreat from the region further into ISIS retreat. As described by Thomas and Chiverrell (2007), the ISIS underwent at least 11 oscillations throughout its retreat, and during a final ISIS oscillation in this area the ISIS advanced over the site (reaching Dinas Dinlle, the most northernly oscillation reported by Thomas and Chiverrell (2007), around 20 ka as per Smedley et al. (2017)). Phase 3 represents the minima before this oscillation, where the ISIS was pinned on Anglesey but had retreated into Liverpool Bay and likely produced the extensive moraine ridge depicted on Anglesey in Fig. 2. The WIC had also actively retreated from the area, which allowed the formation of the ice-marginal Lake Greenly. Such a scenario is more likely than the one presented by Hart in Edge et al. (1990) from what is now known about the dynamics of the ISIS and its emplacement over the Llŷn Peninsula. As above, it is important to acknowledge the uncertainties in mapping the edge of this lake. Fig. 11 presents one scenario for the location of Lake Greenly, where the north margin of the lake is bounded by the ISIS pinned on Anglesey, but the extent of Lake Greenly may have been much larger (as in Hart, 1995). The full extent and precise margins of Lake Greenly, as well as the temporal constraints on its evolution, remain uncertain and require further investigation to be accurately resolved.

Post lake formation, a distal ice margin allowed a low-energy environment to form, still being fed by icebergs – annual varves interrupted by dropstones. Sediment likely came from both the ISIS and WIC, but icebergs, due to topographic restrictions, came from the impinged ISIS. Phase 4, Fig. 11, details the advance of the ISIS into the area, this may have been after some time as marked the presence of the peat ball in the till matrix (enough time for plant colonisation to begin). An advancing ice margin increased the grain size of lacustrine sediments with evidence of turbidites as well. When the ISIS was close enough, gravel outwash was deposited. Soon after, during phase 5, the area was overrun and subglacial deformation underneath the advancing ice stream cannibalised sediment underneath into stratified diamictons. OSL dates from nearby Aberogwen in Smedley et al. (2017) date this transition to 20.3 $\pm$ 0.6 ka. The ice margin did not reach its maximum extent at Glan-y-môr Isaf but continued southwards, likely to Dinas Dinlle, as indicated by the glaciotectonic structures recorded by Thomas and Chiverrell (2007). The ice margins presented in Fig. 11 in Phase 5 are uncertain, especially on Anglesey, represent out best interpretation based on the available evidence but remain uncertain and would benefit from further investigation. After reaching maximum position, the ISIS retreated, the WIC became independent (Glasser et al., 2012; Patton et al., 2013b) and any remanence of sandur during deglaciation has since been eroded. Post-deglaciation, the area was subject to periglacial modification (Phase 6) creating the cryoturbed structures observed.

6.2. Formation of stratified Diamicton

Presented here is an updated 3D model (Fig. 12) for the formation of stratified diamicton and till assemblages at Glan-y-môr Isaf. Notably, pinning of ice on Anglesey confirms that stratified diamictons are common in areas where a stillstand was first able to deliver large quantities of sediment to the ice margin (Ó Cofaigh et al., 2011). Importantly, to update the model exhibited by Ó Cofaigh et al. (2011), stratified diamictons have been shown to form from glaciolacustrine deposits even when completely overridden – the deformation of till underneath an ice sheet continues to cannibalise underlying sediments into stratified diamictons. Glaciomarine sediments are not required for genesis, further reinforcing the dismissal of the glaciomarine hypothesis (Eyles and McCabe, 1989). Exemplified by other deposits of stratified diamicton (Dackombe and Thomas, 1991), sediments detail increasing homogeneity with ice flow – as is recorded by the decreasing number of gravel strings from log 5 to 8 at Glan-y-môr Isaf. Compared to similar sediments displayed by Eyles and McCabe (1991) there are fewer clearly-defined, laminated strata in the diamictons at Glan-y-môr Isaf, however, this is likely because the deforming Irish till is cannibalising larger gravel sediments here. Where finer-grained sediments have been rafted, banding is preserved, similar to Douglas (1974). The preservation of lamination was one contributing factor which led Eyles and McCabe (1989, 1991) to ascribe a glaciomarine genesis, but as detailed in this study, banding in the cannibalised stratified diamictons can be preserved for a short time before complete homogenisation.

