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Invited Paper

The micromorphology of glaciolacustrine varve sediments and their use for reconstructing palaeoglaciological and palaeoenvironmental change

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ABSTRACT

Former glaciolacustrine systems are an important archive of palaeoglaciological, palaeoenvironmental and palaeoclimatic change. The annually laminated (varved) sediments that, under certain conditions, accumulate in former glacial lakes, offer a rare opportunity to reconstruct such changes (e.g. glacier advance and retreat cycles, glacier ablation trends, permafrost melt, nival events) at annual or even sub-annual temporal resolution. Data of this kind are desirable for their ability to guide and test numerical model simulations of glacier dynamics and palaeoclimatic change that occur over rapid time intervals, with implications for predicting future glacier response to climatic change, or the effects of weather and climate events on lake sedimentation. The most valuable records preserved in glaciolacustrine systems are continuous varved sequences formed in the distal parts of glacial lakes, where microscale lamination structures can accumulate relatively undisturbed. Technological advances, in the last few decades, have enabled improved characterisation of glaciolacustrine varve microfacies and the precise measurement of varve thickness at the micrometre scale. However, unlike in cognate fields (e.g. soil science), protocols for the robust and consistent description and interpretation of glaciolacustrine varve sediments are lacking. To fill this gap, and to provide a resource for future studies of glaciolacustrine varved sediments, this paper reviews the processes of sedimentation in glacial lake basins, and presents the defining microfacies characteristics of glacial varves using a descriptive protocol that uses consistent examination of grain size, sorting, structure, nature of contacts, development of plasmic fabrics and features such as dropgrains and intraclasts within individual laminations. These lamination types are then combined into lamination sets, whose structures can be interpreted as glaciolacustrine varves. Within this framework, we define five principal assemblages of glaciolacustrine varve microfacies which, if clearly identified in palaeoglaciolacustrine settings, enable more detailed palaeoenvironmental interpretations to be made. Finally, we discuss the utility and complexities of reconstructing the evolution of former glacial lake systems using varve microfacies and thickness datasets.

1. Introduction

Annually-laminated lake sediments (varves) provide high temporal resolution records and precise chronologies of modern and palaeoenvironmental change (Ojala et al., 2012; Zolitschka et al., 2015). Varved sediments accumulate due to persistent and distinctive patterns in the supply of sediment to lake basins, which are the result of variations in sediment supply, usually on a seasonal basis, although also sometimes as a consequence of high-magnitude events at a glacier or surrounding terrain of the lake's catchment. The preservation of varves from high to low latitude terrestrial systems ensures a wide spatial coverage of high-resolution environmental records across most climatic regimes (Zolitschka et al., 2015). Variations in varve thickness of interannual, decadal and centennial duration can record climatic and environmental changes such as hydroclimate (Tiljander et al., 2002), palaeofloods (Glur et al., 2013), precipitation (Lapointe et al., 2012), temperature (Hardy et al., 1996; Glur et al., 2015;

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Amann et al., 2017) and wind (Martin Puertas et al., 2012), whilst also recording the role of solar forcing on the earth system (Haltia-Hovi et al., 2007). Lacustrine varve archives can also be compared as independent chronologies to those of other annually resolved records such as the polar ice-cores, speleothem, marine varves and tree rings (Schlolaut et al., 2012; Brauer et al., 2008). This enables opportunity for unparalleled precision in understanding reorganisations of ocean and atmosphere systems during Earth's past, and the response of terrestrial systems to such changes (Brauer et al., 2008; Lane et al., 2013; Bendle et al., 2019).

Specifically, varve lake sediments are composed of material from a number of different sources. Anderson (1996) grouped these into three domains: the mechanical domain composed of minerogenic material; the bio-chemical domain, composed mainly of organic detritus, pollen, diatoms and chemical precipitates; and a mixed domain that is composed of different proportions of the mechanical and bio-chemical domains that can be derived from allochthonous or autochthonous pathways to the lake. Distinguishing between all of these different components is essential to generating a model of varve formation that can be used to delimit the seasonal layers that comprise varves and count varves. Zolitschka et al. (2015) considered there were five key stages in demonstrating that annual layers formed in modern lake systems: 1) detailed varve lithostratigraphic investigations; 2) sediment trap studies from the water column that are compared to the layers accumulating on the lake floor; 3) detailed biostratigraphic analyses; 4) repeat sampling over consecutive years and 5) lateral consistency of annual laminations across the same lake basin. In extant lake systems, each of these elements can be investigated directly and the varve model tested, albeit at a lower level of resolution and confidence, using independent radiometric dating techniques, such as ^{210}Pb and ^{137}Cs isotopes (Lamoureux, 1999; Tylmann et al., 2013), through radiocarbon dating of plant remains preserved in the varve sediments, or tephrochronology (Hajdas et al., 1995; MacLeod et al., 2011; Bronk Ramsey et al., 2012).

However, in palaeolake basins establishing the presence of annual layers is more challenging as by definition it is not possible to carry out in-lake monitoring. In former lake systems either the accommodation space was lost by the basin completely infilling with sediment (e.g. Marks Tey, Essex; Turner, 1970) or the former lake system being drained due to, for example, the removal of an ice dam or a moraine dam failure (Jamieson, 1892; Sissons, 1978; Boygle, 1993; Ridge et al., 2012; Bendle et al., 2017; Thorndycraft et al., 2019). Alternatively, an existing lake system operates under limnological controls that differ from the recent geological past when annual sedimentation was occurring. This includes, for example, terrestrial systems that no longer support glaciers but contain evidence for glaciation and glacial lake formation (e.g. Palmer et al., 2008a,b). These issues, specifically the latter, could affect any lake varve archive and are particularly challenging in the high- and mid-latitudes where past climate variability led to ice sheet/cap fluctuations through glacial to interglacial cycles, causing significant changes in lacustrine sedimentological processes compared to the present day. Thus, to examine the potential presence of varve sedimentation in palaeolake settings requires reliable sedimentological models, of what are often very fine sediment structures.

To address this, the microfacies approach has been adopted (Brauer, 2004) and is routinely used for analysis of sub-mm scale bio-chemical or bioclastic and mixed domain structures of modern and palaeolake basins (Brauer et al., 1999; Mangili et al., 2005; Martin Puertas et al., 2012). Microfacies analytical techniques including Scanning Electron Microscopy (SEM; Delaney, 2007), thin section analysis (Ringberg and Erlström, 1999; Palmer et al., 2010; Devine and Palmer, 2017), core surface photography, downcore X-ray Fluorescence (μXRF) scanning (MacLeod et al., 2011) and micro-CT scanning (μCT; Bendle et al., 2015), provide the capacity to examine small-scale sediment structures and internal sediment composition, ultimately allowing precise measurement of lamination composition and boundaries to establish varve chronologies.

Glaciolacustrine varve chronologies are often generated through examination of structures visible to the naked eye and measured directly from the core surface or from photographs/digital images (De Geer, 1912; Antevs, 1922; Caldenius, 1932; Ridge et al., 2012; Bendle et al., 2017), although greater use of microscopic analytical techniques for these clastic sediments is becoming more common. However, whilst the microfacies approach is used for clastic varves forming in modern lake systems it has not been commonly used for the analysis of distal glaciolacustrine sediments in palaeolake basins, and the terminology used to describe microfacies in both settings is often inconsistent. Consequently, it is difficult to assess comparisons between active and palaeo-lake sediments when a terminology, common to both, does not exist. Therefore, consistent microfacies analysis is needed to explore the full potential of palaeoglaciolacustrine sediments for palaeoglaciological, palaeoclimatic and palaeoenvironmental investigations.

This paper focuses on the rationale for developing a microfacies approach to distal glaciolacustrine sediments by presenting microfacies of laminated sediments from palaeoglaciolacustrine sequences. The paper is presented in three parts. Firstly, it synthesises and reviews glaciolacustrine sedimentology, covering sources of sediment, modes of transport, and seasonal sedimentation patterns in laminated lake sediments (with a specific focus on the delivery of sediment to distal locations) and summarises key studies that have presented microscopic analysis of extant and palaeo-glacial lake sediments. This provides context for the second part of the paper that establishes the reasoning behind a consistent descriptive framework for a microfacies system. This system focusses on the description and interpretation of fine and very fine laminated structures in order to generate robust sedimentological models and the ability to discriminate varve structures at the microscale. This system is then applied to finely laminated sediments recovered from three palaeoglaciolacustrine systems to represent a range of geodynamic contexts: two from the British Isles and one from South America. We discuss these findings in order to develop a new framework for identifying the position of deposition within a former lake basin relative to the glacier margins. Finally, we evaluate how this information can be used to refine palaeoclimatic and palaeoenvironmental reconstructions.

2. Limnological and sedimentological processes in glacial lakes

2.1. Sediment sources for glacial lakes

Bennett et al. (2002) summarised sediment sources, transport pathways, processes and products of sedimentation in glaciolacustrine systems (Fig. 1). Sediment can be sourced directly from the glacier in ice-contact lake systems, via meltwater streams connected to glaciers in ice distal lakes, or nival meltwater streams. In ice-contact systems, sediment release occurs directly from subglacial and supraglacial transport networks, iceberg rainout and supraglacial slumping that contribute flows, slides and slumps (Fig. 1). Sediment can also be sourced from subaqueous and subaerial outwash and fluvial inputs that behave as either quasi-steady flows, surge-like flows, or evolve from quasi-steady flows to surge-like flows. Bennett et al. (2002) also distinguish between two major sediment facies: silt and clay (mud-rich) facies, which are mainly derived from flow, slides and slumps, and sand and gravel facies,

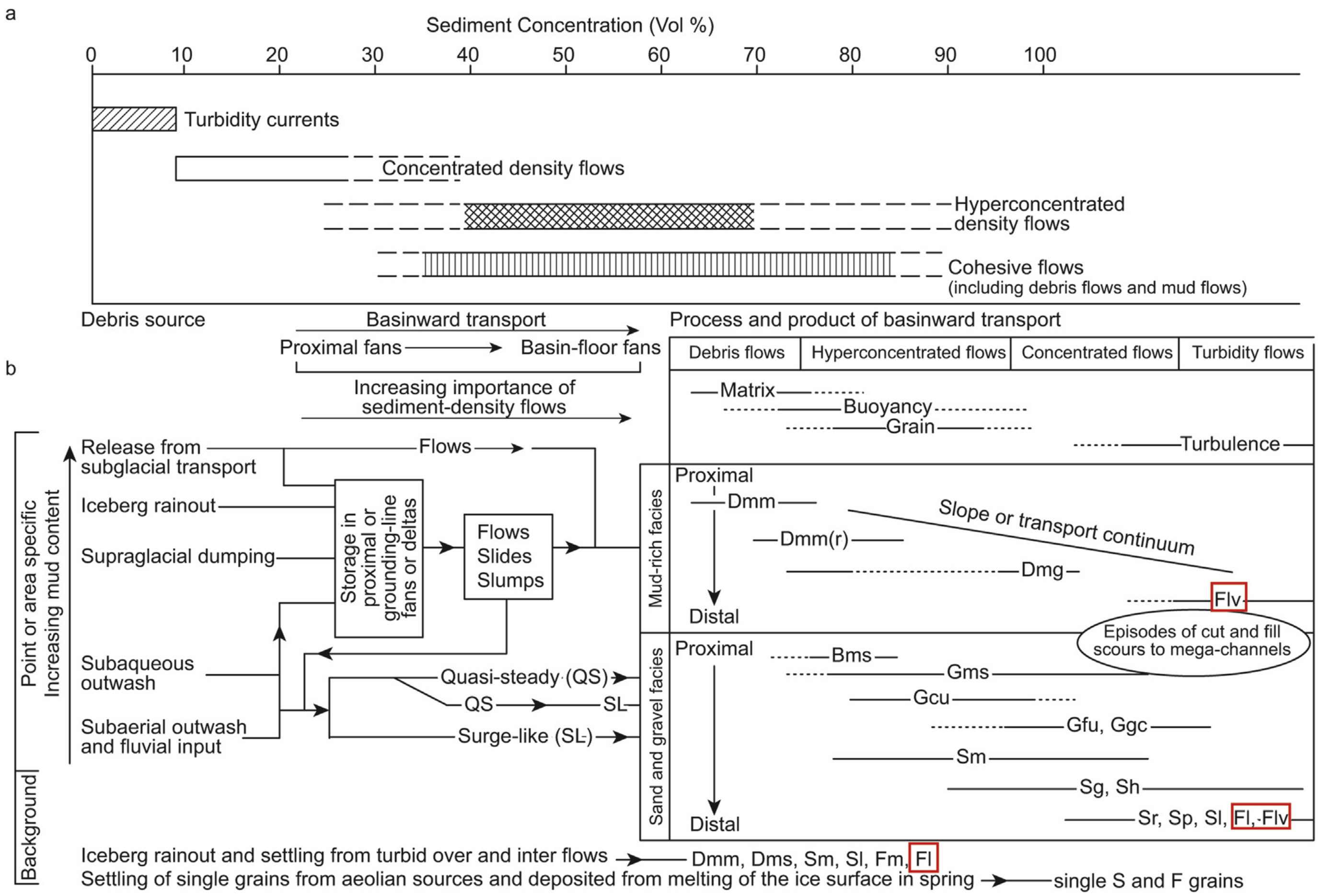


Fig. 1. Sediment sources and characteristics of flows in glaciolacustrine systems (adapted from Mulder and Alexander, 2001 and Bennett et al., 2002). a) Mulder and Alexander (2001) presented a redefinition of terminology associated with subaqueous density currents. Cohesive density flows, hyperconcentrated density flows, with sediment concentration greater than 35%, are associated with diamictons and coarse gravel facies deposited close to the ice contact or glaciofluvial outwash and deltas (1b: from Bennett et al., 2002). Turbidity currents can be a product of these same flows with deposits forming in distal positions of the basin to the ice contact or be generated from distal ice glaciofluvial or fluvial systems. These will produce Fl and Flv in these distal positions (from Bennett et al., 2002; highlighted with red boxes), which can be very fine and require examination and description using the microfacies approach. Also included on the Bennett et al. (2002) summary is the addition of single isolated sand and silt grains identified by Lewis et al. (2002) as from an aeolian source. Lithofacies codes are from Bennett et al. (2002), which are modified from Eyles et al. (1983) and Eyles and Miall (1984). Dmm - Massive diamict; Dmm(r) - re-sedimented diamict with included soft sediment clasts and water escape structures; Dmg - Normally graded diamict; Dms - Stratified diamict, laminated matrix with numerous clasts; Bms - Massive boulder gravel in laterally persistent units (matrix-poor); Gms - Massive boulder gravel in laterally persistent units (matrix-rich); Gcu - Inversely graded sand/granule to pebble gravel. Horizontally stratified with conformable bases; Gfu - normally graded sand/granule to pebble gravel. Horizontally stratified with conformable bases; Ggc - Graded gravel (channelled). Pebble gravel grading upwards into coarse and medium sand, with erosional channelled bases; Sm- Massive sand. Coarse, medium or fine sand; Sg - Graded sand. Thin multiple coarse to fine sand graded co-sets; Sh - Horizontally stratified sand. Coarse to medium sand, with isolated pebble/granule gravel clasts. Occasional thin graded and rippled units. Sr - Rippled sands. Type A, B and S climbing ripples; Sp - Planar cross-stratified sand. Troughs in coarse to medium sand; Sl - Parallel laminated sand. Thinly laminated fine sand. Occasional pebble gravel clasts and granule gravel lines. Fl - finely laminated silt and clay; Flv - Rhythmites of silt, clay and fine sand. Fm - Massive silt and clay.

