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Quaternary of Wales

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Quaternary stratigraphy: north-west Wales

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Introduction

The coastal margins of north-west Wales are one of the key areas for the elaboration and interpretation of Late Pleistocene and Holocene events and processes. In common with Gower, the coasts of Anglesey and the Llŷn Peninsula exhibit complex sequences of glacial, periglacial and some interglacial sediments which show changing environmental conditions during the Late Pleistocene. In particular, these sediments provide evidence for the interaction of Irish Sea and Welsh ice masses, and they, in addition, record changes in relative sea-levels. A number of themes are important. First, the area figured prominently in the development of the Glacial Theory and attempts to sub-divide the Pleistocene. Second, recent studies have elaborated the provenance and directions of movement of various ice masses affecting the area. Third, attempts have been made to establish a chronology for the region, based largely on lithostratigraphy and radiocarbon dating. One sequence, at Glanllynnau, has been compared with modern glacial depositional systems. A comprehensive chronology for the region, however, has not been developed, a situation made worse by a general lack of interglacial indicators and the uncertain significance of a number of weathering horizons. The Late Pleistocene record in north-west Wales is particularly important for demonstrating possible evidence for a readvance of Late Devensian Stage ice.

Early sub-division

Historically, the area is important in two respects. It figured prominently in the development of the Glacial Theory; Trimmer's (1831) early account of the shelly sand and gravel deposits on Moel Tryfan marked an important milestone in glacial geomorphological research, because it began approximately seventy years of fierce debate centred on the contending theories of the 'glacialists' and 'diluvialists'. Moreover, the site continued to play a central role in the development and resolution of the debate.

The area is also notable for some of the earliest attempts in Britain to sub-divide the Pleistocene sequence. By the 1850s, enough was known about the glacial deposits in North Wales for Ramsay to postulate a threefold division – 1) a Lower Boulder Clay deposited by local Welsh glaciers, 2) the Middle Sands and Gravels and the shelly till of Moel Tryfan and 3) an Upper Boulder Clay deposited by a readvance of small valley glaciers (Davies 1969). Although Ramsay accepted a glacial origin for the boulder clays, he still found it necessary to invoke a period of marine submergence to account for the shelly drift deposits on Moel Tryfan. Thomas Belt's (1874) perceptive paper concerning the Moel Tryfan deposits, however, did much to advance the Glacial Theory, but even as late as 1910, Edward Hull, former director of the Irish Geological Survey, still regarded the shelly drift as evidence for marine submergence (Davies 1969).

Following these early pioneering studies in North Wales, Jehu (1909) and Greenly (1919) published detailed accounts of the Pleistocene deposits of the Llŷn Peninsula and Anglesey, respectively. Jehu (1909) considered that Llŷn had been glaciated twice by ice from northern Britain (Northern or Irish Sea ice). At many sites around the Llŷn coast he described Upper and Lower Boulder Clays separated by Intermediate Gravels and Sands; the latter he considered to have formed probably during interglacial melting of the first ice-sheet. Jehu assumed that similar advances of Welsh ice had also issued from Snowdonia. Above all, he established that the Pleistocene deposits in north-west Wales had resulted from the interaction of ice masses from the Irish Sea Basin and Snowdonia. Greenly (1919) produced a comprehensive account of the Pleistocene geology of Anglesey and established that the island had been overrun by Irish Sea ice on two occasions. Using glacial striae and erratics trains as indicators of former ice movement directions, Greenly was able to show that Anglesey had been glaciated by Irish Sea ice from the north-east while coeval ice from Snowdonia may have impinged upon the south-east coast of the island. Like Jehu (1909), Greenly (1919) suggested that the directions of movement of the Irish Sea ice-sheet had been similar during both glaciations. The tripartite sub-division of deposits on Llŷn by Jehu (1909) is particularly relevant, because many of the GCR stratigraphical sites in the region were originally described and interpreted using this classification. Both Gwydir Bay and Dinas Dinlle, for example, were regarded by Jehu as showing all three members of the tripartite scheme.

Recent approaches to Pleistocene problems

Although most studies agree that Llŷn and probably much of north-west Wales was affected by ice from two main sources during the Late Pleistocene, interest in the coastal sections in recent years has centred upon a) establishing a chronological framework for Late Pleistocene events and b) determining the characteristics and extent of the ice masses affecting the region. Consequently, the GCR site coverage in the coastlands of north-west Wales demonstrates the major sedimentary units and the most important themes that have featured in the emerging Pleistocene chronology.

Ice-sheets and ice movement directions

Studies of till fabric patterns and clast lithology at sites throughout Llŷn (Saunders 1963, 1968b, 1968d; Simpkins 1968) have helped to determine more clearly former patterns of ice movement directions. During the first inferred glaciation, Irish Sea ice is believed to have moved onto Llŷn from the north and north-west, while much of Arfon and south-east Llŷn was crossed by ice from the Snowdonian massif. During the second inferred advance, there is some evidence to suggest that the Irish Sea ice-sheet moved onto both the North Wales coast and the Llŷn Peninsula from the north and east, and that it was probably confluent with south-west moving Welsh ice in the Menai Straits region (Whittow and Ball 1970). During this second phase, it has been suggested that neither the Welsh nor Irish Sea ice masses was as extensive as previously, and certain parts of Llŷn may have remained ice-free. The GCR sites at Hen Borth, Red Wharf Bay and Lleiniog on Anglesey, show the dominant onshore and generally south-west movement of the Irish Sea ice, probably during the last of the inferred major glacial events. In the same context, coastal stratigraphical sites on Llŷn also demonstrate the movements of the Irish Sea and Welsh ice-sheets at different times. From fabric and clast lithology measurements (for example, Saunders 1963, 1968b, 1968d; Simpkins 1968), in combination with lithostratigraphic interpretations, three patterns of ice-movement have been identified. First, the coastal sections in northern Llŷn show evidence for a generally southward movement of Irish Sea ice. The evidence suggests that sites in the west, for example Porth Oer, were exclusively overrun by Irish Sea ice, whereas from Gwydir Bay northwards to Dinas Dinlle, the combined effects of Irish Sea and Welsh (Snowdonian) ice-sheets are evident. Second, on the southern coast of the peninsula, sites in the east such as Morannedd and Glanllynnau show evidence for glaciation by ice of Welsh provenance, from sources in Snowdonia. Third, exposures such as those at Porth Ceiriad and Porth Neigwl on the southern coast, show that the western part of the peninsula (in the area around St Tudwal's) may have been a zone of transition between Welsh and Irish Sea ice-sheets on one or more occasions.

The work of Saunders (1968b, 1968d), Simpkins (1968) and Whittow and Ball (1970) has also established that an upper till on Llŷn is found widely outside Synge's (1963, 1964) proposed maximum limit for Late Devensian (Late Weichselian) ice.

Chronology

While the broad pattern of Late Pleistocene ice movements is well established, their timing is less certain, as is the precise extent of each glaciation. In determining a chronology for the region, the well exposed coastal sites are important. In an investigation of the coastal stratigraphy around Llŷn, Synge (1963, 1964) suggested that ice of Late Devensian age only impinged on its northern coastal margins. More weathered and cryoturbated glacial sediments to the south of this limit at, for example, Criccieth (Morannedd) and Glanllynnau, were, therefore, considered to be older. Synge's classification was based on correlation with a stratigraphic model developed in Ireland, in which raised beach sediments such as those at Porth Oer in western Llŷn were ascribed to the Hoxnian Stage. Such a view, however, has not been widely accepted, and most workers including Saunders (1968a, 1968b, 1968c, 1968d) and Bowen (1973a, 1973b, 1974, 1977a, 1977b) considered the raised beach sediments at Porth Oer to be of Ipswichian age and the till on Llŷn to have been deposited during the Devensian Stage. These views have developed from three main lines of evidence outlined below.

Regional correlations

Bowen (1973a, 1973b, 1974, 1977a, 1977b) proposed a classifiction for the Pleistocene of Wales. In this, the widespread raised beaches of South Wales were ascribed to the Ipswichian Stage. Raised beach sediments in North Wales have been recorded only at Porth Oer, and at Red Wharf Bay in eastern Anglesey. Like Saunders (1968a), Bowen (1973a, 1973b, 1974, 1977a, 1977b) considered that the glacial and periglacial sediments which overlie the raised beach at Porth Oer and Red Wharf Bay were Devensian in age. Bowen also supported Saunders' contention that the Bryncir-Clynnog moraine as well as additional deposits to the south represented a readvance of a Late Devensian ice-sheet.

Weathering horizons

Weathering horizons described from a number of coastal sections in north-west Wales have had a major bearing on classification. Simpkins (1968) classified the Pleistocene deposits in central Caernarvonshire into formal lithostratigraphic units. These units have been applied over wider areas and they have been subsequently used in the individual accounts of the GCR sites. According to Simpkins (1968) the earliest glacial advance in Llŷn was shown by the Criccieth (Welsh) till found along the southern Llŷn coast at, for example, Criccieth and Glanllynnau. Weathering of the surface of the Criccieth Till suggested a possible pre-Devensian age to Simpkins, who like Synge (1963, 1964) believed the weathering to have occurred in an interglacial. The Criccieth Till is overlain by Welsh fluvioglacial sediments of the Afon Wen Formation and by the Llanystumdwy Till ascribed to the Devensian by Simpkins (1968). In contrast, Saunders (1968a, 1968d) partly on the basis of radiocarbon evidence (see below), suggested that the surface of the Criccieth Till had been weathered during an interstadial in the Devensian, a view upheld by Whittow and Ball (1970) and Bowen (1973a, 1973b, 1974, 1977a, 1977b).

On the northern coast of Llŷn, Simpkins described a similar threefold sequence to that of Jehu (1909) with a succession of – 1) lower Irish Sea till (Trevor

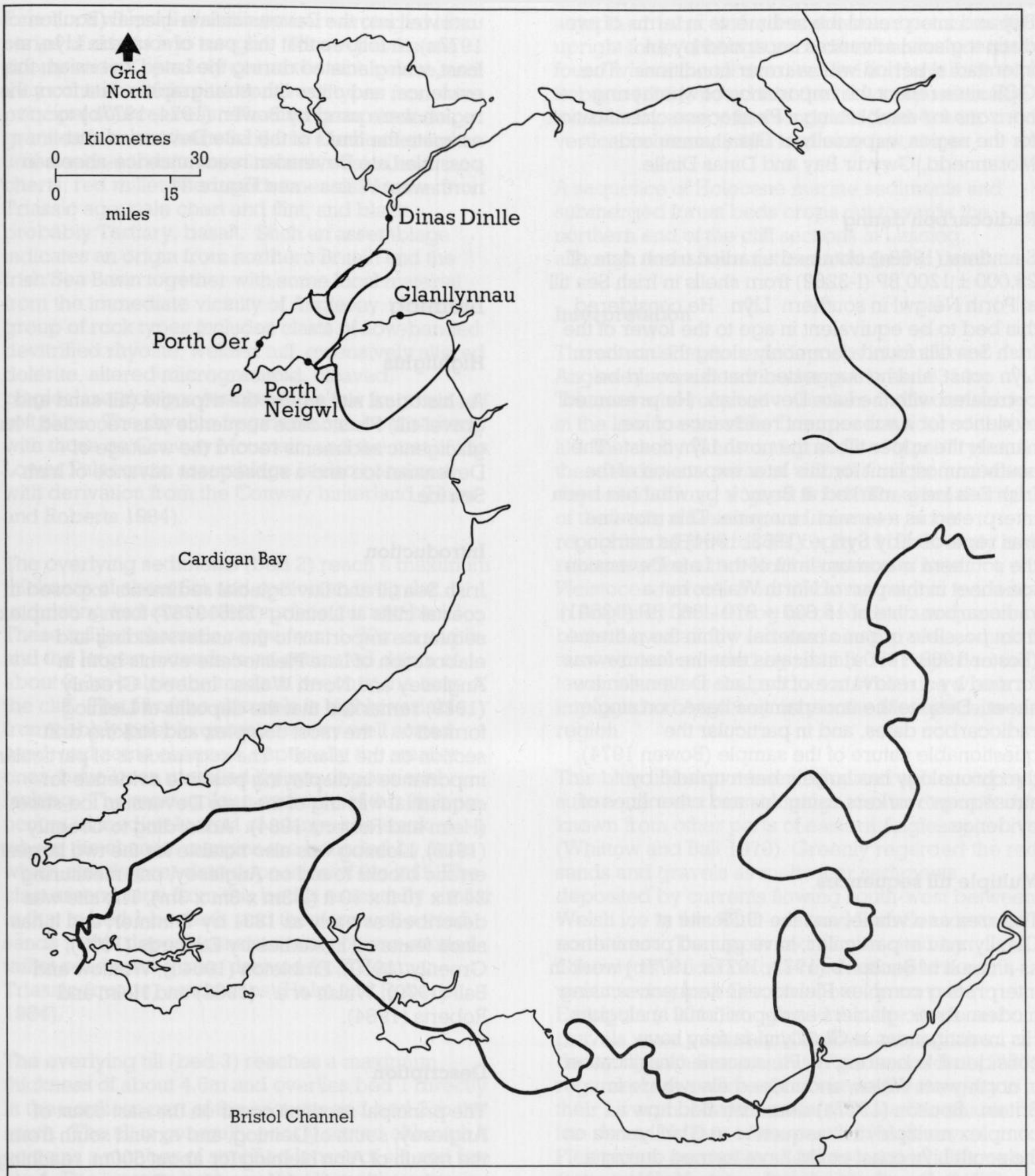

Figure 27 Late Devensian and Late Devensian readvance ice limits (from Bowen 1974, 1977b)

Till), 2) fluvioglacial sediments (Aberafon Formation), and 3) an upper Irish Sea till (Clynnog Till). No weathering horizon was seen by Simpkins (1968) in this sequence and the tills were, therefore, considered to have been deposited by two closely-spaced advances of the Late Devensian ice-sheet. Saunders (1968a, 1968b, 1968c, 1968d), however, recognised evidence for weathering between deposition of the two till units at Gwydir Bay and interpreted the sediments in terms of two distinct glacial advances separated by an interstadial period with warmer conditions. The GCR sites reflect the importance of weathering horizons for establishing a Pleistocene classification for the region, especially at Glanllynnau and Morannedd, Gwydir Bay and Dinas Dinlle.

Radiocarbon dating

Saunders (1968a) obtained a radiocarbon date of 29,000 ± 1200 BP (I-3262) from shells in Irish Sea till at Porth Neigwl in southern Llŷn. He considered this bed to be equivalent in age to the lower of the Irish Sea tills found commonly along the northern Llŷn coast, and he suggested that this could be correlated with the Late Devensian. He presented evidence for a subsequent readvance of ice, namely the upper till on the north Llŷn coast. The southernmost limit for this later expansion of the Irish Sea ice is marked at Bryncir by what has been interpreted as a terminal moraine. This moraine was regarded by Synge (1963, 1964) as marking the southern maximum limit of the Late Devensian ice-sheet in this part of North Wales, but a radiocarbon date of 16,830 + 970 - 860 BP (I-2801) from possible organic material within the moraine (Foster 1968, 1970a) indicates that the feature was formed by a readvance of the Late Devensian ice-sheet. Despite the uncertainties based on single radiocarbon dates, and in particular the questionable nature of the sample (Bowen 1974), the chronology has largely been upheld by subsequent workers using this and other lines of evidence.

Multiple till sequences

The area as a whole, and the GCR site at Glanllynnau in particular, have gained prominence as a result of Boulton's (1972, 1977a, 1977b) work in interpreting complex Pleistocene sequences using modern Arctic glaciers as depositional analogues. His investigations at Glanllynnau may have considerable bearing on Pleistocene classification in north-west Wales, and indeed elsewhere in Britain. Boulton (1977a) demonstrated how a complex multiple drift sequence at Glanllynnau on the south Llŷn coast could have formed during a single Late Devensian glacial event. He suggested that similar complex sequences at Gwydir Bay and Porth Neigwl, and elsewhere in Llŷn could also be accounted for by this simple model, without recourse to further sub-division.

Evidence from Glanllynnau has been used to reconstruct a detailed record of Late Devensian late-glacial and Holocene environmental changes (Simpkins 1968, 1974; Coope and Brophy 1972). Radiocarbon, pollen and particularly fossil beetle evidence from the sequence have made the site a cornerstone for Late Devensian late-glacial studies in lowland North Wales, as well as giving the site national importance. Faulting structures in the late-glacial sequence provide crucial evidence to tie the glacial and late-glacial sequences together; showing that buried glacier ice did not finally melt until well into the Devensian late-glacial (Boulton 1977a). It follows that this part of southern Llŷn, at least, was glaciated during the Late Devensian, this evidence, and other lithostratigraphic data from the region were used by Bowen (1974, 1977b) to estimate the limits of the Late Devensian and possible Late Devensian readvance ice-sheets in north-west Wales – see Figure 27.

Lleiniog

Highlights

An historical site where the tripartite (till-sand and gravel-till) Pleistocene sequence was recorded. Its glacigenic sediments record the wastage of Devensian ice and a subsequent advance of Irish Sea ice.

Introduction

Irish Sea till and fluvioglacial sediments exposed in coastal cliffs at Lleiniog (SH619787) form a complex sequence important to the understanding and elaboration of Late Pleistocene events both in Anglesey and North Wales. Indeed, Greenly (1919) remarked that the deposits at Lleiniog formed "..... the most complex and striking drift section on the island". The sequence is of particular importance in displaying possible evidence for sequential wasting of the Late Devensian ice-sheet (Helm and Roberts 1984). According to Greenly (1919), Lleiniog was also notable for the two largest erratic blocks found on Anglesey, one measuring 24 ft x 10 ft x 10 ft (7.3m x 3m x 3m). The site was described as early as 1831 by Trimmer, and it has since featured in studies by Edwards (1905), Greenly (1919), Embleton (1964c), Whittow and Ball (1970), Walsh *et al.* (1982) and Helm and Roberts (1984).

Description

The principal sections occur on the east coast of Anglesey, south of Lleiniog, and extend south from the mouth of Afon Lleiniog for about 500m, reaching a maximum height of about 12m. Exposures of Quaternary sediments form the low cliffs and foreshore at Trwyn y Penrhyn and can also be found on the foreshore near Gored-bach lifeboat station. The most extensively exposed sediments occur in cliff sections, and in plan on the foreshore, just to the south of the mouth of Afon Lleiniog. The succession consists of well stratified outwash (the Lleiniog Gravels of Greenly (1919)), overlain by a more homogenous, unstratified, red Irish Sea till.

Helm and Roberts (1984) divided the gravel and sand deposits at Lleiniog into two units; a lower Grey-brown Sand and Gravel Member (bed 1), and an upper Red-brown Sand and Gravel Member (bed 2). Bed 1 crops out only towards the base of the cliff, where it reaches a maximum thickness of about 2.5m, and also extensively in plan on the foreshore where the sediments are arranged in a series of ridges and troughs. These gravels are poorly sorted, sparsely cemented with calcite, and they contain a wide variety of rock types from two principal source areas. The first group includes granites from southern Scotland; Carboniferous limestones, sandstones, siltstones, shales and cherts; red millet-seed sandstones of Permian or Triassic age; pale chert and flint; and black, probably Tertiary, basalt. Such an assemblage indicates an origin from northern Britain and the Irish Sea Basin together with some local material from the immediate vicinity of Anglesey. A second group of rock types includes clasts of flow-banded devitrified rhyolite, welded tuff, extensively altered dolerite, altered microgranitoid, cleaved, plagioclase-rich greywacke and a few fragments of soft slate. The rhyolite fragments can be matched with those on Conway Mountain, and the rest of this Lower Palaeozoic assemblage is also consistent with derivation from the Conway hinterland (Helm and Roberts 1984).

