



Contents lists available at ScienceDirect

Proceedings of the Geologists' Association

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

The Late Quaternary sediment successions of Llangorse Lake, south Wales

A.P. Palmer^{a,*}, I.P. Matthews^a, A. MacLeod^b, A. Abrook^a, K. Akkerman^c, S.P.M. Blockley^a, I. Candy^a, C. Francis^a, W.Z. Hoek^d, F. Kingston^a, D. Maas^e, S.R. El-Hady^f, R. Gulliford^a, P. Lincoln^a, M. Perez-Fernandez^a, R.A. Staff^g

^a Centre for Quaternary Research, Department of Geography, Royal Holloway, University of London, Egham, Surrey TW20 0EX, UK

^b Department of Geography, University of Reading, Whiteknights Campus, Reading RG6 6AB, UK

^c Department of Geography, Loughborough University, Loughborough LE11 3TU, UK

^d Faculty of Geosciences, Princetonlaan 8a, 3584 CB Utrecht, the Netherlands

^e German Research Centre for Geosciences, Geomorphology, Telegrafenberg, Building F, Room 457, 14473 Potsdam, Germany

^f Flat 24, Viscount Point, 199, The Broadway, London SW19 1NL, UK

^g Scottish Universities Environmental Research Centre, Rankine Avenue, East Kilbride G75 0QF, UK

ARTICLE INFO

Article history:

Received 24 August 2020

Received in revised form 20 January 2021

Accepted 21 January 2021

Available online 18 April 2021

Keywords:

Last Glacial-Interglacial Transition

Lithostratigraphy

Llangorse Lake, south Wales

ABSTRACT

The last British-Irish Ice Sheet (BIIS) created a landscape with many sedimentary basins that preserve archives of paleoenvironmental and paleoclimatic change during the Last Glacial-Interglacial Transition (LGIT; ~18–8 ka BP). The typical lithostratigraphic succession of these archives is composed of minerogenic/allogenic sediments formed during cold climatic conditions and organic-rich/authigenic sediments during warmer climates. This paper presents a multi-core lithostratigraphy compiled from the extant lake and surrounding basin at Llangorse Lake, south Wales, a basin lying within the southernmost limits of the last BIIS. This lake contains one of the longest continuous terrestrial sediment successions in the UK. Uncertainty previously existed concerning the presence and distribution of sediments at the site related to the Windermere Interstadial (~14.7 to ~12.9 ka BP) and Loch Lomond Stadial (~12.9 to 11.7 ka BP). A new borehole survey demonstrates that LGIT-age sediments are present at the site with nekron mud (gyttja), corresponding to the Lateglacial Interstadial, deposited in the deeper part of the lake waters and that these deposits are equivalent in age to marl deposits found at shallower depths at the margins of the basin. These deposits are associated with warmer conditions experienced during the Windermere Interstadial and Holocene, whilst minerogenic-rich sediments were deposited during the colder climatic conditions of the Dimlington Stadial and the Loch Lomond Stadial with rangefinder radiocarbon dates confirming this attribution. A model of lake level changes shows that drainage of the Dimlington Stadial glacial lake caused the largest fall, but there was also a further, smaller lake level fall at the end of the Windermere Interstadial and/or the start of the Loch Lomond Stadial, before the level rose in the early Holocene. The lithostratigraphic results presented here form the framework for further paleoenvironmental and paleoclimatic research at Llangorse Lake.

© 2021 The Geologists' Association. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The Last Glacial Interglacial Transition (LGIT; ~18–8 ka BP; Rasmussen et al., 2014) was an interval of paleoenvironmental change characterised by abrupt shifts in ecology and landscape that occurred over millennial and centennial timescales and influenced the entire British Isles (Walker and Lowe, 2017). Evidence for these changes exists in terrestrial lacustrine systems with a wide spatial coverage suggesting that climate was a key driver in forcing these changes (Marshall et al., 2002; Brooks et al., 2012, 2016; Whittington et al., 2015). LGIT lake sequences themselves are generally characterised by tripartite

sediment successions with minerogenic-rich, allogenic sediment commonly associated with the cold climatic conditions of the Dimlington Stadial (broadly equivalent to GS-2; ~31.0 to 15 ka BP; Rasmussen et al., 2014) and Loch Lomond Stadial (broadly equivalent GS-1; ~12.9 to 11.7 ka BP; Rasmussen et al., 2014), whilst warmer conditions were characterised by increased authigenic productivity and organic and carbonate-rich sediment deposition during the intervening Windermere Interstadial (broadly equivalent to GI-1; ~14.7 to 12.9 ka BP; Rasmussen et al., 2014). After 11.7 ka BP there was a return to increased authigenic sedimentation associated with the onset of the warmer conditions of the Holocene. The lithological evidence of these climatic oscillations is supported by biological and geochemical proxies for climate that provide estimates of paleotemperature, such as stable isotope analysis and chironomid-

* Corresponding author.

E-mail address: a.palmer@rhul.ac.uk (A.P. Palmer).

inferred mean July temperature reconstructions (van Asch et al., 2012; Palmer et al., 2015; Candy et al., 2016) that validate interpretations of lithological responses to climate forcing.

In northern hemisphere mid-latitudes, evidence for a terrestrial environmental response to these climatic changes is often complicated by a number of factors including the spatial distribution of sites sampled and the inconsistent application of methods able to constrain both the responses and timings of key climatic and environmental transitions. For example, there is an inconsistent spatial coverage of LGIT-age records over the British Isles, which is partly driven by the landscape inherited after retreat of the last British-Irish Ice Sheet (BIIS; Walker and Lowe, 2017). Within the BIIS limit, major landscape change occurred including disrupted drainage networks favouring the formation of topographic lows across the landscape (Palmer et al., 2015) that after deglaciation became lake basins which acted as sediment sinks. These sedimentary basins are concentrated across the northern and western margins of the British Isles, whereas there are relatively few, long, well-preserved LGIT sequences found in southern Britain, where the drainage network was unaffected by the most recent glaciation (Clark et al., 2012). This tends to skew the record to sites found in northern Britain (Walker and Lowe, 2017) and prevents the assessment of gradients of environmental change across the British Isles. The spatial disparity in preservation of archives also hinders the placement of paleoenvironmental changes or human activities into their broader paleoclimatic context. For example, there is a tendency to compare archaeological records with the more distant Greenland

ice-core records rather than to local proxy records with independent chronologies (e.g., Jacobi and Higham, 2009). There is, therefore, a pressing need for high-quality paleoclimate reconstructions from southern Britain.

On the British mainland, the most southerly, terrestrially glaciated margins of the BIIS where LGIT lake sequences have been identified are in south Wales (Walker, 1982a, 1982b; Walker and Harkness, 1990; Walker et al., 2003). Whilst the biostratigraphic and lithostratigraphic data at sites in south Wales have provided critical information on past environmental changes that broadly correspond with the wider British pattern, the chronological models for the timing of these changes are less reliable. For example, at Llanilid, the accuracy and precision of these age models are questionable with mineral carbon, humic acid percolation and plant macrofossil reworking all identified as possible mechanisms for undermining the chronological model for the site (Walker et al., 2003), allied to the loss of the site for re-sampling due to quarrying. Other locations (e.g., Craig y Fro, Craig Cerrig-gleisiad, Traeth Mawr; Fig. 1) have low numbers of bulk sediment ¹⁴C dates that have potential issues with mineral carbon errors and require further testing (Lowe and Walker, 2000). Consequently, it is difficult to date and chronologically constrain the stratigraphy of the LGIT in this region and to provide precise and accurate age estimates for the rates of key environmental transitions.

In south Wales, Llangorse Lake (Llyn Syfaddan; Figs. 1 and 2) has excellent potential for providing a high-resolution record of Late Quaternary paleoenvironments. Chambers (1999) reviewed the

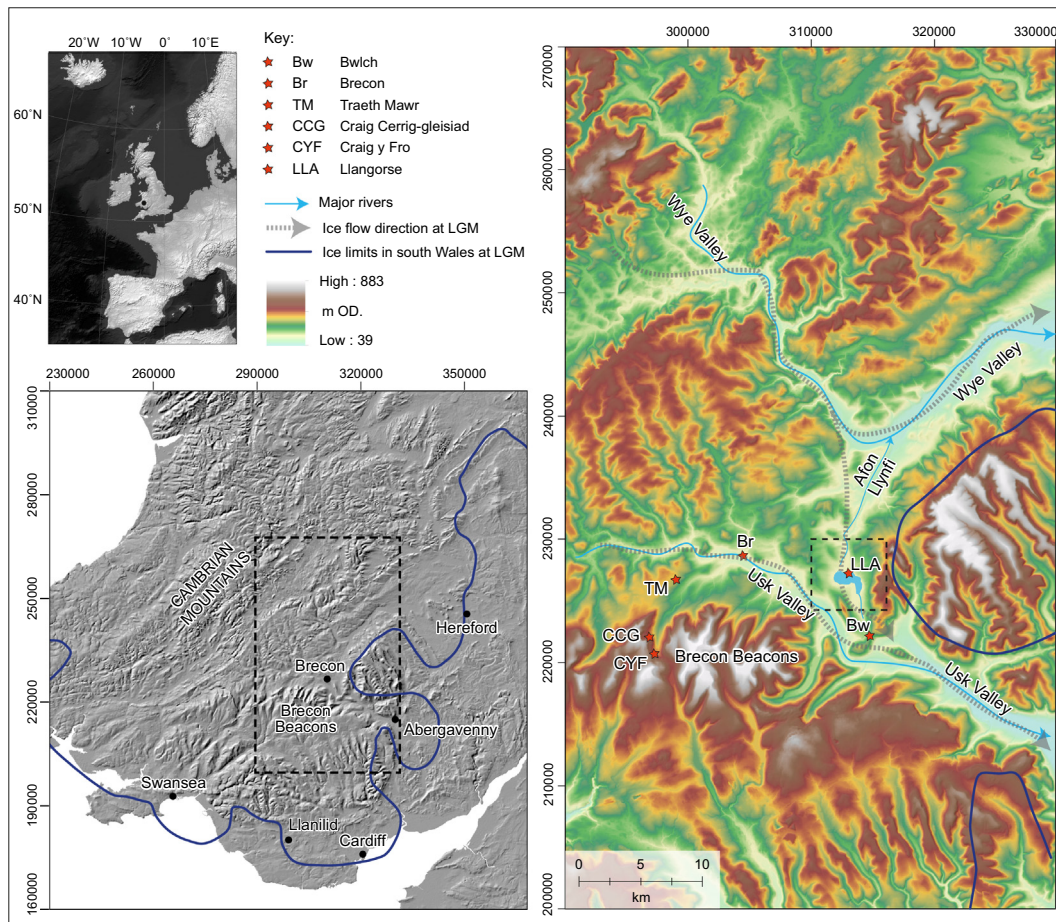


Fig. 1. Location of Llangorse Lake, Wales. The site lies within the eastern limits of the Last Glacial Maximum ice sheet (Clark et al., 2004, Chiverrell and Thomas, 2010). Ice sourced from the central part of the Brecon Beacons flowed down the Usk valley and merged with ice sourced from the Cambrian Mountains of mid-Wales and along the Wye valley to reach its maximum extent in the Abergavenny region. During retreat, Llangorse basin emerged from ice cover when Usk and Wye ice separated near Bwlch (Lewis, 1970). Other local Late Quaternary archives are highlighted. The basemap uses OS Terrain 5 DTM data available and downloaded from digimap.edina.ac.uk © Crown Copyright and database rights (2017) Ordnance Survey (100025252). Grid references are OSGB except for top left that uses UTM.