Fig. 12 details a four-stage development model for formation, corresponding to phases 3 to 5 in the timestep reconstruction (Fig. 11) for the transition from Lake Greenly to ice advance. Suspension settling of glaciolacustrine interflows and underflows dominates initial sediment genesis (Stage 1) (Ó Cofaigh and Dowdeswell, 2001), aided by the calm environment created between the submerged moraines ridges. Stage 2 documents the advance of the ice margin, suspension settling still occurs, but higher energy processes involving gravity flows, turbidity currents and gravel outwash become more important to form a deltaic sequence. Sediments, such as those at Glan-y-môr Isaf, display Bouma sequences

and localised thickening occurs above pre-existing sediments (Evans and Hiemstra, 2005). During stage 3, the ice margin overrides the site beginning to tectonise the recently deposited sandur, lacustrine sediments, and push moraines. Finally, in stage 4, the deforming Irish till layer cannibalises the lacustrine and outwash deposits up into the till in

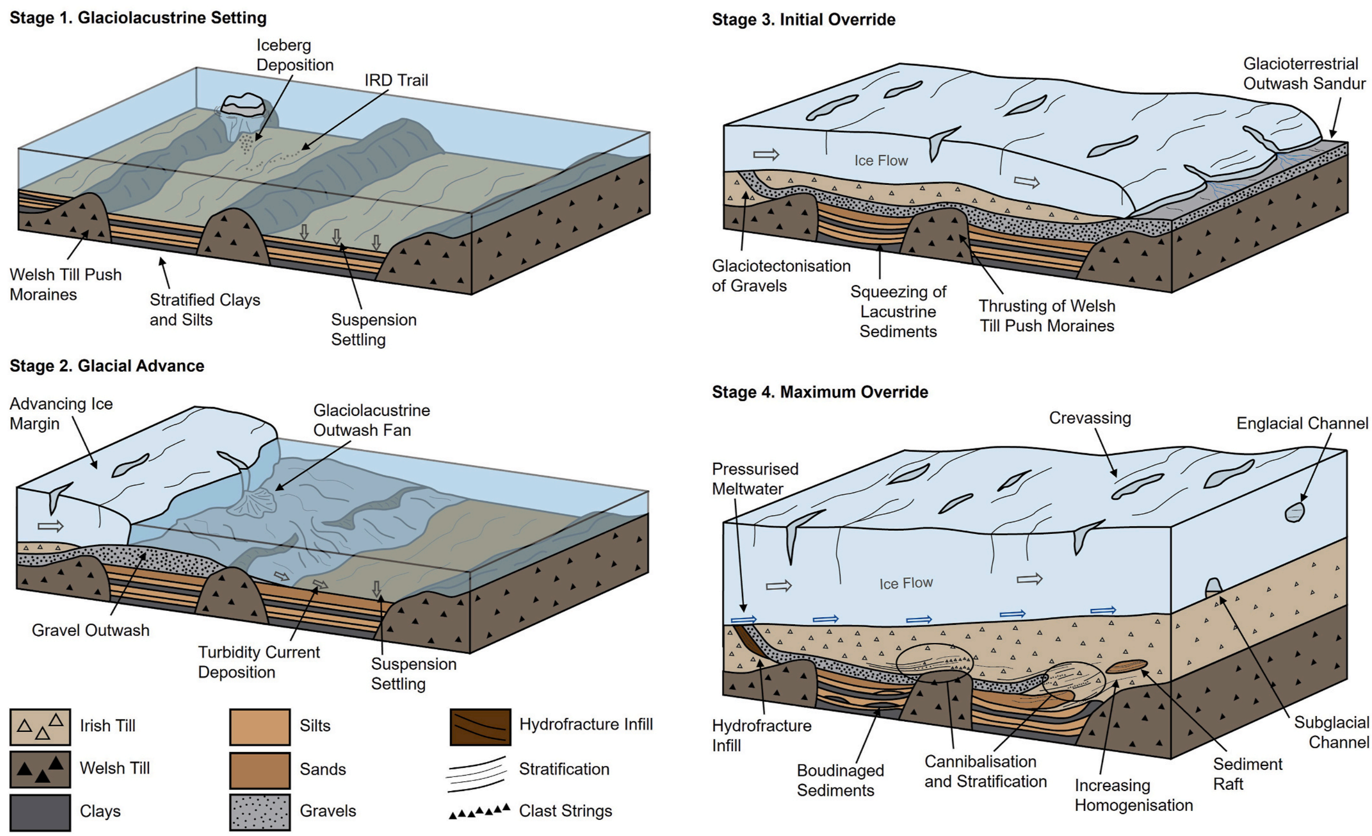

Fig. 12. Four-stage 3D conceptual model for the formation of stratified assemblages from glaciolacustrine and outwash sediments at Glan-y-môr Isaf. Note that sediments are vertically exaggerated in relation to ice thickness presented. In stage 1, glaciolacustrine deposition, consisting of suspension setting forms laminated rhythmites. In stage 2, an advancing ice margin increases the glaciofluvial energy of the system causing turbidity currents and gravity flows. During initial ice override (Stage 3), ice loading causes the glaciotectonisation and thrusting of gravels and underlying Welsh push moraines. In the last stage (4), the continued overriding of the sediments and formation of a subglacial deforming layer causes the continued deformation of soft glaciolacustrine sediments and cannibalisation at the base of the till enabling the development stratified diamictons and homogenisation into stratified tills.