which are derived from quasi-steady (quasi-continuous) and surge-like flows. The silt and clay facies generally form massive and matrix supported diamictons in proximal locations where the presence of a slope or renewed flows can propagate finer sediment sizes further into the basin, or distal locations where the transport dynamics has taken the coarser fraction out of the sediment mix. Whilst sorted sand and gravel facies are deposited closer to the glacier margin (Bms, Gms, Gcu, Gfu, Ggc; Bennett et al., 2002), it is common to observe a decrease in particle size (Sm, Sg, Sh; Bennett et al., 2002) to eventually deposit laminated silts and clays or fines (Fl and Flv; rhythmites or varves; Bennett et al., 2002) in the distal parts of the basin. Bennett et al. (2002) argue that the decrease in grain size is driven by changes in the transportation process with cohesive flows (such as debris flows) evolving into hyperconcentrated to concentrated flows (30–90% sediment concentration by volume) until transportation is dominated by turbidity current processes (1–10% sediment concentration by volume) in the distal part of the basin (Mulder and Alexander, 2001). Consequently, there is a decrease in sediment concentration from proximal zones, which are dominated by matrix material, to distal zones that are characterised by increasing buoyancy and grain-to-grain interactions, and where turbulence is the main medium of transportation.

Other sources of sediment include secondary remobilisation of sediment sinks such as surge-type movements across subaqueous fans and on deltas, and from subaqueous and subaerial locations of the valley sides (Bennett et al., 2002; Johnsen and Brennand, 2006). Material can be transported into the middle of lake systems from icebergs and deposited as ice-rafted debris (IRD) (Thomas and Connell, 1985) or wind-blown particles that fall onto the lake surface whether it be open-water or a frozen surface (Lewis et al., 2002). All of these sediment sources have an imprint on the characteristics of the sediment deposited at the lake bottom, but the mechanisms of sediment transport with the potential to supply sediment over the greatest spatial extent in glaciolacustrine systems are either turbidity currents or overflows and interflows (Gustavson, 1975). These are discussed below in more detail and in relation to the limnological characteristics of glacial lakes.

2.2. Limnological properties and in-lake flow types

Glacial lake limnological properties have been determined through direct measurements in extant glacial lake waters or implied through laboratory modelling experiments of turbidity currents. In the early 20th Century, glacial lake sedimentation processes were understood on theoretical grounds (De Geer, 1912) or inferred from modelling of turbidity current processes in flume experiments (Keunen, 1951; Middleton, 1966). Direct measurement of glacial lake systems in the mid-1970's (Gustavson, 1975; Østrem, 1975 ; Ashley, 1975; Weirich, 1986) combined with sedimentological analysis of the basin fills provided new detailed insights into temporal changes in the properties of the lake waters during the year. These findings are synthesised by Smith and Ashley (1985) who identify three main pathways of sediment transport: underflows (hypopycnal), interflows or overflows (hyperpycnal). The type of flow is dependent on the density difference between the inflowing water and the lake water body, whose density is controlled by temperature and the sediment concentration (Fig. 2). For example, a sediment-laden inflow will often have a higher density than the lake water and will therefore form an underflow, whilst lower sediment concentrations, which are less dense than the lake waters, will form overflows. If a thermocline forms, an interflow can develop at the point where the inflowing water is of equal density to the lake waters. The type of flow may vary spatially across the lake basin depending on whether the source of the sediment is derived either directly from the ice contact or from nival streams. In both cases discharge variability will cause differences in sediment concentration which may also differ through time.

Temporal changes in lake water density can occur in lake systems that experience strong seasonal fluctuations in temperature and often glacial lakes are either monomictic or dimictic. Monomictic lakes experience stratification during the winter, with the lake surface freezing, and mixing during the brief summer period, whereas dimictic lakes experience mixing and isothermal water temperatures during the spring and autumn, with a thermocline developing during the summer. This process is enhanced by wind shear that allows redistribution of heat in the upper parts of the water column, with less dense waters collecting in the epilimnion and colder denser waters in the hypolimnion. Air temperatures decrease in the autumn, combined with heat loss from the water body by evaporation, causing the surface waters to cool. This in turn leads to surface water sinking as it becomes denser, enabling mixing with the warmer waters of the epilimnion and the breakdown of the thermocline as an isothermal water profile is achieved. Further cooling during the winter may cause the lake surface to freeze. A strong thermal gradient through the water column during summer causes density differences to develop in the lake waters, with less (more) dense waters in the epilimnion (hypolimnion).

Variations in sediment concentration through the water column can also cause lake stratification. Gustavson (1975) demonstrated this by measuring lake water temperature profiles, suspended sediment concentrations within the lake, velocity and sediment concentration of inflowing streams. The lake waters were stratified by sediment concentration rather than by changes in temperature profile through depth. Turbidity currents formed in the lake because water entering from sub- and en-glacial streams had higher sediment concentrations, and thus density, than the lake waters and lead to the formation of sediment structures similar to those described in later sections.

More recently, underflows have been detected using Acoustic Doppler profiling (Kostachuk et al., 2003) in glacier-fed Lilloet Lake, Canada. This enables the live monitoring of flows, generated, in this case, by high discharge events associated with high precipitation, as they propagate through the lake system. The velocity of the flows can be measured including the variations in velocity within the flow itself above the lake floor. In this specific lake system,

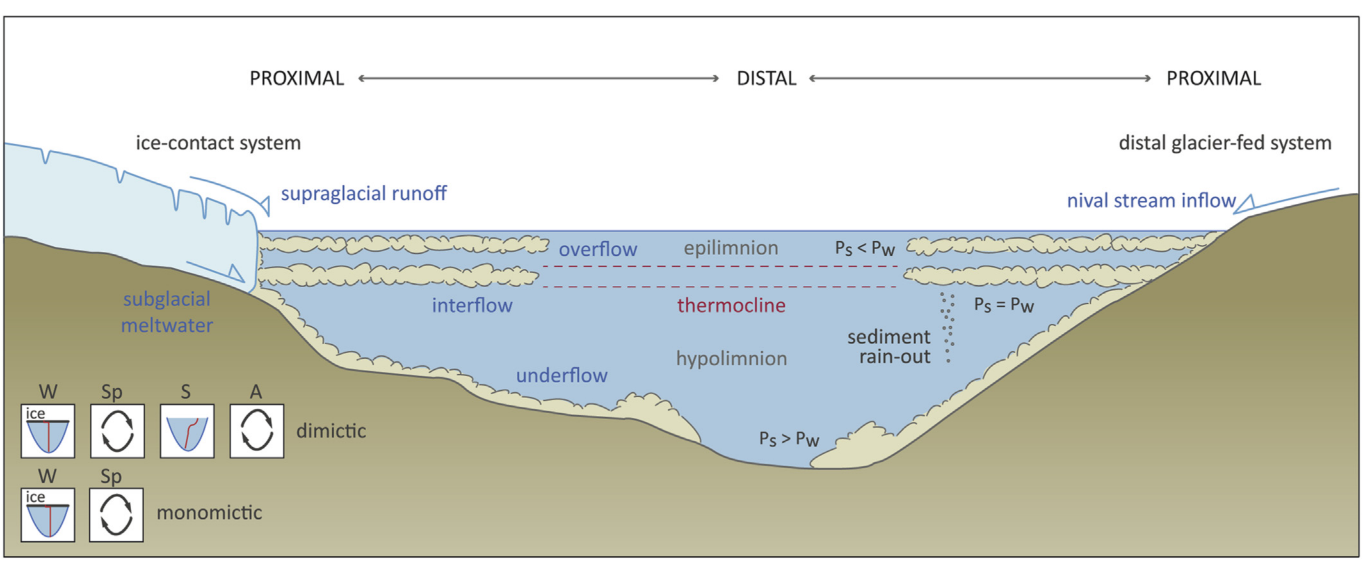


Fig. 2. The nature of flows within ice-contact and distal glaciolacustrine systems. In this example the lake is thermally stratified with density differences occurring during the summer period such that the position the sediment attains within the lake water will be driven by the comparative density of sediment inflow (Ps) and the lake water (Pw). This will produce underflows, interflows and/or overflows. Density differences will be enhanced by the sediment concentration within the flow, suspended sediment concentration. Temperature stratification can breakdown either once or twice in a year with the temperature profiles during the winter (W), spring (Sp), summer (S) and autumn (A) summarised in the left-hand corner of the figure.

underflows typically transmit material at velocities between 10 and 30 cm s^{-1} and possibly up to 40 cm s^{-1}. Grain sizes less than 2 mm will be entrained and transported in such flows, but deposition will start as the velocity drops below 10 cm s^{-1} deposition with grain sizes below ~250 μm deposited when flow velocities decrease to less than 2 cm s^{-1} (Hjulström, 1935). Crookshanks and Gilbert (2008) measured underflow velocities being between 3.5 and 6 cm s^{-1} with the maximum velocity decreasing to 15 cm s^{-1} 3.8 km from the point of inflow. This study also identified that underflows can flow around obstacles and then recombine, whilst the concentration of sediment within the flow decreases with lakeward transport caused by mixing of the head of the flow with the lake water and the boundary between the flow and the lake water becomes less distinct with sediment moving into higher parts of the water column.

Whilst underflows/turbidity currents are dominant within the Malaspina lake, Gustavson (1975) also identified that overflows and interflows existed simultaneously with underflows. In the Malaspina lake overflows from a subaerial stream formed due to the temperature of the inflowing stream being greater than the lake waters into which it flowed. Smith (1978) examined the sediment within Hector Lake and was the first to identify a glacial lake system dominated by overflow sedimentation through in-lake monitoring. Smith and Ashley (1985) argue that the difference between interflows and overflows is theoretical rather than observable on the basis that they are interchangeable depending on the relative density of the lake water. Interflows and overflows are recorded as flowing between 2 and 15 cm s^{-1} and small declines in flow velocity will enable the grain sizes smaller than 250 μm to fall from suspension. Consequently, the ability to differentiate between these types of flows through the analysis of the laminated sediment sequences may prove challenging.

Such phenomena have also been identified in distal glacial lake systems. For example, Menounos and Clague (2008), examining varve sediments from Cheakamus Lake, Canada, suggest that sediment is delivered to this distal glacier lake basin mainly by two modes. The first is a nival melt signal which produces high sediment concentrations leading to underflow transport mode during the spring and the early summer, whilst inter- and overflows dominate in the late summer and autumn when persistent glacier runoff driven by summer melting enters the basin in presumably lower sediment concentrations. In addition to the identification of these flows, flood events driven by autumn precipitation can also supply material to this basin. Lewis et al. (2002) and Lamoureux et al. (2002) also note that, in distal lake systems, two modes of sedimentation can prevail with underflows identified in proximal monitoring stations, whilst flows can evolve into homopycnal flows in more distal parts of the basin. A sill in the middle of the basin was sufficient to attenuate underflows from reaching a second more distal depocenter of the lake system.

The timing of sediment delivery to ice contact and distal glacial lakes is focused toward the spring and summer period (Church and Gilbert, 1975; Gustavson, 1975; Østrem, 1975; Gilbert, 1975; Lamoureux, 1999; Kostaschuk et al., 2005; Best et al., 2005; Lewis et al., 2002). Glacier ablation will evacuate sediment from englacial and subglacial meltwater portals to feed ice contact systems (Loso et al., 2006). Distal glacial lakes will also receive higher meltwater discharge through streams and consequently sediment inputs due to ablation during this interval (Lamoureux et al., 2002; Crookshanks and Gilbert, 2008). Nival melt in the spring will also enhance this effect in both distal glacial lakes and non-glacial lakes, and precipitation events during the summer have the capability to transfer high sediment concentrations to the basin through fluvial systems with as much as 50% of the annual suspended sediment transfer to the basin occurring during single run-off events (Church and Gilbert, 1975).

To summarise, in-lake monitoring of sediment delivery provides crucial information on deciphering the influence of different sediment sources and pathways influencing sedimentation in the proximal and distal regions of a lake basin. In the next section, we review information from detailed analysis of sediment facies distributed within lake basins.

3. Varve (micro-)facies of glaciolacustrine systems

The following section summarises the main facies encountered in glaciolacustrine varve sequences. These examples have been selected specifically to distinguish between active or palaeolake systems, the main source of sediment and transportation mode (glacial ice or subaerial nival stream), and proximal to distal relationships from the point of input. These are presented as schematic logs that visually synthesise the common structures observed and the thickness of the varves within glaciolacustrine and distal glacial lake systems (Fig. 3). Few studies have consistently used a microfacies approach in (palaeo)glaciolacustrine basins and therefore Fig. 3 includes facies for those sequences that provide either detailed descriptions of palaoeglaciolacustrine deposits, preferably at the microscale, or combine detailed limnological studies of existing glaciolacustrine systems with microfacies descriptions. Other studies do provide detailed descriptions at the macroscale, but it is not feasible to report all of these in this summary as many of the descriptions duplicate those described here.

