Seasonal Controls on Deposition of Late Devensian Glaciolacustrine Sediments, Central Ireland

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ABSTRACT

Laminated proglacial glaciolacustrine sediments dating from the Late Devensian (22-10 Ka BP) from central Ireland were examined using a combination of detailed logging and Scanning Electron Microscope (SEM) microfabric analyses. The sediments are rhythmically laminated and consist of coarser, pale silt layers which alternate with darker clay layers containing occasional thin laminae of fine sand and coarse silt. The pale silt layers contain single or multiple normally graded laminae, erosional surfaces and soft sediment deformation structures, indicating deposition from multiple high density underflows. The dark clay layers have sharp upper and lower contacts and an internal fabric consistent with deposition from a combination of flocculation and grain-by-grain deposition. Silt laminae within the clay layers are interpreted as sporadic turbidity underflows. The sediments are interpreted as annually laminated (varved). Varves deposited close to the ice margin showed considerable spatial variation in thickness and adjacent sequences could not be correlated; however sequences of medial varves separated by 500m were correlatable by thickness. As glaciolacustrine deposits are widespread throughout the Irish midlands, it is likely that a varve chronology could be constructed.

Key words Varve, microfabric, flocculation, turbidity current, Ireland

INTRODUCTION

Annually laminated lake sediments (termed varves) have been used extensively to establish high resolution chronologies and examine environmental change on a local and regional scale. In proglacial lakes, clastic varves are formed due to seasonally-controlled changes in meltwater discharge: summer layers of sand and silt are formed from deposition from underflows and interflows, while winter layers are formed by deposition of clay after autumn overturning of the thermocline (Ashley, 1995). Varve thickness is controlled by interannual variation in discharge and sediment fluxes. Long-term chronologies are constructed by measuring varve thicknesses at sites across hydrologically linked proglacial lake basins and correlating from site to site to establish the relative ages of varve sequences. These chronologies have been used to reconstruct the timing and dynamics of deglaciation, to date particular events and to correlate events on land with ice core and marine records (Andrén *et al*., 1999; Ridge, 2003). Such chronologies have improved understanding of the interactions between changing terrestrial ice volumes, meltwater discharges, ocean circulation and climate change (e.g. Andrén *et al*., 1999; Lindeberg and Ringberg, 1999; Boulton *et al*., 2001). However, to date, this method of dating has been of limited use as no chronology has been extended to before 15.4 ^{14}C Ka BP.

The aim of this paper is to establish whether glaciolacustrine sediments in the Irish Midlands are annually laminated, and whether they can be correlated in order to create a varve chronology. Glaciolacustrine deposits laid down around the margins of the decaying British-Irish Ice Sheet (BIIS) after 20 Ka BP are found across the Irish Midlands, extending northwards along the Shannon basin and southwards as far as the Southern Ireland end moraine (SIEM) and beyond (Fig. 1; Van der Meer and Warren, 1997; Delaney, 2002). The sediments are rhythmically laminated (Van der Meer and Warren, 1997; Long and O'Riordan, 2001), and are similar in appearance to proven varved sediments found elsewhere. Potentially, they could be used to construct a varve chronology to date the recession of the BIIS. from 20-10 Ka BP. During this time the BIIS was characterised by rapidly changing dynamics, including multiple shifts in ice flow directions, the establishment of deforming bed conditions, and episodic retreat and readvance of ice margins (McCabe, 1996; McCabe and Clark, 1998; Clark and Meehan, 2001; Delaney, 2002). These changes have been suggested to correlate with Atlantic-wide changes in thermohaline circulation, meltwater pulses from other ice sheets, abrupt sea-level rise and Heinrich (ice-rafting) events (McCabe and Clark, 1998; Scourse *et al*., 2000, Clark *et al.,* 2004). However, accurate correlations of the timing of these changes is problematic, as suitable material for dating is hard to find, and the methods used to date these materials are subject to errors of over 1,000 years for this period (Waelbroeck *et al.* 2001; Bowen *et al*., 2002). A varve chronology could provide a high-resolution chronology for this period which could be tied to ice and marine records using tephrachronology and isotopic dating.