The overlying sediments (bed 2) reach a maximum thickness of about 6m and rest on an irregular, undulating and channelled surface cut into bed 1. These infilled channels range from 1-60m in width and the largest extends to an estimated depth of about 2-3m below the modern beach at the base of the cliff. The fill of the channels is highly variable, from cobbly pebble gravels to very well sorted sand, and some channels, especially the smaller ones, have been modified by syn-depositional faulting. The most striking example of this faulting occurs immediately west of a large sea-stack, where the channel margins are bounded by faults which clearly post-date deposition of the infill. The clast assemblage from this bed is essentially similar to that in bed 1 beneath, and the very well sorted sands in this deposit consist mainly of iron-stained millet seed sand grains derived from Permian-Triassic (quartz) sandstones (Helm and Roberts 1984).

The overlying till (bed 3) reaches a maximum thickness of about 4.5m and overlies bed 1 directly in the northern part of the sections and bed 2 to the south. The till is generally poorly sorted although it contains a number of stratified lenses of silt and fine sand. The junction between the till and the gravels beneath is frequently marked by a boulder bed, interpreted by Helm and Roberts (1984) as washed, matrix-free till. Boulders up to 1.5m across occur in the till, and many larger boulders occur on the foreshore which have evidently been liberated from the till. The large limestone erratics recorded by Greenly (1919) and now perched on a low alluvial apron at the mouth of Afon Lleiniog, may also have originated from the till. Most boulders and cobbles in the till range from rounded to subangular in shape and comprise mostly Carboniferous rocks, mainly limestone, with a smaller proportion of farther-travelled rocks including the distinctive Ailsa Craig microgranite (Edwards 1905; Helm and Roberts 1984). Where the till directly overlies bed 1, but only there, the latter sometimes shows evidence of deformation to a depth of 1-2m, with recumbent and occasionally upright folds; although such disturbances are not found where the till overlies bed 2. Helm and Roberts (1984) noted that the till was sporadically overlain by a very fine sandy silt (bed 4) with vertical columnar joints and very few stones.

A sequence of Holocene marine sediments and submerged forest beds crops out towards the northern end of the cliff sections at Lleiniog, although these have not been studied in detail.

Interpretation

The coastal Pleistocene deposits in south-east Anglesey were described as early as 1831 by Trimmer who referred to broken shells occurring in the low coastal cliffs. Trimmer considered that, like the shelly sands and gravels of Moel Tryfan, these sediments were of 'diluvial' origin, and were deposited during a 'great flood'. The glacial origin of the beds at Lleiniog was, however, soon recognised (Edwards 1905). By 1919, Greenly had reconstructed a threefold sequence of Late Pleistocene events from lithostratigraphic evidence in Anglesey. At Lleiniog he recorded a sequence of blue till overlain by red sands and gravels, which in turn were succeeded by red till. He regarded the lower blue till as the product of Welsh ice which impinged on Anglesey only in the Menai Straits region.

This blue till has not been relocated at Lleiniog by subsequent workers, although similar deposits are known from other parts of eastern Anglesey (Whittow and Ball 1970). Greenly regarded the red sands and gravels as meltwater sediments deposited by currents flowing south-west between Welsh ice to the south-east and Irish Sea ice to the north-west. The upper red till was cited by Greenly as evidence of a readvance of the south-west moving Irish Sea ice-sheet. In contrast, Embleton (1964c) suggested that the sands and gravels were probably laid down beneath the decaying Irish Sea ice, but Whittow and Ball (1970) regarded the sediments as outwash belonging to their Liverpool Bay Phase of the Late Devensian ice-sheet. No part of the eastern Anglesey Pleistocene succession has been dated, although recently Whittow and Ball (1970), Bowen (1977a, 1977b) and Boulton (1977a) have regarded similar sequences in the region as Late Devensian in age. Alternatively, Thomas (1976) considered that Anglesey lay outside the maximum limit for Late Devensian Irish Sea ice, implying that the glacial sediments in Anglesey must be older.

Walsh *et al.* (1982) investigated the palynology and provenance of coal fragments contained in the Pleistocene sequence at Lleiniog. The coal occurs both as isolated fragments and more occasionally as hydraulic concentrates (Walsh *et al.* 1982) or 'seams' (Greenly 1919). The largest of the coal layers described by Walsh *et al.* (1982) measured about 4m long by 0.20m thick. Greenly (1919) recorded that the largest seam then exposed was

27 feet by 3 inches (8.2m x 0.076m). Walsh *et al.* (1982) established that coal clasts in the Lleiniog gravels contained a varied assemblage of early Westphalian spores. Directional data such as sedimentary structures, glacial striae and erratics trains in the local area showed the sediments had been derived from the north-east. Walsh *et al.* (1982) therefore considered, like Greenly (1919), that the coal clasts were probably derived from an, as yet, unidentified submarine coal outcrop located only a few kilometres to the north-east of Lleiniog. The possibility that the coal clasts had been derived from the breaking-up, locally, of far-travelled rafts of the Coal Measures was also discussed. Roundness studies of limestone clasts taken from the gravels showed that at the time of deposition the ice front probably lay across the eastern approaches of the Menai Straits, perhaps not more than 1 or 2 km from Lleiniog (Walsh *et al.* 1982).

In the most comprehensive account of the sections to date, Helm and Roberts (1984) reconstructed a detailed sequence of events and processes. They divided the sequence into four main members (as described earlier) which they interpreted as the sequential products of a single downwasting Irish Sea ice lobe of Late Devensian age. They believed that bed 1 (Grey-brown Sands and Gravels) formed when subglacial streams from the ice-front, just offshore, debouched into a proglacial lake. Bed 2 (Red-brown Sands and Gravels), a series of channel sands and gravels, was deposited by proglacial streams, while bed 3 (Red-brown Till) was interpreted as a melt-out till, deposited following a readvance of the ice-front. The last member of the sequence (bed 4 - Red-brown Sand) is wind-blown material deposited in temporary pools on the surface of the till. The composition of the sediments indicates that they have mostly originated from northern Britain, the Irish Sea Basin and Anglesey, in particular the north and north-east of the island. A small but persistent input of clasts, however, occurred from the Welsh mainland, probably from the Conway area. Two alternative explanations were put forward to account for this mixture of erratics. Most likely, the mixture of erratics probably indicated a confluence of Irish Sea and Welsh ice immediately north-east of Penmon during the Late Devensian; or the locally derived erratics may have been reworked from pre-existing Welsh glacial sediments offshore (Helm and Roberts 1984).

The exposures at Lleiniog are the finest through Pleistocene glacial and fluvioglacial deposits in Anglesey, and they provide one of the most complete Late Pleistocene to Holocene stratigraphical records in north-west Wales. The site first featured in a number of pioneering studies which were fundamental to the firm establishment of the Glacial Theory in Great Britain and to the early sub-division of the Pleistocene record. Continued reference to the site has reinforced its importance for Pleistocene palaeoenvironmental studies.

In particular, the thick red till at the site provides some of the clearest evidence for the incursion onto Anglesey of ice from the Irish Sea Basin. In combination with stratigraphic reference sites elsewhere in Anglesey and in Llŷn, Lleiniog is important for establishing a network of sites that can be used to determine patterns of ice movements across north-west Wales during the Late Pleistocene.

The site is one of very few in north-west Wales where a variety of detailed sedimentological techniques has been applied to reconstructing palaeoenvironments. Lithostratigraphical and sedimentological data from Lleiniog suggest that till was deposited as a melt-out product following a readvance of the Irish Sea ice-sheet over a thick sequence of earlier proglacial sediments. Analysis of the latter have shown them to be the product of sequential downwasting of Irish Sea ice. The sections at Lleiniog are therefore important in providing some of the most detailed evidence from Wales for former glacial and fluvioglacial processes at or near the margins of an oscillating ice-sheet.

Although a Late Devensian age is probable for the glacigenic sequence at Lleiniog, it is not clear whether the till can be correlated with the upper till found in north Llŷn, where it has been interpreted as a readvance feature of the Late Devensian ice-sheet. It is conceivable that the Lleiniog till represents an even later readvance or minor oscillation of the Late Devensian Irish Sea ice-sheet. Lleiniog is therefore significant in demonstrating possible climatic complexity during the Late Devensian.

The interest of the site is further enhanced by Holocene marine and submerged forest beds which have considerable potential for palaeoenvironmental and sea-level studies.

Lleiniog provides one of the finest sequences through glacigenic sediments in north-west Wales. It shows a detailed sequence of events during a cycle of deglaciation and subsequent readvance of the Late Devensian Irish Sea ice-sheet. The site demonstrates the onshore movement of the Irish Sea ice-sheet onto Anglesey.

Conclusions

The succession of ice age sediments at Lleiniog is one of the finest in north-west Wales. It shows evidence for the cycle of glaciation and subsequent ice wastage during the last major glacial phase.

Red Wharf Bay

Introduction

This locality provides rare evidence in North Wales of interglacial conditions. Its possible Ipswichian raised beach occurs beneath till deposited by Irish

Sea ice during the subsequent and last glacial phase.

Introduction

Red Wharf Bay (SH532816) and Porth Oer are the only two sites in northern Wales where raised beach sediments have been recorded. As such, they provide a basis for lithostratigraphical correlation with sequences in South Wales. Red Wharf Bay shows evidence for a sequence of environmental changes from temperate interglacial conditions, as inferred from the high sea-level shown by the raised beach, to colder, and then to fully glacial conditions. The Pleistocene sequence at Red Wharf Bay was first noted by Edwards (1905) and was later described by Greenly (1919). The site has been discussed by Whittow and Ball (1970), Bowen (1973a, 1973b, 1974, 1977b) and Peake *et al.* (1973).

Description and interpretation

Two separate exposures of Pleistocene sediments occur at Red Wharf Bay. At Trwyn Dwlban (SH532820) in the northernmost part of the bay, a low cliff consisting of up to about 4m of red Irish Sea till overlies a fine example of a grooved and striated Carboniferous Limestone shore platform. To the south, beneath Castell Mawr Quarry (SH532816), raised beach and head deposits overlie a raised shore platform of Carboniferous sandstone at about 3m OD. The lowest member of the Pleistocene succession is a calcite-cemented limestone head deposit up to 7m thick (Whittow and Ball 1970). A thin development of raised beach sediments occurs as a wedge within this limestone head; this is also cemented with secondary calcite. Occasionally, this deposit rests directly on the rock platform but mostly it occupies what Whittow and Ball described as a wave-cut notch in the head, some of which is incorporated into the raised beach wedge. The raised beach is composed entirely of local, Carboniferous rocks. Overlying the head is a red-brown Irish Sea till, much of which is disturbed and mixed with quarry spoil. The relationship of the head to the till is obscured by slumping, but in nearby sections red till clearly overlies the head (Whittow and Ball 1970).

A brief description of the site was given by Edwards (1905) who recorded the red till resting on an ice-scratched limestone surface. Indeed, it was the striated and furrowed bedrock surface at Red Wharf Bay rather than the overlying sediments that attracted most of the early interest in the site. Greenly (1919) referred to the "large glaciated floors of limestone" at Trwyn Dwlban with "the remarkable deflections and under-cuttings". Although striae on the pavement generally trend north-east to south-west, Greenly remarked on the deflected striae that occurred in the trumpet-shaped hollows (palaeokarstic pits) found on the platform. These large hollows up to 2m diameter are plugged with pipes of Carboniferous sandstone. Around the plug margins, where the edges of the pits are clearly visible, the striae can be seen to curve into the pits resuming their normal direction where they emerge. Greenly described one particular example where the striae swept completely round the moat-like hollow surrounding a plug, until on its south-west side, the striae pointed 20° north of west, having therefore undergone a deflection of nearly 90° within the space of about 2m. Undercut furrows were also recorded, and Greenly noted that the ice "must have adapted itself as a practically plastic body to every irregularity in the surface of the rock". He also recorded about 4m of red till resting on the ice-worn limestone, with in places a little blue till visible beneath; the latter, however, has not been relocated.

Whittow and Ball (1970) also described the sequence at Red Wharf Bay and considered that the rock shore platform was representative of the most widespread geomorphological feature pre-dating the Pleistocene drifts in North Wales, although of uncertain age. The fact that the raised beach was separated from the platform by a limestone head indicated that the platform had been fashioned during an earlier period of high sea-level. The red till was assigned to their Liverpool Bay Phase of the Late Devensian (Whittow and Ball 1970).

Bowen (1973a) noted that exposures similar to those at Red Wharf Bay, with head in close association with the raised beach gravels, also occurred in south Pembrokeshire and Gower. It seemed likely that they represented cliff fall material which accumulated contemporaneously with the beach sediments, and were therefore broadly Ipswichian in age. By analogy with the Pleistocene deposits in Gower, it would appear likely that head overlying the raised beach at Red Wharf Bay was formed during some part of the Devensian Stage prior to the ice advance that deposited the red Irish Sea till. These chronostratigraphic assignments were also followed by Bowen (1973b, 1974, 1977b) and Peake *et al.* (1973).

From the foregoing, it is clear that Red Wharf Bay is an important site for a number of different reasons. It is only at one or two sites in North and north-west Wales that raised beach deposits are found; these not only provide a record of interglacial conditions during times of high sea-level, but allow lithostratigraphic correlation with sequences in South Wales. Although an Ipswichian age has been suggested for the raised beach at Red Wharf Bay, its precise age is uncertain. Amino acid geochronological studies in South Wales and south-west England have shown that a complicated sequence of raised beaches occurs. An Ipswichian age for the raised beach at Red Wharf Bay would help to constrain the age of the overlying Irish Sea till to some part of the Devensian Stage, but correlations are at present tentative.

The Irish Sea till at Red Wharf Bay demonstrates the incursion of ice from the Irish Sea Basin onto eastern Anglesey, and with GCR sites at Hen Borth and Lleiniog, and those in Llŷn, helps to establish regional patterns of ice movement by use of diagnostic clast lithology and till fabric measurements. Although a Late Devensian age for the till at Red Wharf Bay is likely, it is not clear if it is the product of the main thrust of Late Devensian ice or a later readvance.

The shore platform at Red Wharf Bay is an excellent example of a widespread geomorphological feature. It is very likely to be composite in age, having been fashioned during a number of high interglacial sea-levels. It is clear from the evidence at Red Wharf Bay that the shore platform and raised beach cannot date from the same high sea-level event because they are separated by head.

Red Wharf Bay demonstrates the finest example of a striated shore platform in north-west Wales. The clear relationship between the striated platform and the overlying glacigenic sediments at the site was important in establishing the Glacial Theory in North Wales. It also shows the close association between erosional and depositional processes in certain subglacial environments, and is therefore important for the study of glacier rock bed forms.

Finally, the sequence of head, raised beach, head and till resting on a striated shore platform at Red Wharf Bay, provides a level of sedimentary and palaeoenvironmental detail rarely found elsewhere in North and north-west Wales. The succession is therefore one of the most complete Pleistocene records in the region and allows a sequence of palaeoenvironmental changes to be reconstructed including the interglacial conditions and high sea-levels shown by the raised beach and the fully glacial conditions shown by the till.

The important stratigraphic reference site of Red Wharf Bay, records some of the best evidence currently available for the Late Pleistocene glacial and interglacial history of North Wales. The sequence contains three chief elements which make the site of special interest. Apart from raised beach deposits at Porth Oer in Llŷn, those at Red Wharf Bay are unique in North Wales and they provide an important record of high sea-levels probably during the Ipswichian Stage; and they enable a degree of stratigraphic correlation with reference sites in South Wales. The till at Red Wharf Bay provides a clear indication of the passage of Irish Sea ice onto the coast of eastern Anglesey. Finally, the shore platform here bears unusually fine deflected glacial striae important in studies of erosion in subglacial environments.

Conclusions

The sequence of deposits at Red Wharf Bay provides evidence for the last interglacial to glacial cycle from about 125,000 years ago. The last interglacial is recorded by a raised beach which provides evidence for a global sea-level higher than at present. Above it, scree deposits provide evidence for a cold (periglacial) climate. The glacial deposits at the site provide evidence for the movement of an Irish Sea ice-sheet onto eastern Anglesey. Only two sites in North Wales provide detailed evidence of this kind.

Hen Borth

Highlights

An excellent example of a drumlin, a landform so well represented in Anglesey but more rare in mainland Wales. Formed beneath the ice-sheet of the last glaciation, this drumlin is shown in cross-section.

Introduction

In Hen Borth Bay (SH321931) on the northern coast of Anglesey, an excellent coastal exposure through a drumlin occurs. The prevailing coastal configuration and the alignment of the drumlin at Hen Borth have allowed marine erosion of the drumlin parallel to its long axis, clearly revealing its internal structure and composition. According to Greenly (1919) it is one of the three finest examples of a dissected drumlin on the island.

Description

Drumlins are common in Anglesey, and Greenly mapped over two hundred examples in the north and west of the island alone. The Hen Borth drumlin is one of a large swarm in the Cemlyn Bay area, which show a striking alignment from north-east to south-west. Such an orientation closely matches that of striae found on local bedrock surfaces; the two therefore provide evidence to show that northern Anglesey was glaciated by Irish Sea ice moving to the south-west (Greenly 1919).

The crest of the drumlin, which has an elliptical ground plan, reaches 13m OD and is dissected by the exposure, revealing a maximum depth of about 5m of sediment. Deposits exposed along the 300m long axis are mainly grey-brown, stony Irish Sea till, with weathering and cryoturbation features in the uppermost layers. In the northern part of the bay, where the solid strata of the headland crop out, the sequence of Pleistocene deposits is more complex. Here, a lower head is overlain and incorporated into the overlying till. Greenly (1919) also observed this incorporated material, referring to the "shattered rock worked up into the boulder-clay". The till is overlain by a thin development of what is probably redistributed till.

Interpretation

Exposures through drumlins are generally rare in Wales, and Hen Borth is an unusually fine example, showing sections end to end through an individual feature. Hen Borth is also representative of the drumlins of northern Anglesey, where such landforms are well developed and where they form important elements in the geomorphology of the island.

The drumlins of northern Anglesey are important historically, as it was recognised at an early stage that debris deposited beneath moving ice was frequently streamlined in the direction of ice movement. Thus, using the orientation of drumlin long-axes together with other ice directional indicators such as striae, Greenly (1919) was able to chart the movement of the Irish Sea ice-sheet over Anglesey. Today, Hen Borth is still important in demonstrating patterns of ice movement across North and north-west Wales. In particular, it provides convincing evidence to show that northern Anglesey was last glaciated by south-westerly moving ice from the Irish Sea Basin. Since drumlins frequently occur in lowland areas where ice flow was probably radiative or dispersive, the swarms on northern Anglesey demonstrate that similar conditions pertained over the northern part of the island.

Despite numerous published studies, drumlin formation is still not fully understood (Menzies 1978), and Hen Borth is therefore important for studying the origin of drumlins and for testing theoretical models of drumlin formation. The site provides an unusual opportunity in Britain to study former glacier dynamics, including indications of basal ice pressures and the rates and type of glacier flow.