3.1. Overflow varve facies

Smith (1978) describes varves in distal Hector Lake, which is 75 m deep and contains two major basins (Fig. 3a). The lake is thermally stratified during the summer with sediment delivered during peak fluvial discharge when air temperature increases in late spring or early summer. Sediment concentrations range between 5 and 10 mgl^{-1} in the epilimnion and 2–4 mgl^{-1} in the hypolimnion and thus overflows and interflows dominate, which lead to four distinct microfacies. First, a proximal facies (0.5–1 cm thickness) with sub-seasonal laminae in the melt season. Second, an intermediate proximal facies (0.2–0.4 cm thick) with mainly two silt laminae in the melt season. In both proximal and intermediate proximal varves, a mix of massive and graded laminae are present. It is common to see normal grading within the melt season layers, but inverse grading is also present in the melt season laminae. The presence of two layers in the intermediate proximal facies relates to an initial nival melt release of sediment to the basin prior to stratification in the lake and succeeded by a lamination derived from sediment associated with glacial melt. A clay laminae is also reported in the melt season which indicates that clay is deposited during the summer and there is some separation in time between the melt season flows. Third, intermediate distal facies (0.1 cm thick) has a summer layer that is too fine to discriminate further lamination structure. Finally, a distal facies is faintly laminated or is composed of massive clays with no distinct varve facies. These are the only facies that have been directly linked to overflow processes.

3.2. Underflow varve facies in ice-contact lakes

Ashley (1975) (Fig. 3a) identifies three groups of varves from former Glacial Lake Hitchcock, USA, with only partial use of microscopy to identify internal structures and composition. Group I varves have a mean thickness of 10 mm with a silt layer (melt season) that is thicker than the clay layer (non-melt season). There

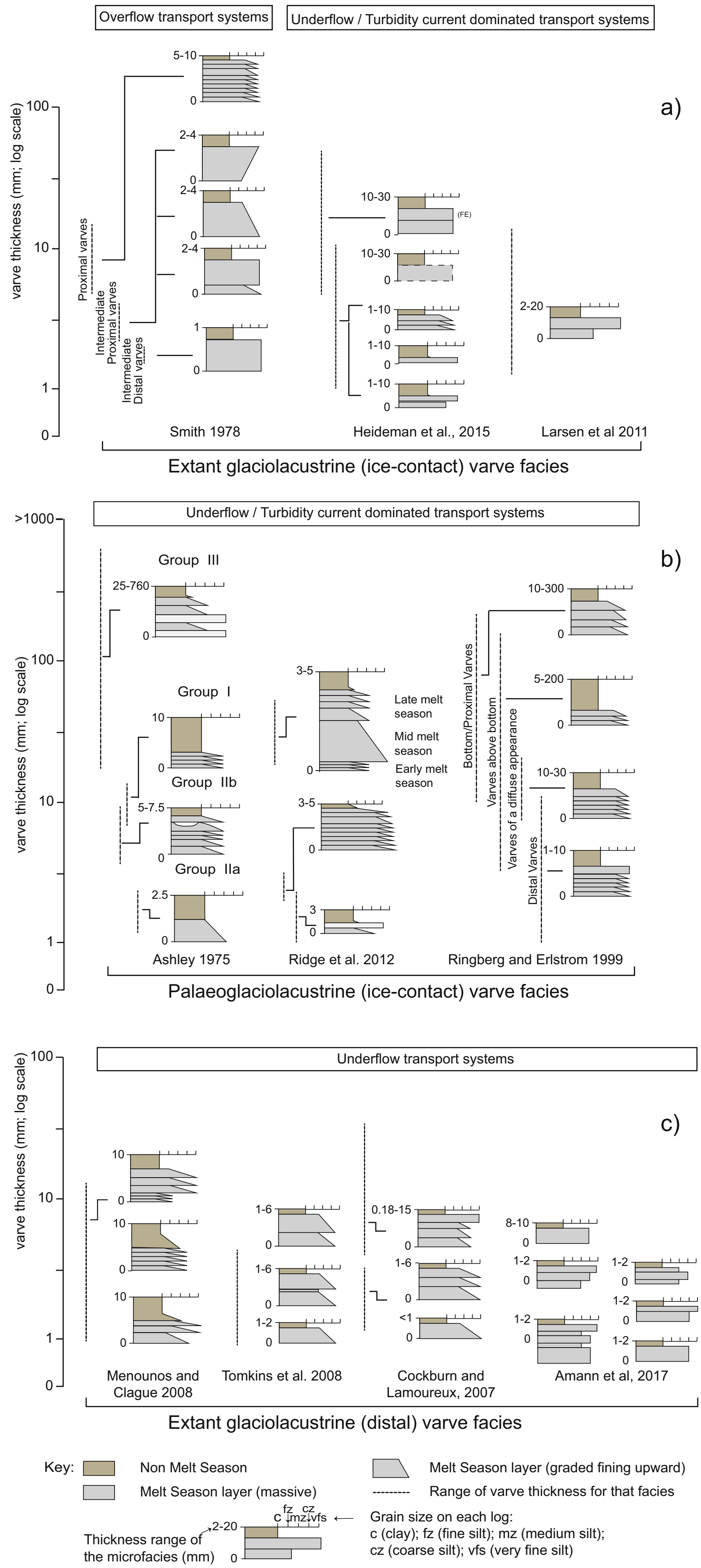


Fig. 3. A synthesis of different glaciolacustrine varve microfacies. These are categorised on the basis of a) extant ice-contact, b) palaeoglaciolacustrine ice-contact or c) distal glaciolacustrine systems, and the inferred mechanism of basinward transport. The schematics are based on the authors interpretation of data described within in each paper for grain size, structure and contacts, although these are not always consistent between studies. There are relatively few modern studies of ice-contact glaciolacustrine systems and therefore comparison between sedimentological models of extant and palaeoglaciolacustrine microfacies is limited. Also proximal palaeoglaciolacustrine (micro-)facies have been included in this synthesis. The y-axis is a logarithmic scale and each log has consistent grain size boundaries defined in the key.

are sharp contacts between the silt and underlying clay, and the clay and underlying silt layers. There are very fine graded beds in the silt layer and the clay layer grades upwards to a nearly pure clay at the lamination top. Within the Group II varves, the silt layer is equal in thickness to the clay layer. Ashley (1975) records three further subdivisions based on variations in thickness and structure. Group IIa varves are on average 2.5 mm thick; Group IIb varves are thicker on average, with a thickness of 5–7.5 mm, and contain multiple normally graded layers in the silt layer and evidence of small-scale cross lamination, erosional contacts within the silt layers and a sharp silt to clay contact. Group IIc is an unusually thick facies, with average thicknesses of 12.5–17.5 mm. The final set, Group III varves, display a silt layer that is thicker than the clay layer and are on average 25 mm–760 mm. Within the silt layer, there are a range of different grain sizes with 'micrograded' structures, which are not always graded or massive and are, in practice, too thin to describe consistently. The early part of the melt season silt layer can display cross lamination in sand, but the remaining silt layer is consistently silt size. Ashley (1975) inferred that the dominant settling grain size in Group I varves is clay. The increased silt layer thickness in Group III varves is inferred to reflect progradation of sediment across the surface of ice-contact subaqueous fans toward the basin centre, and hence silt is the dominant settling grade. Decrease in the silt layer thickness and mean grain size is caused by diminished sediment supply associated with glacier retreat. The presence of silt layer current structures also decreases in frequency with greater distance from the ice-margin.

Ringberg and Erlström (1999; Fig. 3b) present a detailed micromorphological description of distal glaciolacustrine varves from the Baltic Ice Lake system that existed at the southern margin of the Scandinavian Ice Sheet. Four microfacies were identified based on proximal to distal relationships with the ice margin, and lake water depth. The grain size of the melt season layers ranges between 10 and 30 μm with angular quartz fragments and concentrations of coarser grains at the base of, or within laminae. The varve types are divided into the following: 1) Bottom/Proximal varves (1–30 cm; summer (s: melt season) > winter (w: non-melt season) with a summer layer consisting of multiple graded laminae (often containing clay intraclasts) and a layer of coarser sediment grains immediately below the winter layer. These layers exhibit a sharp and often erosional contact with the underlying winter layer, which is composed of homogenous clay. Ringberg and Erlström (1999) infer that the summer layer was deposited via underflows, given the presence of erosional contacts and clay intraclasts, with continuous settling of clay continuing into winter, when the coarser sediment load has been exhausted. The sediment was inferred to be deposited in close proximity to the ice margin in water depths of around 35–50 m; 2) 'Varves above bottom' (0.5–20 cm; s < w) with a summer layer of multiple graded laminae containing matrix supported silts and some clay. There is a sharp upper contact to the texturally finer winter layer, which is normally graded from very fine silt to clay, with some evidence of shear within the clays. Like Bottom/Proximal varves, these couplets reflect summer underflow activity that disrupts the continuous settling of clay; 3) 'Varves of diffuse appearance' (1–3 cm; s > w) with fewer multiple graded laminae in the summer, and a greater amount of clay present. The lower part of the summer layer may contain clay intraclasts, and the contact with the underlying winter layer is erosional. These features are suggestive of underflow transport and deposition. The contact to the overlying winter layer is, by contrast, more obviously graded, giving these varves a diffuse appearance. This is perhaps a product of greater sediment supply from meltwater streams, whereas the relative thickening of the summer layer is likely a consequence of delta progradation. 4) Distal varves (0.1–1 cm; s > w) with up to eleven graded laminae in the summer layer and grain sizes of fine to coarse silt. These layers show a sharp upper contact, and often coarser silt laminae are observed just below the boundary between summer and winter. Overall, these structures are consistent with underflow deposition. The winter layer is graded from very fine silt to clay and has a sharp and erosional upper contact with the summer layer.

Ridge et al. (2012, Fig. 3b) analysed the surface of partially dried core material, rather than thin section micromorphology, sampled from the Connecticut Valley (New England, USA) where sediment was deposited in ice dammed lakes that formed during the retreat of the Laurentide ice sheet. There are a range of glacial varve facies that tend to be the thickest in the system, but there are also 'paraglacial' varves, that are the thinnest varve units in the system, but these varve 'types' have no formal definition. They identify three criteria that are common to all confidently measured varves: 1) the presence of pure clay in winter layers; 2) a sharp clay to silt contact and a graded silt to clay contact; and 3), an internally complex summer layer with multiple graded laminae. Importantly, the internal stratigraphy of proximal varves formed close to the retreating ice-front, which have varve thickness of >80 mm, exhibit three characteristic structures in the melt season layer that are defined by their position relative to one another in the sediment stack:

1. Early melt season layers composed of more clayey silt and rhythmic 'micrograded' laminae that perhaps reflect diurnal meltwater fluctuations.
2. Main melt season layers of fine sand or very coarse silt that are irregular in thickness. Often these layers form the coarsest sediment in the melt season and reflect high sedimentation during periods of high subglacial discharge, as well as nival flooding and/or larger rainfall events.
3. Late melt season layers that are more clay-rich and comprise 'micrograded' laminae. These laminae are less well-defined than in the early melt season layers, perhaps reflecting waning meltwater discharges at the end of the melt season. These structures grade into the overlying clay layer.

Heidemann et al. (2015, Fig. 3a) identified six different varve facies in Lillooet Lake, Canada, from a sequence that formed over the last millennia. Structures were examined from fresh core surfaces or photographs. Sediment is delivered to the basin by the Lillooet River, within an early melt season nival (snowmelt) peak, and later contributions from snow and glacier melt at higher elevations. Complex varve structures were observed in the melt season layers of sediments proximal to the Lillooet delta front, including thick flood deposits that were sometimes associated with a thicker clay cap in comparison to other varves. In more distal localities, the varves tended to be thinner, and contain a single melt season layer composed of medium silt, with occasional late melt season events observed. Varve thicknesses in proximal areas were on average between 20 and 30 mm, whereas distal varves were between 10 and 15 mm thick. In general, the melt season layers are thicker than non-melt season layers.

3.3. *Underflow varve facies in distal glacier-fed lakes*

Lamoureux et al. (2002) and Lewis et al. (2002) provide contemporary measurements of distal glacial lake Bear Lake from Devon Island in Canada and how they are used to interpret sedimentation patterns in two basins. Underflow currents enter the southern basin, which is directly fed by glacial meltwater in the summer, with a velocity of between 10 and 20 cm sec^{-1} during major discharge events. The underflow velocity is greatest in the lower 1 m of flow but the flows have a height that was greater than

3 m. In the northern basin, which is stream fed from a smaller non-glacierised catchment, homopycnal flow is identified as the dominant form of sediment distribution within the basin. Varves have been identified in the southern glacial meltwater-fed basin and are composed of two types of: 1) couplets with complex melt season layers of silt laminations reflecting high discharge events with a clay cap deposited during the non-melt season; or 2) couplets with a simple silt lamination grading into clay which has a sharp upper contact. The couplets are between 5.4 and 0.025 cm in thickness. Single grain layers of sand are derived from aeolian transport onto the frozen lake surface in winter, which are deposited at lake ice breaks up during the spring and summer melt season.

Cockburn and Lamoureux (2007; Fig. 3c) identified a series of varve structures within distal glacial Summit Lake (Canada). The consistent recurrence of clay layers at the top of graded silt laminae represent an annual layer of between 0.1 and 1.0 cm thickness. Sediment transfer to the basin during the early melt season occurs either as nival melt or glacier melt. This produces very fine laminations of 'clay-rich' grain sizes with the clay content gradually increasing toward the top of these series. Later melt season events are detected in the varve structure as coarse laminations with little clay, reflecting late summer rainfall events before grading into the non-melt season layer of a clay cap. More simple annual structures also exist in the form of graded silt to clay forming a single couplet and the sequence is interspersed with turbidites ranging from coarse silt/sand to fines and being substantially thicker the annual varve structure. Similar structures are identified in other extant distal glacier lake systems such as Mirror Lake (Tomkins et al., 2008, Fig. 3c) and Cheakamus Lake (Menounos and Clague, 2008, Fig. 3c) . In the latter example, seven lamination forms were identified in the summer layer that distinguishes, on microstratigraphic evidence, between early, mid and late summer runoff events, other inflow events and sustained glacier runoff, highlighting the complexity and opportunity that exists within detailed analyses of these glaciolacustrine sediments.