the direction of ice flow, producing stratified diamictons which homogenise into tills. Abducted are rafts and strings of sands and gravels, which laterally homogenise with increasing distance from the site. Subglacial traction tills do not deform uniformly, there are different faults and movements within the active sediment as marked by irregular gravel and sand strings – similar to the results presented by Ó Cofaigh et al. (2011). Large quantities of pressurised meltwater and sediment allow hydrofracture infills to develop, and continued glaciotectonic thrusting deforms soft sediments into boudin and flame structures. The till reacts to the sediment underneath, reducing the strength of the strain signature (decrease from log 3 to log 7 and 8 in Fig. 10, similar to Ó Cofaigh et al. (2011)). Post deglaciation, despite periglacial processes, stratified assemblages are preserved across short transport distances – a snapshot of this continual process preserved in the sedimentology.

7. Conclusion

Analysis of the sediments exposed at Glan-y-môr Isaf update the interaction of the WIC and ISIS across North Wales, the behaviour and dynamism of the ISIS during the last deglaciation, and presents a model for the production of stratified till from the glaciotectonic cannibalisation of glaciolacustrine sediments. A multiphase depositional process is reconstructed, beginning with the emplacement of a subglacial traction till from the WIC, contradicting other sites along the North Wales coast where the ISIS was first to deposit till. The confluence between the ISIS and WIC was therefore further west in this region than it is along the Llŷn Peninsula, aided by the topographic pinning provided by Anglesey. Active retreat from both ice masses left recessional moraine ridges at Glan-y-môr Isaf, and Irish ice still pinned on Anglesey allowed the formation of Glacial Lake Greenly – a glaciolacustrine environment forming clay and silt rhythmites from a sediment-laden ice margin. Readvance of ISIS ice over the region deposited a graded sand to gravel sequence and then an actively-deforming, subglacial traction till carrying shells from the ISB. There is no evidence that the margin came to a standstill at Glan-y-môr Isaf, but rather fast, warm-based ice continued over the site and drumlinised the region. Results illustrate that large meltwater and sediment quantities existed at the margin of the ISIS, exemplifying the importance of the ISIS and BIIS in actively transporting and depositing large quantities of sediment and shaping the geomorphology of North Wales and Irish Sea.

Glan-y-môr Isaf presents an exemplar model for the production of stratified tills. The four-stage model presented in Fig. 12 illustrates how an advancing ice margin can override and cannibalise previously deposited sediments whilst contemporaneously depositing new outwash sandur at the margin. Strings and rafts of pre-existing sediment deform semi-horizontally within the subglacial traction till, homogenising over short transport distances. Unique for this site, compared to other sites where stratified tills are found, is that there is no evidence for ice-marginal stillstand as the ISIS overrode Glan-y-môr Isaf during one of its advancing oscillations, this infers that the processes that form stratified tills as discussed in the model by Ó Cofaigh et al. (2011) and this study, can continue to occur well after readvance. More specifically, the cannibalisation of underlying pre-existing deposits continues to occur after readvance and is not restricted to ice-marginal environments, such that stratified diamictons and tills can be found outside of sites classified as ice-marginal. More broadly, sediments laid down by the last BIIS suggest an intricately more complex dynamic ice sheet and history than originally thought, essential information to take forward when modelling the behaviour of our contemporary ice sheets.

Statement of author contributions

Conceptualization: Cameron J. Powell conceptualised the study, formulating the overarching research goals and aims with revision at multiple points including the proposal by Rachel P. Oien.

Methodology: Cameron J. Powell developed the methodology, including the design and implementation of sedimentological and stratigraphic analyses, with feedback and guidance from Rachel P. Oien.

Validation: Rachel P. Oien supervised the validation process, ensuring the reproducibility of results and the robustness of the interpretations.

Formal analysis: Cameron J. Powell conducted the statistical and computational analyses, synthesising the study data under the mentorship of Rachel P. Oien.

Investigation: Cameron J. Powell performed the fieldwork, laboratory experiments, and evidence collection, which formed the foundation of the study.

Resources: Rachel P. Oien secured access to laboratory facilities and computing resources necessary for the project.

Data Curation: Cameron J. Powell managed the research data, annotating and maintaining the datasets for initial analysis and future reuse.

Writing - Original Draft: Cameron J. Powell prepared the initial draft of the manuscript, incorporating the key findings and visual representations of the study.

Writing - Review & Editing: Rachel P. Oien provided critical feedback on the drafts, contributing to significant revisions, and both authors collaboratively worked on refining the manuscript and addressing the reviewers' comments.

Visualization: Cameron J. Powell designed and created the figures and tables to effectively communicate the data and interpretations.

Supervision: Rachel P. Oien provided oversight and mentorship throughout the research process, guiding the project's direction and execution.

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Both authors have read and approved the final version of the manuscript and have contributed equally to the preparation of the revised version and responses to reviewers.

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.

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Data availability

All data and/or code is contained within the submission.

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