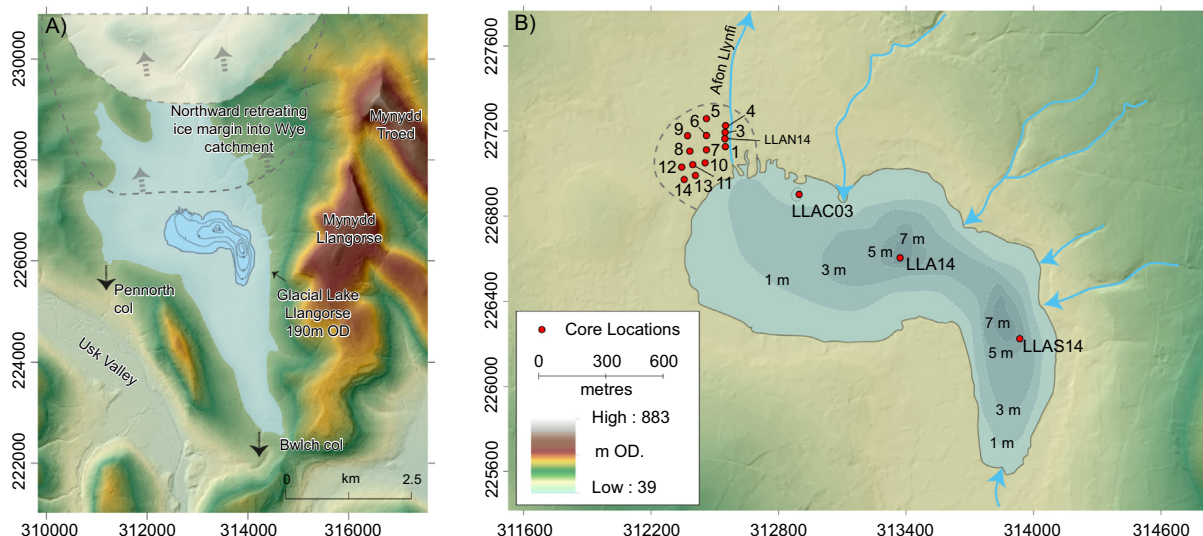


Fig. 2. Local detail of the Llangorse Lake basin. A) Evolution of Glacial Lake Llangorse (adapted from Lewis, 1970) as the Wye valley ice retreated northward. B) Bathymetry of the lake displaying two basins in the central and southern parts of the current basin (updated after Jones et al., 1985). Locations of boreholes used in this study are identified by red circles with the densest cluster of boreholes within the dashed area referred to in the text as the ‘northern basin’. LLAS14 is located close to the LL1980 core of Jones et al. (1985). The multiple stream inflows to the lake are highlighted with a single outflow northward along the Afon Llynfi. The basemap for A) and B) uses OS Terrain 5 DTM data available and downloaded from digimap.edina.ac.uk © Crown Copyright and database rights (2017) Ordnance Survey (100025252). Grid references are OSGB.

research undertaken at Llangorse, identifying knowledge gaps that exist owing to the uncertainty in the distribution of the LGIT sediments within the basin. Since 2014, research has focused on a basin-wide survey of the sediment infill of the basin(s). We present new sedimentological evidence for a revised lithostratigraphy that helps to constrain the timing of changes during the Late Glacial and relate these findings to changes in lake-water level during the LGIT. This work includes a comprehensive borehole survey of sequences from the margins of the extant lake, and links this to new core material recovered from similar locations to Jones et al. (1978, 1985) within Llangorse Lake, and the crannóg core studied in detail by Walker et al. (1993) and Palmer et al. (2008) (the crannóg here is an island constructed within the lake during the early Medieval). All core material examined is supplemented by new targeted laboratory analyses to confirm lithological correlation and subsequently corroborated by rangefinder radiocarbon dates. Finally, this paper provides the lithostratigraphic framework for ongoing work and forthcoming publications that will provide more detail on the paleoclimatic and paleoenvironmental archives present in Llangorse Lake from the LGIT.

2. Site context

Lake Llangorse, situated 8 km to the east of Brecon, lies at the head of the Afon Llynfi catchment (Fig. 1). The present-day lake surface is at 153 m OD and the lake is drained by a northward-flowing, south-bank tributary stream of the River Wye. The watershed shared with the eastward-flowing Usk system lies ~3 km to the south of the lake, marked by low cols with abandoned channels at 190 m OD in the vicinity of Bwlch and Pennorth (Figs. 1 and 2a). On its eastern margins the ground rises steeply to Mynydd Llangorse which reaches 515 m, whilst to the south-west a low ridge reaches 391 m OD. The main bedrock geology within the catchment is Devonian Old Red Sandstone (St Maughans and Senni Formation: Howells, 2007), which outcrops above the 200 m contour, with Devensian glacial sediments exposed at the surface below this contour around the immediate margins of the lake. The bathymetry of the current lake is shallow and irregular with two deeper basins reaching a maximum depth of ~7 m (Jones et al., 1985). These basins are separated by a shallow sill, at a depth of 4 m

below the water surface, and probably linked to a peninsula that extends into the lake from the south-west (Fig. 2b).

Previous investigations provide a broad understanding of events at Llangorse during the LGIT. The area was most recently shaped by the advance of ice-sheet lobes during the Last Glacial Maximum. Whilst there remains debate concerning the nature and extent of glaciation during this period (cf., Lewis, 1970; Lewis and Thomas, 2005; Jansson and Glasser, 2008; Shakesby and Matthews, 2009), it is likely that ice sourced from the Brecon Beacons advanced eastwards down the Usk valley and merged with ice from mid-Wales to reach its maximum in the Abergavenny area, forming part of the south eastern sector of the Welsh Ice Cap (Jansson and Glasser, 2008). Modelling experiments reconstruct the initiation of ice retreat to ~23.55 ka BP (Patton et al., 2013) with empirical field evidence suggesting a series of stillstands in the Usk valley during that retreat (Lewis, 1970; Thomas and Humpage, 2007). Around Bwlch, this ice is thought to have separated into two valley glacier lobes: one within the Usk valley and the other within the catchment of the Wye (Lewis, 1970; Figs. 1 and 2a). The Wye catchment ice retreated northwards creating an ice-contact glaciolacustrine system with a water level at 190 m OD that was controlled by the cols at Bwlch and Pennorth (Lewis, 1970; Fig. 2a). Palmer et al. (2008), using glaciolacustrine varve microfacies analysis, suggested that the glaciolacustrine system evolved from an ice-contact lake into a distal glaciolacustrine lake fed by nival streams within 75 years of the system's inception, the lake continuing in this form for a minimum of 440 years.

Paleoenvironmental work at the site has focused on Holocene vegetation history (Jones et al., 1978, 1985; Chambers, 1999; Walker et al., 1993). Initially, Jones et al. (1978) extracted two cores from the two basins in the extant lake, whilst a longer, 12.35 m core (LL1980) was extracted from the eastern basin by Jones et al. (1985; Fig. 2b). This later core revealed three bands of marl within laminated clay in the lower ~4 m overlain by 4 m of organic sediments (nekron mud or gytja). The upper ~4 m of sediment was characterised by an increase in minerogenic material to form a silty clay with some organic material. Radiocarbon dating has been confined to samples taken from the upper nekron mud demonstrating deposition during the Holocene. Palynological evidence suggests that increased sedimentation rates began after the elm decline (~6.3–5.2 cal ka BP; Parker et al., 2002) and accelerated during the past 1800 years due to increasing human

impact in the catchment causing soil erosion and increased minerogenic input to the lake (Jones et al., 1985).

Walker et al. (1993) outlined a more detailed picture of the early Holocene from a core sequence extracted (here renamed LLAC03) from the crannóg (Fig. 2b), located close to the north-western lake shore. A combined palynological, malacological and ostracod study (Walker et al., 1993) demonstrated that, during the first 2000 years of the Holocene, there was a rapid expansion of tree species in the local area. Evidence also exists for small changes in lake level in the early Holocene with further signs of a short-lived climatic event within the early Holocene, inferred from a decline and then recovery in *Juniperus* due to its sensitivity to variations in thermal and environmental conditions.

This previous work provides a detailed understanding of the Late Quaternary history of Llangorse basin, specifically during the Holocene. However, a research gap evident from these studies is the lack of an extensive survey of the basin's sediments. The crannóg core used by Walker et al. (1993) and Palmer et al. (2008) lacks a clear Lateglacial Interstadial and Stadial complex and yet sediments representing these interludes were reported by Jones et al. (1985) and Chambers (1999) within the deeper parts of the extant lake, albeit with limited multi-proxy or chronological data to substantiate their ages. The present study combines new lithostratigraphic evidence from within the lake and at its margins with the information generated by these previous studies.

3. Methods

The new material presented in this study has been collected over several field campaigns carried out between 2014 and 2018. The core survey can be divided into two areas: 1) the deeper lake cores of Llangorse South 14 (LLAS14), Llangorse 14 (LLA14) and previously described Llangorse crannóg (LLAC03); and 2) the area to the north of the lake and west of the Afon Llynfi (LLAN 14 and other boreholes; Fig. 2b). The bathymetry of the extant Llangorse Lake was reassessed to locate its deepest parts, in order to extract two cores that replicated the work of Jones et al. (1978, 1985, Fig. 2b) in the two basins of the extant lake. This was achieved using a Garmin handheld GPS and portable UWITEC sonar. A UWITEC coring platform was used to extract the two parallel and partly overlapping core sequences (A and B) at both sites LLA14 and LLAS14 to a depth of 19.9 and 19.0 m respectively. Recovered cores were 75 mm in diameter and, when extracted, were in 3 m lengths, which were subsequently cut into 1 m lengths for transport and storage.

In the now infilled northern basin, cores were extracted from the ground surface using 0.5-m and 1-m long Russian corers with diameters of 50, 75 and 100 mm. The wider diameters were used to target particular parts of the succession in order to extract sufficient terrestrial plant macrofossil material for radiocarbon dating. At all sites in the northern basin, the upper soil horizon was first removed using a screw or bucket auger. LLAC03, the Llangorse crannóg sequence, was extracted using a 1-m long and 50-mm diameter Russian corer and an Eijkelkamp Stitz piston corer. All core material was stored at 4 °C. During the coring campaign in 2014, a temporary benchmark was established on the bridge over the Afon Llynfi to the north of the lake. This enabled establishment of the surface altitude of the cores extracted from the field to the north-west of the crannóg and the altitude of key lithological units below the ground surface and also the lake floor sediments. All measurements were made using a TopCon Total Station GTS463.