3.4. Summary

This sample of key studies describes the types of sediment structures observed at different sampling points within contrasting glacial and distal glacial lake systems. The sediment structures described decrease in thickness from proximal to distal locations with decreasing complexity in the melt season part of the varve (e.g. Ashley, 1975). This reflects the reduced number of relatively higher energy flows that reach distal parts of the basin. In distal parts of extant ice-contact lakes there appear to be variations in the nature (graded and massive laminations), thickness and number of flow events recorded in the melt season (e.g. Heideman et al., 2015), although these are not always consistently reported. In addition, the features that are recorded in these extant ice-contact lake sediments are common to extant distal lake facies if sediment is delivered as either underflows or overflows, although the overflow melt season laminations tend to be fewer and less complex.

Nonetheless, it is possible to observe key sedimentological characteristics that are common to all glaciolacustrine varves:

1) A sharp contact between the clay (non-melt season) layer and the overlying coarser (melt season layer), which may be visible at the macroscale.
2) A melt season layer at the macroscale is generally composed of very fine sand and silt but with variations in structure and thickness. These layers comprise either multiple graded or massive laminae. Coarse sediments are commonly observed at or just below the contact to the non-melt season (clay) layer.
3) When observed at the macroscale, there is a sharp contact between the melt season layer and the overlying non-melt season layer.
4) The non-melt season layer is composed of nearly pure clay, or a unit that grades from very fine silt clay to clay.

Other commonly reported features are:

1) The presence of clay in melt season layers, probably due to near continuous settling through the summer. This is predominantly observed in distal basin localities or in sediments associated with overflows (Ringberg and Erlström, 1999; Cockburn and Lamoureux, 2007).
2) Underflow sedimentation products in proximal locations, evidenced as melt season layers with multiple graded beds, small-scale cross lamination in sediment grades, erosional contacts between layers, and clay intraclasts (Ashley, 1975; Ridge et al., 2012).

The methods used to describe these features vary from direct examination of the core surface or outcrops, to the use of thin section micromorphology on laminations from existing lake systems. Therefore, it is not immediately clear whether the similarities and differences highlighted above are either: i) real; ii) driven by the resolution that can be achieved through the different analytical methods used; iii) discrepancies in the use of descriptive terminology in the analysis or: iv) a combination of these factors. As such, there remains a potential disconnect between consistent descriptive protocols and terminology between the different methods, limiting our ability to establish equifinality within these types of sediments.

Herein we explore glaciolacustrine varve structure at the microscale, using material from three former glaciolacustrine basins. These examples are used to exemplify a modified method of sediment description, utilising lamination types and lamination sets (assemblages) as terms, to detail the diversity of varve (micro-) facies and interpret processes of varve formation with links to the point of sedimentation in the lake basins. This is the first time that such a review has been undertaken for glaciolacustrine sedimentation. The specific site contexts are introduced below and followed by a summary of sampling and sediment description protocols. This last point is critical in order to examine the similarities and differences observed in multiple sediment sequences.

4. Site selection

The three palaeoglaciolacustrine basins used in this study are the Lago General Carrera/Buenos Aires lake system in Patagonian South America, the Llangorse lake system in South Wales, and the Lochaber glacial lakes system in Scotland. These former lakes vary in size, setting, and in the control on their formation, i.e. either the initial retreat of the glacier (Lago General Carrera-Buenos Aires and Llangorse Lake), or glacier advance and retreat to and from ice maxima, with influences on lake water depth (Lochaber glacial lake sequences).

4.1. Lago General Carrera/Buenos Aires, Chile/Argentina (LGC/BA)

The LGC/BA basin, located at 46.5°S in central Patagonia, is a large, currently existing, transnational lake system that presently drains to the Pacific Ocean via the Río Baker. Seasonal meltwater from the North Patagonian Icefield currently supplies a limited amount of sediment to the western end of LGC/BA (Elbert et al., 2013). During the local Last Glacial Maximum (LGM), expansion of the North Patagonian Icefield blocked westward lake drainage to the Pacific via the Río Baker, and meltwater was instead diverted eastward to the Atlantic Ocean (Turner et al., 2005; Glasser et al., 2016; Thorndycraft et al., 2019). During the early stages of regional deglaciation, dated to ~18.1 cal ka BP by Bendle et al. (2017), an ice-contact proglacial lake developed, with the water level controlled by an overflow col cut through the local LGM (Fenix) terminal moraine complex (Fig. 4). A series of ice-front stillstands occurred within several kilometres of the local LGM ice extent. Examining exposures of laminated silt and clay, Caldenius (1932) first interpreted these deposits as glaciolacustrine varves. More recently, Bendle et al. (2017), confirmed the annual nature of sedimentation using macro- and microscale sedimentology, and developed the Fenix Chico Master Varve Chronology (FCMC17) of 994 ± 36 varve years deposited between 18.1 ± 0.21 and 16.9 ± 0.1 cal ka BP. This basin provides an example of a very large glacial catchment with a long (~8–30 km) ice-contact lake margin, where the glacier supplied the vast majority of sediment to a relatively small glacial lake that has a lake area that changes from 15 km^2 to 185 km^2.

4.2. Llangorse, South Wales

The Llangorse basin formed as this sector of the British-Irish Ice Sheet retreated toward the north at the onset of deglaciation following the local LGM. Two lobes of ice unzipped in the Usk and Wye catchments (Lewis, 1970) with an ice-contact glaciolacustrine system developing at the head of the Wye catchment (Fig. 5). The reconstructed glaciolacustrine system had a relatively short ice-contact lake margin of 5–7 km in length, and a height of the ice-front in excess of 50 m. Palmer et al. (2008a,b) reported a succession of 575 glaciolacustrine varves that formed in this basin using thin sections sampled from a single core in the north of the extant lake (Fig. 5), although this is currently a floating chronology not fixed to an absolute timescale. In contrast to the LGC/BA basin, there is a small catchment beyond the limits of the ice margin dominated by moderately high relief to the east and with no glacial input from distal ice masses through streams, although nival melt may have been a significant source of sediment.

4.3. Glen Roy/Glen Spean, Scotland

These Scottish lake systems formed during the latter part of the Loch Lomond Readvance, broadly equivalent to the latter part of the Younger Dryas event (Palmer et al., 2010, 2012; Palmer and Lowe, 2017). The advance of ice into the lower part of the Spean catchment blocked drainage pathways, forming a series of glaciolacustrine systems that changed in configuration and surface altitude according to the advance and retreat of the ice (Sissons, 1978, 1979, 2017). Palmer et al. (2010) produced the 515-year Lochaber Master Varve Chronology (LMVC), the first for glaciolacustrine systems in the UK that combines several varve chronologies, which has enabled the position of the ice front to be linked to varve thickness variations (Fig. 6). This site is useful as it records both changes in the lake water depth and position of the ice margin in Glen Roy, but a consistent water depth combined with advancing and retreating ice in Glen Spean. The consequence of the changing water depth in Glen Roy is that relatively shallow areas of the lake system become deeper as the ice advances and then shallow as the ice retreats, allowing an assessment of changes in water depth on varve microfacies. The drainage of the glacial lake systems and Holocene river activity in steep mountain catchment caused many of the lake bottom records to be eroded and therefore only a fragmentary record now remains. However, two sequences are discussed from Glen Roy where water level varied: the Glen Turret Fan and on the Burn of Agie Fan (Fig. 6). Exposures of laminated silts and clays on subaqueous fan surfaces were sampled. Glen Turret Fan has a

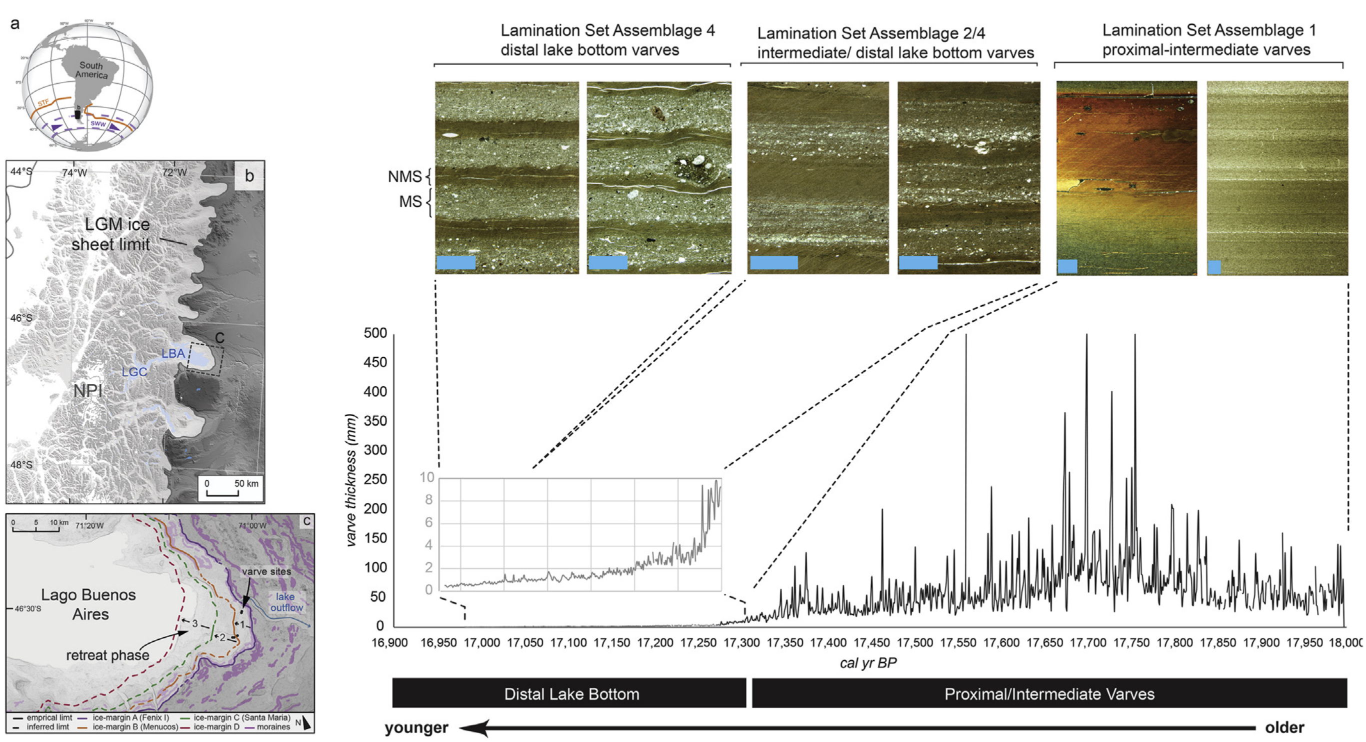


Fig. 4. Lago General Carrera/Buenos Aires (a–c) locates the basin that formed at the eastern margins of the Last Glacial Maximum North Patagonian ice sheet. The glaciolacustrine system formed within the Fenix 1 moraine with the varve thickness record progressively becoming finer, which reflects the retreat of the ice margin. In this study, the varve record is placed on an absolute timescale through the identification of the Ho Tephra horizon (Bendle et al., 2017) and examples of the microfacies of the lamination set assemblages mainly from the latter part of the record (main plate) are described in this paper. All microphotographs are in plane polarised light and the blue bar represents 1mm.

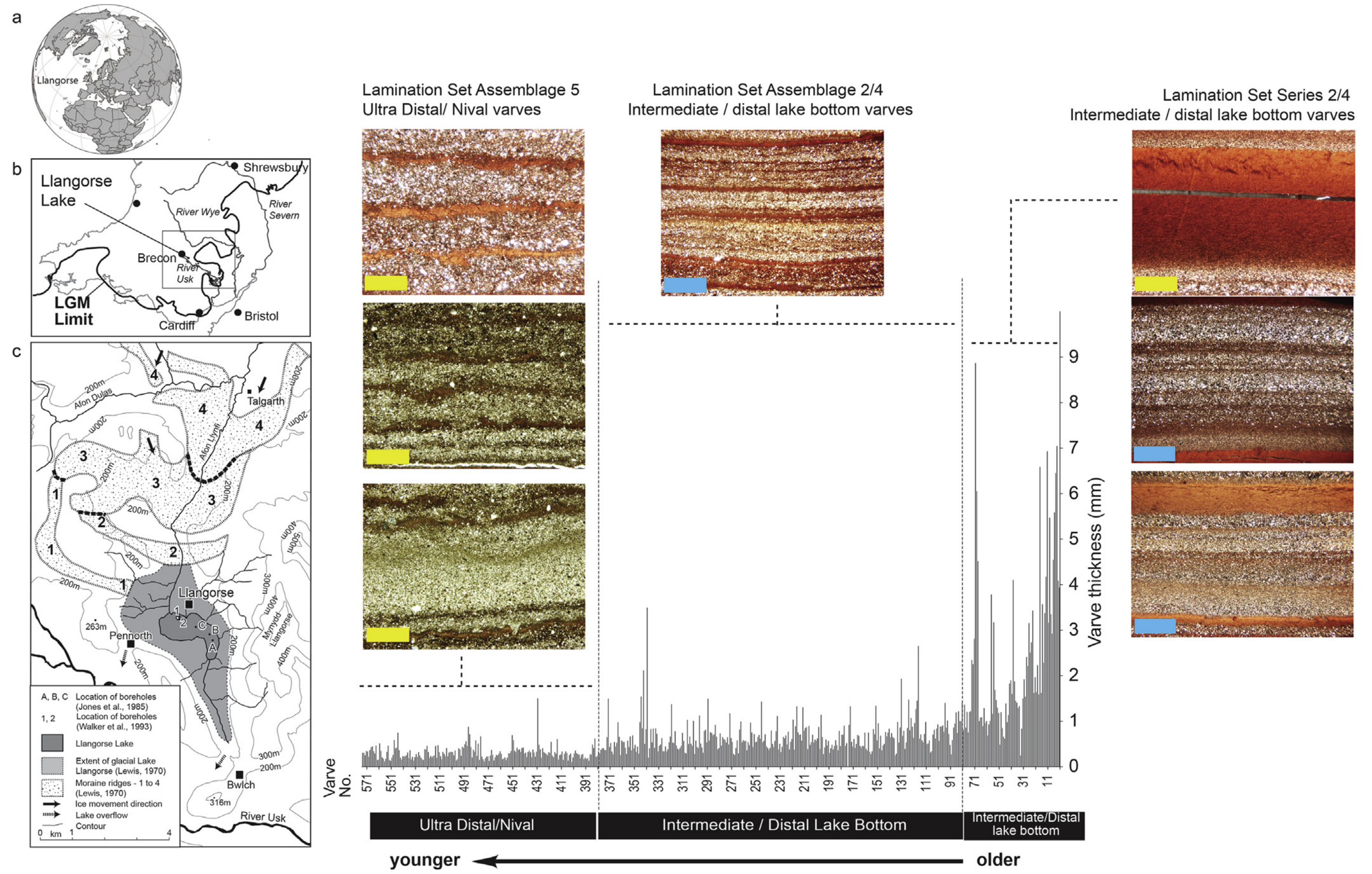


Fig. 5. Llangorse Lake South Wales that developed initially as a glaciolacustrine system during the retreat of the Last Glacial Maximum ice (a–c). The lake system evolved into distal glacial lake when ice no longer formed a competent ice damn also causing the lake level to fall. The putative position of the retreating ice margin is related to four sediment complexes that lie to the north of the glaciolacustrine system. The main plate provides examples of the microfacies of the lamination set assemblages and where they occur in the varve thickness records. This forms only a floating annual chronology at present. All microphotographs are in plane polarised light with the blue bars representing 1 mm and the yellow bars representing 0.5 mm.