VARVE FORMATION

Rhythmically laminated, coarse-fine couplets consisting of a lower, silt-dominated and an upper, clay-dominated layers are common in glaciolacustrine sediments, and can form due to a variety of processes. These include: (1) diurnal variation in inflow (e.g. Ringberg, 1984); (2) subseasonal variations due to short-term (hours to days) changes in inflow (e.g. Lambert and Hsü, 1979; Hambley and Lamoureux, 2006); (3) seasonal variations resulting in two separate peaks in sediment input due to late spring snowmelt and summer ice melt (e.g. Smith, 1978); (4) deposition from slump-generated surge currents, usually turbidity currents, from unstable lake margins (Ashley, 1975; Hambley and Lamoureux, 2006); (5) and annual variation in discharge involving summer deposition from underflows, overflow-interflows and surge currents in summer and suspension settling of fine silts and clays in winter, resulting in the formation of varves (Smith and Ashley, 1985; Ashley, 1995). Annually laminated, or varved, sediments form within lakes deep enough to be thermally stratified, so that during autumn overturning fine particles in the epilimnion are brought towards the bottom. This clears the lake of suspended sediment and depositing a clay drape across the entire lake (Ashley, 1995).

Based on differences in transport and depositional processes, Smith and Ashley (1985) and Ashley (1995) have identified a number of sedimentary criteria for distinguishing true varves from other deposits. These are: (1) a relatively sharp contact between the summer and winter layers which suggests a break in sedimentation, and may represent the autumn overturn; (2) no overall grading of the summer layer, as the layer accumulates from a variety of flows over weeks to months; (3) Fining upwards within the winter layer, reflecting suspension deposition of a limited sediment supply; (4) the presence of trace fossils (Lebensspuren) on bedding planes within the summer layer and on top of the winter layer, indicating periods of non-deposition; (5) winter layer thickness shows little variation from year to year, as it represents approximately the same amount of time, while summer layer thickness can vary considerably, reflecting variation in rapid sedimentation events from year to year.

Scanning Electron Microscope (SEM) analysis of microfabrics within rhythmites can also be used to infer depositional mechanisms. O'Brien and Pietraszek-Mattner (1998) have shown that most of the sediment in glaciolacustrine rhythmites has a microfabric consistent with deposition by flocculation, indicating episodic deposition rather than continuous rain-out of dispersed sediment, but that the final millimetre of each rhythmite has a strong preferred orientation, which they interpreted as due to the reorientation of clay grains by bioturbation during periods of non-deposition.

While it is clear that clay deposited in winter is likely to have a distinctive sedimentological signature, it is also possible to form false varves by splitting this winter layer. Turbidity currents which occur within the winter months could easily be misinterpreted as summer deposits (Ashley, 1975; Shaw and Archer, 1978; Shaw et al. 1978).

GEOLOGICAL SETTING AND SITE DESCRIPTION

The sediments to be discussed were deposited in a proglacial lake, Glacial Lake Riada, which formed in this basin during the late Midlandian (Weichselian) after 22 Ka BP and covered much of the Midlands during the last glacial termination (Figs. 1b, 2a; Van der Meer and Warren, 1997; Delaney, 2002). The area is underlain by Carboniferous Dinantian limestones (Gatley et al., 2005) and forms a lowlying (c. 30-100m O.D; Fig. 2a) basin which rises slowly westwards, northwards and eastwards. Within the basin pre-Quaternary topography is masked by extensive glacigenic deposits and by Holocene raised bog. Glaciofluvial deposits, including eskers and kames, form the topographic high points over much of the basin (Fig. 2a; Warren and Ashley, 1994; Delaney, 2002).