Conclusions

Hen Borth is an exceptional example of an exposure through a drumlin (a streamlined mound of glacial drift), a type of Pleistocene landform well developed in northern Anglesey, but relatively uncommon elsewhere in Wales. It demonstrates that the last glaciation of northern Anglesey was by Irish Sea ice moving from north-east to south-west, and is therefore important for reconstructing regional patterns of ice movement. It is also important for testing theoretical models of drumlin formation.

Moel Tryfan

Highlights

An historical site in the development of the Glacial Theory. It shows outstanding evidence for the Devensian glaciation of upland North Wales by Irish Sea ice, in the form of shelly sea-bed sediments transported to 400m above sea-level.

Introduction

Since their discovery by Trimmer in 1831, the shelly drifts of Moel Tryfan have formed a classic topic of study for glacial geologists. Indeed, as Reade (1893) stated, the site had become "a battleground of contending theories" between the "Diluvialists" and the "Glacialists". Although the theory that marine submergence accounted for the drifts was abandoned by the early twentieth century, the site has remained controversial where the origin and the dating of the sediments are concerned. The site provides unique and important evidence for Late Pleistocene events in north-west Wales, and forms a classic landmark in the development of glacial geology. The site has perhaps the longest history of research of any site in Wales, having been described and referred to by numerous workers in the last century (for example, Trimmer 1831; Buckland 1842; Ramsay 1852, 1881; Darbyshire 1863; Lyell 1873; Belt 1874; Jeffreys 1880; Mackintosh 1881, 1887; Blake 1893; Reade 1893; Greenly and Badger 1899; Hicks et al. 1899). More recently, the site was discussed by Foster (1968, 1970a), Whittow and Ball (1970) and Bowen (1977a). Amino acid ratios were provided by Davies (1988).

Description and interpretation

The shelly drift is located in the disused Alexandra slate quarry to the south-east of the Moel Tryfan summit at 426m OD. The exposures have always been endangered, particularly during the expansion of the quarry (Greenly and Badger 1899; Hicks *et al.* 1899; Greenly 1900), and the sequence of beds is far from clear. From Hicks *et al*'s (1899) description of the stratigraphy, it appears that the shelly sands and gravels probably occurred as a large wedge between till deposits. They recorded about 7.6m of drift deposits lying on a slate floor at 390m OD on a small ridge between the then expanding Moel Tryfan and Alexandra slate quarries, and suggested that two main formations could be seen in the drifts – a shelly sand and gravel sequence occurring to the north-west and being replaced to the south-east by boulder clay. The sands and gravels were described as yellow, and containing pockets of gravel in which numerous marine shell fragments were present, and in which bedding was very irregular. The junction between the sands and gravels and the till was contorted into sharp folds. The till was described as a strong, unstratified deposit, dark grey in colour and full of stones, up to one metre in size. Most of the stones were subangular, many well striated, and most were of Welsh origin; the riebeckite microgranite of Mynydd Mawr being especially abundant (Hicks *et al.* 1899). The drift beds overlay slate bedrock and the lowest layers contained numerous angular slate fragments. The slate floor beneath the deposits showed terminal curvature towards the ESE. According to Hicks *et al.* (1899) and Greenly (1900) there was some suggestion that the sands and gravels were interdigitated with the till. Unfortunately, today there is little evidence for such a sequence although the till and shelly sand and gravel deposits are still visible in small exposures in separate parts of the quarry.

In contrast to many other classic Pleistocene sites in Wales, most of the references to Moel Tryfan were made during the latter part of the nineteenth century, and since that time the site has received relatively scant attention. This no doubt has been due to the destruction of key parts of the site, forecasted by earlier workers.
Trimmer (1831) was the first to record the high

level drifts of Moel Tryfan with their contained fauna. Importantly, he noted that these supposed "diluvial" or flood-formed sands and gravels were extensive in this part of Caernarvonshire, a fact also supported by Ramsay (1852) who traced the 'marine' drift to the height of 701m (2,300 ft) OD in the recesses of Carnedd Dafydd and Carnedd Llewellyn, and two miles west of Snowdon near Maenbras. At this early stage, most authors favoured a marine origin for the Moel Tryfan shelly sands and gravels, and the opinions then prevalent were summed up by Sir Charles Lyell in 1873 who believed that "these shells show that Snowdon and all the highest hills which are in the neighbourhood of Moel Tryfaen were mere islands in the sea at a comparatively late period" (Davies 1969). Such was the entrenchment of the belief that Trimmer (1831), in describing striae and furrows on slate bedrock in Snowdonia, concluded that they had been caused by the 'diluvial currents'.

Despite advancement of the Glacial Theory elsewhere in Europe, Buckland (1842) rectified Trimmer's mistake and cited striations in the Llanberis Pass as clear evidence of glaciation, but still invoked a period of marine submergence to account for the shelly sands and gravels on Moel Tryfan. Darwin (1842), while refuting the concept of a flood to account for the beds on Moel Tryfan, however, also concurred with the idea that the beds were emplaced beneath the sea. Such an origin, he argued, would help to account for the presence in the sections of erratic boulders (Trimmer 1831) which he considered had been transported by floating ice. The first detailed faunal analysis of the drift beds at Moel Tryfan was carried out by Darbyshire (1863) who recognised fifty six different species of molluscs. While the majority of these was considered to be Arctic in character, there was also an infusion of more temperate, British and Atlantic species. The list was updated by Jeffreys (1880) and collectively such faunal analyses helped to reinforce the idea that the beds were of marine origin.

A marine origin was also upheld by Mackintosh (1881, 1887) who noted that the sands and gravels were obliquely laminated in a manner similar to that seen on a modern beach. Similarly, Reade (1892, 1893) undertook a microscopic examination of sand grains from the Moel Tryfan beds and concluded that their extraordinary roundness and polish could only have resulted from marine agencies. Reade (1892) additionally showed that these 'marine' sands were overlain by till, probably of local derivation, whereas the sands and gravels were full of erratics from Scotland and the Lake District. However, like Darwin (1842), Reade (1893) envisaged that local glaciers had caused the submergence and consequent flooding of the land. It was during this marine submergence that the sea lapped against the Snowdonian hills depositing the shelly marine drift. Exotic, distantly derived erratics such as Shap Fell granite and Ailsa Craig microgranite in this deposit had, according to Reade, been rafted on floating ice. In contrast, Reade (1892) believed the overlying till to be a locally derived glacial deposit.

Against the tide of opinion, Thomas Belt (1874) published a perceptive paper in which he refuted the theory of marine submergence to account for the Moel Tryfan beds. He noted that "..... the shells are broken and worn ..... they are just where they ought to be found on the supposition that an immense body of ice coming down from Northern Ireland, Scotland and from Cumberland and Westmorland, filled the basin of the Irish Sea, scooped out the sand with the shells that had lived and died there, and thrust them far up amongst the Welsh hills that opposed its course southward....." (Belt 1874). He therefore concluded that there was no evidence for the submergence of Great Britain either during or since the 'Ice Age'.

Like Belt (1874), Blake (1893) favoured a glacial origin for the superficial deposits at Moel Tryfan. He foresaw no great difficulty in "getting the Irish Sea glacier to so great a height" and suggested that the shelly drifts of Moel Tryfan were the earliest of the glacial deposits in North Wales and that the shells themselves must have lived in pre-glacial times. However, even as late as 1910, the Moel Tryfan shelly sands were still regarded by Edward Hull, former director of the Irish Geological Survey, as evidence of marine submergence (Davies 1969).

Shortly before the turn of the century it became clear that expansion of the slate quarries on Moel Tryfan would result in the destruction of some of the key sections. A rescue operation to record and photograph the sections was therefore called for by Greenly and Badger (1899) and the results of the operation were later reported by Hicks *et al.* (1899) and by Greenly (1900). The latter two reports, which are identical, furnish what is perhaps the most detailed account of the sections, and since that time little detailed research has been undertaken.

The dating of the sediments at Moel Tryfan has proved difficult. Whittow and Ball (1970) suggested that the shelly sands represented the earliest glacial deposits in North Wales, perhaps being equivalent in age to the Criccieth Advance deposits (Simpkins 1968) in southern Llŷn and therefore of pre-Devensian age. They considered that the sands and gravels had been dredged from a pre-existing sea-floor at the onset of a glaciation, following their accumulation during a substantial interglacial period. Foster (1968, 1970a) undertook the radiocarbon dating of a bulk shell sample from the Moel Tryfan site. He obtained a date of 33,740 +2,100 -1,800 BP (I-2803) and concluded that because the shell material was derived, the glaciation responsible for its deposition must therefore post-date *c.* 34,000 BP. A Late Devensian age was therefore attributed by Foster to the beds. While a Late Devensian age would place the deposits firmly within the glacial succession established elsewhere in North Wales (for example, Saunders 1968a), such an age does little to explain the restricted and high-level occurrence of such deposits, which in fact may be explained more easily by an earlier glacial episode (Whittow and Ball 1970). Many doubts have also been expressed concerning the reliability of radiocarbon dates from bulked shell samples (for example, Shotton 1967, 1977a; Boulton 1968). Amino acid measurements on the fauna, notably on *Macoma*, suggest that the sediment is Late Devensian in age (Davies 1988).

The site, first and foremost, is a landmark in glacial geology and geomorphology. It has the longest and most detailed history of early research at any site in Wales and was paid significant attention by both the pioneers and the opponents of the Glacial Theory. In this respect, it has been important in the development of geomorphological and geological thought in Great Britain.

Moel Tryfan also provides an important lithological record of the high-level shelly drift widely recorded from other locations in the Snowdonian foothills. It is both representative, and the best exposed of these deposits.

Further, the shelly drift demonstrates a penetration of the Irish Sea ice-sheet a considerable distance inland, and a vertical movement of the ice-sheet amounting to *c.* 400m in just about 10 km (Flint 1971). This southward and onshore movement of Irish sea ice, as shown by discontinuous Irish Sea sediments in Snowdonia generally and at Moel Tryfan in particular, has major repercussions for the timing and interaction of Irish Sea and Welsh ice-sheet advances. The evidence at Moel Tryfan clearly implies that the shelly drift was deposited when Welsh ice was neither sufficiently developed nor powerful enough to deflect the Irish Sea ice in this area.

The age of the Moel Tryfan deposits has been a matter of debate. It is one of very few sites in Wales where a radiocarbon date has been obtained. Recent amino acid data from the fauna have, however, supported a Late Devensian age (Davies 1988).

This locality is important for having been one of the first and also one of the most controversial Pleistocene sites described in Britain. It has been a key site in the development of scientific thought and establishment of the Glacial Theory. It provides a unique lithostratigraphical record of the high-level, shelly Irish Sea deposits, which are important for determining the sequence and pattern of Late Pleistocene glacial events in north-west Wales.

Conclusions

Moel Tryfan is an internationally famous site. Its shelly glacial deposits figured prominently in the debate which led to the acceptance of the Glacial Theory in Britain. Before 1840 or so, the view was that these deposits represented the Biblical deluge. Acceptance that they were deposited by an ice-sheet was important for changing that opinion and led directly to the acceptance of the effect of glaciers on the landscape.

Dinas Dinlle

Highlights

A remarkable site showing spectacularly folded and faulted Devensian glacigenic sediments. Such effects have been attributed to the Late Devensian ice advance over previously deposited till and gravels.

Introduction

Dinas Dinlle (SH436563) is a coastal exposure through a complex drift sequence which provides possible evidence for a readvance of Late Devensian ice. It was first investigated by Reade (1893) and later in some detail by Jehu (1909). The site has also featured in studies by Synge (1963, 1964), Saunders (1963, 1968a, 1968b, 1968c, 1968d, 1973) and Whittow and Ball (1970).

Description

The sections at Dinas Dinlle are cut through two large drift mounds, the northernmost of which approaches 25m in height. The sequence extends laterally for about 900m and comprises a complex series of tills and associated fluvioglacial sediments. Below this sequence, a lower till of limited extent is sporadically exposed. This red to purple weathered till (blue to grey in its unweathered condition) is thought to extend beneath the foreshore. It is a tough, homogenous and highly calcareous deposit. The thick sequence of stratified sands and gravels above contains marine shell fragments. These deposits are often coarse with the upper horizons iron-stained. Well developed iron pans are displaced by faulting. These sands and gravels form almost the entire southern drift mound. Both the lower till and the sands and gravels are affected by isoclinal folds, accompanied by thrust and reverse faulting in the northern part of the section – see Figure 28. This steep bedding which approaches 80° is replaced to the south by more gentle folding and the beds are arranged in a low anticline. The sands and gravels are succeeded by a yellow-grey, stony upper till. A weathering horizon up to 0.5m thick and showing deep iron-staining, induration and frost-heaving has been described between the upper till and the underlying sands and gravels (Saunders 1968a, 1968c, 1968d), and this was considered to mark a stratigraphic break between these two units. The upper till is also cryoturbated in places and it is overlain by hillwash sediments and blown sand.

Interpretation

Major differences in interpreting the sediments at Dinas Dinlle have occurred. Reade (1893) first described the sections in detail and considered that the till deposits were conclusive evidence of former glacial conditions. The sands and gravels, however, had formed by marine submergence. In contrast, Jehu (1909) interpreted the same sequence in terms of the tripartite scheme, with two

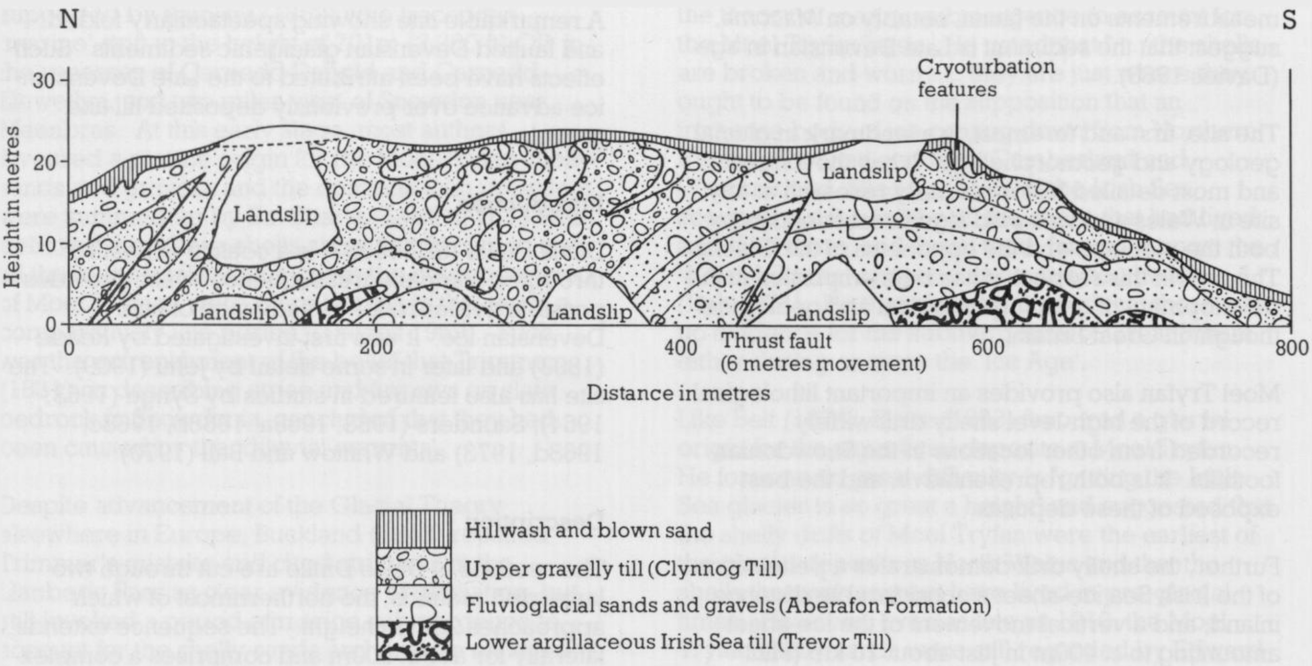

Figure 28 Quaternary sequence at Dinas Dinlle (from Whittow and Ball 1970)

major glacial episodes separated by a more temperate, possibly interglacial, period. The concept of marine submergence to account for the sand and gravel horizons was finally abandoned and the sediments were interpreted by Jehu (1909) as being fluvioglacial. The occurrence of marine shell fragments in the upper till, together with common Chalk flints, pebbles of Ailsa Craig microgranite, Goat Fell granite (Arran), Dalbeattie granite, and schists and serpentinites from Anglesey was taken by Jehu to indicate that the deposits had been derived from the Irish Sea Basin to the north.

Synge (1963, 1964) also recorded two tills separated by sands and gravels. He suggested the lower till and associated sediments were probably Saalian in age but that the upper till was Weichselian (Late Devensian) and was associated with the nearby Bryncir-Clynnog moraine; a moraine which he considered marked the maximum extent of Late Devensian ice in north-west Wales. Synge (1963, 1964), however, made no mention of the glaciotectonic structures at Dinas Dinlle.

Like previous workers, Saunders (1963, 1968a, 1968b, 1968c, 1968d, 1973) also recognised two tills at Dinas Dinlle separated by waterlain sands and gravels, but suggested these beds had been folded as a result of pressures exerted by the advancing ice which later deposited the upper till. Fabric analysis (Saunders 1963, 1968b, 1968d) showed that the lower till was deposited by ice moving north-west to south-east and that the later advance was from north-east to south-west. A study of clast lithology by Saunders (1963, 1968d) also tended to confirm a generally northern (Irish Sea) origin for the sediments, many of the rock types being derived from Anglesey. Indeed, the disposition of the glaciotectonic structures themselves provided strong evidence that the second recorded ice advance came from the north-east. Of significance was Saunders' (1968a, 1968c, 1968d) recognition of a weathering horizon between the upper Irish Sea till and the underlying coarse outwash sands and gravels. This evidence together with radiocarbon dates from other Late Pleistocene sites on Llŷn suggested to Saunders that the lower till was Late Devensian in age, while the upper till could be attributed to a later readvance of Late Devensian ice, then correlated with the Scottish Readvance (Saunders 1968a). The Late Devensian readvance, according to Saunders, was therefore responsible for the upper till at Dinas Dinlle and for contorting the underlying fluvioglacial sediments and the lower till. This readvance was also considered to have produced the upper northern till found along much of the north Llŷn coast, for example at Gwydir Bay, and the Bryncir-Clynnog moraine.

Simpkins' (1968) work in central Caernarvonshire did not extend to Dinas Dinlle, but it is clear that the tripartite succession is broadly comparable to that at Gwydir Bay and elsewhere along the north Llŷn coast (Simpkins 1968). The lower till at Dinas Dinlle may be broadly equated to the Trevor Till, the sands and gravels to the Aberafon Formation and the upper till to the Clynnog Till. Simpkins (1968) suggested that this tripartite sequence was probably the result of an oscillating Late Devensian ice margin rather than the result of two distinct glacial episodes separated by interstadial conditions proposed by Saunders (1968a, 1968c, 1968d).