1.25 m thickness of sediments and Burn of Agie has a 1.5 m long succession of which 0.5 m is laminated. Sediments from the Laggan East site (Fig. 6) were accessed through a core bored through an artificial, reservoir beach at the eastern end of Loch Laggan with the varve records forming in approximately 10 m water depth.

5. Methods

5.1. Sediment sampling

The principle form of microfacies analysis for this study was thin section micromorphology. Thin sections were prepared from sediment sampled from fresh exposures from the Fenix Chico valley of LGC/BA and in Glen Roy. The material recovered from Loch Laggan East required a rotary drill. All of the Llangorse Crannog material was sampled from a 1 m long, 50 mm diameter Russian corer. All samples were dried by either air-drying (Lago General Carrera/Buenos Aires) or the acetone replacement method (Llangorse and Glen Roy/Spean sequences) and impregnated using polyester resins using standard procedures at Royal Holloway University of London (Palmer et al., 2008a,b). Thin sections were examined using an Olympus BH 2 petrological microscope or a Leica M205C stereo zoom petrological microscope. Images of the thin sections were captured using a Penguin Pixera 600es digital camera and measurements made using Image Pro-express 4.5, with a measurement precision of 64 μm at x 0.78 zoom.

5.2. Developing a descriptive scheme for the microscale

For clastic laminated sediments from former glaciolacustrine basins, it is not always immediately apparent if the observed structures relate to annual sedimentation patterns (varves) or sudden compositional changes that relate to a range of events of different timescales (Cockburn and Lamoureux, 2007; Menounos and Clague, 2008). Structures suspected of being annually laminated require independent dating, but glaciolacustrine settings tend to lack significant quantities of dateable material (e.g. organic remains) making a robust sedimentological model a prerequisite (Zolitschka et al., 2015). This in turn requires that a consistent descriptive protocol is adopted at a range of scales that separates descriptive and interpretative terminology (Schnurrenberger et al., 2003). The classification scheme of Schnurrenberger et al. (2003) was developed for the analysis of lacustrine sediments based on the range of different components that accumulate in the diverse array of lake systems. The treatment of the clastic components by Schnurrenberger et al. (2003) is biased toward macroscale description of sedimentary structures and grain size, allied to the roundedness, sorting and fabric. Unfortunately, these are not always applicable to the range of structures that are observed at the microscale. The microscale description of laminated sediment structures has evolved from the micromorphological analysis of soils (e.g. Kemp, 1999) and glacial sediments (van der Meer, 1993; Menzies and van der Meer, 2012), which use a range of different

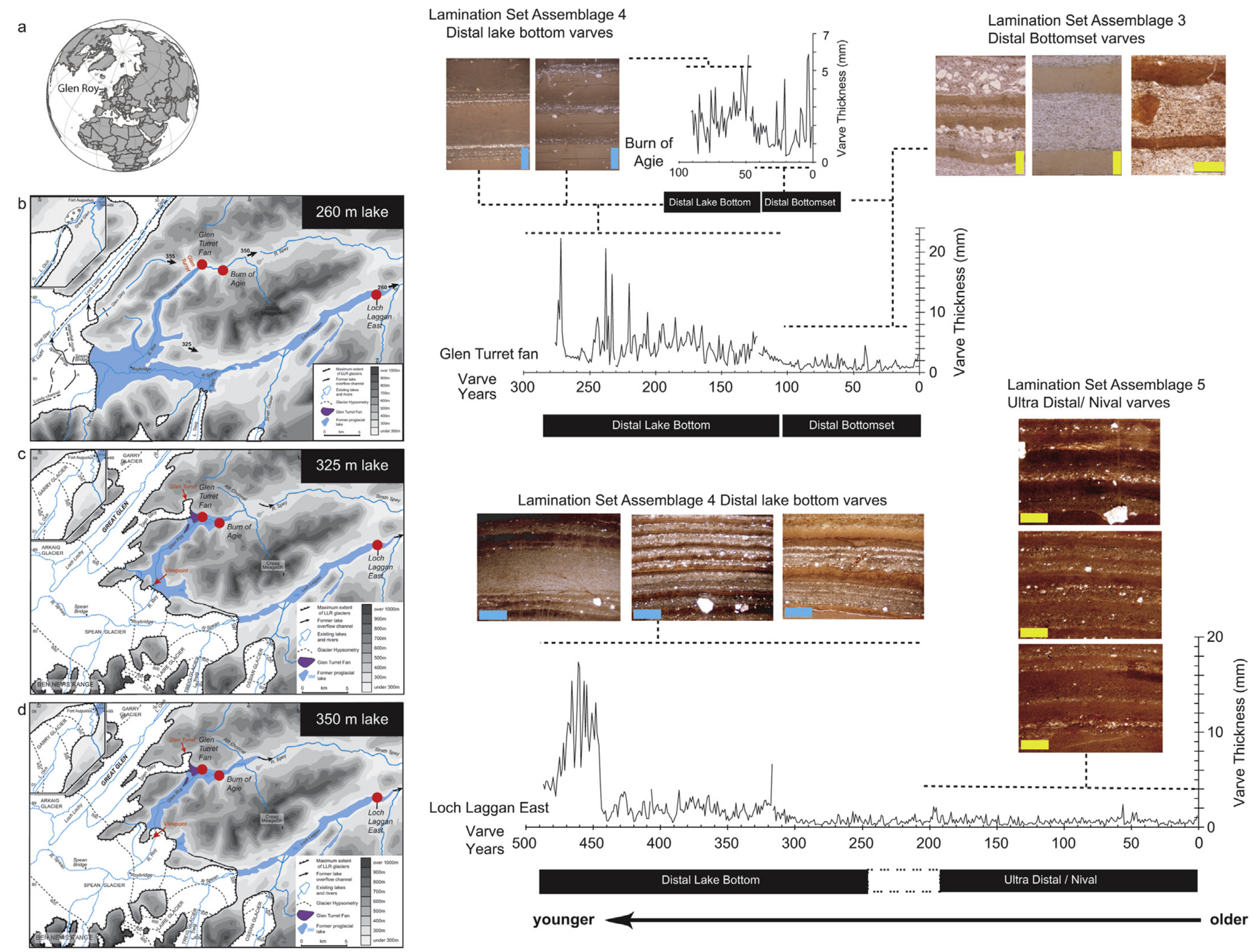


Fig. 6. Context for the Lochaber Lake glaciolacustrine systems in Scotland (a–d). The advance of the Loch Lomond Readvance glaciers (broadly synchronous with the Younger Dryas/GS-1) caused the formation of glaciolacustrine systems initially in the Spean and Roy valleys (Sissons, 1978) with further ice advance causing separation of the lake into two lake systems. The Spean was maintained at 260 m, whereas the water level in the Roy valley rose initially to 325 m and then 350 m. Sissons (1978) suggested that the same lake levels were attained as the ice retreated. The location of the three samples sites (Loch Laggan East (LLE), Glen Turret Fan (GTF) and Burn of Agie (BOA)) are located with red circles. The main plate provides examples of the microfacies of the lamination set assemblages and where they occur in the varve thickness record. This is presented as a floating annual chronology at present. All microphotographs are in plane polarised light with the blue bars representing 1 mm and the yellow bars representing 0.5 mm.

and shared terminologies and qualitative, semi-quantitative and quantitative techniques to examine the nature of in-situ alteration and/or synsedimentary or post-sedimentary deformation of the succession to allow reconstructions of the palaeopedological and sedimentary settings. By comparison, laminated sediments retain many of their primary sediment structures, with less evidence of direct and pervasive deformation. Therefore, the descriptive scheme (below) can be seen as a scaled version of macroscale descriptive practices in other sedimentary environments (Miall, 1977), which also links to the description of beds and laminations in geological convention (Table 1).

Laminations are distinguished from beds by their thickness, with beds greater than, and laminations thinner than, 10 mm thickness (Ingram, 1954). Laminations have been further subdivided into thick lamina (30–100 mm), medium lamina (10–30 mm), thin lamina (3–10 mm), and very thin lamina (<3 mm) (Campbell, 1967), which contradicts the definition of Ingram (1954). A further level of distinction is made through the definition of laminasets that is ' …. a group or set of conformable laminae that consist of distinctive structures within a bed'. *Set* is

Table 1
Definitions of bed and lamination thickness (Campbell, 1967; Reineck and Singh, 1980). Thin and very thin beds can be used interchangeably with thick and medium lamina within this system.

Beds	Thickness (cm)	Laminations	Thickness (mm)
Very thick bedded	100		
Thick bedded	30–100		
Medium bedded	10–30		
Thin bedded	3–10	Thick lamina	30–100
Very thin bedded	1–3	Medium lamina	10–30
		Thin lamina	3–10
		Very thin lamina	<3

used in this context 'as a group of essentially conformable strata or cross strata, separated from other sedimentary units of surfaces of erosion, non-deposition or abrupt changes in character …. ' (McKee and Weir, 1953). Campbell (1967) actually uses varves as examples of defining beds and bedsets. Limitations do exist as the definitions of thickness have provided contradictory definitions at the macroscale. Indeed, Reineck and Singh (1980) argue that the term laminaset as defined by Campbell (1967) actually conforms to the definition of beds. Terminology such as 'microlamination' and 'micrograded' has no formal definition, and there is no clear boundary between microscale and macroscale. Thus, in this study we have mainly concentrated on structures that are less than 10 mm in thickness and encompass thin lamination (3–10 mm thickness) and very thin lamination (<3 mm thickness). Structures of medium lamination size have also been included in the descriptions, but fewer examples are provided. It should be noted that thickness is not used as a means of classifying the lamination types, but is used as part of the interpretative process when combined with the sediment structures observed within a lamination set (see Section 7).

Specifically, for glaciolacustrine sediment descriptions, the proposed scheme develops the terminology and protocols used by Smith and Ashley (1985) and the microscale analysis of Ringberg and Erlström (1999) and Palmer et al. (2012). These earlier works use the descriptors: particle size of laminations, type of structures, and the nature of the contacts between laminations. Here we also include the sorting of the laminations, and the presence of other structures, including clay intraclasts, dropgrains, soft sediment deformation structures, and the development of plasmic fabric (birefringence models of plasma grains based on their optical properties caused by orientations of particles relative to one another).

The scheme first defines individual *lamination types*, and then groups these into *lamination sets* based on common cycles of sedimentation, following the convention outlined above. Lamination sets may or may not represent a single year of sedimentation, but since, by definition, a glaciolacustrine varve is formed of at least two thin or very thin lamination types then a varve will always have the properties of a lamination set. Most importantly this scheme allows a full description of the microfacies characteristics of the varve sediments. This process permits the identification of specific sedimentation events in the early, middle or later part of the melt season and allows the examination of the frequency of these events during the evolution of the glaciolacustrine system (Palmer et al., 2012).

6. Application of the descriptive scheme

6.1. Lamination types

These are summarised in Table 2 with eighteen lamination types commonly identified at the microscale and examples provided in Fig. 7. The maximum grain size is fine sand and decreases to clay. The structure can vary from massive to normally or inversely graded. The sorting of laminations ranges from well sorted to poorly sorted, with the latter tending to contain coarse silt or very fine sand grains within a matrix of medium and/or fine silt.

6.1.1. Lamination types - persistent flow

Lamination types i, ii, iii, iv (Fig. 7) show evidence of persistent flow, through the presence of well-sorted laminations with structures ranging from massive to normally and inversely graded. The massive structure of i, ii, iii, iv show that this persistence of flow is maintained throughout the period of input, with incremental, grain by grain addition of sediment through an undefined duration of time. Lamination type i and ii sometimes contain clay intraclasts, which illustrate that in the coarser grain sizes there is sufficient energy in current flows at the sediment-water interface to erode fragments of previously deposited clay and entrain very coarse silt and very fine sand grains. These features suggest that underflow sedimentation is most likely (Ringberg and Erlström, 1999). The coarser sediments are likely to be transported as traction or saltation loads (LT i, ii) but in finer grade sediments (LT iii, iv) transport will occur higher in the water column as part of the turbid plume and be deposited from suspension.

6.1.2. Lamination types - variable flow

Lamination types v, vi, vii, viii, ix, x, xi (Fig. 7) show evidence of variability in the flow strength of a single input event. Whilst most flows show a decline in flow energy as normally graded beds enabling progressively finer sediment grades to reach the lake bed (LT v, vi, vii, viii, ix), increasing flow strength is indicated by inversely graded beds (LT x, xi). The normally graded lamination types are the most common lamination types observed in these

Table 2
Sedimentological properties of the lamination types observed in the microfacies of glaciolacustrine laminated sediments. These laminations exist up to thin lamination thicknesses, but the overall thickness of the laminations is not important to their description. These lamination types are can form a range of different lamination sets that are summarised in Fig. 7. Abbreviations: FS = fine sand; VFS = Very fine sand; VCZ = very coarse silt; CZ = coarse silt; MZ = medium silt; VFZ = very fine silt and C = Clay. Structure: Ma = massive; IGr = inverse grading; NGr = normal grading; Sorting: WS = well sorted; MS = moderately sorted; PS = Poorly sorted; Contact; Sh = sharp; Other: Dg = dropgrain; In = intraclast; WD = Well-developed.