Standard lithological descriptions were applied to all core sediment in both the field and the laboratory. For specific cores, LLAN 14, LLA14 and LLAS14, further analyses under laboratory conditions were made. Nekron mud was used to describe the organic-rich lake sediments from the extant lake by Jones et al. (1978, 1985). Here we use the same term although it is common for the term, gyttja, also to be used to describe similar sediments. Calcium carbonate and organic content

measurements were undertaken for the first time on LLAN14 and LLAC03 and the new core material from LLA14 and LLAS14. Calcium carbonate (%) determinations were made using the Bascomb calcimeter method (Avery and Bascomb, 1982), and organic content (%; TOC) was calculated using either the Walkley-Black methodology (Schumacher, 2002) or loss-on-ignition methods. For radiocarbon dating, LLAN14 core material was sampled at 1 cm intervals to extract terrestrial plant macrofossils to reduce the impact of mineral carbon and hard-water error. LLAN14 sediment was sieved with a 250 µm mesh using deionised water and plant macrofossil material identified using Motec low-powered, stereo-zoom microscopes. Adjacent 1 cm samples were combined where necessary to produce sufficient material for a viable radiocarbon determination. Samples were processed at the Scottish Universities Environmental Research Centre (SUERC) following a standard acid-base-acid (ABA) pre-treatment protocol (1 M HCl at 80 °C for 30 min; 0.2 M KOH at 80 °C for 20 min; and 1 M HCl at 80 °C for 1 h; with each stage followed by thorough rinsing with ultrapure water), and subsequent accelerator mass spectrometry (AMS) measurement performed at both the SUERC and University of California, Irvine (UCI) AMS facilities.

4. Results

Six lithofacies units are identified (Fig. 3; Table 1), varying in altitude across the basin (Fig. 4; Tables 2 and 3). Here we separate the whole basin into cores extracted from within the limits of the extant lake and those recovered from the northern basin adjacent to the current lake margins. Quantitative data from three cores are provided as depth functions (Fig. 5). The following section summarises the distribution of the lithofacies (LF) in the two main areas of the Llangorse basin.

4.1. Extant Lake: LLA14, LLAS14 and LLAC03

Core LLA14 has 6 m of laminated silts and clays (LF 2a and 2b; Fig. 3k, l) at its base. There is a sharp transition to a thin, 0.26 m bed of olive-coloured, calcareous nekron mud (LF 4a; Fig. 3h), which contains a small amount of CaCO₃ (~10–20%) also recorded in the overlapping core. This is then overlain through a sharp contact by massive and thin laminations of silty clay (LF 2c; Fig. 3f, g) which contain a marl intraclast at 140.10 m OD (Fig. 3f). There is a sharp contact with the overlying dark brown or black nekron mud (LF 4a; Fig. 3c, d) becoming a red brown silty clay (Fig. 3b) toward the top of the unit suggesting an increased mineral content (Fig. 3b). The top of the core is at 144.60 m OD, 7.7 m below the current lake water level.

LLAS14 has laminated silts and clays (LF 2a; Fig. 3j, k, l) at the base which are 2.8 m thick and have a sharp contact with the overlying calcareous olive-coloured nekron mud (0.2 m thick; LF 4a; Fig. 3h) between 136.8 and 140 m OD. Organic content rises to between 15 and 20% and CaCO₃ peaks at 30%. This unit is overlain by massive and faintly laminated silts and clay (LF 2c; Fig. 3g) which is 1.83 m thick, with low organic and carbonate content. There is a sharp contact with olive green nekron mud at 138.83 m OD with organic content of between 40 and 60% with a low carbonate content (LF 4a; Fig. 3c, d). Within this olive green nekron mud, there are three thin beds with small increases in carbonate values recorded (>5%) associated with a reddish silty clay (Fig. 3d; Table 3). LF 4a changes to red brown silty clay at 142.65 m OD until the top of the core. The top of the core is at 145.60 m OD, which is 6.6 m below the current water level.

Core LLAC03, which is 8 m in length, was reported in Palmer et al. (2008) and has a diamicton (LF 1) at the base overlain by 4.2 m of fine laminations of silt and clay (LF 2a and 2b, Fig. 3g–i). There is a diffuse contact composed of either laminated or massive silts and clay interbedded with fine laminations of marl (LF 3a; Fig. 3k–l) before transitioning upwards into a predominantly marl deposit (LF 3b; Fig. 3l) that is present until the ground surface. New data show that the



Fig. 3. Examples of lithofacies present in LLA14, LLAS14 and LLAN14. White arrows highlight specific sedimentological features referred to in the labels. The oldest sediments are presented in the bottom right and become progressively younger toward the top left. All images are oriented with base to the right and top to the left with the tape measure used as a scale. There is some down-core drag at the margins of the cores evident in the photographs of LLA14 and LLAS14.

Table 1
Lithofacies units from the sediments recorded in the cores recovered from Llangorse basin and interpretation of the sedimentary environment.

Litho-facies	Code ^a	Sediment characteristics	Interpretation	Ref.	Observed in:
LF 4c	Peat	Well to moderately humified peat, sometimes with large wood fragments.	Fen and carr woodland peat developing as the basin infills.	Cloutman, 1988; Cloutman and Smith, 1988; Taylor, 2011.	LLAN14. Where observed also all cores in northern basin
LF 4b	Silty clay	Red brown silty clay with organic content values of 10–20% and CaCO ₃ of 1–10% (Jones et al., 1985)	High authigenic productivity with increased mineral content in a lake. Higher mineral inwash to the basin with increased sedimentation rates due to land use change in the catchment.	Jones et al., 1978, 1985.	LLA14; LLAS14.
LF 4a	Nekron mud (gyttja)	Black, brown or olive-green mud with rare plant macrofossil material that occurs as 1) a thin lower calcareous nekron mud bed; and 2) as a thicker unit (~4 m) in the upper part of the sequence. TOC values mainly of 20–50% with a peak of 60%. Three mineral-rich beds with peak CaCO ₃ values of 20% with marl pebbles and capped by a thick lamination of red silty clay occur in the lower part of the nekron mud, which is also calcareous in the lower 20–25 cm thick bed.	High authigenic biological productivity lake sedimentation. Develops in deeper lake waters. In the lower unit there is higher CaCO ₃ content, probably related to marl productivity. In the upper unit there are discrete events of allochthonous mineral material being transported to the lake basin suggesting instability of the land surface or high energy events entering the basin.	Jones et al., 1978, 1985.	LLA14; LLAS14.
LF 3b	Marl	Marl units that predominantly have CaCO ₃ values of 60–80% and TOC values of 2.5–15%. LLAN14 lower marl unit has lower TOC and larger shell fragments compared with upper marl unit. <i>Chara</i> oospores visible throughout the marl units. Evidence of increased mineral inwash in the upper marl unit in LLAC03 and low marl deposition in LLAN14.	Marl sedimentation. High biological productivity around shallow lake margins reduces CO ₂ in lake waters and increasing pH of waters. This enables the precipitation of CaCO ₃ within the lake. Lake water may also contribute to this process.	Pentecost, 2009; Whittington et al., 2015; Palmer et al., 2015; Candy et al., 2015, 2016	LLAN14; all cores in northern basin
LF 3a	Fl, Sl, Marl	Thick laminations of massive silty clay similar to LFA 2a/2b, but contains very thin laminae of marl. CaCO ₃ values 0–25% and TOC values 1–25%	Low energy lake sedimentation. Allochthonous sediment supply (silty clay) dominates but evidence for increased authigenic input as biological activity in the shallower parts of lake increases producing occasional marl laminae.	Palmer et al., 2015.	LLAN14; all cores in northern basin
LF 2c	Fm, Fl, Sm(d)	Massive silty very fine sand/silt and laminated silty clay although the laminations are poorly defined in shallower cores. Deeper cores (LLAS14 and LLA14) contain isolated sand and gravel sized soft sediment intraclasts of marl, which, in LLAS14, is associated with a thick coarse sand bed with convoluted silty clay pods. CaCO ₃ values <1% (unless intraclasts present) and TOC values <1%.	Low energy lake sedimentation. Allochthonous sediment supply to the basin with no separation in flow in shallower parts of the basin but laminations in deeper waters indicate settling through the water column. Erosion of marl as intraclasts in shallower waters suggests lake waters have fallen and transported over short distances to the lake floor.	Ashley, 1975; Palmer et al., 2015	All cores
LF 2b	Flv, Fl, Sg(u)	Alternating layers of silt and clay with combined thickness of <1 cm and normally <0.5 cm. In places structures are too fine to observe at the macroscale, but lamination is observed at the sub-mm scale in thin section. Sharp contact between silt/clay and clay/silt layers. Multiple laminations observed in the silt component and occasional dropgrains of coarse sand. Thick graded sand beds (up to 1 cm thick) also present.	Ultradistal/nival melt glaciolacustrine varve sediments (LSA 5) with sediment sourced from the immediate lake catchment and supplied by streams rather than directly from a glacier. Occasional flood events recorded in the sequence as graded sand beds.	Palmer et al., 2008, 2019	All cores
LF 2a	Flv, Fl, Sl, Sm	Alternating layers of silt and clay with combined thickness of >1 cm. Sharp contact between silt/clay and clay/silt layers. Multiple laminations observed in the silt laminations and occasional dropgrains of coarse sand. Thick graded sand beds (up to 10 cm thick) are also present.	Distal glaciolacustrine varve sediments (ice-contact lake system – LSA 1) with surge-type deposits, sand beds, representing stochastic high energy flow events from the glacier meltwater channels.	Palmer et al., 2008, 2019	LLAC03; LLA14; LLAS14.
LF 1	Dmm	Silty sand diamict, massive, matrix-supported with pebble-sized subangular and subrounded clasts of Old Red Sandstone and vein quartz.	Proximal subaqueous fan deposits in a glacial lake or subglacial till.	Bennett et al., 2002; Mulder and Alexander, 2001; Evans et al., 2006.	LLAC03;

^a cf. lithofacies codes of Evans and Benn (2004).

upper marl CaCO₃% values rise rapidly from 0 to 70–80% and are maintained at this high level throughout the remainder of the core, whilst total organic content rises to 2.5–5%. The core spans 145–153 m OD with the lithological change between the LFs 2 and 3 occurring at 150.37 m OD.

The cores from the lake show variability in sediment distribution and composition. The LLAC03 sequence differs from the other two cores (LLA14 and LLAS14) in being at a higher altitude and resting on diamict and has a simpler stratigraphy of laminated silts and clays that transition through a mixed horizon into marl. In addition, the stratigraphies in the latter two cores differ from that of LLAC03 with the inclusion of a thin calcareous nekron mud. Finally, it is important

to note that the depth of the basin reduces from ~6–9 m to 4 m between LLA 14 and LLAS14 (Fig. 2b), although the sediments that compose this topographic high have not been sampled to date.