Whittow and Ball (1970) outlined a broadly comparable sequence of events at Dinas Dinlle to Saunders (1963, 1968a, 1968b, 1968c, 1968d), although they considered the upper till to be Welsh (from a Snowdonian ice stream) rather than of northern (Irish Sea) origin. They argued that the sections represented the northernmost occurrence of the Trevor Till, deposits of this advance being excluded from the remainder of Arfon due to the magnitude of the Welsh ice cap of the equivalent Criccieth Advance. Like Whittow and Ball (1970), Bowen (1974) cited the glaciotectonic structures at Dinas Dinlle as evidence for a Late Devensian readvance of ice in North Wales, although he disputed the validity of the sample used by Foster (1968) for radiocarbon dating from the Bryncir area.

Dinas Dinlle shows some of the most convincing evidence in north-west Wales for a readvance of the Late Devensian ice-sheet. Although sections characteristic of the tripartite sequence in northern Llŷn occur at Dinas Dinlle, the sequence is more completely exposed at nearby Gwydir Bay. It is the large-scale glaciotectonic structures which make Dinas Dinlle especially significant, because they have been used as evidence in support of a Late Devensian readvance. Work at Glanllynnau in southern Llŷn (Boulton 1977a, 1977b) and on contemporary glacial environments (Boulton 1972; Boulton and Paul 1976) has shown that multiple till sequences similar to that at Dinas Dinlle, with associated folded and faulted structures, are common features of supraglacial landforms and sediment associations – and need not therefore be the product of multiple glaciations. However, the glaciotectonic structures at Dinas Dinlle vary considerably from those at Glanllynnau, indicating that they were not formed in the same manner. In particular, the large thrust blocks of till, the steeply dipping gravels and sands and the overthrust structures at Dinas Dinlle are more easily explained as the result of stresses caused by a readvance of ice associated with the upper till. Boulton's simple model of ice wastage would not seem to be applicable to Dinas Dinlle. The site is therefore fundamentally important in demonstrating that the wastage of the Late Devensian ice-sheet in north-west Wales was not a uniform process, being interrupted by a readvance of the ice front.

Although clast lithology and fabric studies at Dinas Dinlle have not been conclusive, there is an indication that the lower till was deposited by Irish Sea ice moving north-west to south-east, while the upper till was probably deposited by confluent Irish Sea and Welsh ice moving south-westwards. Dinas Dinlle is the northernmost known occurrence of the lower (Trevor) till, and the lithostratigraphic record therefore helps to delimit the patterns of ice movement during both of the glacial advances which occurred during the Late Devensian.

Glacigenic sediments here provide important evidence for the sequence and pattern of movements of Irish Sea and Welsh ice masses during the Late Pleistocene. Although evidence for renewed glacier activity following wastage of the Late Devensian ice-sheet has been shown to be equivocal in some areas of Great Britain, Dinas Dinlle is notable for the fine series of glaciotectonic structures which provide evidence for a possible readvance of the Late Devensian ice-sheet in north-west Wales.

Conclusions

The glacial sediments at Dinas Dinlle show evidence for major structural deformation. This was caused by some form of overriding by an ice-sheet. This may possibly have been caused by a marine-based ice-sheet grounding on the margins of the land.

Gwydir Bay

Highlights

This is a key site for the study of the glacial and fluvioglacial sediments deposited in Llŷn by Irish Sea and/or Welsh ice. It is a reference locality for Devensian glacigenic stratigraphy in North Wales.

Introduction

Glacial sediments derived from the Irish Sea Basin are commonly exposed along the north Llŷn coast. Sections at Gwydir Bay, however, provide an unusually complete and detailed sequence that can be used to reconstruct Late Pleistocene glacial events in north-west Wales. The site was studied by Reade (1893) and Jehu (1909), and more recently was described by Synge (1964), Saunders (1968a, 1968b, 1968c, 1968d, 1973), Simpkins (1968) and Whittow and Ball (1970).

Description

The sections at Gwydir Bay run from near Porth Trevor northwards to beyond Afon Hen. Three main units occur –1) a lower till, 2) intervening gravels and sands and, 3) an upper till. These typify the tripartite succession widely described in northern Llŷn by Jehu (1909). The sequence is shown in Figure 29 and the beds correspond to the Trevor Till, Aberafon Formation and Clynnog Till, respectively, of Simpkins (1968).

The Trevor Till is a homogenous Irish Sea till, the base of which is not seen in central Caernarvonshire (Simpkins 1968). It attains a maximum exposure height in Gwydir Bay of some

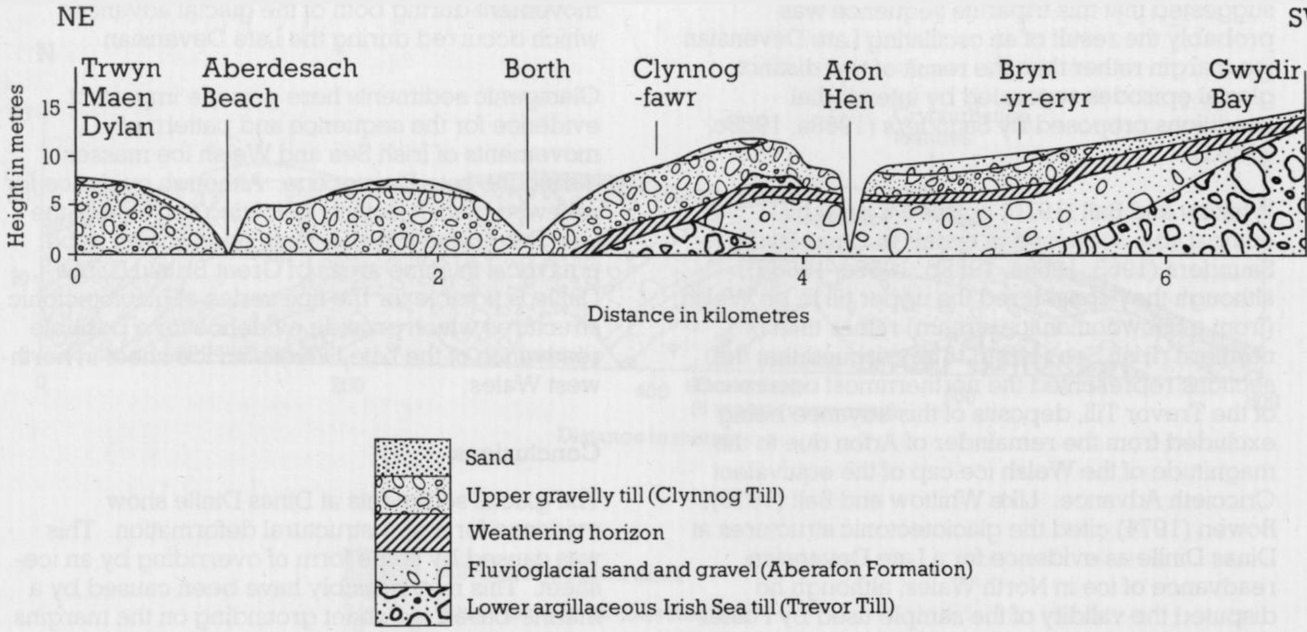

Figure 29 Pleistocene sequence at Gwydir Bay (from Saunders 1968d)

30m. It is argillaceous and contains shell fragments and distantly derived erratics. The Trevor Till was, however, described as purple and stoneless by Synge (1964), although others have described it as red (Reade 1893), blue-grey (Jehu 1909) and dark grey-brown (Simpkins 1968). It is prone to slumping, and sections through it in Gwydir Bay are stepped, with individual exposures rarely amounting to more than 6m (Saunders 1968d). The Trevor Till is highly calcareous – up to 42.5% carbonate (Simpkins 1968).

The junction between the Trevor Till and the overlying sands, silts and gravels of the Aberafon Formation is not clearly exposed. The latter thickens to the north-east and comprises a series of almost horizontal beds of sorted, olive brown sands, silts and gravels. Near Afon Hen (Figure 29), the coastal cliff is cut almost entirely in these deposits, which average between 12 and 15m height. In places, the upper 2m of sand reveals elaborate convolution and festoon structures, a series of possible frost wedges, indurated zones and iron-pan formations. Collapse structures caused by the melting of buried ice have also been noted in the Aberafon Formation which, like the Trevor Till, contains Irish Sea erratics. Conversely, the sands and gravels are only slightly calcareous. Dislocated masses of Trevor Till occur within the sands and gravels of the Aberafon Formation (Simpkins 1968).

The Aberafon Formation is replaced laterally and vertically by a stony deposit, the Clynnog Till (Simpkins 1968). Towards Clynnog Fawr, the Clynnog Till forms most of the cliffline and the Trevor Till and Aberafon Formation are only seen sporadically towards the base of the cliff. The texture of the Clynnog Till is variable and, in places, shows a degree of fluvial sorting. It is yellow-brown and slightly calcareous (up to 4.7%) and it contains a mixture of Irish Sea and Welsh rock types (Simpkins 1968). Where the surface of the till is exposed, it is cryoturbated to the same degree as the Aberafon Formation and leached to a depth of 1-2m (Simpkins 1968). A thin development of cryoturbated sands and gravels has been described overlying the Clynnog Till in places (Synge 1964; Saunders 1968d) – see Figure 29.

This tripartite sequence has been consistently recognised by successive workers (for example, Reade 1893; Jehu 1909; Saunders 1963, 1968a, 1968b, 1968c, 1968d, 1973; Simpkins 1968; Whittow and Ball 1970), but disagreement as to the presence or absence of a weathering horizon at the top of the Aberafon Formation at the site has led to radically different interpretations of the sequence of Late Pleistocene events in the area. Figure 29 illustrates the stratigraphic context of the weathering horizon described by Saunders (1968d).

Interpretation

Reade (1893) was the first to study the Pleistocene deposits of the north Llŷn coast in detail. He described a range of northern rock types from the Trevor Till, his Lower Boulder Clay, and established a source from the Irish Sea Basin. A microscopy study of sand grains from the overlying sands and gravels (Aberafon Formation) led Reade to suggest that the beds had been deposited, at least in part, by marine submergence.

Jehu (1909) identified two tills separated by fluvioglacial sands and gravels. He confirmed that the lower or Trevor Till contained rock types from sources in Anglesey and in the Irish Sea Basin, and interpreted the sequence in terms of two glacial events separated by warmer, possibly interglacial conditions.

More recent studies at Gwydir Bay fall into two main categories and have established the source and patterns of movement of the invading ice-sheets, and allowed a reconstruction of the sequence and chronology of Late Pleistocene events.

Early studies established an Irish Sea origin for the sediments at Gwydir Bay (Reade 1893; Jehu 1909), when a range of exotic rock types, including Ailsa Craig microgranite and porphyrites from the Dalbeattie area of Scotland, was described. Recent studies have applied pebble lithology measurements and till fabric analyses to try to determine the sediment provenance at Gwydir Bay (Saunders 1963, 1968b, 1968d; Simpkins 1968; Whittow and Ball 1970). Saunders confirmed that the Trevor Till contained a predominance of rocks from Anglesey and more northern (Irish Sea) sources, and showed that the Clynnog Till contained a more varied pebble lithology, with an assemblage indicating derivation from local sources in Anglesey and Snowdonia. Irish Sea pebble lithologies, however, were still common in the Clynnog Till. These findings were broadly confirmed by Simpkins (1968) who demonstrated that many pebbles in the Clynnog Till were relatively local in origin, including Cambrian grit, felsite, feldspar porphyry from Porth Trevor and slates and Ordovician volcanic rocks from Snowdonia. She suggested that the variable lithological and textural characteristics of the Clynnog Till indicated deposition as an end-moraine, whereas the more homogenous properties of the Trevor Till indicated deposition as ground-moraine or lodgement till.

Till fabric studies, however, proved less conclusive (Saunders 1963, 1968b, 1968d; Simpkins 1968). Although Saunders' measurements suggested that the Trevor Till was deposited by ice moving from north-west to south-east, and the Clynnog Till by ice moving almost due south, a considerable degree of fabric variability within units did not allow precise differentiation between the tills. However, the lithological and fabric evidence from Gwydir Bay have together been widely taken to indicate that the Trevor Till was deposited by Irish Sea ice which pushed across Anglesey before invading Llŷn. Comparable evidence from the Clynnog Till has also been used to suggest that during the second glacial advance, the area was invaded by confluent Irish Sea and Welsh ice moving almost due south (Saunders 1963, 1968b, 1968d; Synge 1964; Simpkins 1968; Whittow and Ball 1970).

Although the source of the invading ice-sheets at Gwydir Bay is reasonably well established, their age is poorly understood. Early attempts to integrate stratigraphic evidence from the north Llŷn coast into a chronology of Pleistocene events were made by Mitchell (1960) and Synge (1963, 1964), who used evidence from Gwydir Bay and elsewhere on Llŷn. Synge recognised Jehu's tripartite division of deposits along the north Llŷn coast and used Irish stratigraphic evidence to derive a framework for Pleistocene events. He suggested that raised beach gravels at Porth Oer (north-west Llŷn) were Hoxnian in age, and consequently that the two tills found along the north Llŷn coast including Gwydir Bay, belonged to the succeeding Saalian and Weichselian (Devensian) glaciations. The limited occurrence of the upper (Clynnog) till, between Clynnog Fawr and Bryncir, led Synge (1963, 1964) and Mitchell (1960, 1972) to regard this area as being at the limit for Late Devensian ice. Indeed, Mitchell (1960) suggested that his Late Devensian limit could be traced offshore, and extrapolated right across St George's Channel to Wexford. The Trevor Till and associated sands and gravels (Aberafon Formation) exhibited signs of weathering and cryoturbation according to Synge (1964), and this weathering was thought to have occurred during the Ipswichian Stage.

The views of Mitchell and Synge on Pleistocene events in north-west Wales have not been accepted by subsequent workers (for example, Saunders 1968a; Whittow and Ball 1970; Bowen 1974), who have suggested that the glacial succession at Gwydir Bay was deposited largely during the Late Devensian. Later workers have generally considered the limited occurrences of raised beach sediments, which occur at Porth Oer and Red Wharf Bay, to belong to the Ipswichian Stage, thereby fixing the glacigenic successions firmly in the Devensian Stage.

Saunders (1968a, 1968b, 1968d) reconstructed the following sequence of events from the evidence at Gwydir Bay and from other sites in north Llŷn. He suggested that the Trevor Till was deposited during the principal thrust of the Late Devensian Irish Sea ice-sheet. In support of this view he cited radiocarbon dates from the Trevor Till and associated Aberafon Formation deposits elsewhere in north and west Llŷn which, he believed, constrained the maximum age of the first recorded ice advance to around 30,000 BP. He argued that the sands and gravels of the Aberafon Formation overlying the Trevor Till at Gwydir Bay, were fluvioglacial in origin and that they were related to wastage of the Late Devensian ice. Saunders placed much emphasis on the weathering horizon which he reported affected the surfaces of both the Aberafon Formation and the Trevor Till – see Figure 29. Unlike Synge, Saunders (1968b, 1968d) attributed this weathering to interstadial conditions in the Devensian. He argued that a return to periglacial conditions should be inferred from the cryoturbation and frost-cracking of this weathered surface, and a return to fully glacial conditions was marked by deposition of the Clynnog Till at Gwydir Bay and northwards to Dinas Dinlle. The Clynnog

Till he suggested, was deposited by a later advance of the Irish Sea and Welsh ice-sheets which impinged on northern Llŷn, and extended as far south as Bryncir, where the maximum limit was marked by prominent moraines. At Bryncir, organic material disseminated within gravels of the moraine was dated by Foster (1968, 1970a) to 16,830 +970 -860 BP (I-2801). Saunders (1968a) tentatively correlated the later expansion of Late Devensian ice with the Scottish Readvance. Although Bowen (1974) disputed the validity of the radiocarbon date from Bryncir because he felt there was no evidence that the deposit sampled was in fact organic, he accepted the concept and other evidence for a Late Devensian readvance in this area.

Simpkins (1968) did not recognise a weathering horizon at Gwydir Bay and therefore defined an alternative sequence of events for the area. Some of the structures attributed to frost-action by Saunders (1968d, 1973) were instead interpreted by Simpkins as due to tectonic disturbances caused by the melting of buried ice. No significant time interval was therefore envisaged between deposition of the three main units at Gwydir Bay and she suggested that the whole sequence was Late Devensian in age with the Clynnog Till representing only a minor oscillation of the ice-sheet.

Gwydir Bay provides the most detailed and extensive exposure through the typical tripartite sequence of northern Llŷn. It can be regarded as a reference site for the Trevor Till, the Aberafon Formation and the Clynnog Till. Although individual members of this sequence are extensively exposed elsewhere in Llŷn, Gwydir Bay is particularly important for showing the stratigraphic relationship between these deposits in a single section. It is the type locality in northern Llŷn for the Trevor Till, which is much better exposed than at Dinas Dinlle to the north.

The sequence provides an important record of changing environmental conditions in north-west Wales during the Late Pleistocene, showing evidence for two separate glacial advances. It is widely held that the sequence is Late Devensian in age, and the stratigraphic detail at Gwydir Bay together with well developed glaciotectonic structures at nearby Dinas Dinlle, provide evidence for a possible readvance of the Late Devensian ice-sheet in north-west Wales.

Gwydir Bay is one of the most intensively studied sites in north-west Wales and has provided significant data for charting the patterns of movement and interaction of Irish Sea and Welsh ice masses. The Trevor Till was deposited by Irish Sea ice which moved across Anglesey before invading Llŷn, while the Clynnog Till may have been deposited by confluent Irish Sea and Welsh ice masses. The weathering horizon described at Gwydir Bay by Synge (1964) and Saunders (1968a, 1968d) is important for interpreting the sequence, particularly in determining a possible ice-free interval between deposition of the Trevor and Clynnog Tills.

This is a reference site for the three principal sedimentary units found along the northern Llŷn coast – the Trevor Till, the Aberafon Formation of sands and gravels and the Clynnog Till. The site demonstrates the stratigraphic relationships of these deposits and shows important evidence for the timing and interaction of the Irish Sea and Welsh ice masses which affected north-west Wales during the Late Pleistocene. The evidence suggests that the coastal margin was first invaded by Irish Sea ice which moved across Anglesey into Llŷn, and then by a confluent Irish Sea and Welsh ice stream. The detailed lithostratigraphic evidence at Gwydir Bay is complementary to the glaciotectonic structures at Dinas Dinlle which have been used as evidence for a readvance of the Late Devensian ice-sheet in north-west Wales.

Conclusions

Gwydir Bay is a reference site for three major units of glacial deposits. These are the Trevor Till (boulder clay), the Aberafon Formation consisting of sands and gravels, and the Clynnog Till. Their mutual relationships show how the Irish Sea ice-sheet and Welsh ice-sheet interacted on the margins of north-west Wales.

Porth Oer

Highlights

This locality shows unique Pleistocene evidence of a high shore platform, interglacial raised beach deposits, and till from the last glacial period. It therefore records rare evidence in North Wales of temperate high sea-levels during the last, Ipswichian, interglacial.

Introduction

Porth Oer (SH167301) is a unique site in the Llŷn Peninsula recording critical evidence for the interpretation of Late Pleistocene events which affected North and north-west Wales. The site is notable for being one of only two sites in the region where pre-Holocene raised beach sediments (presumed interglacial) have been recorded. The site was first described by Jehu (1909) and has since featured in studies by Whittow (1957, 1960, 1965), Mitchell (1960), Synge (1963, 1964, 1970), Saunders (1963, 1967, 1968a, 1968b, 1968c, 1968d, 1973), Whittow and Ball (1970), Bowen (1973a, 1973b, 1974, 1977b), and Peake *et al.* (1973). The most detailed accounts of the site were provided by Saunders (1963, 1968d, 1968d).