Lamination Type	Grain Size (Dominant)	Structure	Sorting	Upper Contact	Other
i	VFS/FS	Ma	WS	Sh	In/Dg
ii	VCZ	Ma	WS	Sh	In/Dg
iii	CZ	Ma	WS	Sh	Dg
iv	MZ	Ma	WS	Sh	Dg
v	VFS/FS - MZ	NGr	WS	Sh	Dg
vi	VCZ-MZ	NGr	WS	Sh	Dg
vii	CZ-MZ	NGr	WS	Sh	Dg
viii	CZ-MZ	Single grain alternations			Dg
ix	CZ/MZ-FZ/C	NGr	WS	Sh	Dg
x	MZ-CZ	IGr	WS	Sh	Dg
xi	MZ-VCZ/VFS	IGr	WS	Sh	Dg
xii	FS/VFS	Ma	PS/Diamict	Sh	Dg
xiii	VCZ	Ma	PS/MS	Sh	Dg
xiv	CZ	Ma	PS/MS	Sh	Dg
xv	MZ	Ma	PS/MS	Sh	Dg
xvi	VFZ-C	NGr (short)	WS	Sh	Masepic WD
xvii	VFZ-C	NGr (long)	WS	Sh	Masepic WD
xviii	C	Ma	WS	Sh	Masepic WD

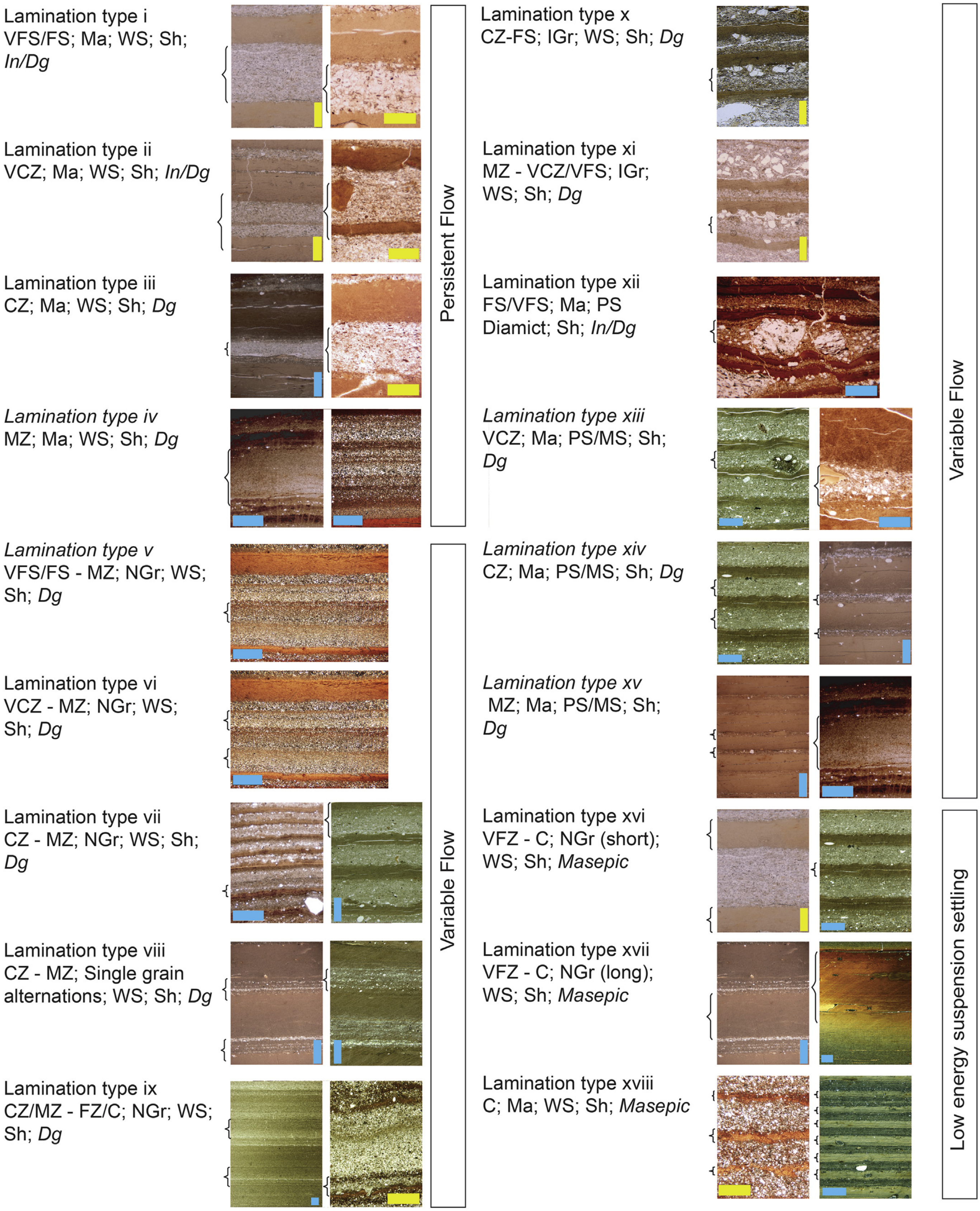


Fig. 7. Examples of lamination types observed within glaciolacustrine varve microfacies. Lamination types *i* to *xv* have grain sizes ranging between medium silt and fine sand whilst lamination types *xv* to *xvii* are very fine silt and clay. All images are under plane polarised light and scale is indicated by either a yellow bar (length 0.5 mm) or a blue bar (length 1 mm) in each photograph. The bracket indicates the position of the lamination type with those properties summarised on the left. Dominant Grain size: FS = fine sand; VFS = Very fine sand; VCZ = very coarse silt; CZ = coarse silt; MZ = medium silt; VFZ = very fine silt and C = Clay. Structure: Ma = massive; IGr = inverse grading; NGr = normal grading; Sorting: WS = well sorted; MS = moderately sorted; PS = Poorly sorted; Contact; Sh = sharp; Other: Dg = dropgrain; In = intraclast.

records, whilst the inversely graded lamination types are rare. Critically, this would suggest that either there is only one significant flow event propagated into this part of the lake basin at this time, or that there might be a lateral migration of a quasi-steady flow such that coarser sediment is delivered to this point of the basin through time. Massive, poorly sorted lamination types (LT xii, xiii, xiv, xv) have relatively fine matrices of medium or fine silt, with occasional coarse silt or very fine sand grains randomly distributed within the matrix. The massive nature of the sediment suggests that there is consistent supply of this material to this part of the basin, but the range of grain sizes hint that, whilst medium or fine silt is continuously deposited from suspension, coarser grained particles are added through low density underflows and subsequently settle in conjunction with the finer sediment grades. Alternatively, coarser sediment grades are mixing by settling into the finer sediment.

6.1.3. Lamination types — very low energy suspension settling

Lamination types xvi, xvii, xviii (Fig. 7) are composed of predominantly clay grade particles, which are either massive or show normal grading from very fine silt to clay. Lamination type xvi and xvii are differentiated on the basis that this grading is restricted to the very start of the clay layer (xvi) or occurs more consistently through the lamination type (xvii). These lamination types clearly show sedimentation from suspension settling through a water column with few currents acting to resuspend these fine sediment grades. Relatively coarser sediment grades fall from suspension first and are generally uninterrupted. Masepic fabrics develop where clay particles are aligned often parallel to bedding in laminated sediments over relatively short distances (van der Meer, 1999). This phenomenon is caused by compaction and orientation of the clay particles through further sediment accumulation that creates extensional forces on the clay particles and their subsequent alignment.

6.2. Lamination sets

The consideration of the processes associated with the formation of individual lamination types is an important step in developing a robust sedimentological model. However, the lamination types cannot be treated in isolation, as glaciolacustrine basins often accumulate sequences of lamination types that show repeating cycles of sedimentation with different thicknesses, as highlighted in Section 3. These 'cycles', which can be defined as 'lamination sets' (Section 5.2), are composed of at least two components (often referred to as couplets) with alternations of either i) one coarser lamination type (LT i to xv; Fig. 7) alternating with one very fine lamination type (LT xvi to xviii; Fig. 7) or; ii) two or more coarser lamination types (LT i to xv; Fig. 7) alternating with finer lamination types (LT xvi to xviii; Fig. 7). We avoid the use of couplet here for two reasons: 1) it is not used within the geologic hierarchy of lamination type to lamination set and 2) couplet gives the impression of the structure composed of two parts, although the microscale analysis demonstrates that the structure is composed of more than one lamination type.

Examples of the *lamination sets* are presented in Figs. 4–6, whilst a summary of their overall properties allied to schematic representation is presented in Fig. 8b. It should be noted that, at this stage, this is not an exhaustive list of all possible lamination sets, rather those with common properties and those that subscribe to the cyclical nature of sedimentation. Critically, these display strong evidence of different relative timing of sediment transportation and deposition (a microstratigraphy) to the lake floor indicating seasonal variations in the supply of sediment to former lake basins. The microstratigraphic relationships are helpful in interpreting sub-annual changes. The interpretation is informed by linking the lamination set characteristics, which include the thickness, to specific parts of the lake basin. For example, Ashley (1988) used this approach when interpreting and naming varve structures in NE America referring to: Proximal I, deposited on the landform of a subaqueous outwash; Proximal II, deposited on the ice contact delta or distal lake delta; Intermediate III and Distal IV, deposited further into the lake basin but at different distances. Where possible this scheme of Proximal, Intermediate and Distal has been adopted when interpreting the laminations sets, although by the very nature of our analysis the microfacies are usually distal (Fig. 8a; 8b).

6.2.1. Interpretation of lamination sets

Lamination Set Assemblage 1 (Fig. 4; 7; 8a, 8b) have an overall thickness of between 20 and 600 mm with a series of coarser grain size lamination sets that are thicker than the finer lamination type. The coarser grain sizes of the lamination set contain multiple graded laminae of very coarse silt to medium silt as previously identified at the macroscale by Ashley (1975) and Ridge et al. (2012) for glaciolacustrine varves in the coarser component of the lamination set. These can also grade from very coarse silt to fine silt in Lago Buenos Aires/General Carrera (Bendle et al., 2017). The rhythmic sedimentation pattern can sometimes incorporate coarser grain sizes, but overall the package is considered a product of quasi steady underflow turbidity currents. This part of the lamination set may also include a thicker lamination with very fine sand grading to coarse silt and this lamination is often the thickest part of the lamination set. This is a product of surge-type sediment flows in the basin, probably from a relatively proximal glacier margin, where meltwater is discharged into the lake basin from sub- and englacial portals (Ridge et al., 2012; Bendle et al., 2017). This source of material is heavily sediment laden forming debris flows or hyperconcentrated flows (Middleton and Hampton, 1973; Mulder and Alexander, 2001; Bennett et al., 2002) at the point of entry into the lake, with these evolving into turbidity flows that produce the distinctive alternation of normally graded coarse and medium silt laminae.

The Lamination set 1 has a sharp contact to the finer lamination type, which grades from very fine silt to clay in the very first part of the lamination type before turning to uniform clay and a sharp contact at the upper part of the lamination type. This is indicative of suspension settling in still waters (Ashley, 1975; Ringberg and Erlström, 1999). The sudden switch from a system dominated by underflow sedimentation driven by currents to one dominated by suspension settling reflects seasonal changes in energy regime between the melt season and non-melt season. Therefore this lamination set is interpreted as a glaciolacustrine varve where the melt season layer is dominated by periods of both quasi-steady flow and surge type deposits which, when combined with their overall thickness characteristics and ratio of thickness between the melt and non-melt seasons, likely indicates that all sediment is delivered to the basin directly from the glacier that is in contact with the lake water. The properties of these lamination sets are referred to as Proximal Intermediate (Fig. 8b) as they most closely link to the Proximal I and II varve classification of Ashley (1988).

Lamination Set Assemblage 2 (Fig. 8a; 8b) are generally between 2 and 20 mm in thickness with the coarser grain sizes of the lamination set thicker than the finer lamination type. The coarse layer is dominated by graded laminations of varying thickness and that grade from the range of very fine sand or coarse silt to medium silt (LT v, vi, vii; Fig. 7). Sometimes, immediately above the sharp contact to the preceding fine lamination type, there is a normally graded medium silt to clayey fine silt (LT xi; Fig. 7)) or a poorly sorted massive medium silt (LT xv; Fig. 7) that was deposited prior a

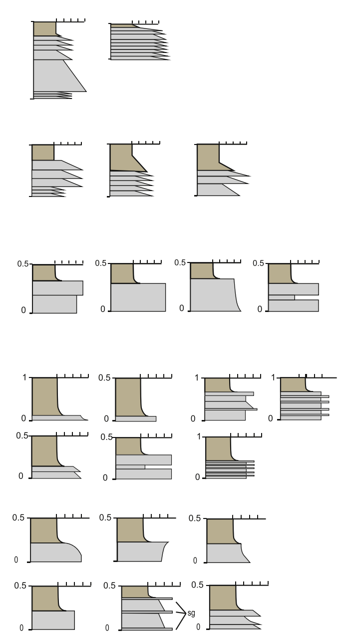
Lamination Set Assemblage	Varve Thickness (mm)	Melt Season (MS) Particle Size (Sorting)	Melt Season (MS) Structure	Melt Season (MS) Upper Contact	Non-Melt Season (NMS) Particle Size	Non-Melt Season (NMS) Structure	Non-Melt Season (NMS) Upper Contact
1	20 - 600 MS > NMS	VCZ - MZ (WS)	multi-lamination; f.u. (CZ-MZ); turbidites f.u. (CS-VFS)	sharp	C (VFZ) (WS)	graded: VFZ f.u. to clay from the first part of the lamination	sharp
2	2 - 20 MS ≥ NMS	VFS; CZ; MZ (WS)	multi-lamination; 1st input MZ; later f.u. (CZ-MZ)	sharp	C (VFZ) (WS)	graded: VFZ f.u. to clay from the first part of the lamina-tion	sharp
3	0.5 - 5 MS ≥ NMS	FS; VFS; VCZ (WS)	normally single, massive lamination or double lamination; contains clay rip-up clasts	sharp	C (VFZ) (WS)	graded: VFZ f.u. to clay from the first part of the lamination	sharp
4	1 - 5 MS ≤ NMS	MZ;CZ (WS)	multiple lamina-tions; alternations of CZ and MZ; CZ sometimes single grain lineations	sharp	C (VFZ) (WS)	graded: VFZ f.u. to clay from the first part of the lamination	sharp
5	<1 MS ≤ NMS	MZ (PS)	single lamination or multi lamination; single grain lineations of CZ	appears graded	C (VFZ) (WS)	graded appearance due to contact from MZ from the NMS layer; f.u. to clay	sharp