4.2. The northern basin including LLAN14

Fourteen boreholes were sunk in the area surrounding the northern basin. The shallowest borehole depth (2.30 m) was reached at the western end of the basin (Fig. 2b). The deepest borehole is LLAN14 at 7.49 m in the eastern end of the basin close to the Afon Llynfi (Fig. 2b) and appears to have the most complete record with six lithological units. From 145.91 m OD m to 147.0 m OD there are very fine laminated

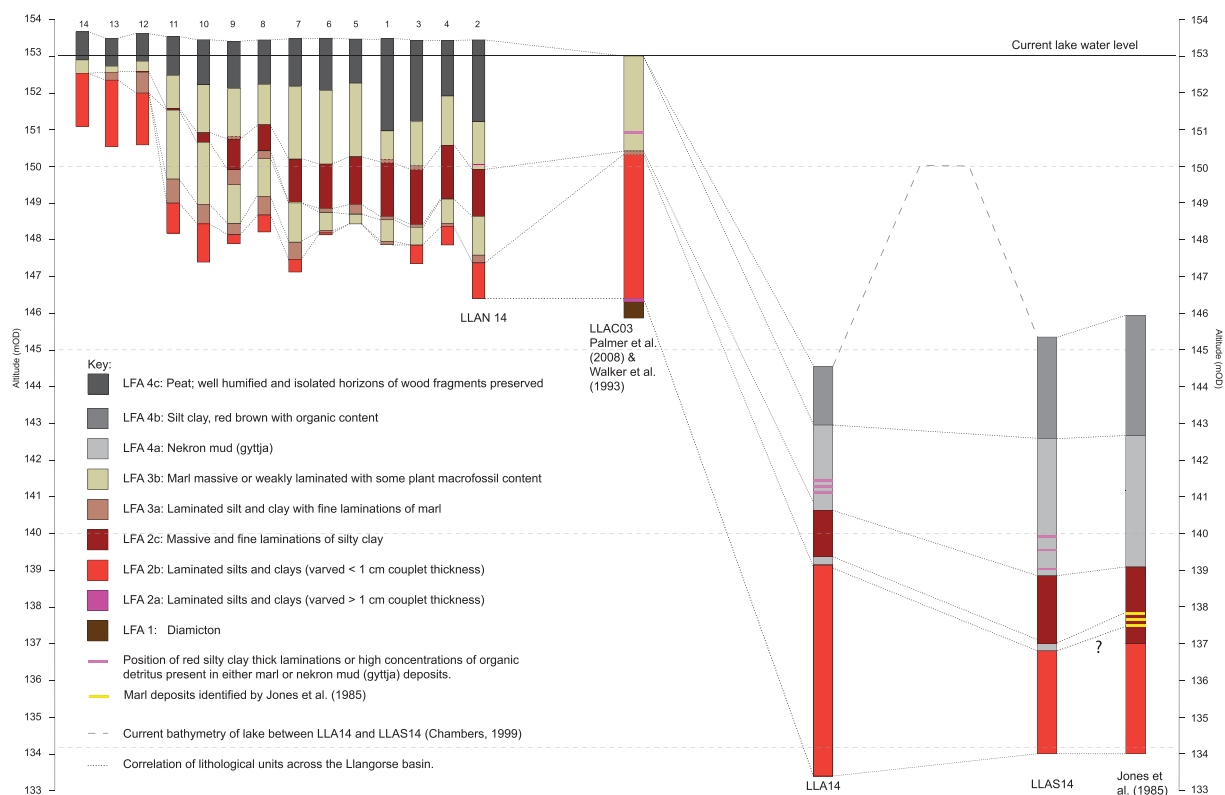


Fig. 4. Schematic cross-section of the borehole records across Llangorse basin. All records are aligned to m OD (see also Tables 1 and 2). The bathymetry between LLAN14 and LLAS14 is inferred from Jones et al. (1985) and it is unclear how the units are distributed across this part of the basin.

silts and clays (LF 2b; Fig. 3g) with no CaCO₃ or organic carbon. This unit is overlain by laminated silt and clay with clearly defined, very fine laminations of marl (LF 3a; Fig. 3l) with 2–30% CaCO₃ between 147 m OD and 147.45 m OD. This changes into a marl (LF 3b; Fig. 3k, l) between 147.45 m OD and 148.54 m OD with CaCO₃ values rising to 70–85%. CaCO₃ content shows considerable change within a relatively small length of core. It falls below 70% between 148.0 and 148.1 m OD, rises above 80% at 148.3 m OD and then falls to zero at 148.54 m OD. The organic content of this unit follows a similar pattern of changes in CaCO₃ values but with considerably lower percentages of 0.5–4.5%. This unit is succeeded by a massive and faintly laminated silt and clay (LF 2c; Fig. 3d, e) which has three distinctive 1–2 cm thick clay laminations between 148.8 and 148.7 m OD. CaCO₃ rises to 10% at 149.8 m OD although the red silty clay is still present up to 149.95 m OD, where there is a graded contact with a marl-dominant unit (LF

3b; Fig. 3k) with a CaCO₃ content of up to ~80%. CaCO₃ values reach a maximum at 150.5 m OD and then fall below 80% at 151.15 m OD. At three intervals, 150.20–150.15, 150.59–152.51 and 150.93–150.72 m OD, CaCO₃ falls below ~70% and organic carbon increases, with fibrous plant macrofossil remains concentrated at the lowest of the three altitudes. From an altitude of 151.22 m OD to the top of the core there is a wood fen peat (LF 4b; Fig. 3j).

This succession is repeated in boreholes 1–11, although there is a variable thickness of the units in these cores; sediment description is based on appearance rather than on quantitative data for the individual units. Further to the west of Llangorse Lake (boreholes 12–14), the core stratigraphy is shallower with the length of cores ranging between ~2.30 and 2.90 m. The base of these cores often comprises sandy or pebble-sized gravels, which prevented further penetration with a hand corer. In these boreholes, the base of the sequence has a minimum

Table 2

Unit depths and thicknesses for LLAN14 and LLAC03. Cores were recovered from ground surface and core depth is distance below ground surface. Measurement is for the upper contact of the unit. LF 2c is a mineral-rich facies with similar properties to the LF 2 facies but is recorded as a higher point in the lithostratigraphy between the two marl units of LF 3.

LLAN14 Lithofacies	Core depth (m)	Thickness (m)	Altitude (m OD)	LLAC03 Lithofacies	Core depth (m)	Thickness (m)	Altitude (m OD)
LF 4c	0	2.18	153.4	LF 3a	0	2.63 ^b	153.00
LF 3a (Upper)	2.18	1.30 ^a	151.22	LF 3b	2.63	0.25	150.37
LF 2c	3.48	1.38	149.92	LF 2b	2.88	3.89	150.12
LF 3a (Lower)	4.86	1.09	148.54	LF 2a	6.77	0.57	146.23
LF 3b	5.95	0.45	147.45	LF 1	7.34	0.66	145.66
LF 2b	6.40	1.09	147.00	Base	8.00		145.00
Base	7.49		145.91				

^a High organic carbon % values and fall in CaCO₃% at 150.20 m OD.

^b CaCO₃ values fall and increased silty clay content at 150.72–150.93 m OD and 152.59–152.51 m OD.

Table 3

Core depth measurements for LLA14 and LLAS14. Cores were recovered from a coring platform and therefore core depth is calculated from the datum of the lake water level at the time of coring and then converted to m OD assuming the lake water level was 153 m OD. Core A depths have been reported here as these are the longest cores with the most complete recovery of material. LF 2c is a mineral-rich facies with similar properties to the LF 2a/b facies but is recorded as a higher point in the lithostratigraphy between the two marl units of LF 3. Each site's Core B sequence broadly corroborates the stratigraphy, although there are offsets between the unit depths between each core.

LLA14 Core A Lithofacies	Core depth (m)	Thickness (m)	Altitude (m OD)	LLAS14 Core A Lithofacies	Core depth (m)	Thickness (m)	Altitude (m OD)
LF 4b	8.40	1.85	144.60	LF 4b	7.40	2.95	145.60
LF 4a (Upper)	10.25	2.20 ^a	142.75	LF 4a (Upper)	10.35	3.82 ^c	142.65
LF 2c	12.45	1.25 ^b	140.55	LF 2c	14.17	1.83 ^d	138.83
LF 4a (Lower)	13.70	0.15	139.30	LF 4a (Lower)	16.0	0.20	137.0
LF 2b	13.85	6.05	139.15	LF 2b	16.2	2.8	136.8
Base	19.90		133.10	Base	19.0		134.0

^a Three mineral-rich beds exist at 140.90–140.95, 141.30–141.40 and 141.60–141.70 m OD.

^b marl intraclasts observed at 140.10 m OD.

^c Three mineral-rich beds present at 139.88–139.90, 139.50–139.60 and 139.05–139.10 m OD.

^d marl flecks and intraclasts in medium sand bed present between 137.60–137.10 m OD.

of 1 m of faintly laminated silts and clays or massive silts and clays (LF 2a; Fig. 3g, h, i). In boreholes 12 and 13, there is a gradual transition from LF 2a into laminated silt and clay with marl laminae or a mix of silty clay and marl (LF 3a; Fig. 3l), which is overlain by a thin unit of marl (LF 3b; Fig. 3k) and then wood fen peat (LF 4b, Fig. 3j). In borehole 14, the laminated silts and clays have a sharp contact with marl (LF 3b; Fig. 3k), above which is peat (LF 4b; Fig. 3j).

4.3. Distribution of the units within both basins (Fig. 4, Tables 2 and 3)

The diamicton, LF 1, is likely to be the true base of the lacustrine records and was only observed in LLAC03. The use of the hand-coring devices probably precluded full recovery of the lake sediment archive within the extant lake and its infilled northern margin. In all other boreholes (excluding BH5) the base of the sequence is represented by LF 2b, the finely laminated lake sediments. In the two deeper lake

cores, the base was reached at ~134 m OD and the top at ~139.5 m OD in LLA14. LF 2a was not identified in the core sediments from the northern basin but the lower contact of LF 2b was present in LLAC03 at ~146 m OD and the upper contact of LF 2b at LLAC03 is the highest at 150.12 m OD (Fig. 4) of any cores where this contact was recognised.

The presence of two marl units (upper and lower) in the northern basin has been identified for the first time (Fig. 4). At the lower contact of this unit, there is commonly a complex transition with minerogenic silts and clays intercalated with marl. If the presence of marl within the laminated silty clay (LF 3a) below the lower marl unit is included, then the lowermost contact in this area is at 147.3 m OD (in borehole 7). This unit is not present in LLAC03 or boreholes 12, 13 and 14. A nekron mud is present in the deeper cores of LLA14 and LLAS14 with the upper contact for LF 4a at 139.30 and 137 m OD, respectively. In these two cores, LF 4a merges with LF 2c with a height for the upper contact of LF 2c at 140.55 m OD (LLA14) and 138.83 m OD (LLAS14).