Description

The site comprises one of the finest examples of a raised shore platform in North Wales, cut across

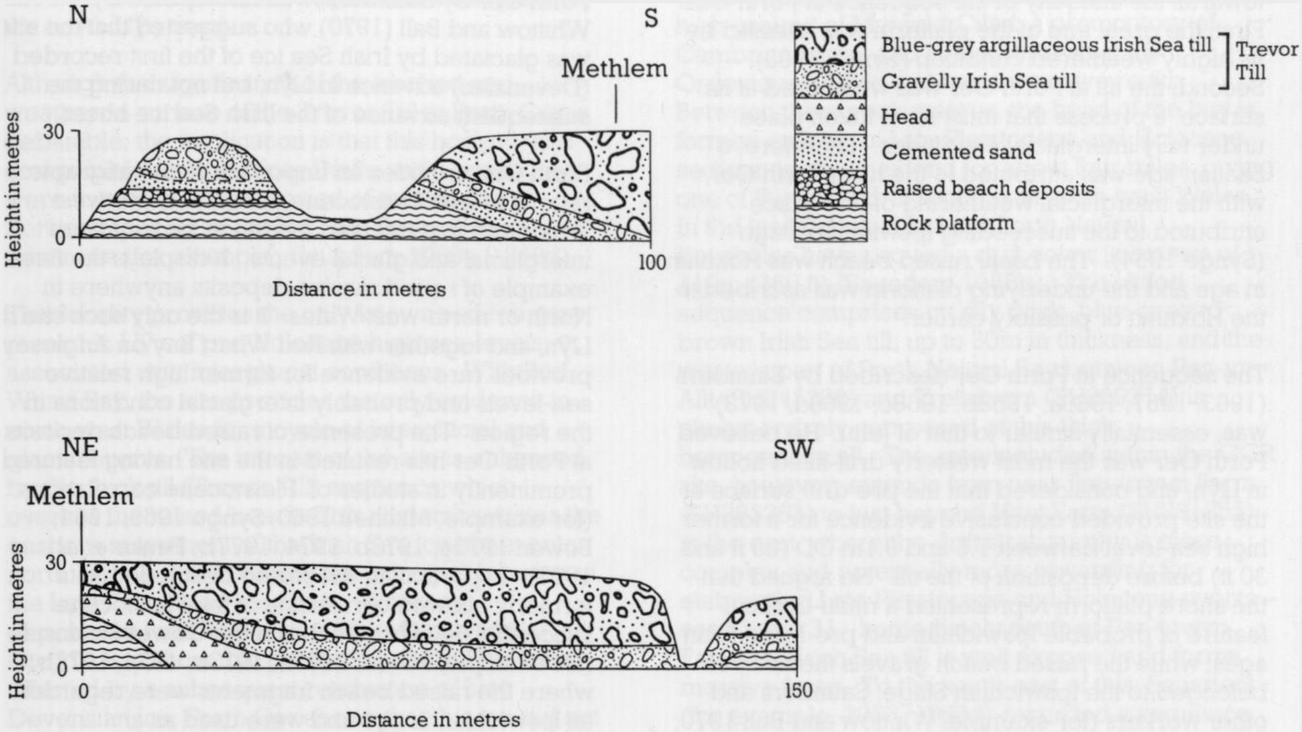

Figure 30 Pleistocene sequence at Porth Oer (from Saunders 1968d)

Precambrian rocks of complex structure at both the northern and southern headlands of the bay – see Figure 30. The most important part of the sedimentary sequence at Porth Oer occurs on a fossil sea stack towards the northern end of the bay – see Figure 30. Here, the platform at *c.* 7.5m OD (Whittow 1960; Bowen 1974) is overlain by up to 0.4m of locally derived head, and by raised beach gravel up to 1.2m thick. The raised beach is succeeded by up to 0.5m of current-bedded ferruginous cemented sand. The remainder of the succession at this location is, however, obscured by slumping and vegetation, although there is some suggestion that the cemented sand is succeeded by periglacial head and then glacial sediments. The latter crop out extensively between the north and south headlands of the bay where the steep cliffs are formed mostly in Irish Sea till up to 15m in thickness. The till is homogenous and relatively stoneless, but contains northern erratics and abundant marine shell fragments. Occasional lenses and layers of gravel and silt occur in the till, and towards the northern end of the bay the till becomes gravelly in character and merges downwards into head. The upper surface of the Irish Sea till is decalcified in places to depths of up to 4m.

Interpretation

The first description of the sections at Porth Oer was by Jehu (1909) who noted the beds of cemented sand and gravel which he regarded as a pre-glacial raised beach. He suggested that the underlying rock platform was succeeded in places by a rock rubble or head which was entirely local in origin and derived from adjacent Precambrian rocks. He suggested it had formed subaerially by freeze-thaw processes in pre-glacial (pre-Pleistocene) times. At the south-west end of the bay, this rock rubble formed a horizon about 0.3m thick on top of the shore platform and beneath thick blue-grey till. This till, which also formed most of the cliff at Porth Oer, belonged to his Lower Boulder Clay series and represented evidence of the earliest of the glacial advances in Llŷn (Jehu 1909). It contained irregular masses of marine sand, and occasionally some gravel in addition to numerous marine shell fragments from the floor of the Irish Sea (Jehu 1909).

Whittow (1957, 1960) originally doubted Jehu's evidence for the beach at Porth Oer, but later accepted it (Whittow 1965). He described the shore platform at Porth Oer, and suggested that the lack of raised beach deposits was not surprising since glacial striae on the platform indicated that it had been severely scoured by Irish Sea ice moving onshore from a northerly direction. He suggested that the age of the platform was uncertain but that it could be Hoxnian or even earlier. This was supported by Mitchell (1960) who correlated the raised beach at Porth Oer with the Fremington raised beach in north Devon, which he believed was Hoxnian in age. Similarly, Synge (1963, 1964) considered Porth Oer to be important because it was the sole locality in Llŷn where an interglacial raised beach deposit could be observed. He considered that a number of factors pointed towards the antiquity of the sequence at Porth Oer. First, the great age of the platform was attested by its highly weathered condition (Synge 1963). Second, the till at Porth Oer was weathered at its surface, a process that must have taken place under fully interglacial conditions. Therefore, a Saalian age was attributed to the till at Porth Oer, with the interglacial weathering of its surface attributed to the succeeding Ipswichian Stage (Synge 1964). The basal raised beach was Hoxnian in age and the underlying platform was ascribed to the Hoxnian or possibly earlier.

The sequence at Porth Oer described by Saunders (1963, 1967, 1968a, 1968b, 1968c, 1968d, 1973) was, essentially similar to that of Jehu. He believed Porth Oer was the most westerly drift-filled hollow in Llŷn, and considered that the pre-drift surface at the site provided conclusive evidence for a former high sea-level between 7.6 and 9.1m OD (25 ft and 30 ft) before deposition of the till. He argued that the shore platform represented a multi-cyclical feature of probable Ipswichian and pre-Ipswichian ages, while the raised beach gravels themselves belonged to the Ipswichian Stage. Saunders and other workers (for example, Whittow and Ball 1970; Peake *et al.* 1973; Bowen 1974) recognised foreign erratics in the raised beach at Porth Oer and alluded to the possibility that they had been derived by marine reworking of glacial deposits from an earlier glaciation. An Ipswichian age for the raised beach at Porth Oer was also proposed by Bowen (1973a, 1973b, 1974, 1977b).

On the basis of radiocarbon dates from till sites elsewhere in Llŷn, Saunders argued that the till at Porth Oer was deposited during the principal invasion of the Late Devensian Irish Sea ice-sheet. He correlated this till with the lower or Trevor Till (Simpkins 1968) of the north Llŷn coast and suggested that it could also be correlated with the lower or Criccieth Till exposed in southern Llŷn (at Criccieth and Glanllynnau), and was supported by Bowen (1973a, 1973b, 1974, 1977b). Deposits from the proposed later readvance of Late Devensian ice (the Clynnog Till of north Llŷn) found, for example, at Dinas Dinlle and Gwydir Bay, have not been recorded at Porth Oer. The weathered surface of the Trevor Till at Porth Oer was correlated with a comparable horizon at Gwydir Bay which affected both the Trevor Till and the sands and gravels of the Aberafon Formation, and pre-dated deposition of the Clynnog Till. Saunders suggested that the weathering at both sites therefore occurred during interstadial conditions in the Late Devensian.

Detailed pebble lithology and till fabric measurements have been undertaken at Porth Oer (Saunders 1963, 1968b, 1968d). Fabric properties have established that the Trevor Till was deposited by Irish Sea ice moving onshore from between the north and ENE, and a generally northern source was confirmed by high percentages of fine- and coarse-grained acid igneous rock types.

The broad sequence of Late Pleistocene events reconstructed from lithostratigraphic evidence at Porth Oer by Saunders, was also upheld by Whittow and Ball (1970) who suggested that the site was glaciated by Irish Sea ice of the first recorded (Devensian) advance in Llŷn, but not during the subsequent advance of the Irish Sea ice-sheet.

Porth Oer provides an important lithostratigrapic record of Late Pleistocene events in north-west Wales and in particular, evidence for a cycle of interglacial and glacial events. It displays the finest example of raised marine deposits anywhere in North or north-west Wales. It is the only such site in Llŷn, and together with Red Wharf Bay on Anglesey, provides rare evidence for former high relative sea-levels and probably interglacial conditions in the region. The presence of raised beach deposits at Porth Oer has resulted in the site having featured prominently in studies of Pleistocene correlations (for example, Mitchell 1960; Synge 1963, 1964; Bowen 1973a, 1973b, 1974, 1977b; Peake *et al.* 1973). In particular, the raised beach deposits formerly allowed correlation of the Pleistocene succession in Llŷn with that in the Gower Peninsula (for example, Bowen 1973a, 1973b, 1974, 1977b) where the raised beach fragments were regarded as Ipswichian in age and were used as a lithostratigraphic marker horizon. Although the age of the raised beach at Porth Oer has not been determined, the site provides rare evidence in North Wales, and the only sedimentary evidence in Llŷn, for former high sea-level, interglacial conditions.

The unusually fine development of a raised shore platform beneath the raised beach sediments at Porth Oer gives a rare opportunity to study earlier elements of the Late Pleistocene sequence. Although the age of this platform is unknown and probably composite, it is representative of the most widespread geomorphological feature pre-dating Late Pleistocene glaciation in Llŷn (Whittow and Ball 1970), and it provides evidence for former high sea-levels before the raised beach event.

The site is also important for establishing details of the glacial history of Llŷn. The till exposure has provided lithological and fabric evidence which indicates deposition by ice moving onshore from the Irish Sea Basin. Porth Oer therefore helps to establish regional patterns of ice movement. Saunders' studies have provided a firm foundation for correlating this till with the lower or Trevor Till found widely elsewhere along the north coast of Llŷn. The occurrence of this till here, on the western tip of Llŷn, helps to establish that virtually the whole northern coast was inundated by Irish Sea ice during this probably Late Devensian glacial episode. The upper or Clynnog Till which occurs in north Llŷn, for example at Dinas Dinlle and Gwydir Bay, is not present at Porth Oer. It follows that the sequences at these sites help to constrain the extent to which north Llŷn was affected by ice during the second recorded advance of Late Devensian ice – the proposed Late Devensian readvance. The site, therefore, helps to establish that parts of western Llŷn were not glaciated by the possibly confluent Irish sea and Welsh ice that affected the Menai Straits region and other parts of the north Llŷn coast.

Although the significance of the leached and weathered surface of the Trevor Till at Porth Oer is debatable, the implication is that this horizon, and comparable ones at Dinas Dinlle and Gwydir Bay, were formed during a period of weathering between the two recorded Late Devensian ice advances (for example, Saunders 1968a, 1968d).

This locality provides the only known sedimentary record in Llŷn of pre-Holocene high sea-levels associated with interglacial conditions. With Red Wharf Bay, the site provides the only evidence in north-west Wales for a cycle of interglacial and glacial events. The interest of the site is enhanced by the thick till (Trevor Till) sequence which overlies the raised beach. This till demonstrates the onshore movement of the Irish Sea ice-sheet onto north and west Llŷn during the principal invasion of the Late Devensian ice-sheet. Whereas depositional evidence from Dinas Dinlle and Gwydir Bay show that parts of northern Llŷn were affected by a subsequent readvance of Late Devensian ice, Porth Oer shows that this ice did not reach western Llŷn.

Conclusions

The raised beach at Porth Oer together with that at Red Wharf Bay in Anglesey, are the only known examples of their kind in North Wales. The overlying deposits show the events of the last glacial cycle, which followed the previous interglacial period when the raised beaches were formed.

Porth Neigwl

Highlights

An important site which records possible evidence for three glacial events in this part of North Wales: a pre-Devensian glacial event, a Late Devensian Irish Sea invasion of ice and a later Welsh ice advance moving in a different direction.

Introduction

Porth Neigwl provides evidence to suggest that southern Llŷn was inundated by southward moving ice from the Irish Sea Basin. The site has a long history of research commencing with the work of Jehu (1909). Porth Neigwl has also featured in studies by Nicholas (1915), Matley (1936), Synge (1963, 1964), Saunders (1963, 1968a, 1968b, 1968c, 1968d, 1973), Whittow (1960), Whittow and Ball (1970) and Boulton (1977a).

Description

Porth Neigwl or Hell's Mouth Bay is situated on the southern coast of Llŷn and opens out to the south-west. To the south-east, the bay is bounded by the high ground of Mynydd Cilan, a promontory of Cambrian rocks, and to the north-west, by Ordovician shales and basic intrusive rocks. Between these rock masses, the head of the bay is formed entirely of Late Pleistocene and Holocene sediments which extend for about four miles, giving one of the finest drift sections in north-west Wales. In the lowland plain behind Porth Neigwl, boreholes have proved a drift cover in excess of 110m (360 ft) (Saunders 1968b). The cliffed sequence comprises mostly thick, blue-grey to brown Irish Sea till, up to 30m in thickness, and the western part of Porth Neigwl Bay between Pen-yr-Allt (SH243286) and Trefollwyn (SH269274) is almost entirely composed of this thick, homogenous till. The area included within the GCR site, however, extends from near Pen-towyn Farm (SH283263) to just beyond Nant Farm (SH291255) in the east, where the drift stratigraphy is more complex and potentially more rewarding for elaborating Late Pleistocene and Holocene events – see Figure 31. Immediately south of Pen-towyn Farm, the Irish Sea till is well exposed and forms massive faces. To the south-east of this, Saunders (for example, 1963, 1968d) recorded a sequence showing –

9 Blown sand
8 Peat with birch and hazelnuts (Pollen Zone VII-VIII?)
7 Gravelly local till (Llanystumdwy Till)
6 Weathered horizon
5 Shelly outwash sands, gravels and laminated clays (Aberafon Formation)
4 Blue-grey, calcareous Irish Sea till (Trevor Till)
3 Soliflucted local till
2 Fine flaky head with pseudo-stratification
1 Coarse, blocky head

The chief elements of this succession are shown in Figure 31.

Interpretation

Jehu (1909) was the first to describe the deposits at Porth Neigwl, which he did as part of a comprehensive classification of drift deposits in western Caernarvonshire. As at Gwydir Bay in northern Llŷn, he described a tripartite sequence of two tills separated by sands and gravels, which, he argued, showed evidence for two glacial advances separated by possible interglacial conditions. He described a wide range of rock types from the lower till (bed 4) including Chalk flints, various granites from southern Scotland and Ailsa Craig microgranite, which he considered indicated derivation from the Irish Sea Basin. The lower till also contained pieces of wood and a comprehensive marine mollusc fauna, further proof that it was deposited by ice which moved south

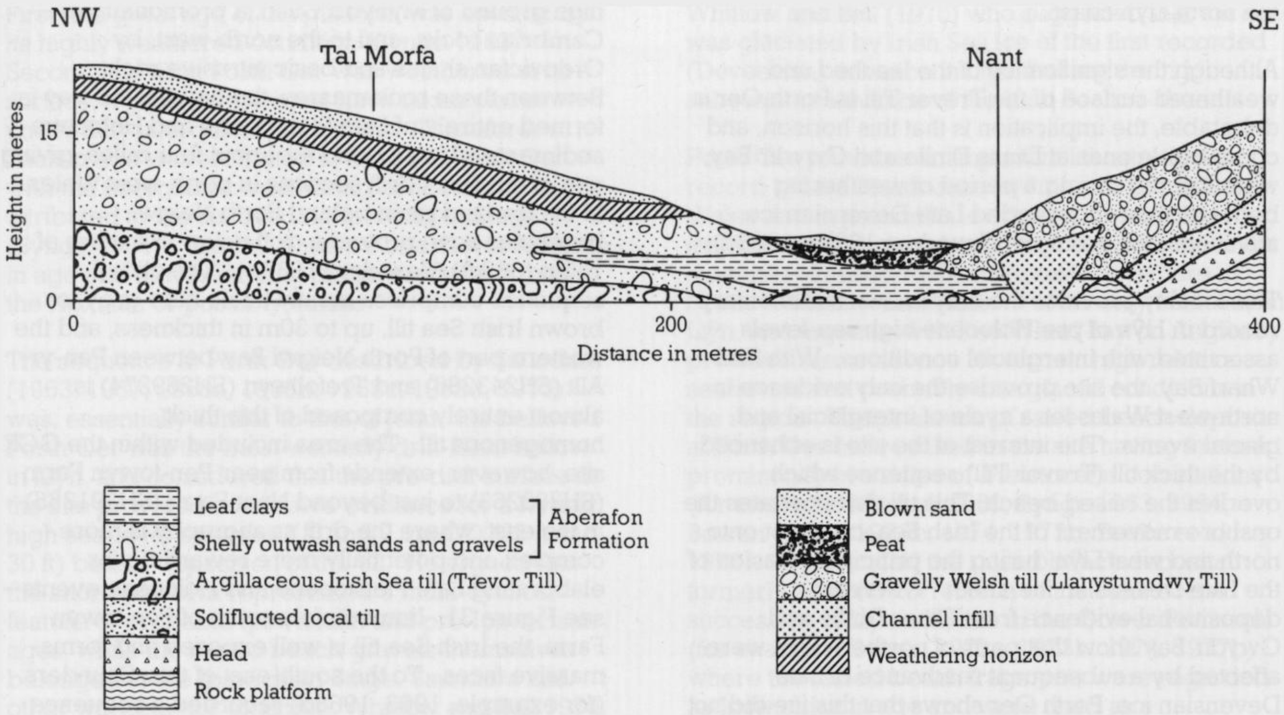

Figure 31 Quaternary sequence at Porth Neigwl (from Saunders 1968d)

over the floor of the Irish Sea. He demonstrated that the overlying sands and gravels (bed 5) also contained typical Irish Sea erratics and shells, and regarded them as sea-floor materials transported by ice and subsequently redeposited by fluvioglacial action. Jehu noted that the upper till (bed 7) was only present in the southern part of the bay; and, because it contained far-travelled erratics and marine shell fragments, argued that it too had been derived, at least in part, from the Irish Sea Basin. In contrast, Nicholas (1915) interpreted the upper till as the product of local Welsh (Snowdonian) ice which had invaded Llŷn following retreat of Irish Sea ice from St Tudwal's Peninsula.