MS = Melt Season; NMS = Non Melt Season; FS = fine sand; VFS = very fine sand; VCZ = very coarse silt; CZ = coarse silt; MZ = medium silt ; VFZ = very fine silt; C = clay; WS = well sorted; PS = poorly sorted; f.u. = fining upwards; QS = Quasi Steady; ST = surge type

b

Lamination Set Assemblage	Basinward Transport	Sediment Source	Lamination Set Assemblage Name
1 *Figure 4*	MS: QS underflow & ST for turbidites NMS: suspension settling	All glacier sourced sediment	***Proximal Intermediate***
2 *Figure 4, 5 and 6*	MS: QS underflow 1st input lower energy (spring melt from catchment) than subsequent laminae. NMS: suspension settling	High glacier sourced sediment	***Intermediate / Distal Lake Bottom***
3 *Figure 6*	MS: QS underflow (traction load) NMS: suspension settling	High fluvial (nival)/glaciofluvial; low direct glacier sourced sediment	***Distal Bottom-set (delta/sub-aqueous fan)***
4 *Figure 4, 5 and 6*	MS: QS underflow; only high discharge events recorded; element of suspension deposition. NMS: suspension settling	High fluvial (nival)/glaciofluvial; low ice contact glacial component	***Distal Lake Bottom***
5 *Figure 5 and 6*	MS: QS underflow; flow velocity is low providing only suspended load. Some mixing of higher flow events NMS: suspension settling	High fluvial (nival) glaciofluvial; no ice contact component	***Ultra Distal / Nival***

Microfacies Schematic



Key:
MS = Melt Season; NMS = Non Melt Season; QS = Quasi Steady; ST = surge type; sg = single grain

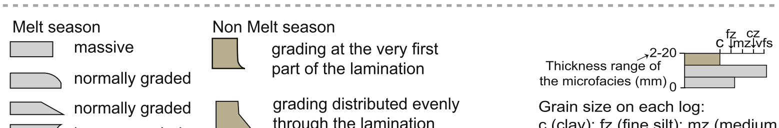


Fig. 8. A new classification for the distal varve microfacies in palaeoglaciolacustrine systems. a) Summary of key characteristics of lamination set assemblages that compose the microfacies divided according to their melt season and non-melt season characteristics. b) Summary of the interpretation of lamination set assemblages including the likely sediment source and dominant basinward transport mechanism. These lamination sets are given names a schematic of the microfacies are provided and cross-reference to the figures with photomicrographs of the lamination set assemblages. Of importance is the thickness characteristics of the ultra-distal/nival varves and also the complexity that is seen in the melt season layers, which in reference to previous studies, can be used to infer the combination of sediment supply from both nival melt and sediment transfer from the ice contact zone or through distal glacier systems delivering sediment via streams.

to the normally graded lamination types. The finer lamination type is composed of very fine silt normally graded to clay with a sharp upper contact (LT xvi; Fig. 7). The coarser grain size lamination types are indicative of sedimentation during the melt season through quasi continuous flows from the glacier. The presence of graded clayey fine silt laminations immediately above the previous non-melt season layer has been reported previously (Ridge et al., 2012; Bendle et al., 2017) and attributed to either (i) low-energy meltwater inputs in the early melt season, or (ii) local resuspension of clay particles at the sediment-water interface as underflows passed across the basin floor, with the material settling after the underflow waned. Similarly, late melt season can also exhibit less energetic flows with no obvious indication of a change from the glacier margin to nival streams as a sediment source. The lamination set structures are a more distal version of the Proximal Intermediate structures described above, with fewer extreme surge-type events reaching this part of the basin and also containing some evidence of relatively low energy flows reaching this part of the basin in the early part of the melt season. It is possible that these lower energy flows are a product of nival melt in the catchment during the spring. These lamination sets are referred to as Intermediate/Distal lake bottom varves (Fig. 8b) and form a link between the Intermediate III and Distal IV facies described by Ashley (1988).

Lamination Set Assemblage 3 are between 0.5 and 5 mm in thickness and the coarser grain size layers are thicker than the finer grain size lamination type. The lamination types with coarser grain sizes of either well sorted fine sand, very fine sand or very coarse silt that are massive, sometimes containing small clay intraclasts (LT i, ii; Fig. 7). There is occasionally more than one layer of these lamination types, but it is common to only have a single lamination. There is a sharp contact to the overlying lamination type that has only limited grading of very fine silt to clay at the base of the lamination type (LT xvi; Fig. 7). The coarse grained massive, well sorted sediments, allied to the presence of rip-up clasts, suggest current flow during the melt season, with flows of sufficient strength to suspend fine sand particles above the bed and larger clasts of clay. A continuous supply of sediment during the melt season is apparent in this package, although there are occasions when the flow strength diminishes allowing very fine silt and clay to fall from suspension. There is a sharp transition into the non-melt season layer where there is less very fine silt in the early part of the non-melt season, probably as a result of this material forming part of the suspended load of the turbidity current and being transported further into the basin. Here the sediment is supplied through flows of high sediment concentrations from glaciofluvial or nival streams and rivers, with no direct glacial input of sediment (see section 3.3) and the sediment supply is quasi-continuous during the melt season. Consequently, these sediments are termed Distal Bottomset varves (Fig. 8b) deposited on the distal margins of deltas and subaqueous fans. These lamination sets might be seen as distal equivalents of Proximal I and II varves (Ashley, 1988).

Lamination Set Assemblage 4 have a total thickness of 1–5 mm and coarser grain size laminations that are thinner than the finer grain size layer (Fig. 8a). The coarser grain sizes are composed of multiple lamination types with alternations of coarse and medium silt grains, where the coarse silt can sometimes be an accumulation of single grains of silt (LT vii, viii, ix; Fig. 7). The finer lamination type is composed of a very fine silt graded to clay with a more even and gradual transition in the normal grading (LT xvii; Fig. 7) and there is a sharp upper contact to the succeeding coarser layers. The coarser grain sizes are deposited during the melt season with the alternations in grain size reflecting different single flow events entering the lake basin floor directly through glacier meltwater streams, nival melt from the catchment and/or precipitation events during the melt season. The dominance of finer grain sizes indicate that much of this material falls as part of the suspended load at the point of deposition until the next major discharge event reaches this distal part of the basin and replenishing some coarser grains. It is probable that these varves are dominated by material from nival melt, precipitation events and distal glacier systems, and there is little significant input directly from where the glacier ice is in contact with the lake. The normally graded finer lamination type shows that there are few inflow events during the non-melt season that interrupt the suspension settling of very fine silt and clay from the water column. These lamination sets are considered to form in distal parts of the lake system and are termed Distal Lake Bottom microfacies (Fig. 8b) using the terminology of Ringberg and Erlström (1999), Ashley (1988), Heideman et al. (2015) and Menounos and Clague (2008).

Lamination Set Assemblage 5 are normally finer than 1 mm in overall thickness and the package of coarser grain size lamination types are thinner than the finer package of lamination types. The coarser grade layers are composed of a single massive and poorly sorted medium silt (LT xv; Fig. 7), or a normally graded medium and fine silt (LT ix; Fig. 7), with grains of coarse silt within this matrix. There is a graded contact at the microscale into the finer grade lamination type that normally grades from fine silt into clay with a sharp upper contact (LT xvii; Fig. 7). The coarser sediments are deposited in quasi-continuous underflows where only these high discharge events have sufficient energy to reach these distal parts of the basin. These flows supply the majority of the material when the main plume of the flow is losing energy through friction at the base of the flow and also when in contact with the lake water, causing sediment to be suspended above the lake floor with medium and fine silt grains constantly supplied during the melt season. Occasional grains of coarser silt being delivered in higher discharge events, which also re-supply medium and fine silt to this part of the lake basin. The majority of sediment is exclusively supplied from nival streams, with little or no material supplied from the ice-contact margin. The finer sediment grades also fall from suspension during the non-melt season period with the appearance of a graded contact to the preceding melt season layer merely reflecting the continuation of suspension settling, but with no further flows taking place to replenish the coarser sediment grades and the removal of currents through lake water freezing. These lamination sets are deposited in ultra-distal locations of the basin with the sediment supply dominated by tributary streams that may be fed by distant glacierized parts of the catchment or are recently deglaciated valleys and are thus responding to paraglacial readjustment. Thus, they are dominated by paraglacial processes and referred to as Ultra Distal/Paraglacial varves (Fig. 8b).

6.2.2. Additional process information on non-melt season layers

Whereas the melt season layers of glaciolacustrine varves exhibit a variety of structures and compositions, the non-melt season layers demonstrate three key variations in sedimentology between the lamination sets. First, the lower contact of the non-melt season in Distal Bottomset varves is very sharp and has a thin layer of very fine silt (in the lower part of the non-melt season) that grades into the clay, which contains a masepic fabric. The sharp contact probably reflects the strong contrast in particle size between the melt season and non-melt season layers, and the grading is due to the lack of very fine silt in the water column at this part of the basin. In contrast, the non-melt season layer in Proximal/Intermediate, Intermediate Distal and Distal Lake Bottom facies are also sharp but tend to have a more prolonged grading of very fine silt into the clay. This is likely a product of greater amounts of these finer sediment grades located in this part of the basin with the continuous settling of fine and very fine silt during the latter periods of the melt season, undisturbed by late summer autumn precipitation events. In the Ultra Distal/Nival varves, the contact between the melt season and overlying non-melt season layer appears graded when the melt season layer has a grain size dominated by medium silt. This suggests that there is continuous rain out of material from suspension with few inflow events during the late melt season with sufficient sediment concentrations to disrupt this sediment settling.

Overall, the non-melt season layers in these finer varve structures are dominated by suspension settling of very fine silt and clay, infrequently disturbed by winter surge-type events, perhaps from subaqueous slumps, winter storm events, or melting of the ice pack. These events are recorded in non-melt season layers as single grain, or very fine laminae.

6.2.3. Additional process information on other sedimentary structures

Other, less regular structures are observed in the different lamination sets. Grains that are greater than 250 μm are likely to represent ice-rafted debris (Thomas and Connell, 1985). The dropgrains tend to be isolated grains but can dominate a single lamination type in areas of low sediment accumulation, such as in ultradistal settings. These grains can cause penetration or rucking of laminations deposited previously. Grains of between 250 and 32 μm that are still anomalously large for a given lamination set, could also be related to deposition as ice rafted debris. However, they are often present as relatively isolated grains deposited at the contact between the non-melt season layer and the overlying melt season layer. Since the grain sizes of these particles are greater than that of the majority of the sediment delivered to a given site by underflows, these grains fall through the water column more quickly and are the first to be deposited on the lake bottom. Consequently, these are likely to be grains that are blown onto the frozen lake surface during the winter and are the first to be released during the spring thaw (Lewis et al., 2002). Here these grains are differentiated from ice rafted debris by being referred to as dropgrains.

Intraclasts of clay can often be found in the melt season layers of Proximal/Intermediate and Distal Bottomset varves. The irregular yet generally rounded edges and the larger size of intraclasts suggest rip-up of previously deposited clay laminae by underflow, and transport within these currents where grain-to-grain collisions lead to rounded edges.

Deformation of the sediment sequences in these distal locations is dominated by the formation of a masepic fabric in the non-melt season layer, which forms due to the weight of successive sediment layers being accumulated above, compressing the sediment stack and aligning the clay particles. The non-melt season layers also show occasional evidence of unistrial fabric formation that suggests pure or lateral shear stresses have been applied to the sediment stack due to extensional or compressional forces. At a more local level the irregular surfaces of some lamination types can be the product of penetration of grains at the sediment/water interface, with local density differences creating these irregular contacts. This may be more pervasive in the melt season layer where laminae are disrupted by a new flow event that either partially erodes the previous sediment layer or settles into it.

Drainage events within the sediment record, such as those that occurred in Glen Roy and Lago General Carrera/Buenos Aires, can cause a sudden decrease in water depth which leads to erosional hiatuses and the deposition of beds/thick laminations of coarser sediment, such as medium coarse sand. The sudden deposition of this material can result in the formation of flame structures that sometimes tilt downstream of the direction of flow propagation.

6.2.4. Summary of sedimentological characteristics

The sedimentological data in combination with the varve thickness data (Table 1) allows a new classification of glaciolacustrine varve microfacies (Fig. 8b). These are divided into five main categories, which are differentiated on the basis of overall thickness, the ratio of coarse component (melt season) to fine component (non-melt season) thickness, and the sedimentary characteristics of the coarse and fine components. Together, this information allows the position of sedimentation within the former lake basin, relative to the point of sediment input, to be inferred, and uses the examples presented in this study in combination with terms used previously in the literature (Ashley, 1975 Smith and Ashley, 1985; Ringberg and Erlström, 1999). The scheme uses terminology that has, in part, been used in earlier studies, but also introduces new terms to categorise previously unclassified varve structures.

The classification comprises five varve microfacies termed: Proximal Intermediate, Intermediate-Distal Lake Bottom, Distal Delta/Subaqueous Fan Bottomset, Distal Lake Bottom, and Ultra Distal/Nival (Fig. 8b). The varve thickness generally decreases from Proximal Intermediate types to Ultra Distal/Nival types, although there may be some overlap in thickness between the different microfacies, with further distinctions made on the basis of the sedimentological characteristics. Generally, the thicker varve microfacies of Proximal Intermediate, Intermediate-Distal Lake Bottom, and Distal Delta/Subaqueous Fan Bottomset, have melt season layers that are thicker or equal to the non-melt season layer, whereas the Distal Lake Bottom and Ultra Distal/Nival microfacies have melt season layers that are equal to or thinner than the non-melt season. In all cases, the non-melt season layer is composed of a clay-rich lamination that grades upwards from very fine silt to clay and has a sharp upper contact. These layers are dominated by suspension settling of the fine fraction in the lake water column. Occasional interruptions to this suspension settling can be observed in the form of silt/sand stringers within the non-melt season layer, but these are very rare primarily reflecting the distal locations in which these sediments are observed and low probability of these higher energy stochastic events reaching this part of the basin.