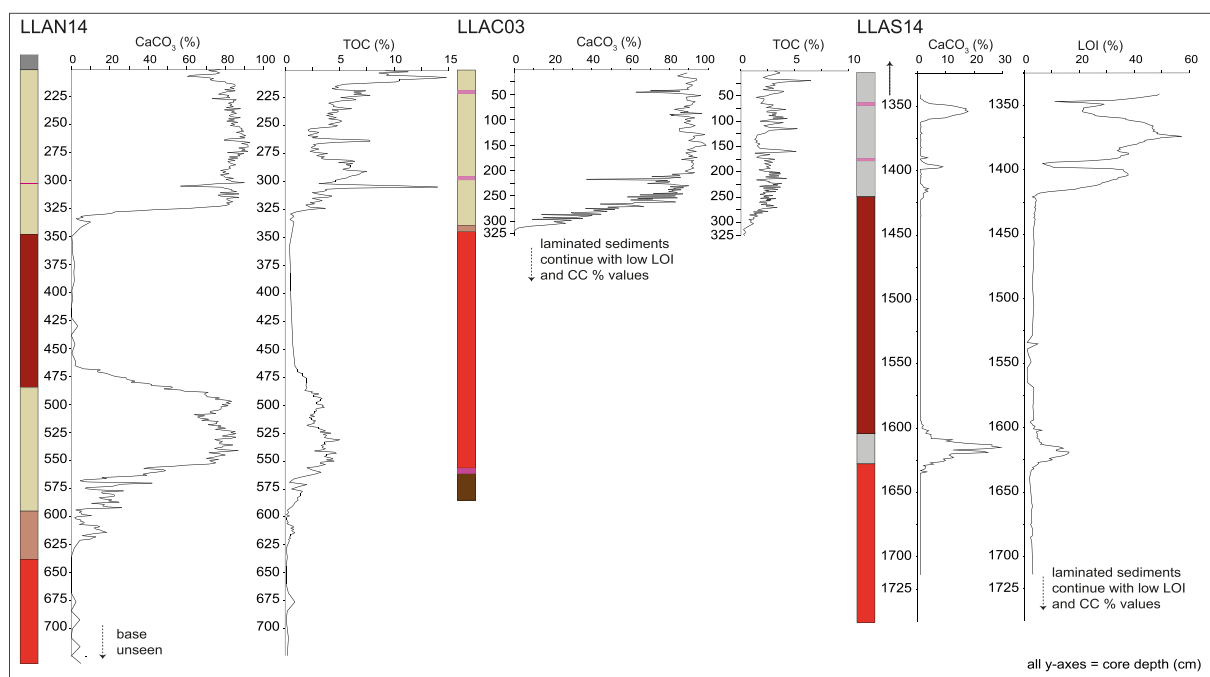


Fig. 5. Schematic logs of LLA14, LLAC03 and LLAS14 including CaCO₃% and TOC% trends in each core. The colours used in the logs are the same as in Fig. 4. LLAC03 only has CaCO₃% and TOC% values for the upper marl unit as both are <1% in LF 2a/b/c. LLAS14 has a sample of CaCO₃ and TOC% from the central portion of the core. CaCO₃ and TOC% values below 1700 cm are <1% and the nekron mud TOC% values above 1350 cm were reported by Jones et al. (1985) to be generally above 30% for 4 m before falling to ~15% for the upper four metres of core.

In the northern basin, LF 2c is thickest in boreholes 1–10 (148.2–151.5 m OD), which are boreholes located mostly closer to the Afon Llynfi. The transition from LF 2c to LF 3a in the northern basin occurs at a range of altitudes between 148.2 m OD and 151.5 m OD, although the most reliable expression of this unit is at 151 m OD (borehole 8). The transition from the base of the upper marl unit (either LF 3a or 3b) to peat (LF 4b) occurs between 150 and 152 m OD, whilst the highest altitude for the top of the marl unit (LF 3b) was found in LLAC03 core at 153 m OD which is just above the altitude of its highest position in boreholes 12–14. Within the two deeper, lake-core sequences the return to nekron mud sedimentation continues to the core surface at 144.6 and 145.6 m OD.

5. Interpretation

5.1. Facies model of sediments

LF 1 is a normally consolidated, massive diamicton with subrounded and subangular clasts with lithologies (Old Red Sandstone and vein quartz) from within the lake's current catchment edges. It is matrix-supported and shows no obvious fissility or structure within the short sequence recovered. From the limited evidence available from the recovered core, it is either a subglacial till or material deposited on a subaqueous fan at the margins of a retreating glacier (Bennett et al., 2002). In the absence of additional material recovered from this unit, more detailed interpretation is not possible.

LFs 2a and 2b (Fig. 3j, k, l) are interpreted as annually laminated (varve) sediments (Palmer et al., 2008, 2019) in two sedimentary settings. The presence of alternating layers of silt and clay reflects seasonal differences in sediment delivery and deposition, where material is transported to the basin during the melt season either directly from the glacier (Ashley, 1975) or from nival melt delivered via streams to the lake (Cockburn and Lamoureux, 2007). The silt and sand particles would have fallen from suspension during the melt season but clay particles would have been re-suspended by currents within the lake. Heat loss from the water surface would have allowed freezing during the non-melt season inhibiting the formation of eddies within the water column and thus allow very fine silt and clay particles to fall from suspension. Consequently, an annual cycle is composed of a silt and/or sand layer capped by a clay layer and these sedimentary characteristics have now been detected in the deep lake cores (LLAS14 and LLA14) as well as those of the crannóg core (LLAC03; Palmer et al., 2008, 2019).

Palmer et al. (2019) present more detailed descriptions of lamination set assemblages (LSA) within LLAC03 that show more complex structures in the melt season layer derived from different sediment sources and transport to the basin. LF 2a displays thicker lamination set assemblages (Palmer et al., 2019) in comparison to LF 2b, with the increased thickness being driven by the transit of multiple flows of relatively high sediment concentrations issuing directly from meltwater channels in the ice across subaqueous fans and depositing either massive or normally graded structures in relatively distal positions in the basin (cf. LSA 2/4; Palmer et al., 2019). LF 2b contains thinner lamination set assemblages than LF 2a and represents sedimentation in a distal glacial lake where sediment was increasingly being transported through either meltwater streams (LSA 4; Palmer et al., 2019) or nival-melt streams (cf. LSA 5, Palmer et al., 2019). The sediment would have been delivered by either underflows or inter-/overflows, with single or multiple pulses recorded through the melt season. Again, the very fine silt and clay would have been deposited from suspension when there are no water currents through the non-melt season. These two lithofacies are dominated by minerogenic sedimentation with structures that are typical of glaciolacustrine varve sediments and then succeeded by cold climate distal lake varve deposits. This demonstrates that cold climatic conditions prevailed at the time of their deposition (Palmer et al., 2019).

LF 2c is characterised by the massive and weakly laminated sediments that tend to be found higher in the cores but suggests that limnological conditions favoured the supply of minerogenic sediments. Colder climatic conditions probably enabled persistent sediment input as a result of periglacial action on skeletal soils in the catchment and/or lower pioneer vegetation growth in the lake's catchment that is unable to impede the wash of mineral material into the streams. Thin beds of clay are present within this unit that could reflect sustained periods of stable cold arid conditions with low-energy streams only supplying fine-grade sediment to the lake, which fell from suspension in the winter when the lake waters were frozen. However, the weakly laminated sediments do not provide sufficient evidence that varve sediments were consistently deposited within this unit.

LF 3a is dominated by minerogenic silts and clay but also has marl present as either distinct very fine laminations of marl or mixed with the silt and clay (Fig. 3i). Both sediment types indicate lake sedimentation processes with material derived from different sources (Palmer et al., 2015). Allochthonous minerogenic material (silt and clay) is thought to have been transported to the basin by streams perhaps only active during high precipitation events in the summer or during the spring snow melt. There would, however, have been occasions when conditions might have permitted authigenic precipitation of marl within the water column. This may have been driven by photosynthesis that would have reduced lake water acidity and caused precipitation of CaCO₃ (Kelts and Hsü, 1978) or comparatively high lake water temperatures. Just below the boundary between LF 3b and LF 3a in LLAC03, there are fewer discrete, continuous marl laminations of LF 3a suggesting that processes operating within the lake did not favour one style of sedimentation over another. This variability could have been driven by relatively shallow lake waters, at a time when the lake system was adjusting to a new dominant sediment source and/or the mixing of previously deposited marl material.

LF 3b is a massive or laminated marl with CaCO₃ values greater than 25% (Fig. 3e, i). This type of sediment tends to form in a mid-latitude, mild temperate climate, supporting relatively high vegetation productivity, so that under these conditions minerogenic flux to the basin would have been restricted (Palmer et al., 2015; Whittington et al., 2015). Additionally, an increased presence of plant macrophytes in lake waters would have then allowed photosynthesis in the water column, increasing the waters' pH and allowing carbonate precipitation (Verrecchia, 2007, Palmer et al., 2015). In certain places there is evidence of increased minerogenic inwash to the basin, such as the upper marl unit in LLAC03, which was possibly caused by the loss of vegetation, sustained erosion of soils in the lake's catchment and/or small decreases in the lake water level exposing former lake beds to erosion (Fig. 4). In addition, the concentration of organic detritus in LLAN14 at 150.73–150.93 m OD indicates a period in the lake's history when sediment accumulation was dominated by organic detritus, either through in-situ accumulation of vegetal matter or localised inwash.

LF 4a, represented by the nekron mud, indicates high levels of organic productivity within the lake basin and the accumulation of fine-grained humic material on the lake floor (Jones et al., 1978, 1985). In LLAS14 and LLA14, the presence of carbonate-rich, thin beds of red silty clay within the lower part of LF 4a (Fig. 3d) indicates a switch in sediment source with organic productivity being replaced by increased flows transporting allochthonous material to the lake basin. These beds could reflect either short-lived (flood) events, longer-term instability in the catchment or even changes in the lake water level. LF 4b, silty clay with organic content, demonstrates an increase in allochthonous inwash into the basin whilst there are also high levels of organic productivity within the lake basin. This unit is equivalent to the silt clay reported by Jones et al. (1978, 1985) reflecting human disturbance within the landscape. LF 4c, the peat, occurs at the top of the sequences in the northern basin and reflects the succession associated with the infilling of the basin from the margins as the lake

shallowed and dried out (hydroseral succession; Cloutman, 1988; Taylor, 2011).