Matley (1936) described the Pleistocene sequence at Porth Neigwl near Tyddyn-y-don Farm. He showed that Jehu's lower till was overlain by a series of laminated clays and sands (leaf-clays), which he argued had been deposited in a marine lagoon largely shut off from the sea by a barrier of ice. These sediments formed part of a 50 ft (15m) terrace which Matley traced at various locations in southern Llŷn, and which he judged to be of 'Late-glacial' age.

The Late Pleistocene and Holocene deposits at Porth Neigwl were also described by Synge (1963, 1964). He argued that the main calcareous shelly till (Jehu's lower till and Saunders' bed 4 – see Figure 31) was probably Saalian in age and that the soliflucted local till (bed 3) showed evidence for an even earlier local glacial phase. Evidence from coastal sections around Llŷn was used by Synge to suggest that only the northern coastal margin had been affected by Devensian Stage ice. He suggested that during this glacial phase a rubbly head (equivalent to Saunders' bed 7 – gravelly local till) was formed at Porth Neigwl. Elsewhere along the south Llŷn coast, Saalian drifts were cryoturbated under periglacial conditions.

The most detailed work at Porth Neigwl was done by Saunders (1963, 1968a, 1968b, 1968c, 1968d, 1973) whose reconstructed succession is shown in Figure 31. He envisaged that before deposition of the Irish Sea till (bed 4), periglacial conditions were experienced in the area and resulted in formation of head deposits (beds 1 and 2) and the redistribution of existing Welsh glacial sediments (bed 3). Detailed pebble lithology and till fabric measurements showed that the till (bed 4) was deposited by Irish Sea ice moving onshore from NNW to SSE. The typical erratic assemblage, including limestones from the central plain of Ireland, metamorphic and fine-grained basic igneous types from Anglesey and northern Llŷn, provided strong evidence of an Irish Sea origin for the till. Saunders correlated the Irish Sea till at Porth Neigwl with the lower till or Trevor Till of the north Llŷn coast. He regarded the shelly sands and gravels (bed 5) overlying the Trevor Till as fluvioglacial deposits associated with decay of the Irish Sea ice and interpreted the laminated leaf-clays as lagoonal or lacustrine deposits probably associated with temporary still water conditions in the fluvioglacial environment. Although no correlation was made by Saunders, these sands, gravels and clays are broadly equivalent to the sands and gravels of the Aberafon Formation (Simpkins 1968) along the north Llŷn coast.

The overlying gravelly till (bed 7) was, according to Saunders, clearly differentiated from the Irish Sea sediments beneath. Both Irish Sea and Welsh erratics were recorded from this till but Saunders emphasised that the preponderance of Welsh erratics, particularly those from southern Snowdonia, suggested a Welsh origin. These conclusions were also supported by fabric analyses which showed that the Welsh till had been deposited by ice moving from north-east to south-west. Because a zone of weathering (unit 6) separated the Welsh till from the Irish Sea sediments beneath, Saunders argued that the upper till represented an entirely separate and later advance of ice from Snowdonia, which in moving south-westwards incorporated Irish Sea erratics from the previous glacial episode.

Fundamental to Saunders' interpretation of the sequence was a radiocarbon date of 29,000 ± 1200 BP (I-3262) from marine shell fragments taken from the lower (Trevor) till. A comparable sample from Porth Dinllaen on the north Llŷn coast gave an age of 31,800 + 1,800 - 1,200 BP (I-3273). On the basis of these dates, Saunders referred the Trevor Till at Porth Neigwl and elsewhere in Llŷn to the Late Devensian. The gravelly upper till at Porth Neigwl he considered to represent a readvance of the Late Devensian Welsh ice-sheet, sometime after *c.* 17,000 BP, on the basis of Foster's (1968, 1970a) radiocarbon date from Bryncir. This readvance was tentatively correlated by Saunders with the Scottish Readvance.

Bowen (1973, 1977b) accepted this interpretation. The weathering horizon (unit 6) described by Saunders, he took to indicate interstadial weathering (Bowen 1973a, 1977b; Saunders 1968a, 1968d; Whittow and Ball 1970), and not fully interglacial conditions as proposed by Synge (1964). Bowen considered that Porth Neigwl represented the most westerly occurrence of the upper Welsh till in southern Llŷn, and correlated it with the gravelly Welsh till farther east at Glanllynnau and Criccieth, named locally the Llanystumdwy Till (Simpkins 1968). Such sedimentary data were used to reconstruct a maximum limit (Figure 27) for the proposed readvance of Late Devensian ice (Bowen 1974, 1977b) with the extreme parts of south-west Llŷn remaining ice-free. The Irish Sea till at Porth Neigwl was correlated with the Trevor Till on the north coast.

An alternative explanation for the sequence at Porth Neigwl was proposed by Boulton (1977a). He suggested that the sequence was similar to that at Glanllynnau where he had demonstrated that the sediments had formed in a supraglacial landform and sediment association, in a single Late Devensian glacial event. In this interpretation, the weathering horizon simply reflected a relatively short break in sedimentation and not a protracted period of deglaciation or interstadial conditions as had previously been suggested.

The age of the deposits at Porth Neigwl is controversial. Mitchell (1960, 1972) and Synge (1963, 1964) stressed the much-weathered and frost-heaved nature of the tills in southern Llŷn, and used the evidence to suggest that it was not glaciated during the Late Devensian, with ice restricted largely to the northern coastal margin. This view has not, however, been widely accepted and most workers (for example, Saunders 1968a, 1968b, 1968c, 1968d, 1973; Bowen 1973a, 1973b, 1974, 1977b; Whittow and Ball 1970) believed that all the till in Llŷn was deposited during the Late Devensian. Porth Neigwl is one of very few Pleistocene sites in North and north-west Wales to have yielded a radiocarbon date, which although potentially unreliable, may provide evidence to confirm that the area was glaciated during the Late Devensian.

Porth Neigwl is the finest exposure through the Irish Sea (Trevor) till in southern Llŷn. It demonstrates that the south-west tip of Llŷn was invaded by Irish Sea ice moving broadly north to south. Both the inferred direction of ice movement and the considerable thickness of the Trevor Till strongly suggest that during the principal invasion of the Late Devensian ice-sheet, Irish Sea ice was dominant on south-west Llŷn and at this time was unimpeded by Welsh ice. In this context, Porth Neigwl provides contrasting evidence to the sites at Porth Ceiriad, Glanllynnau and Morannedd (Criccieth) which display sediments of predominantly Welsh derivation.

The upper gravelly Welsh till at Porth Neigwl, of proposed Late Devensian readvance age, demonstrates a later incursion of ice moving broadly east to west into the area. Its limited exposure at Porth Neigwl has been used to demonstrate that Late Devensian readvance Welsh ice was here near to its most westerly limit. The site therefore provides important evidence to constrain the limit of Welsh ice on south-west Llŷn during the proposed Late Devensian readvance. Porth Neigwl further demonstrates that the area around St Tudwal's Peninsula was glaciated by both Welsh and Irish Sea ice masses during the Late Pleistocene.
The sequence at Porth Neigwl is also important for demonstrating a period of periglacial conditions before deposition of the thick Irish Sea till, when head was deposited and pre-existing glacial sediments redistributed by solifluction. The site provides sedimentary evidence in north-west Wales for a glacial event prior to deposition of the main Irish Sea (Trevor) till.

The site was once regarded as important for a Holocene raised beach which occurred at the base of the coastal cliffs near high water mark (Whittow 1960). West (1972) has since shown that this feature was merely part of the present day beach, cemented by inorganic calcite and providing no evidence for the height of a Holocene raised beach in north-west Wales. The Holocene peat and sand cliffed in the southern part of the bay provide additional interest.

Porth Neigwl is important for reconstructing the Late Pleistocene history of north-west Wales. It provides the finest sections in southern Llŷn through till of Irish Sea provenance (Trevor Till). A radiocarbon date on shell gives evidence to suggest that the Trevor Till was deposited by Late Devensian ice. The upper gravelly till at Porth Neigwl demonstrates a later incursion of Welsh ice into the area. The sequence helps to establish the directions of ice movement and the relative strength and interactions of the Irish Sea and Welsh ice masses during both recorded glacial episodes. The site also shows evidence for periglacial conditions prior to deposition of the Trevor Till. Redeposited Welsh erratics in the periglacial sediments record possible evidence for an even earlier glacial episode.

Conclusions

The extensive exposures of ice age sediments at Porth Neigwl are important for reconstructing the ice age history of north-west Wales. The Irish Sea ice-sheet deposit (Trevor Till) has been interpreted as a boulder clay: that is, the sedimentary product of a land-based ice-sheet. On the other hand, it could perhaps be a glacio-marine deposit representing deposition in a sea, adjacent to the Irish Sea ice-sheet.

Porth Ceiriad

Highlights

This locality with its periglacial sediments above and below glacial till may show that this part of Llŷn was glaciated by confluent Irish Sea and Welsh ice during the Late Devensian, but lay in a periglacial area beyond the western limit of a later advance of Welsh ice.

Introduction

Porth Ceiriad is an important coastal exposure which shows that the St Tudwal's Peninsula may have been a zone of transition between Irish Sea and Welsh ice masses during the Late Pleistocene. The sections were first noted by Ramsay (1881) and have since featured in studies by Jehu (1909), Saunders (1967, 1968a, 1968b, 1968c, 1973) and Whittow and Ball (1970).

Description

The sections at Porth Ceiriad extend laterally for about 700m, and they reach a maximum height of 30m. Whittow and Ball (1970) recorded the following generalised sequence, shown in Figure 32.

6	Hillwash
5	False-bedded shale head (cryoturbated)
4	Solifluction deposits
3	Grey-brown non-calcareous Welsh till
2	Fine shale head
1	Blocky head

Bed 4 contains a large lens of calcareous Irish Sea till, reworked Welsh till from bed 3 and beds of laminated clays and sands with gravel lenses.

Interpretation

Although Ramsay (1881) described the head deposits at Porth Ceiriad as an angular breccia of post-Tertiary age resting on slaty strata, Jehu (1909) was the first to describe the sections in detail. He noted that many of the boulders and pebbles in the till were of Welsh origin although other farther-travelled, probably Irish Sea, erratics were also recorded. He regarded the till at Porth Ceiriad as representing the Upper Boulder Clay of his tripartite succession, representing the most recent of two glacial advances in Llŷn.

The sections at Porth Ceiriad were next studied by Saunders (1967, 1968a, 1968b, 1968c, 1973). Using pebble lithology and till fabric measurements, he ascertained that the till at Porth Ceiriad (bed 3) had been deposited by Welsh ice moving from north-east to south-west. This suggested that when the Welsh till was deposited at Porth Ceiriad, the area to the west was probably free from Irish Sea ice, which otherwise would have caused a major southward deflection of the Welsh ice-sheet. The Welsh till was therefore considered younger than the main Irish Sea till (Trevor Till) at nearby Porth Neigwl, which Saunders ascribed to the main invasion of the Late Devensian ice-sheet in Llŷn. He correlated the Welsh till at Porth Ceiriad with the younger of the two Welsh tills exposed elsewhere along the south coast of Llŷn, (the Llanystumdwy Till of Simpkins (1968)), for example at Glanllynnau and Morannedd. Saunders suggested that the till at Porth Ceiriad had been deposited during the second glacial advance on Llŷn of proposed Late Devensian readvance age. The till at Porth Ceiriad was consequently seen to be equivalent in age to the gravelly Welsh till at Porth Neigwl.

These correlations were not, however, accepted by Whittow and Ball (1970) who suggested that the Welsh till at Porth Ceiriad belonged to the first of the recognised glacial advances in Llŷn and could therefore be correlated with the lower of the Welsh tills on the south Llŷn coast, at Criccieth (Morannedd) and Glanllynnau (the Criccieth Till of Simpkins (1968)). A lens of calcareous Irish Sea till (in bed 4) was noted by Whittow and Ball but was not considered to be *in situ*. It appeared to have been soliflucted from a nearby deposit of the Irish Sea till, and it was used as evidence to suggest that St Tudwal's Peninsula had been a zone of transition between the Welsh and Irish Sea ice masses during

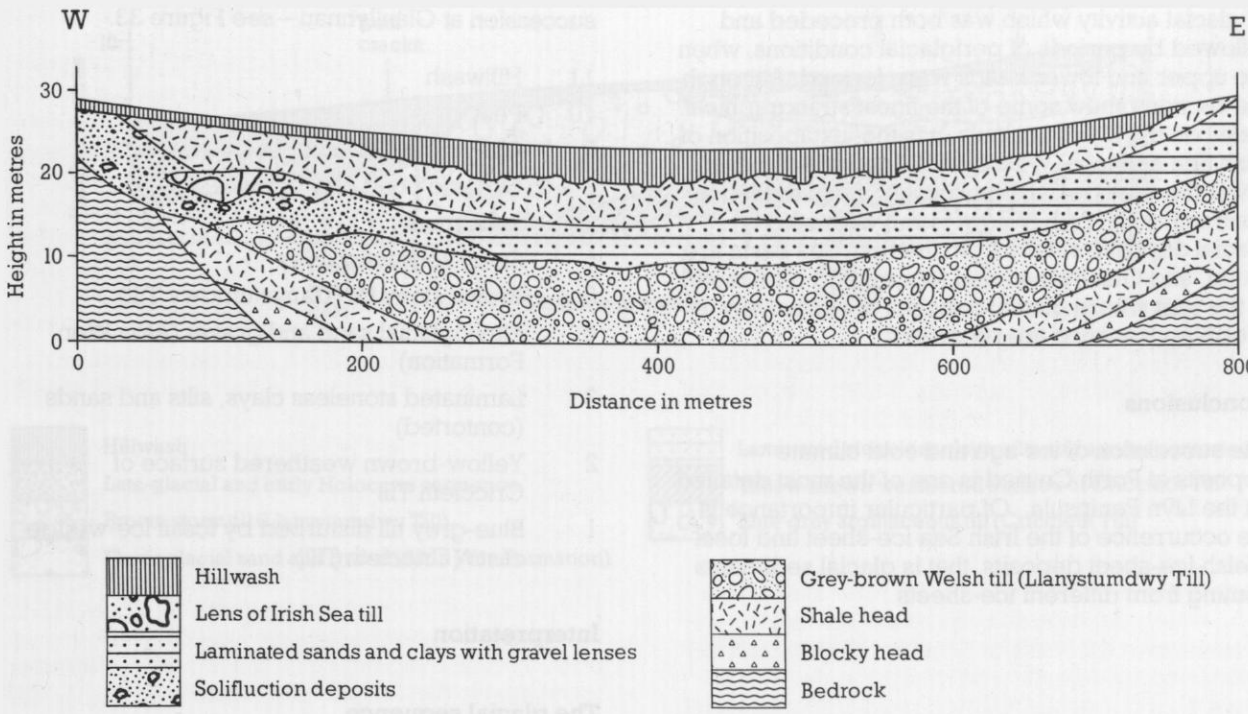

Figure 32 Quaternary sequence at Porth Ceiriad (from Whittow and Ball 1970)

this first glacial episode. The till and soliflucted till at Porth Ceiriad (beds 3 and 4) were succeeded by cryoturbated head deposits. The implication was that the head deposits and the structures were formed during a later glacial episode, when periglacial conditions were experienced at Porth Ceiriad and an upper till was deposited elsewhere in Llŷn. Saunders (1973) later accepted this interpretation.

Porth Ceiriad is particularly important for showing evidence for the interactions and movements of the Irish Sea and Welsh ice-sheets in south-west Llŷn during the Late Devensian.

Saunders originally presented lithological and fabric data to correlate the Welsh till at Porth Ceiriad with the upper of two tills found farther east along the south Llŷn coast, the Llanystumdwy Till – broadly equivalent to the Clynnog Till of north Llŷn and of postulated Late Devensian readvance age. This evidence was used to suggest that western Llŷn was free from Irish Sea ice during a later advance of the Late Devensian ice-sheet. However, most subsequent authors, including Saunders (1973), have correlated the Welsh till at Porth Ceiriad with the Irish Sea till at Porth Neigwl and the lower of the two tills found commonly elsewhere in Llŷn (the Trevor and Criccieth Tills of Irish Sea and Welsh provenance, respectively). Such a correlation together with the close association of soliflucted Irish Sea and Welsh glacial sediments at Porth Ceiriad has led to the proposal of an entirely different sequence of Late Pleistocene events in south-west Llŷn. In particular, this evidence has been used to suggest that St Tudwal's Peninsula was a zone of transition between the Irish Sea and Welsh ice masses during the principal invasion of the Late Devensian ice-sheet. With lithological evidence from Porth Neigwl to the west and Glanllynnau and Criccieth to the east, the evidence from Porth Ceiriad suggests that south-west Llŷn was glaciated by a Late Devensian Irish Sea ice-sheet moving southwards, while southern Llŷn was invaded contemporaneously by an ice-stream moving north-east to south-west from Snowdonia. From the evidence at Porth Ceiriad it appears that both ice-streams were confluent in the St Tudwal's area.

The absence of an upper till at Porth Ceiriad that could be correlated with the Welsh Llanystumdwy Till, found eastwards along much of the south Llŷn coast, places an important constraint on the maximum westward limit of the subsequent expansion of the Late Devensian ice-sheet which deposited that till. It has been shown that a gravelly Welsh till of limited extent occurs to the west, at Porth Neigwl. This implies that only a tongue of Welsh ice impinged on the coast of south-west Llŷn in this area, leaving Porth Ceiriad in the glacier-free zone during the inferred Late Devensian readvance. The presence of head, solifluction deposits and cryoturbation structures in the sequence above the Welsh till, lends some support to the proposal that the site and its immediate environs were situated in the periglacial zone during the later expansion of the Late Devensian ice.

The stratigraphic record at Porth Ceiriad is difficult to interpret although it would appear that the sequence contains evidence for at least one phase of glacial activity which was both preceded and followed by periods of periglacial conditions, when the upper and lower heads were formed. Although the sections show some of the finest stratigraphical detail on the Llŷn Peninsula, it is the juxtaposition of Irish Sea and local Welsh glacial sediments which gives the site special significance. Such evidence contrasts with Porth Neigwl to the west where glacial deposits mainly from the Irish Sea Basin are found, and Glanllynnau and Morannedd (Criccieth) in the east where glacial deposits of exclusively Welsh provenance are recorded.

Conclusions

The succession of ice age and cold climate deposits at Porth Ceiriad is one of the most detailed on the Llŷn Peninsula. Of particular importance is the occurrence of the Irish Sea ice-sheet and local Welsh ice-sheet deposits, that is glacial sediments coming from different ice-sheets.

Glanllynnau

Highlights

A complex site showing evidence for a fluctuating Devensian ice front. Its sediments, pollen, beetles and absolute dates have afforded one of the most detailed records of climatic change and, in particular, glacial retreat in Wales.

Introduction

Glanllynnau is a site of considerable importance for understanding glacial and late-glacial events in Wales. The glacial sediments have been interpreted as the product of two separate ice advances, but may also be explained as the result of a single glaciation. The deposits at Glanllynnau were first studied by Jehu (1909), and then by Matley (1936), Saunders (1963, 1967, 1968a, 1968b, 1968c, 1968d, 1973), Synge (1964, 1970) and Whittow and Ball (1970). Accounts of the Devensian late-glacial and Holocene successions were provided by Simpkins (1968, 1974) and Coope and Brophy (1972). The lithostratigraphy of the site was recently re-examined by Boulton (1977a, 1977b), and the succession has been discussed in a wider area by Bowen (1973a, 1973b, 1974, 1977b). It has also been referred to by Moore (1970, 1977), Shotton and Williams (1971) and Coope (1977).