7. Drivers of varve thickness and microfacies in glaciolacustrine systems

Establishing a robust sedimentological model for the microfacies of glaciolacustrine varve sediments permits the varve thickness record to be explored as a proxy for glacier, climate and/or environmental change. Previous studies suggest that centennial-scale trends in the thickness of varves, in either ice-contact and distal glacier-fed lake systems, are primarily a consequence of variations in glacier extent within the lake catchment (Leonard, 1986; Leonard, 1997; Leeman and Niessen, 1994; Ohlendorf et al., 1997; Larsen et al., 2011; Ridge et al., 2012), which are driven by longer-term changes in palaeoclimate that influence glacier mass balance and advance-retreat cycles. At the decadal scale, the interpretation of varve thickness trends can be more complex (Leonard, 1997; Larsen et al., 2011; Bendle et al., 2019). Increased varve thickness, for example, has been associated with transitional changes at the glacier margin, such as a relatively short-lived glacier advance/stillstand, or the early decades of ice-margin retreat where increased meltwater volumes mobilise relatively large sediment loads (Leonard, 1997). Interannual varve thickness changes have been shown to reflect regional meteorological factors, such as changes in spring/summer temperature (e.g. Leeman and Niessen, 1994; Ohlendorf et al., 1997; Loso et al., 2006; Glur et al., 2015) and annual variability in hydroclimate that affect summer and winter precipitation patterns (Lamoureux, 2001; Cockburn and Lamoureux, 2007; Chutko and Lamoureux, 2008; Ólafsdóttir et al., 2013). Indeed, Lamoureux (2001) and Leeman and Niessen (1994) have demonstrated that it is possible to identify and extract the thickness of subannual laminations formed during high run-off events caused by precipitation in the summer, in order to isolate the background variability in regional temperature.

To provide accurate reconstructions of palaoeglaciolacustrine systems, varve microfacies data should be combined with inferences drawn from varve thickness data and the geomorphological context of the sequence. It is essential to utilise these complementary lines of evidence because the record of many former glaciolacustrine systems can be highly fragmentary, due to either lake drainage that leads to erosion of some, or much, of the lacustrine archive, and/or coring campaigns that yield spatially restricted data. It is important to be able to reconstruct where in former glaciolacustrine systems varve sediments are likely to be best preserved in unbroken sequences. This, in turn, will allow the most complete annually-resolved records in a given basin to be exploited and a stronger understanding of the different factors that control sedimentation rates. To this end, using the evidence from the three sites as examples, we discuss some of these controlling factors.

7.1. Basin specific factors

7.1.1. Thickness relationships driven by proximity to ice position

The phenomena of varve thickness decreases being driven by the distance from the ice contact to deposition is well established (De Geer, 1912; Ridge et al., 2012) at the macroscale. This study demonstrates that a pattern of decreasing varve thickness at the centennial scale can also be identified by combining macro- and micro-scale analysis at Lago General Carrera/Buenos Aires (Bendle et al., 2017) and solely at the microscale at Llangorse, South Wales (Palmer et al., 2008a,b). In both cases, the retreating ice mass can be detected by decreases in the number of pulses of graded or massive lamination types recorded in the melt-season (see Figs. 4 and 5 that shows the varve thickness summaries) and with evidence of interannual variability in the types of varve microfacies (lamination sets) observed. During the retreat of the ice front, which recedes from the point of deposition, the amount of sediment supplied decreases, with only the highest energy flows reaching these more distal parts of the basin. The likelihood of one-off surge type events reaching more distal parts of the lake basin diminishes and thus reduces the chance of persistently thicker varves forming in this part of the basin.

The fluctuations in varve thickness are observed over centennial to decadal scales and can be interrupted by short-lived increases or reductions in sedimentation rate. At Lago General Carrera/Buenos Aires (Fig. 4), there are periods when sedimentation rates in the microfacies increase. Over centennial scales increased sedimentation rates mark the transitions from Proximal Intermediate varves (LSA 1; Figs. 4 and 8) to Intermediate/Distal lake bottom varves (LSA 2/4; Figs. 4 and 8) to Distal lake bottom varve (LSA 4; Figs. 4 and 8) microfacies. The mix of LSA 2/4 varves in the central part of the record demonstrates that there is a continuum between the microfacies within the scheme representing the evolution of the lake basin as the ice margin retreats. The thickness increases could relate to short-lived stillstands in the position of the ice front or re-advances (Bendle et al., 2017), or alternatively due to rapid retreat associated with high ablation rates, that lead to increased meltwater discharge with the capacity to mobilise and transport eroded sediment within the subglacial hydrological system (Larsen et al., 2011; Bendle et al., 2017). This could be enhanced by increases of sediment availability as deposition occurs during ice retreat. These are observations that have been made previously in ice-contact lake systems (Leonard, 1986; Desloges, 1994), but further confidence in ice-margin position can be extracted from the analysis of the microfacies. For example, in the LGC/BA sequences there is no clear evidence that the decrease in varve thickness is caused by anything other than the position of the ice margin. Indeed, the detection of higher concentrations of ice-rafted debris in the microfacies in the younger parts of the sequence indicate that ice-calving had an increasingly important role in ice retreat as the ice terminated in increasingly deeper waters (Bendle et al., 2017, 2019).

The example of palaeoglacial lake Llangorse is of interest in that Palmer et al. (2008a,b) suggested that the three microfacies changes reflect the retreat of the ice margin to three successive moraines, identified by Lewis (1970), over a 570-year period. Here we note the Intermediate/Distal varves (LSA 2; Figs. 5 and 8) dominating for the first 75 years, then changing to Distal lake bottom varves (LSA 4; Figs. 5 and 8), which dominate the system for the following ~310 years. Reinterpretation of the microfacies suggests that the period of direct ice contact in the basin was between 370 years and possibly as short as only 75 years, before the ice no longer formed a competent dam. The characteristics of the varve record then switch to predominantly ultra-distal/nival varves (LSA 5; Figs. 5 and 8) relying on nival melt and summer precipitation events to transport sediment to the lake basin. Crossing of the direct contact threshold resulted in changes in varve thickness as sediment supplied from the glacier was replaced by sediment transported to the basin by nival melt and/or summer precipitation. The ability to identify when this transition occurs is important to reconstructions of palaoeglaciolacustrine basins when trying to define the timing of the change in influence of sediment supply and how to use varve thickness as a proxy of palaeoenvironmental change.

7.1.2. Thickness relationships driven by lake level

Theoretically, changes in lake level should also be detectable within the microfacies of palaeoglaciolacustrine systems. If water levels fall, driven by either retreat of the ice, opening lower altitude drainage cols or subglacial drainage, distal varve thickness records should become thicker as they are closer to sediment sources and they should display characteristics of Delta Bottomset varves if in close proximity to the stream inputs. If lake water levels rise due to, for example, glacier advance, the opposite should apply and the varves should display Distal Lake Bottom characteristics.

Here, we use Glen Roy varve thickness records to highlight complexities associated with lake depth controls on varve sedimentation. An increase in lake water depth of 25–90 m in Glen Roy (Sissons, 1978; Palmer et al., 2010) at sites GTF and BOA (Fig. 6) caused a transition in varve microfacies from Delta Bottomset (LSA 3; Figs. 6 and 8) to Distal Lake Bottom varves (LSA 4; Figs. 6 and 8) However, when the lake waters fell from 350 m to 325 m at GTF and BOA (Fig. 6), driven by retreat of the glacier ice in contact with the lake (Sissons, 1978; Palmer et al., 2010), the microfacies did not revert to Delta Bottomset varves (LSA 3; Figs. 6 and 8). In particular, the longer sequence of varves at GTF, which remained under at least 65 m of water after a fall in water level, does not show a major change in microfacies or varve thickness, and this uniformity persists despite a further fall of the lake waters to 260 m and water depths of 10 m.

It is evident, therefore, that the currently available varve thickness records at Lochaber do not provide a consistent picture of the complexities associated with changing lake levels, likely because other controlling factors persisted at the site during lake level fall. This highlights the importance of constraining the geomorphological context of a varve record to isolate controls specifically related to lake level change. At Lochaber, ongoing research focused on the geomorphology of Glen Roy palaeolake evolution aims to identify distal varve records controlled by lake level only (Palmer et al., (in prep), In summary, the available geomorphological and varve microfacies evidence indicates that changes in lake water level, along with the site-specific geomorphological context, determine flow hydraulics across subaqueous deltas. Varve thickness and microfacies records, therefore, have the potential for improving our understanding of palaeolake evolution, however further research is needed, from a range of geomorphological contexts, to robustly characterise lamination set assemblages.

7.2. Palaeoclimatic significance of varve microfacies

Distal varve microfacies and thickness are sensitive diagnostic indicators of factors controlling sediment supply to the basin. As discussed above, changes in the lake water level that impact proximal to distal relationships of flows across subaqueous fans or deltas in the lake can be assessed through the geomorphological context of the sampling site, allied to the varve thickness and microfacies of the sequence. Similarly, the pattern of varve thickness variations combined with the glacial land system context, enable the position of the ice margin to be inferred. If these intra-basin controls on varve thickness and microfacies can be isolated, it is possible to investigate the role of palaeoclimate or palaeohydroclimate forcing on the varve thickness and microfacies variability in the record (Palmer et al., 2012). For example, in the Llangorse sequence, identifying the change from an ice-contact glaciolacustrine system with proximal intermediate varves to an ultra-distal/nival microfacies is important. At this point the glacier is no longer in the lake catchment or dominating sediment supply, and the main source of sediment is from the immediate catchment via surface run-off into the lake basin. The control on surface run-off will be driven by the spring nival melt (winter precipitation in the form of snow) or summer precipitation events (Cockburn and Lamoureux, 2007). A similar situation exists throughout the Loch Laggan East sequence, where the glacier appears to have little influence on the sedimentation patterns, a conclusion which is reenforced by similar changes in the distal record at GTF in Glen Roy (Palmer et al., 2010) and indicates that the varve thickness record most likely reflects variations in the palaeoclimate.

Sampling in more distal localities has further advantages when their microfacies can be characterised and thickness measured. The distal varve sequences are less likely to be disturbed by either high-energy flows from the glacier margin, subaqueous slumps from delta fronts and/or drainage events have less erosive capacity. Consequently, longer and more complete sequences of the palaeoglacial lake's history will be preserved allowing more precise minimum durations for the lake system to be established (Bendle et al., 2017).

In the two British sequences, the ability to identify ultra-distal/nival palaeoglaciolacustrine microfacies enables more reliable models of the evolution of the glacial systems. In addition, the use of Proximal Intermediate and Intermediate Distal Lake Bottom microfacies is important, and in the case of Lago General Carrera/Buenos Aires provides a link to varve structures that are observed at the macroscale. These Proximal Intermediate and Intermediate Distal Lake Bottom microfacies, combined with macroscale varves, receive a greater proportion of sediment directly from the glacier and therefore the varve thickness is perhaps more sensitive to variations in the supply of sediment controlled by internal glacier dynamics, which may only be partially controlled by climate. Indeed, it is possible that short-term climate variability will be detected in inter-annual changes in meltwater supply and hence sediment discharge to the glaciolacustrine system that in turn is reflected in varve thickness data. This maybe complicated by small changes of meltwater portal position on the ice front that could also cause subtle variations in the supply of sediment across a subaqueous fan in contact with the ice. Nonetheless there still remains the potential to extract important palaeoclimatic information from these parts of the lake basins.

Clearly, palaeoglaciolacustrine systems have complex sediment patterns, as demonstrated by the Glen Roy segment of the Lochaber lake systems. However, the application of the microfacies approach to this and other lake systems allow a more rounded interpretation of the evolution of the system than previously afforded with the possibility of examining the role of palaeoclimate using varve thickness and structure as a proxy. There are complexities in how this climatic signal can be extricated as examples from modern glaciated lake catchments have highlighted, but it should remain as a goal when examining these types of records.

8. Conclusions

1) Glaciolacustrine varves are an important, yet underutilised, component of the palaeoglaciological sediment archive, with vast potential for developing high-resolution chronologies for, and tracking, palaeoenvironmental changes in glaciated catchments.
2) The very fine (often sub-millimetre scale) laminated structures that characterise distal parts of (palaeo-)glacial lakes necessitate microfacies techniques for robust and consistent sedimentary descriptions.
3) Using examples of distal varve microfacies from Northern and Southern Hemisphere palaeoglaciolacustrine settings, this paper has outlined a descriptive protocol for the identification, classification, and interpretation of microscopic varve structures, which is essential in generating a robust sedimentological model.
4) Using this consistent descriptive protocol, five key glaciolacustrine depositional contexts have been classified within the study referred to as Proximal Intermediate, Intermediate/Distal Lake Bottom, Distal Bottomset, Distal Lake Bottom and Ultra Distal/Nival with the potential of reducing the impact of equifinality in interpreting these sediment packages.
5) This classification will enable improved reconstructions on, for example, the position(s) of the active glacier margin over time and, therefore, on the direction and rates of past glacier change in former glaciolacustrine basins.
6) The classification also has the potential for determining changes in palaeoglacial lake levels and the determination of palaeoclimate changes associated with varve formation, although in both cases the quality of the interpretation is improved by additional geomorphological context.
7) It is expected that by using this system, additional varve microfacies will be described in due course, testing and enhancing the classification system. This will include improved understanding of process in the relative importance of various sediment inputs through continued examination of the physical controls on sediment inflows and their links to sediment structures (e.g. Cockburn and Lamoureux, 2007; Crookshanks and Gilbert, 2008).
8) Technological advances in high resolution x-ray fluorescence scanning of sediment cores (MacLeod et al., 2011) and the construction of three-dimensional models of varve sequences using μCT scanning facilities (Bendle et al., 2015) hold great

potential for further rapid and non-destructive analysis of these microscale structures.

Author contribution

Adrian Palmer: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Writing – Original Draft, Writing – Review and Editing, Visualisation, Supervision, Funding Acquisition. **Jacob Bendle**: Conceptualization, Methodology, Formal Analysis, Investigation, Writing – Original Draft, Writing – Review and Editing, Visualisation. **Alison MacLeod**: Conceptualization, Methodology, Formal Analysis, Investigation, Writing – Original Draft, Writing – Review and Editing, Visualisation. **James Rose:** Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Writing – Original Draft, Writing – Review and Editing, Visualisation, Supervision, Funding Acquisition. **Varyl Thorndycraft:** Investigation, Writing – Original Draft, Writing – Review and Editing, Visualisation, Supervision, Funding Acquisition.

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Appendix A. Supplementary data

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