6. Synthesis and inferred lake level changes through the LGIT

This is the most comprehensive survey of the sediment fills within and around the margins of the current Llangorse Lake basin and its catchment. The sediments in the basins record different lacustrine facies associated with changes in 1) the balance of allogenic and authigenic sediment supply to the lake basin; and 2) spatial differences caused by sedimentation in different water depths. Local variability in sediments is important but the broader changes likely reflect known climatic changes that affected environmental responses in terrestrial systems during the LGIT (Abrook et al., 2020a). Here we discuss the likely age of the sequences and identify a series of lake-level changes inferred from the distribution of lake sediments across the basins.

6.1. The age of the sediment sequences

The Llangorse sediment sequences are broadly characteristic of many lake sequences deposited during the LGIT in Britain. At these other localities, the minerogenic material is often assigned to paraglacial and periglacial activity causing increased erosion of soils and regolith (Palmer et al., 2015; Walker and Lowe, 2017). It is envisaged that a sparse vegetation cover dominated by herbs increased the erosivity of the soil under these colder climatic conditions resulting in enhanced sediment transport to the lake basin (e.g., Abrook et al., 2020b). In contrast, the nekron mud and marl deposits are indicative of increased organic productivity within and around the lake system associated with warmer climatic conditions resulting in the lake sediments being dominated by either higher organic content and/or CaCO₃ (Palmer et al., 2015; Walker and Lowe, 2017).

Building on earlier interpretations summarised by Chambers (1999), we infer that the Llangorse archive details a change from a glacial lake to a cold climate lake during the Dimlington Stadial (LF 2a and 2b). These conditions were succeeded by a climatic amelioration in the Windermere Interstadial producing the lower marl (LF 3a and 3b) and nekron mud deposits (LF 4a), followed by a climatic deterioration associated with the Loch Lomond Stadial (LF 2c) identified by the return to minerogenic sediment input. Eventually, warmer climatic conditions associated with the Holocene were established, inferred from the return of marl (LF 3b) and nekron mud (LF 4a) sedimentation. The upper marl unit in LLAC03 was originally assigned to the Holocene using paleoecological criteria by Walker et al. (1993), and here it is linked to the upper marl units observed across the northern basin. Similarly, radiocarbon dating of the nekron mud by Jones et al. (1985) indicated a Holocene age for these upper deep lake deposits.

Rangefinder calibrated radiocarbon dates (Table 4), using IntCal20 with 2 sigma ranges, show that the lower marl unit was formed during the Windermere Interstadial with its lower boundary dated at 14.81 to 14.08 cal ka BP and the upper boundary to 13.4 to 13.18 cal ka BP. The upper marl unit was deposited during the early Holocene as indicated by dates of 11.39 to 11.19 cal ka BP and 10.24 to 9.63 cal ka BP. All radiocarbon dates have been calibrated using IntCal20 and are presented at 95.4% highest probability density ranges (Reimer et al., 2020). These dates further support the correlation of the upper marl

unit with the sequence reported by Walker et al. (1993) and also the upper nekron mud unit in the deeper lake cores of Jones et al. (1985).

6.2. Changes in the Llangorse lake system during the LGIT

This extensive basin survey allows refinement of the lake level model for Llangorse and addresses the mismatching stratigraphy noted by Walker et al. (1993). The initial glaciolacustrine system formed as ice from the Usk and Wye valleys separated in the vicinity of Bwlch with further northward retreat of the Wye ice enabling an ice-contact lake to form (Lewis, 1970; Palmer et al., 2008, 2019). The 190 m lake level is controlled by the outflow through Bwlch and Penorth, which was close to 37 m above the current lake level (Lewis, 1970; Fig. 6). Further retreat of the ice is thought eventually to have caused the ice dam to fail and water drainage to be diverted northward through the Afon Llynfi and into the River Wye (Lewis, 1970; Palmer et al., 2008). The glacial activity at Llangorse conditioned later sedimentation patterns in the basin. A shallow ridge runs NE-SW between LLA14 and LLAS14 and there is another area of high ground in the vicinity of LLAC03. These features could represent subaqueous ice-contact fans or moraines that formed at the retreating ice margin. Thus, during the LGIT, the whole basin inherited a lake with several depocentres at different altitudes which influenced the composition of the deposits and, at certain points, sediment accumulation and preservation (Fig. 6). The lake at this time had a greater surface area as it extended further to the north and north-west than the current lake's area.

The highest altitude at which ultra-distal or nival glacial lake deposits occur is ~152 m OD and, therefore, it is likely that the lake level was a little higher than at present for these fine structures to be preserved in boreholes 12, 13 and 14. The exact timing of this lake level fall could have been as early as varve year 75 in the floating varve chronology of Palmer et al. (2008, 2019), where the microfacies analysis would suggest a switch in the dominant sediment source from the retreating glacier to the north to subaerial streams from the southern part of the catchment (Fig. 6; level 1).

There is a change in the lithological characteristics of the Llangorse sediment sequences to marl or nekron mud around the transition from the Dimlington Stadial to the Windermere Interstadial. In the northern basin, marl is preserved at a maximum altitude of 151.5 m OD in BH11 (Figs. 4, 6). Marl can form as 'benches' in the littoral zone of lake waters at water depths normally of between 1.5 and 2 m water depth (Murphy and Wilkinson, 1980). Therefore, the minimum lake level at this time would have been between 153 and 153.5 m OD, which is similar to the present day if not a little higher, and also to the water level during the latter stages of the Dimlington Stadial (Fig. 6). Despite the change in lithological characteristics at this time, there are no obvious indicators of lake level change within the sediments of the deeper core sequences. Also, after the lake level fall, the lake's area would have extended to the north beyond the margins of the current lake.

The lithological transition from the Windermere Interstadial to Loch Lomond Stadial deposits provides improved understanding of the lake basin evolution (Fig. 6; level 2). The relatively short sequences of the Windermere Interstadial nekron mud in the deeper lake cores change to minerogenic-rich sediments of silt and clay of Loch Lomond Stadial age, which include a marl intraclast in the finer silts and clays of LF 2c

Table 4

Summary table of rangefinder radiocarbon dates calibrated using IntCal20 (Reimer et al., 2020). $\delta^{13}\text{C}$ values are only available for measurements made at SUERC.

LLAN14 core depth (cm)	Sample code	Conventional radiocarbon age (^{14}C yrs BP $\pm 1\sigma$)	$\delta^{13}\text{C}$	Cal yrs BP (μ ; IntCal 20)	Range (95.4; IntCal 20)
199–200	UCIAMS-210605	8890 (100)	–	9963	9630–10235
303–305	SUERC-81796	9845 (40)	–27.6	11253	11194–11389
508–511	UCIAMS-210603	11420 (35)	–	13283	13178–13404
565–566	SUERC-82300	12306 (47)	–27.8	14331	14083–14810

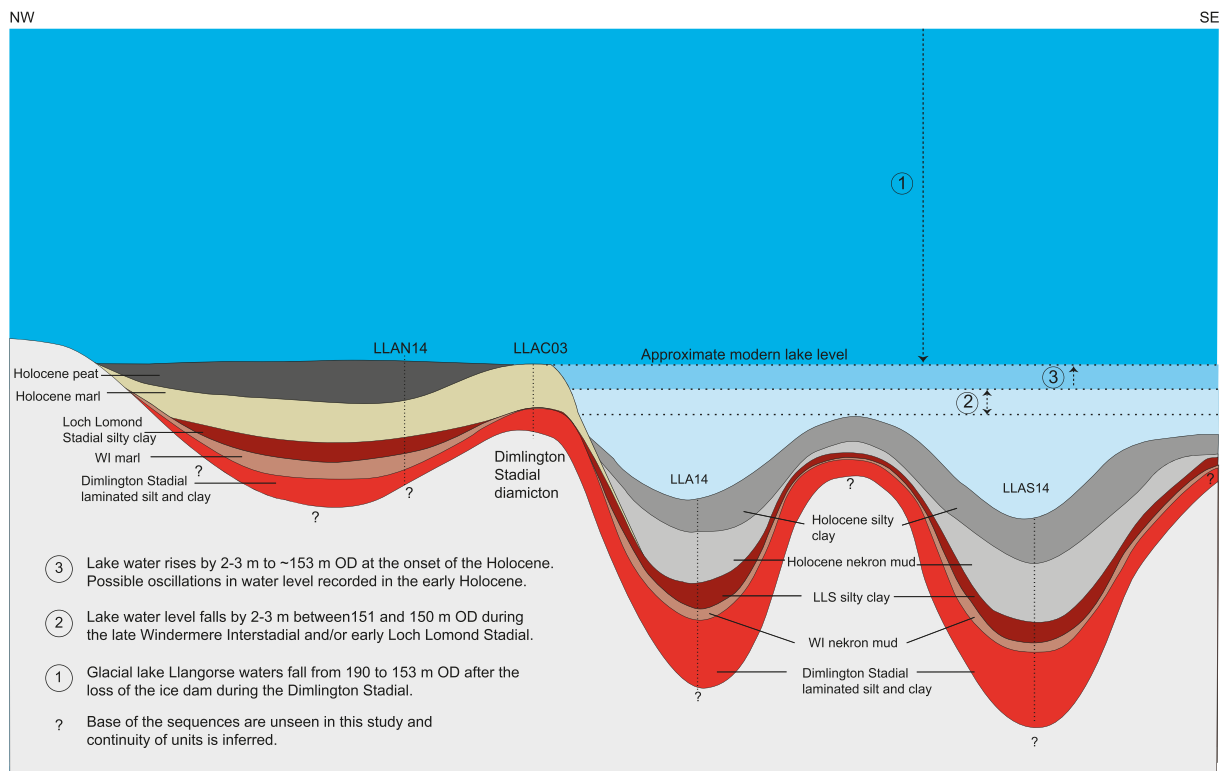


Fig. 6. Schematic representing the distribution of the sediments within Llangorse basin and lake level changes during the LGIT. The base of the sequence resting on diamicton has only been observed in one core and therefore the floor of the basin is inferred. Marl would only have accumulated in the shallower parts of the northern basin and is correlated with the calcareous nekron mud deposited in the deeper lake basin. Estimations for lake level decreases and increases together with the order in which the changes occurred during the LGIT are also highlighted.

(LLA14; Fig. 3f) within a coarser sand bed in LLAS14 (Fig. 3g) and sand-sized 'grains' of marl distributed within the lower part of this unit (Fig. 3g). In LLAC03, there are no deposits that can be attributed clearly to either the Windermere Interstadial or Loch Lomond Stadial and yet at a lower altitude to the north-west of the crannóg, a depression continued to accumulate minerogenic sediments of Loch Lomond Stadial age and in some places the Loch Lomond Stadial sediment is at a higher elevation than at the crannóg. These findings can be explained by a fall in lake level either during the latter part of the Windermere Interstadial or the early phases of the Loch Lomond Stadial. This fall in lake water level would have enabled erosion of exposed Windermere Interstadial marl beds at the margins of the lake by subaerial streams. These streams would have transported, in the suspended load, marl intraclasts toward the centre of the lake basin either through the regular flow of the stream or from flood events. The presence of Loch Lomond Stadial age lake deposits in the northern basin suggests that these sediments were perhaps submerged for much of this cold interval and not exposed to erosional processes. The lake surface is likely to have been at a maximum of 151 to 152 m OD, as this is the highest altitude in LLAC03 and BH11 where Windermere Interstadial marl deposits are not recorded (Fig. 6; level 2). In the LLAC03 sequence, the presence of LF 2c may represent the mixing of former Windermere Interstadial marl with minerogenic sediment of Loch Lomond Stadial age in very shallow waters at the margins of the lake. The preservation of what is interpreted as a complete Windermere Interstadial record at LLAN14 suggests the water level cannot have fallen below 148.54 m. Consequently, the fall in lake water at this time is estimated at between 1.5 and 3.5 m.