Description

The coastal cliffs at Glanllynnau (SH456372) reveal a sequence of tills and fluvioglacial sediments, the latter displaying well developed glaciotectonic structures. The area inland is studded with kettle holes, some of which have been breached by coastal erosion to reveal a succession of Devensian late-glacial silty clay, peat and sand horizons.

Whittow and Ball (1970) described the following succession at Glanllynnau – see Figure 33.

11	Hillwash
10	Peat
9	Grey silt with boulders
8	Organic pond clay
7	Lake mud
6	Stony solifluction clay
5	Brown stony till (Llanystumdwy Till)
4	Fluvioglacial sand and gravel (Afon Wen Formation)
3	Laminated stoneless clays, silts and sands (contorted)
2	Yellow-brown weathered surface of Criccieth Till
1	Blue-grey till disturbed by fossil ice-wedge casts (Criccieth Till)

Interpretation

The glacial sequence

When the exposures were described by Jehu in 1909, the lower till (bed 1) was not exposed. He recorded only one till (bed 5) lying above sands and gravels, and classified these as the upper two thirds of his tripartite sequence in Llŷn. He established that the deposits were of Welsh provenance. Matley (1936) suggested that the sequence had been trimmed into a terrace, which commonly occurred at about 50 feet (*c.* 15m) in southern Llŷn, formed either by marine agencies or at the margins of a glacially-impounded lake in 'Late-Glacial' times.

Saunders (1963, 1967) was the first to record the lower blue-grey till (bed 1) beneath the sand and gravel at Glanllynnau. Saunders (1968a, 1968b, 1968c, 1968d, 1973) also described additional lithological and till fabric evidence. He showed that the lower till was argillaceous with an erratic suite dominated by slate (over 85%) derived from the Nantlle-Bethesda slate belt; its fabric indicating deposition by ice moving from ENE to WSW. He suggested it was overlain by a thin band of weathered and soliflucted till (bed 2) of the same origin, which in places, filled well developed fossil ice-wedge casts in the surface of the lower till. The weathered horizon was succeeded by a thin bed of wavy laminated silts (bed 3), which sealed the top of the ice-wedge casts, and which he considered could have been caused by freeze-thaw activity or by subsequent overriding of the sediments by the ice of a later advance. The silts are overlain by the fluvioglacial sand and gravel (bed 4) described by earlier workers, and by the upper till (bed 5) which shows well developed cryoturbation structures. Saunders showed that, like the lower till, the upper till was also Welsh in origin and it contained erratics from the Vale of Ffestiniog, deposited by ice moving from east to west. On regional lithostratigraphic grounds he suggested that large

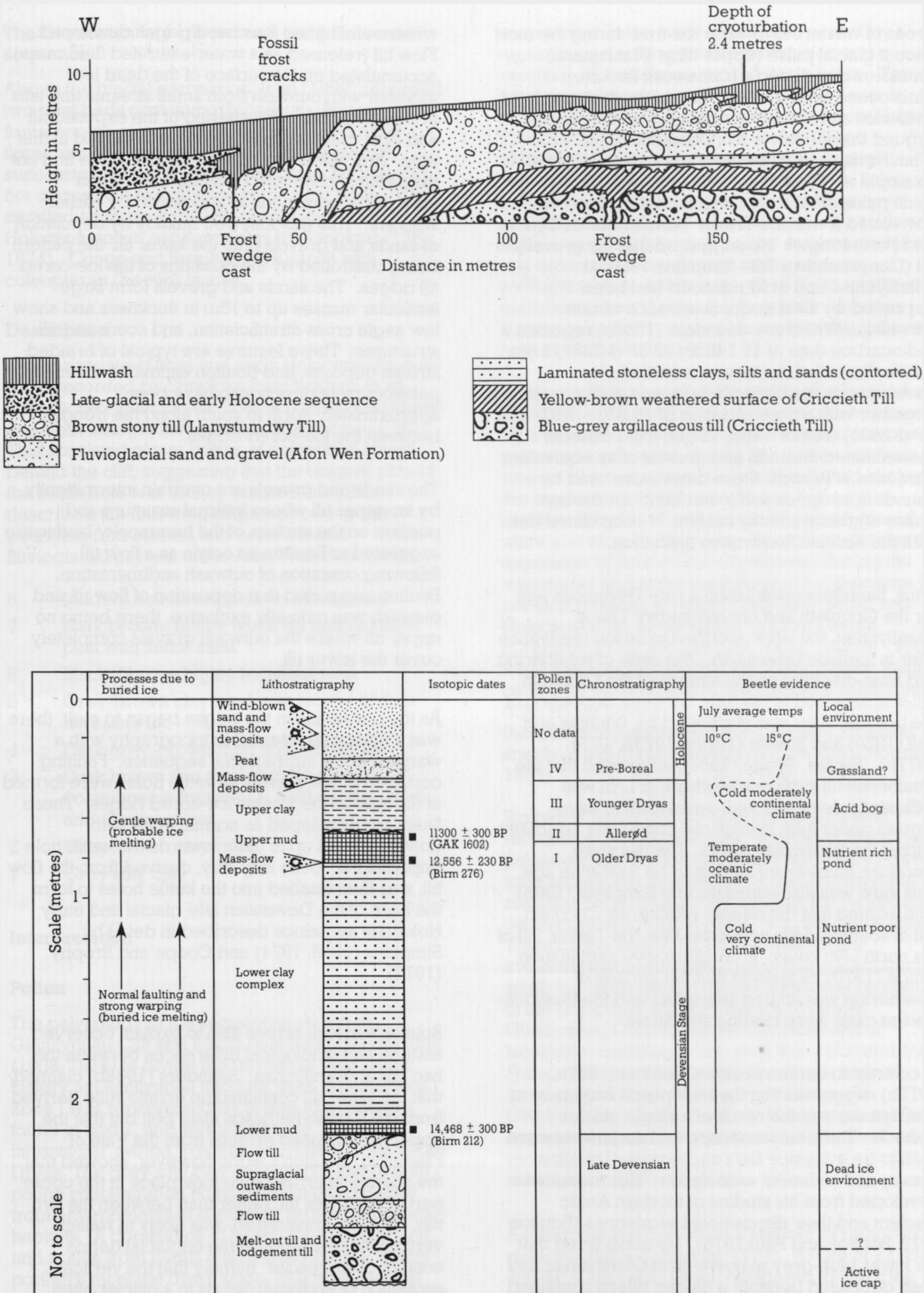

Figure 33 Quaternary sequence at Glanllynnau (after Whittow and Ball 1970; Boulton 1977a)

areas of western Llŷn were ice-free during the most recent glacial pulse (upper till at Glanllynnau). Saunders developed a framework for Late Pleistocene events in Llŷn using lithostratigraphical evidence supported by radiocarbon dating. He argued that the lower till (Criccieth Till) at Glanllynnau and elsewhere in southern Llŷn, for example at Morannedd, was deposited during the main pulse of the Late Devensian ice-sheet. He correlated it with the Trevor Till of northern Llŷn and Porth Neigwl. He suggested that the gravelly till (Llanystumdwy Till - Simpkins 1968) at Glanllynnau and at Morannedd had been deposited by a subsequent advance of Late Devensian Welsh ice. Saunders (1968a) reported a radiocarbon date of 11,740 ± 170 BP (I-3261) from peat collected at the base of a kettle hole developed in the fluvioglacial sands and gravels. Together with a determination of 16,830 + 970 - 860 BP (I-2801) (Foster 1968, 1970a) from material disseminated in sands and gravels of an equivalent formation at Bryncir, these dates were used by Saunders as upper and lower limits for the last phase of glacial activity in Llŷn. He correlated this with the Scottish Readvance glaciation.

Thus, Saunders established a Late Devensian age for the Criccieth and Llanystumdwy Tills at Glanllynnau, the latter ascribed to an ice readvance later in the Late Devensian. The zone of weathering and frost-cracking on the surface of the Criccieth Till was ascribed to the time between deposition of the two tills. This was supported by Whittow and Ball (1970) and Bowen (1973a, 1973b, 1974, 1977b). Earlier, Synge (1964), suggested that the weathered till surface elsewhere in Llŷn was sufficiently deep and well developed to have formed under fully interglacial conditions, probably during the Ipswichian Stage. The tills were therefore considered by him to be Saalian in age. This view was also supported by Simpkins (1968) who argued that the deeply weathered Criccieth Till of southern Llŷn was older than the Trevor Till of the north Llŷn coast. In an alternative explanation, Synge (1970) suggested that the horizon of weathering was an iron-pan effect and the fossil ice-wedge casts were loading structures.

In contrast to earlier workers, Boulton (1977a, 1977b) suggested that the multiple till sequence at Glanllynnau was the result of a single glacial episode. The local landscape and sediments were seen to be evidence for a supraglacial landform system and sediment association. This model was developed from his studies of modern Arctic glaciers and their depositional sequences (Boulton 1972; Boulton and Paul 1976). He considered that the lower blue-grey massive till at Glanllynnau had been deposited beneath a glacier which contained a thick sequence of englacial debris. This glacier had moved from east to west as shown by Saunders' (1968b) fabric analyses and Boulton's determinations of magnetic anisotropy susceptibility. During ice wastage, englacial debris melted out onto the glacier surface and protected underlying ice from further ablation, when well defined ice-cored ridges developed. Flow till (released as a water-saturated fluid mass) accumulated on the surface of the dead ice, together with outwash from small streams and silts in surface ponds. Weathering of the exposed till and frost-cracking may also have occurred at this time. Any hiatus was only a brief interlude and not the result of protracted interstadial or even interglacial conditions as suggested by earlier workers. This was followed quickly by deposition of sands and gravels onto the lower till, the pattern being controlled by the positions of the ice-cored till ridges. The sands and gravels form large lenticular masses up to 15m in thickness and show low angle cross-stratificiation, and scour and fill structures. These features are typical of braided stream deposits, and Boulton estimated the mean palaeocurrent direction to have been approximately north to south along the troughs between the ice-cored ridges.

The sands and gravels are overlain intermittently by an upper till whose internal structure and position on the surface of the hummocky landscape suggested to Boulton an origin as a flow till following cessation of outwash sedimentation. Boulton suggested that deposition of flow till and outwash was mutually exclusive, there being no upper till where the outwash gravels completely cover the lower till.

As the buried ice in the ridges began to melt, there was a complete reversal in topography with a warping of the supraglacial sequence. Faulting occurred in the gravels as kettle holes were formed at the sites of the former ice-cored ridges. These faults are developed as normal faults with downthrows of up to 0.5m towards the kettle hole depressions. Grey silty clay, derived from the flow till, was then washed into the kettle holes to form the base of the Devensian late-glacial and early Holocene sequence described in detail by Simpkins (1968, 1974) and Coope and Brophy (1972).

Boulton's model serves also to explain observed textural and lithological differences between the two tills at Glanllynnau. Saunders (1968b) claimed that the lower till contained an erratic suite derived from the Nantlle-Bethesda slate belt but that the upper till contained erratics from the Vale of Ffestiniog. Boulton's work, however, showed that the change in erratic suite took place in the upper part of the lower till, rather than between the two tills. This, he considered, was likely to reflect vertical differentiation in the englacial debris content of the glacier: namely that the vertical sequence of englacial debris in a glacier often reflects in reverse order the lithologies over which the glacier has moved; giving a sequence in which the farther-travelled debris is at the top. Therefore, the lower, fine-grained till may have been derived subglacially, although the upper till may have originated from coarser-textured supraglacial material.

The Devensian late-glacial and early Holocene sequence

Above the glacial succession, Jehu (1909) recorded two peat beds containing *Sphagnum*, *Potamogeton* fruits, scraps of birch bark and wood and other floral remains, and separated from the glacial succession by a rootletted blue-grey clay. He did not discuss the significance of the peat beds. The detailed analysis of the late-glacial and early Holocene pollen sequence was by Simpkins (1968, 1974). Coope and Brophy (1972) dealt with coleopteran (beetle) faunas.

Description

Devensian late-glacial and early Holocene deposits were recorded by Simpkins from borings in an unbreached inland kettle hole at Glanllynnau Marsh and from a single kettle hole in Glanllynnau Cliff. This consisted of two basins of deposition linked behind the cliff, suggesting that the original plan of the kettle hole was kidney-shaped. Simpkins described the following sequence of deposits overlying iron-stained and cryoturbated fluvioglacial gravels of the Afon Wen Formation –

8	Modern soil developed on blown sand
7	Dark brown, highly humified and oxidised peat with some sand
6	Black, fibrous highly humified peat
5	Grey-brown clay-mud with leaves of *Salix herbacea* L.
4	Dark grey-brown mud with some clay
3	Dark brown fine mud with many *Potamogeton* fruitstones, *Menyanthes* seeds and *Carex* nutlets
2	Grey-brown clay-mud
1	Grey silty clay

Interpretation

Pollen

The palynology of the sequences shown in Glanllynnau Cliff and Marsh was used by Simpkins (1968, 1974) to divide the terrestrial vegetation history at Glanllynnau into four main pollen zones. Zone I was represented by pollen assemblages found in bed 1, and was termed the 'pre-interstadial' period, roughly equivalent to the Older Dryas. The grey silty clay contained a low overall pollen concentration comprising mainly species from environments of disturbed ground and open-habitats. A dominance of grass and sedge pollen, and pollen from plants which today have a mainly northern montane distribution, indicated that this was a dominantly cold period. Simpkins suggested that the dominance of *Artemisia* pollen probably reflected the importance of solifluction processes at this time. This early cold phase was succeeded by a warm 'interstadial' period represented in the rock record by beds 2-4. This phase was characterised by a dominance of *Rumex* and *Juniperus* pollen, and was marked in the early interstadial period by a rapid change to biogenic sedimentation and a cessation of solifluction into the kettle holes. The latter part of this warm interstadial phase was characterised by a *Betula-Filipendula* assemblage. The 'post-interstadial' period (Pollen Zone III/Younger Dryas) was marked by an overall decline in pollen production. A decline in *Betula* and increased percentages of pollen from open and disturbed habitats – for example, *Artemisia* and *Rumex* – characterise this period and bear witness to a deterioration in climate and a return to solifluction in the kettle holes (bed 5). Macrofossil evidence shows that least willow *Salix herbacea* may have grown in close proximity to the cliff kettle hole at that time (Simpkins 1974).

The early Holocene (pre-Boreal) is represented at Glanllynnau by beds 6 and 7, and is characterised by a cessation of solifluction and a rapid increase in pollen concentration. During this period, thickets of juniper may have become quickly shaded out by the expansion of birch woodlands, although a number of herbs characteristic of the late-glacial were also slow to disappear. It is of interest that the expansion of *Juniperus* at Glanllynnau during the interstadial and at the beginning of the Holocene is not as marked as at other Welsh late-glacial and Holocene sites, for example, at Cors Geuallt (Crabtree 1972) and the Elan Valley (Moore 1970). It has been suggested that the lower juniper values cannot be explained in terms of simple altitudinal differences between these sites, and it is possible that peaks in juniper pollen may reflect localised stands of this shrub during these periods (Moore 1977).

Simpkins' palynological analysis also allowed reconstruction of the aquatic vegetation history and palaeoecology at Glanllynnau. Pollen Zone I (pre-interstadial) was dominated by the development of marginal reed swamp, while lacustrine conditions were experienced during the warmer interstadial. Towards the end of the late-glacial there is evidence that reed swamp and/or fen developed, while the diminution of all aquatics at the beginning of the Holocene, with the change to peat at Glanllynnau Cliff, marks the displacement of lacustrine conditions. The peat was colonised by *Sphagnum*, ferns, herbs and shrubs capable of growing in damp and boggy situations. At Glanllynnau Marsh, the early Holocene is marked by the widespread accumulation of fine mud, which records the continued existence of pond conditions in this particular kettle hole.

A timescale was based on a number of radiocarbon determinations (Simpkins 1974). A date of 12,050 ± 250 BP (Gak - 1603) was considered to mark the beginning of the interstadial, and a date of 11,300 ± 300 BP (Gak - 1602) the end of purely organic deposition marked by the close of the *Rumex* pollen zone and the beginning of the *Betula-Filipendula* zone.

The Devensian late-glacial pollen diagrams from

Glanllynnau therefore indicate a continuous ecological succession from pre-interstadial time, where the pollen spectra represent local pioneer vegetation, through to the warm interstadial period beginning at about 12,000 BP, comprising the *Rumex, Juniperus* and *Betula-Filipendula* zones. This climatic amelioration is also indicated by a lithological change from dominantly clastic to organic sedimentation. Evidence for vegetational recession and renewed solifluction in the post-interstadial period is suggested, and the early Holocene is shown by the immigration of thermophilous tree species and forest development in response to rapid climatic improvement.

Coleoptera (beetles)

Coope and Brophy's (1972) study was designed to compare the environmental inferences made from fossil beetles with those from Simpkins' (1968, 1974) palynological data. The Devensian late-glacial and early Holocene sequence described at Glanllynnau by Coope and Brophy was similar to that described by Simpkins, and contained four distinctive faunal units.

The oldest fauna, from bed 1, indicates an environment of bare ground with a thin patchy vegetation cover, possibly of short grasses and moss. Coope and Brophy considered that bed 1 had probably accumulated in a pool of standing water. The outstanding feature of this fauna was a high proportion of species which today have an entirely arctic or montane habitat. There was little doubt that the fauna indicated a rigorously cold climate with thermal conditions at least as cold as those in the alpine zones of Scandinavia today. Coope and Brophy estimated the average July temperature at least as low as 10°C, and several species suggested that the climate at this time may have been distinctly continental. The constancy of specific composition suggests that there was no deviation from this arctic climate during deposition of the lower layers of bed 1.

A second fauna characterises the upper part of bed 1 and part of the more organic sequence above (beds 2-4). This fauna proves a gradual improvement in environmental conditions, although vegetation was still sparse until the uppermost sample of this bed. Near the top of the bed, species occur which suggest a meadow-like vegetation, with no evidence of trees. Many species lived in a pool which may also have supported *Potamogeton natans* L. The beetle specimens collected also provided evidence for a rich flora developed around the edges of the pool, where there may have been bush willows. Coope and Brophy suggested that there could be no doubt of the thermophilous character of this fauna; all the stenothermic species of the preceding fauna were absent. There was, however, no evidence for a gradual transition from fauna 1 to fauna 2, and the sharp faunal break occurred at a level in bed 1 where no lithological break could be detected. Chemical investigations by Coope and Brophy revealed that sedimentation had probably been continuous and they concluded that the sharp faunal break was proof of a real change in climatic conditions. Average July temperatures during this warmer period were estimated at least as high as 17°C, and there was no evidence that the climate at that time was any more continental than today.

A third fauna occurred in the upper part of bed 4 and bed 5 and was characterised by a loss of thermophilous species and their replacement by species whose distributions today are predominantly northern. This change at Glanllynnau, however, was overshadowed by a profound change in local conditions. The habitat became decidedly more acidic and substantially colder, and the kettle hole pond became choked by *Sphagnum*. Although Coope and Brophy noted the difficulty in assessing the average July temperature for this fauna, the beetles clearly indicated a considerable deterioration in the thermal environment, and this drop must have been rapid. It was estimated that the average July temperature may have been in the region of 14°C, and the climate was probably still no more continental than today.