Recovery of the lake water level must have occurred by the time marl formed in the early Holocene if not before (Fig. 6; level 3). The lowest altitude for the onset of the upper marl sedimentation in the northern basin occurs at 149.80 m OD and is broadly consistent across

this basin. Therefore, the lake level had recovered to between ~152 and 154 m OD during marl formation and the presence of thin marl deposits in boreholes 12, 13 and 14 would suggest that a return to present day lake level had occurred. However, it is possible that this recovery was interrupted for short periods as there is evidence for intermittent marl sedimentation in the northern basin and also three periods when erosion of marl and minerogenic material interrupted the nekron mud sedimentation in the deeper parts of the basin. These early Holocene events may relate to the short-lived climatic event previously reported by Walker et al. (1993). Whether these reflect pauses in the recovery of lake waters or further falls is unclear currently.

In summary, the retreat of the ice margin caused the initial fall in lake levels of ~37 m (Lewis, 1970; Chambers, 1999) before lake level stabilised at levels similar to that of the present day. However, smaller lake-level changes are recorded, and these potentially are related to changes in the amount of precipitation and its impact on maintaining the level of the local water table at a range of temporal scales. Falling lake level in response to a climatically controlled hydrological budget is a feature of lakes during the LGIT period (Magny and Ruffadi, 1995; Magny et al., 2007) and the results from Llangorse fit this broad pattern. By increasing the number of cores sampled and analysed for bulk properties, the apparent lack of Windermere Interstadial sediments in the crannóg core (Walker et al., 1993) can be explained by a lake level fall during the later stages of the Windermere Interstadial and/or during the Loch Lomond Stadial. These data can also be used to constrain the magnitude of lake-level fall during the Loch Lomond Stadial. The lowering of lake levels may also be observed in Yorkshire (Palmer et al., 2015; Lincoln et al., 2020) and Lancashire (Jones et al., 2002) but the timing of such events is not concurrent. In Yorkshire, lake levels remained depressed below modern values from ~13.6 ka until the onset of the Holocene with small increases in the generally low lake level between 12.9 and 12.6 ka and in the second half of the Loch

Lomond Stadial (Lincoln et al., 2020). Conversely, at Hawes Water, lake level was thought to have remained low throughout the Windermere Interstadial and to have experienced a rise at some point within the Loch Lomond Stadial (Jones et al., 2002). This discrepancy may reflect differences in the locations and methods of sampling in these basins or show that other factors are important for determining lake level (e.g., sea-level variations). The Llangorse succession follows closely the examples from Yorkshire with lake level lowering at some point in the Windermere Interstadial or early Loch Lomond Stadial with some suggestion of a rise in lake level either in the second half of the Loch Lomond Stadial or very earliest Holocene. In addition, abrupt climate events in the early Holocene have been detected in marl deposits in Yorkshire from isotope and chironomid proxy data (Blockley et al., 2018), which may have driven short-lived adjustments in lake level that appear to have occurred in the Llangorse system.

Many LGIT-aged lake records come from a relatively, geographically restricted area and, in some cases, fairly shallow lake basins, but the lack of sufficient core sampling density at these sites makes evaluating the influence of lake level change difficult. If many UK lakes did undergo similar changes in level, then this will affect paleoenvironmental reconstructions. For example, either paleoecological macro- and micro-fossil source areas may have changed through time and/or interpretations of isotope analyses may be influenced by evaporative effects. While the lake levels themselves might be useful for reconstructing hydroclimatic oscillations, they could potentially have significant repercussions for reconstructing the climate and environment of a region, which have not been considered in detail to date.

7. Conclusions

This study presents new lithological data from a survey across the Llangorse basin that provides extra detail on the evolution of the Llangorse lake systems during the LGIT. The core sequences improve our understanding of the spatial distribution of the sediment facies deposited during the LGIT and demonstrated that the lake-water level was susceptible to change. Radiocarbon dating of Windermere Interstadial age deposits in the Llangorse basin confirms the identification of Dimlington Stadial age sediments in the lower part of the sediment succession (Chambers, 1999; Palmer et al., 2008). The lake system was initially a glacial lake with a higher lake water level that decreased from ~190 to ~153 m OD when the ice dam had been breached during the Dimlington Stadial and then maintained at this lower level through the Windermere Interstadial. Evidence exists for further decreased water levels by 1–2 m either during the late Windermere Interstadial or the early part of the Loch Lomond Stadial and then returned to ~153 m OD by the early Holocene. After the glacial lake drained, the new lake system extended further to the north and north-west and thus had a greater surface area than the current lake system, although this northern basin gradually infilled during the early Holocene. Ongoing work will focus on i) changes in the Dimlington Stadial cold climate lake system; ii) generating a robust independent radiocarbon chronology using terrestrial plant macrofossils preserved in the longer LGIT sequence of LLAN14; and iii) examine the nature and timing of abrupt sub-centennial scale changes in the paleoecological and paleoclimatic proxy archives of the LGIT sequences. These data will provide a more detailed record of the evolution of the lake system from full glacial to characteristic interglacial (i.e., Holocene) conditions in the UK.

Declaration of competing interest

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

Acknowledgements

The Quaternary Research Association is acknowledged for its support through a Quaternary Research Fund award made to support the 2014 deep water coring campaign. Rangefinder radiocarbon determinations were supported through NERC Radiocarbon Facility award 2116.0418. Sedimentological work was supported by a Royal Holloway, University Research Strategy Fund award. Access to extract the cores from the crannóg area in 2003 was granted by the Ancient Monuments, CADW; the Countryside Council for Wales; and to Mr J.A. V. Blackham. Clive Jones is gratefully acknowledged for his continued support in allowing access to the field in the north west corner of Llangorse basin. Rebecca Smith is thanked for the use of data collected during an undergraduate dissertation. Jen Thornton and Joshua Pike are also thanked for their considerable help in developing the figures. Rachel Avery and two anonymous reviewers are thanked for their constructive comments on an earlier version of the paper.

References

- Abrook, A.M., Matthews, I.P., Candy, I., Palmer, A.P., Francis, C.P., Turner, L., Brooks, S.J., Self, A., Milner, A.M., 2020a. Complexity and asynchrony of climatic drivers and environmental responses during the Last Glacial-Interglacial Transition (LGIT) in north-west Europe. *Quaternary Science Reviews* 250, 106634.
- Abrook, A.M., Matthews, I.P., Milner, A.M., Candy, I., Palmer, A.P., Timms, R.G.O., 2020b. Environmental variability in response to abrupt climatic change during the Last Glacial-Interglacial Transition (16–8 cal ka BP): evidence from Mainland, Orkney. *Scottish Journal of Geology* 56, 30–46.
- Ashley, G.M., 1975. Rhythmic sedimentation in glacial Lake Hitchcock, Massachusetts, Connecticut. In: Jopling, A.V., McDonald, B.C. (Eds.), *Glacioluvial and Glaciolacustrine Sedimentation*. Society of Economic Paleontologists and Mineralogists (SEPM), Special Publication 23, pp. 304–320.
- Soil Survey laboratory methods. In: Avery, B.W., Bascomb, C.L. (Eds.), *Soil Survey Technical Monograph*, revised edition 6 (83 pp.).
- Bennett, M.R., Huddart, D., Thomas, G.S., 2002. Facies architecture within a regional glaciolacustrine basin: Copper River, Alaska. *Quaternary Science Reviews* 21, 2237–2279.
- Blockley, S., Candy, I., Matthews, I., Langdon, P., Langdon, C., Palmer, A., Lincoln, P.C., Abrook, A., Taylor, B., Conneller, C., Bayliss, A., 2018. The resilience of postglacial hunter-gatherers to abrupt climate change. *Nature Ecology and Evolution* 2 (5), 810–818.
- Brooks, S.J., Matthews, I.P., Birks, H.H., Birks, H.J.B., 2012. High resolution Lateglacial and early-Holocene summer air temperature records from Scotland inferred from chironomid assemblages. *Quaternary Science Reviews* 41, 67–82.
- Brooks, S.J., Davies, K.L., Mather, K.A., Matthews, I.P., Lowe, J.J., 2016. Chironomid inferred summer temperatures for the last glacial–interglacial transition from a lake sediment sequence in Muir Park Reservoir, west-central Scotland. *Journal of Quaternary Science* 31 (3), 214–224.
- Candy, I., Farry, A., Darvill, C.M., Palmer, A., Blockley, S.P.E., Matthews, I.P., MacLeod, A., Deeprose, L., Farley, N., Kearney, R., Conneller, C., Taylor, B., Milner, N., 2015. The evolution of Palaeolake Flixton and the environmental context of Star Carr: an oxygen and carbon isotopic record of environmental change for the early Holocene. *Proceedings of the Geologists' Association* 126 (1), 60–71.
- Candy, I., Abrook, A., Elliot, F., Lincoln, P., Matthews, I.P., Palmer, A., 2016. Oxygen isotopic evidence for high-magnitude, abrupt climatic events during the Lateglacial Interstadial in north-west Europe: analysis of a lacustrine sequence from the site of Tirinie, Scottish Highlands. *Journal of Quaternary Science* 31 (6), 607–621.
- Chambers, F.M., 1999. The Quaternary history of Llangorse Lake. *Aquatic Conservation* 9 (4), 343–359.
- Chiverrell, R.C., Thomas, G.S.P., 2010. Extent and Timing of the Last Glacial Maximum (LGM) in Britain and Ireland: a review. *Journal of Quaternary Science* 25 (4), 535–549.
- Clark, C.D., Gibbard, P.L., Rose, J., 2004. Pleistocene glacial limits in England, Scotland and Wales. In: Ehlers, J., Gibbard, P.L. (Eds.), *Quaternary Glaciations: Extent and Chronology. Part 1: Europe*. Elsevier, Amsterdam, pp. 47–82.
- Clark, C.D., Hughes, A.L., Greenwood, S.L., Jordan, C., Sejrup, H.P., 2012. Pattern and timing of retreat of the last British-Irish ice sheet. *Quaternary Science Reviews* 44, 112–146.
- Cloutman, E.W., 1988. Palaeoenvironments in the Vale of Pickering, Part 1: stratigraphy and palaeogeography of Seamer Carr, Star Carr and Flixton Carr. *Proceedings of the Prehistoric Society* 54, 1–19.
- Cloutman, E.W., Smith, A.G., 1988. Palaeoenvironments in the Vale of Pickering, Part 3: environmental history at Star Carr. *Proceedings of the Prehistoric Society* 54, 37–58.
- Cockburn, J.M.H., Lamoureux, S.F., 2007. Century-scale variability in late-summer rainfall events recorded over seven centuries in subannually laminated lacustrine sediments, White Pass, British Columbia. *Quaternary Research* 67 (2), 193–203.
- Evans, D.J.A., Benn, D.I. (Eds.), 2004. *A Practical Guide to the Study of Glacial Sediments*. Edward Arnold, London.

- Evans, D.J.A., Phillips, E.R., Hiemstra, J.F., Auton, C.A., 2006. Subglacial till: formation, sedimentary characteristics and classification. *Earth-Science Reviews* 78 (1–2), 115–176.
- Howells, M.F., 2007. *British Regional Geology: Wales*. British Geological Survey, Nottingham (230 pp.).
- Jacobi, R.M., Higham, T.F.G., 2009. The early Lateglacial re-colonization of Britain: new radiocarbon evidence from Gough's Cave, southwest England. *Quaternary Science Reviews* 28 (19–20), 1895–1913.
- Jansson, K.N., Glasser, N.F., 2008. Modification of peripheral mountain ranges by former ice sheets: the Brecon Beacons, Southern UK. *Geomorphology* 97, 178–189.
- Jones, R., Benson-Evans, K., Chambers, F.M., Seddon, Abell, B., Tai, Y.C., 1978. Biological and chemical studies of sediments from Llangorse Lake, Wales. *Verhandlungen - Internationale Vereinigung für Theoretische und Angewandte Limnologie* 20 (1), 642–648.
- Jones, R., Benson-Evans, K., Chambers, F.M., 1985. Human influence upon sedimentation in Llangorse lake, Wales. *Earth Surface Processes and Landforms* 10 (3), 227–235.
- Jones, R.T., Marshall, J.D., Crowley, S.F., Bedford, A., Richardson, N., Bloemendal, J., Oldfield, F. (Eds.), 2002. *Journal of Quaternary Science* 17 (4), 329–340.
- Kelts, K., Hsü, K.J., 1978. Freshwater carbonate sedimentation. In: Lerman, A. (Ed.), *Lakes, Geology and Chemistry*. Physics. Springer Verlag, New York, pp. 295–323.
- Lewis, C.A., 1970. The Upper Wye and Usk regions. In: Lewis, C.A. (Ed.), *The Glaciations of Wales and Adjoining Regions*. Longman, London, pp. 147–173.
- Lewis, C.A., Thomas, G.S.P., 2005. The upper Wye and Usk regions. In: Lewis, C.A., Richards, A.E. (Eds.), *The Glaciations of Wales and the Adjacent Areas*. Logaston Press, Hereford, UK, pp. 101–128.
- Lincoln, P.C., Matthews, I.P., Palmer, A.P., Blockley, S.P.E., Staff, R.A., Candy, I., 2020. Hydroclimatic changes in the British Isles through the Last-Glacial-Interglacial Transition: multiproxy reconstructions from the Vale of Pickering, NE England. *Quaternary Science Reviews* 106630.
- Lowe, J.J., Walker, M.J.C., 2000. Radiocarbon dating the last glacial-interglacial transition (ca. 14–9 ¹⁴C ka BP) in terrestrial and marine records: the need for new quality assurance protocols. *Radiocarbon* 42 (1), 53–68.
- Magny, M., Ruffadi, P., 1995. Younger Dryas and early Holocene lake-level fluctuations in the Jura mountains, France. *Boreas* 24 (2), 155–172.
- Magny, M., Vannière, B., De Beaulieu, J.L., Bégeot, C., Heiri, O., Millet, L., Peyron, O., Walter-Simonnet, A., 2007. Early Holocene climatic oscillations recorded by lake-level fluctuations in west-central Europe and in central Italy. *Quaternary Science Reviews* 26 (15), 1951–1964.
- Marshall, J.D., Jones, R.T., Crowley, S.F., Oldfield, F., Nash, S., Bedford, A., 2002. A high resolution late-glacial isotopic record from Hawes Water, northwest England: climatic oscillations: calibration and comparison of palaeotemperature proxies. *Palaeogeography Palaeoclimatology Palaeoecology* 185 (1), 25–40.
- Mulder, T., Alexander, J., 2001. The physical character of subaqueous sedimentary density flows and their deposits. *Sedimentology* 48 (2), 269–299.
- Murphy, D.H., Wilkinson, B.H., 1980. Carbonate deposition and facies distribution in a central Michigan marl lake. *Sedimentology* 27 (2), 123–135.
- Palmer, A.P., Lowe, J.J., Rose, J., Walker, M.J.C., 2008. Annually laminated late Pleistocene sediments from Llangorse Lake, South Wales, UK: a chronology for the pattern of ice wastage. *Proceedings of the Geologists' Association* 119 (3–4), 245–258.
- Palmer, A.P., Matthews, I.P., Candy, I., Blockley, S.P.E., MacLeod, A., Darvill, C.M., Milner, N., Conneller, C., Taylor, B., 2015. The evolution of Palaeolake Flixton and the environmental context of Star Carr, NE Yorkshire: stratigraphy and sedimentology of the Last Glacial-Interglacial Transition (LGIT). lacustrine sequences. *Proceedings of the Geologists' Association* 126 (1), 50–59.
- Palmer, A.P., Bendle, J.M., MacLeod, A., Rose, J., Thorndycraft, V.R., 2019. The micromorphology of glaciolacustrine varve sediments and their use for reconstructing palaeoglaciological and palaeoenvironmental change. *Quaternary Science Reviews* 226, 105964.
- Parker, A.G., Goudie, A.S., Anderson, D.E., Robinson, M.A., Bonsall, C., 2002. A review of the mid-Holocene elm decline in the British Isles. *Progress in Physical Geography* 26 (1), 1–45.
- Patton, H., Hubbard, A., Glasser, N.F., Bradwell, T., Golledge, N.R., 2013. The last Welsh Ice Cap: part 2 – modelling and its evolution, sensitivity and associated climate. *Boreas* 42 (3), 471–490.
- Pentecost, A., 2009. The marl lakes of the British Isles. *Freshwater Reviews* 2 (2), 167–198.
- Rasmussen, S.O., Bigler, M., Blockley, S.P., Blunier, T., Buchardt, S.L., Clausen, H.B., Cvijanovic, I., Dahl-Jensen, D., Johnsen, S.J., Fischer, H., Gkinis, V.M., Guillevic, M., Hoek, W.Z., Lowe, J.J., Pedro, J., Popp, T., Seierstad, I.K., Steffensen, J.P., Svensson, A.M., Vallelonga, P., Vinther, B.M., Walker, M.J.C., Wheatley, J.J., Winstrup, M., 2014. A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. *Quaternary Science Reviews* 106, 14–28.
- Reimer, P., Austin, W., Bard, E., Bayliss, A., Blackwell, P., Bronk Ramsey, C., Butzin, M., Cheng, H., Edwards, R., Friedrich, M., Grootes, P., Guilderson, T., Hajdas, I., Heaton, T., Hogg, A., Hughen, K., Kromer, B., Manning, S., Muscheler, R., Palmer, J., Pearson, C., van der Plicht, J., Reimer, R., Richards, D., Scott, E., Southon, J., Turney, C., Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S., Fogtmann-Schulz, A., Friedrich, R., Köhler, P., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A., Talamo, S., 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal k BP). *Radiocarbon* 62, 1–13.
- Schumacher, B.A., 2002. Methods for the Determination of Total Organic Carbon (TOC) in Soils and Sediments. Ecological Risk Assessment Support Center Office of Research and Development US. Environmental Protection Agency NCEA-C-1282, EMASC-001, pp. 1–25.
- Shakesby, R.A., Matthews, J.A., 2009. Comments on Jansson, K.N. and Glasser, N.F. (2008) "Modification of peripheral mountain ranges by former ice sheets: the Brecon Beacons, southern UK". *Geomorphology* 110, 217–225.
- Taylor, B., 2011. Early Mesolithic activity in the wetlands of the Lake Flixton Basin. *Journal of Wetland Archaeology* 11 (1), 63–84.
- Thomas, G.S.P., Humpage, A.J., 2007. The glacial geomorphology of the lower and middle Usk valley. In: Carr, S.J., Coleman, C.G., Humpage, A.J., Shakesby, R.A. (Eds.), *Quaternary of the Brecon Beacons Field Guide*. Quaternary Research Association, London.
- van Asch, N., Lutz, A.F., Duijkers, M.C., Heiri, O., Brooks, S.J., Hoek, W.Z., 2012. Rapid climate change during the Weichselian Lateglacial in Ireland: chironomid-inferred summer temperatures from Fiddaun, Co. Galway. *Palaeogeography Palaeoclimatology Palaeoecology* 315, 1–11.
- Verrecchia, E., 2007. Lacustrine and Palustrine Geochemical sediments. In: Nash, D.J., McLaren, S.J. (Eds.), *Geochemical Sediments and Landscapes*. Blackwell Publishing, p. 465.
- Walker, M.J.C., 1982a. The Lateglacial and early Flandrian deposits at Traeth Mawr, Brecon Beacons, South Wales. *The New Phytologist* 90 (1), 177–194.
- Walker, M.J.C., 1982b. Early and mid-Flandrian environmental history of the Brecon Beacons, South Wales. *The New Phytologist* 91, 147–165.
- Walker, M.J.C., Harkness, D.D., 1990. Radiocarbon dating the Devensian Lateglacial in Britain: new evidence from Llanilid, South Wales. *Journal of Quaternary Science* 5 (2), 135–144.
- Walker, M.J.C., Griffiths, H.I., Ringwood, V., Evans, J.G., 1993. An early Holocene pollen, mollusc and ostracod sequence from lake marl at Llangorse Lake, South Wales, UK. *The Holocene* 3 (2), 138–149.
- Walker, M.J.C., Coope, G.R., Sheldrick, C., Turney, C.S.M., Lowe, J.J., Blockley, S.P.E., Harkness, D.D., 2003. Devensian Lateglacial environmental changes in Britain: a multi-proxy record from Llanilid, South Wales, UK. *Quaternary Science Reviews* 22, 475–520.
- Walker, M.J.C., Lowe, J.J., 2017. Lateglacial environmental change in Scotland. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh* 110 (1–2), 1–26.
- Whittington, G., Edwards, K.J., Zanchetta, G., Keen, D.H., Bunting, M.J., Fallick, A.E., Bryant, C.L., 2015. Lateglacial and early Holocene climates of the Atlantic margins of Europe: stable isotope, mollusc and pollen records from Orkney, Scotland. *Quaternary Science Reviews* 122, 112–130.