The fourth fauna (bed 5) shows no abrupt change from the preceding one. Rather, a series of faunal changes reflected a more or less continuous deterioration in the thermal environment. A precise figure for the average July temperature was not established, but it was clear that temperatures were low.

A further and final fossil beetle assemblage was discerned from the overlying beds 6 and 7, although remains were sparse, and poorly preserved, and inadequate to make any detailed observations; the fauna from these beds, however, was thought to indicate climatic amelioration.

Both the sequences of beetle assemblages and the pollen spectra at Glanllynnau were, therefore, interpreted in terms of a single Devensian late-glacial climatic oscillation, although the possibility was noted that the interstadial floras and faunas at Glanllynnau represented a combination of the Continental Bølling and Allerød Interstadials (Moore 1977). However, the climatic events inferred from these separate suites of data differ from one another, both in their timing and in their intensity. Whereas the pollen indicates that the thermal maximum of this warm oscillation occurred during Pollen Zone II, the beetles suggest that the episode of greatest warmth was earlier than this, occurring during Pollen Zone I. Despite the pollen evidence, the beetles show that by Pollen Zone II times, the environment had deteriorated considerably.

Coope and Brophy identified a visible increase in pollen in the profile where the organic content of the sediment was dominant. The lithology therefore mirrored the expansion of the local flora at this time. The beetles show, however, a sharp improvement in the thermal climate at a level 0.20-0.25m lower in the section, where no consistent lithological break can be discerned in the grey silty clay (bed 1). Chemical investigations of this bed showed there was no evidence for a break in sedimentation during deposition of bed 1. The change in the thermal environment indicated by the beetles cannot therefore be attributed to a hiatus in deposition. Thus, the evidence points to a real and sudden shift in climate in which the mean July temperature rose from about 10°C to about 17°C. Coope and Brophy explained the anomaly between the palynological and beetle evidence in terms of the differential rate of plant and animal responses to rapid changes of climate.

Their study also provided new radiocarbon dates. First, a date of 14,468 ± 300 BP (Birm 212) was obtained from moss towards the base of bed 1, at the start of the Late Devensian late-glacial sequence – see Figure 33. Second, dates of 12,050 ± 250 BP (Gak-1603) and 11,300 ± 300 (Gak-1602) were obtained by Simpkins (1974) from bulk samples from the basal 2cm and uppermost 2cm of bed 3. The possibility of contamination, however, was recognised in these samples, and a specially collected and prepared sample of seeds from the base of the mud was dated by Shotton and Williams (1971) to eliminate the possible sources of error. The date obtained, 12,556 ± 230 BP (Birm 276), was some 500 years older than the older of the two obtained by Simpkins. Third, samples were obtained from sparse plant remains from just above and just below the faunal break interpreted in bed 1. These samples yielded dates of 11,617 ± 270 BP (Birm 233) and 11,714 ± 255 BP (Birm 232), respectively (Shotton and Williams 1971). These samples, however, were obtained from plant debris made up largely of rootlets that penetrated the deposit from above. The dates, which are younger than those obtained 0.2-0.3m higher in the section, confirm the suspicion of rootlet contamination.

The estimated age of the faunal break, determined by calculations of average rates of sedimentation, and the onset of temperate conditions was placed at 12,850 ±250 BP (Coope and Brophy 1972). Further estimates suggest that the 5cm of grey silty clay (bed 1) during which the sudden climatic shift took place, must have accumulated in about 75 years. This indicates a dramatic rate of change in the average July temperature of about 1°C per decade. A summary of the beetle evidence from Glanllynnau and its significance was later given by Coope (1977).

Boulton (1977a) also made several observations about the Devensian late-glacial succession at Glanllynnau. First, faulting occurs in both the fluvioglacial gravels and in the lower part of the late-glacial succession. The basal silty clay has joints and faults throughout, while, in places, the overlying mud is also jointed and warped. This was considered as evidence for the melting of buried ice beneath the kettle hole after 14,468 ± 300 BP (Birm 212) – see Figure 33. There is evidence that the melting of buried ice continued at least until the end of the Older Dryas (12,556 ± 230 BP (Birm 276)) and possibly into the Allerød and Younger Dryas periods. Second, the intensity of faulting is greatest in the silty clay but is substantially reduced in the overlying beds, which suggests that the greatest rates of ice melting occurred towards the end of the period of deposition of these silty clays. Evidence for jointing in the upper clays and the pattern and distribution of the peat bed suggests, however, that the buried ice may have survived even longer, into the warm interstadial period inferred from the palynological and beetle evidence.

Glanllynnau displays a representative section through the tripartite sequence of southern Llŷn. Whereas Morannedd has come to be regarded as a reference site for the Criccieth and Llanystumdwy Tills, the fluvioglacial sands and gravels of the Afon Wen Formation are best developed at Glanllynnau. The sequence of Welsh sediments provides information for interpreting patterns of ice movement across southern Llŷn. Before Boulton's (1977a) interpretation, the sequence was interpreted as the product of two glacial advances separated by ice-free conditions.

From evidence at Glanllynnau, however, Boulton argued that the beds of the traditional tripartite sequence could be explained in an alternative manner. He suggested that much of the surface topography at Glanllynnau represented a foundered sediment surface let down by the melting of buried ice. He considered that the sequence of deposits was evidence for only a single Late Devensian glacial episode. This model of sedimentation has regional stratigraphic implications. Sequences essentially similar to that at Glanllynnau occur elsewhere in Llŷn, for example at Porth Neigwl and Gwydir Bay, where large lenticular masses of sand and gravel lie above dense tills with an undulating surface. These outwash deposits are also overlain sporadically by a thin upper till. Although Boulton's model explains a number of observed stratigraphic, textural and lithological changes in the sequence at Glanllynnau, it does not satisfactorily account for the deeply weathered surface of the Criccieth Till. Boulton argued that the Criccieth Till was subaerially weathered as the surface became transiently exposed in a supraglacial environment, prior to deposition of outwash and flow till. He concluded that the surface did not therefore mark a significant break in sedimentation. Others, including Bowen (1974, 1977b), have maintained that the scale of weathering at Glanllynnau, and particularly at Morannedd, indicates a protracted hiatus in deposition. The lack of an acceptable explanation for the weathering horizon in Boulton's sedimentation model is, therefore, a major impediment to applying the model to other sequences.

Whether the sequence at Glanllynnau was the product of one or two glacial advances, the composite age of the glacial sequence is clearly indicated by the evidence for melting of buried ice well into the Late Devensian late-glacial. This provides some of the strongest evidence in North and north-west Wales to confirm that widespread inundation of the region by ice occurred in the Late Devensian. The date of 14,468 ± 300 BP (Birm 212) from the base of the late-glacial succession is significant. It is one of the earliest radiocarbon dates for Late Devensian deglaciation in Wales. Glanllynnau also provides a record of late-glacial and early Holocene palaeoenvironmental conditions. It is the only sequence in Wales yielding both pollen and beetles that has been calibrated by radiocarbon methods. It gives one of the most detailed records of environmental changes in the late-glacial and early Holocene at any lowland site in North and north-west Wales. Together with sites in Snowdonia, the pollen record at Glanllynnau serves to demonstrate regional and altitudinal variations in vegetation history during these times.

Glanllynnau displays evidence for Late Pleistocene and early Holocene events in north-west Wales, and is perhaps the most intensively studied glacial to late-glacial sequence in Wales. Furthermore, it is the only late-glacial site in Wales where fossil beetle faunas have been investigated and is thus the only site where late-glacial palaeotemperature estimates have been possible. Although coastal erosion has removed part of the late-glacial and early Holocene sequence at Glanllynnau Cliff, the remaining kettle holes inland are likely to show comparable stratigraphic, pollen and faunal sequences, and this reference site therefore retains an outstanding potential for further research. Although some consider the glacigenic sequence to represent two ice advances, Boulton's work has shown that the sequence may have formed during a single Late Devensian glaciation. The site may, therefore, provide an important model for re-evaluating multiple drift sequences elsewhere. Radiocarbon analysis and studies of pollen and beetles in the late-glacial sediments significantly enhance the interest for environmental reconstructions.

Conclusions

Glanllynnau is one of the most intensively studied glacial sites in the World. An on-going debate continues on the precise origin and age of the different deposits exposed here. Exposures also occur through the infill of kettle holes. These have provided evidence from pollen and fossil beetles which shows how the climate changed from the end of the ice age, to the present. A radiocarbon date of 14,468 years, obtained from the base of one of the kettle hole deposits, is one of the earliest known dates for the disappearance of the last major ice-sheet in Wales.

Morannedd

One of the best available sequences of Late Pleistocene glacial sediments in North Wales, this site provides evidence for two Welsh ice advances

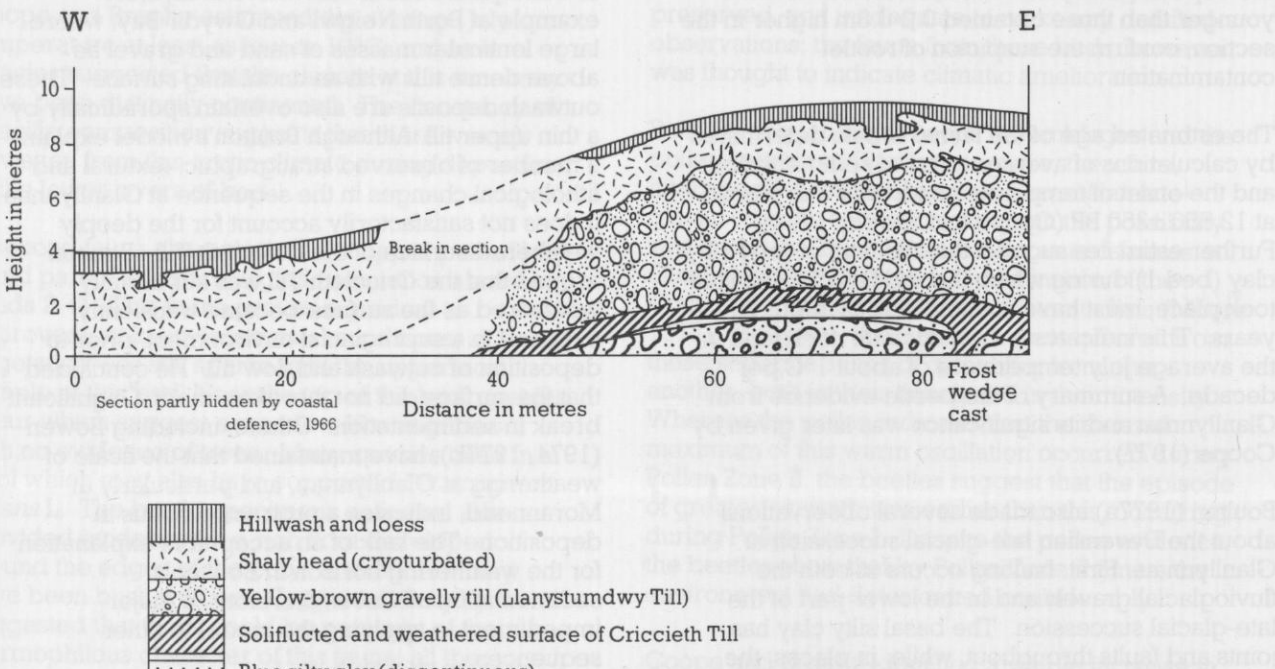

Figure 34 Quaternary sequence at Morannedd (from Whittow and Ball 1970)

probably during the Late Devensian. Controversy has arisen over the time gap between these two events.

Introduction

Morannedd shows an important sequence through Pleistocene deposits in the eastern Llŷn Peninsula. Evidence from the site has been used to show that the area was glaciated by ice from the Welsh highlands on two separate occasions. Although the chronology of events at the site remains uncertain, the sections are amongst the finest in Llŷn that expose tills of local Welsh provenance. The site has a long history of research commencing with Jehu (1909). It has featured in studies by Fearnsides (1910), Synge (1963, 1964, 1970), Saunders (1963, 1967, 1968a, 1968b, 1968c, 1968d, 1973), Simpkins (1968), Whittow and Ball (1970) and Campbell (1985a). The site has been discussed in the context of the Irish Sea Basin and Wales by Bowen (1973a, 1973b, 1974, 1977b).

Description

The exposures at Morannedd (SH507381) extend along the coast for about 250m and attain a maximum height of about 9m. Whittow and Ball recorded the following generalised succession, shown in Figure 34.

6 Hillwash and loess
5 Shaly head (cryoturbated)
4 Yellow-brown gravelly till (Llanystumdwy Till)
3 Soliflucted and weathered surface of Criccieth Till
2 Blue silty clay (discontinuous)
1 Blue-grey argillaceous till (Criccieth Till) with fossil ice-wedge casts

Their sequence, however, has been debated and the interpretation of the sediments is controversial.

Interpretation

Jehu (1909) recognised only a single till at the site (probably bed 4), and established that it contained neither shell fragments nor far-travelled (Irish Sea) erratics. The common occurrence of greenstones in the till led him to suggest that it had been deposited by ice from Snowdonia. He regarded the till as representing the Upper Boulder Clay of his tripartite succession in Llŷn. However, according to Fearnsides (1910), the till also contained boulders from west Caernarvonshire and Anglesey.

The sections at Morannedd were also noted by Synge (1963, 1964) who correlated the drifts of North and north-west Wales with successions in Ireland. At that time, he recognised only a single Welsh till, derived from the east. He regarded the yellow-brown till (bed 4 -the Llanystumdwy Till of Simpkins (1968)) as the weathered surface of the blue-grey till (bed 1) near the base of the section. He also noted that the upper surface of the weathered till was severely disturbed by frost-action, with many vertical stones. On the basis of the weathering and frost disturbance, Synge argued that the till had been deposited probably during the Saalian Stage. He suggested that its deep weathering occurred during the subsequent Ipswichian Stage, while cryoturbation of the upper layers had taken place during periglacial conditions in the Weichselian (Devensian) Stage.

Subsequent workers including Saunders (1963, 1967, 1968a, 1968b, 1968c, 1968d), Simpkins (1968), Whittow and Ball (1970) and Bowen (1974, 1977b) have recognised two tills at Morannedd. Simpkins (1968) termed the blue-grey argillaceous till and the yellow-brown gravelly till, the Criccieth and Llanystumdwy Tills, respectively. She considered that the surface of the Criccieth Till had been weathered during the Ipswichian Stage. The Criccieth Till was therefore taken to belong to the Saalian Stage, and the overlying Llanystumdwy Till, to the Late Devensian.

Saunders also noted the Criccieth Till and its badly weathered and frost-heaved surface, overlain by a gravelly upper till. He presented detailed pebble lithology and till fabric measurements to demonstrate that both tills were of Welsh origin, having been deposited by ice moving ENE to WSW, from the Vale of Ffestiniog. The close correspondence between till fabrics in both horizons was taken to indicate that the direction of ice movement had been substantially similar during both ice advances. It is, however, possible that the most recent of the ice movements caused a marked reorientation of pebbles in the lower till, and that this overprinting masks any original clast fabric patterns.

On the basis of a model developed from lithostratigraphical evidence elsewhere in Llŷn and supported by radiocarbon determinations, Saunders argued that the Criccieth Till had been deposited during the main invasion of the Late Devensian Welsh ice-sheet, and he correlated it with the lower, Irish Sea till of the north Llŷn coast and at Porth Neigwl (the Trevor Till). He suggested that the upper gravelly till at Morannedd had been deposited by a subsequent advance of Late Devensian Welsh ice, and that it could be correlated with the upper till of the north Llŷn coast (the Clynnog Till). Saunders believed that the frost-cracked and weathered surface of the lower till at Morannedd was critical to the interpretation of the sequence. He argued that it indicated a clear hiatus between deposition of the tills, reinforcing his argument that they were the product of two separate ice advances which crossed southern Llŷn during the Late Devensian.

Whittow and Ball (1970) accepted Saunders interpretation of the sequence at Morannedd and considered that the blue-grey till was the product of the first of the inferred glacial advances in Llŷn, and followed Simpkins' (1968) terminology and called it the Criccieth Till. They also noted tectonic structures in its upper layers which could have formed as slump structures during a phase of weathering or as drag features from an overriding ice mass. Whittow and Ball suggested that the upper Llanystumdwy Till (Simpkins 1968), represented a subsequent advance of Welsh ice. A final phase of periglacial conditions was interpreted from the cryoturbated shale head which capped the sequence.

In 1970, Synge likewise distinguished two tills at Morannedd, although he argued that there was no hiatus between deposition of the two. He suggested that the lower till had been deposited by Welsh ice moving in a slightly different direction to that which deposited the upper. The weathering horizon judged by Saunders and Whittow and Ball to have formed during interstadial conditions, and by Synge (1964) and Simpkins during fully interglacial conditions, was reinterpreted by Synge (1970) as an iron-pan effect, and the fossil ice-wedge casts as load structures.

The debate on the exposures at Morannedd is typical of many of the problems in interpreting Late Pleistocene successions in the region (Campbell 1985a). Two features make the site significant. First, Morannedd can be regarded as a reference site for the Criccieth and Llanystumdwy Tills of southern Llŷn. These glacigenic sediments provide evidence that southern Llŷn was glaciated by Welsh ice, probably on two occasions. The strongly preferred ENE to WSW trend of clasts in the Llanystumdwy Till shows that western Llŷn was free from Irish Sea ice during the second of these proposed glacial advances, which otherwise would have impeded and deflected the Welsh ice to a different course.

Second, the fine development of weathering and frost-crack features on the surface of the Criccieth Till provides evidence for a time separation between deposition of the Criccieth and Llanystumdwy Tills. This evidence, however, has proved controversial. Synge and Mitchell argued that the deep weathering at Morannedd and elsewhere in southern Llŷn indicated that only the northern coastal fringe of Llŷn was glaciated during the Late Devensian. They considered that drifts south of their reconstructed Late Devensian maximum limit, therefore, dated from the Saalian Stage and that they had been deeply weathered during the Ipswichian.

Whereas Boulton (1977a, 1977b) interpreted a similar sequence from Glanllynnau in southern Llŷn as the result of a single Late Devensian glacial episode, and suggested that the weathering horizon there did not represent a significant break in sedimentation, the evidence from Morannedd has been continually used as support for there having been two ice advances during the Late Devensian. Bowen (1973a, 1973b, 1974, 1977b) considered that the fine development of the weathering horizon and the fossil ice-wedge casts at Morannedd was evidence for an interval between deposition of the Criccieth and the Llanystumdwy Tills.

Morannedd provides evidence for the glacial history of southern Llŷn. The sections are among the finest in the region through tills of local Welsh provenance. The site can be regarded as a reference site for the Criccieth and Llanystumdwy Tills. The status of the weathering horizon between these tills is critical to the interpretation of the sequence, but has proved controversial. The development of the weathered and frost-cracked surface of the Criccieth Till here could provide evidence for a time interval between the deposition of the Criccieth and Llanystumdwy Tills.

Conclusions

Morannedd is the type site for the main glacial deposits of the southern Llŷn peninsula. It is a reference site for the Criccieth and Llanystumdwy Tills (boulder clays). Between the two tills is a horizon of weathering. Its exact significance is still unknown but it continues to figure prominently in debates about the glacial history of North Wales.