The existence of Glacial Lake Riada was controlled by a combination of topography and the existence of ice lobes to the north, west and southwest (Delaney, 1995). Recession of these lobes is likely to have caused changes in lake extent and water depth; however, temporal variations in lake extent are not yet understood. The extent of the lake immediately prior to the start of deposition at the sites discussed below has been mapped using ice-contact deltas and subaqueous outwash fans; the evidence indicates that water levels were at around 92m O.D. during this time and the sediments were deposited in water depths of around 30m (Fig. 2a; Delaney, 1995, 2002)

The two cores described below were taken from underneath reclaimed raised bog Knocknanool (Kn) and Rooskagh (Ro) townlands, west of Lough Ree in Co. Roscommon, Ireland (Fig. 2b). The core sites are thought to lie a short distance north of the most southerly position reached by a readvance during deglaciation (Fig. 2; Delaney, 2001, 2002), some time between c.17-11 Ka BP (Knight *et al.*, 2004). This readvance appears to be a relatively local event, since associated margins further east are not associated with readvance (Delaney, 2002; Meehan, 2004). The core sites lie towards the edge of the main glacial lake basin, within a sub-basin infilled with raised bog which has been partly cut for turf and then reclaimed. The basin is separated from other peat-filled basins to the east and south by eskers and other deglacial deposits (Fig. 2). The sides of the basin are delimited by bedrock to the west, by kames and the Rooskagh Esker to the east and north east, and by the Athlone Esker to the south. The core sites lie approximately 1500m north of the Athlone Esker, 1600m

(Knocknanool) and 1000m (Rooskagh) west of the Rooskagh Esker, approximately 600m south of the Knocknanool delta kame and are c.500m apart (Fig. 1).

METHODS

Cores were retrieved in 0.5m long sections using a hand-operated Russian corer to minimise compaction of the sediments and to avoid contamination of the cores. Two cores were collected at each site; the sampling depth in the second borehole was offset by approximately 0.25m in relation to the first core, so that a complete undisturbed sequence was retrieved. The cores were wrapped in clingfilm and tinfoil to retain moisture and brought to the laboratory for description.

In the lab, each core section was unwrapped and air-dried overnight, so that any laminations would be clearly visible. When dry, the core surface was cleaned off using a sharp knife, an initial examination made, any potential winter layers marked with pins, and the core section then photographed. Cores were then examined in detail and logged at a sub-millimetre scale using a moving stage microscope with an 8x magnification. Features noted included colour, estimate of particle size, grading, any lamination and soft sediment deformation structures. A preliminary identification of winter clay laminae was made, based on colour, sharpness of upper and lower contacts and grain size estimates. The thickness of individual clay laminae and the total thickness of sediment between consecutive clay laminae was measured to the nearest 0.01mm. Individual core sections were visually correlated with overlapping sections and laminae numbered accordingly. Where individual laminae appeared in more than one core section, the average thickness was calculated and the range was obtained based on maximum and minimum thicknesses.

Samples for SEM microfabric analysis were taken from the Knocknanool core. Samples were prepared for microfabric analysis following the method of O'Brien and Pietraszek-Mattner (1998), but using a sharp knife instead of a diamond disc to trim blocks to size.

RESULTS

The stratigraphy is shown in Figure 3 and is similar in both cores – c. 0.35m thick peat overlies c.2.2m of calcareous silts and clays (marls) before passing into c.1.6m of alternating organic and inorganic diffusely laminated clay-silts, interpreted as Lateglacial deposits, and then into inorganic laminated silts and clays. The upper 1.1-1.2m of this sequence consists of laminated silts and clay-silts without distinct clay laminae and is not discussed here. The final 1.4m(Kn) – 2.3m(Ro) of each core consisted of rhythmically laminated silts and clays. These can be divided into three sedimentary facies types.

Sedimentary Facies

Sedimentary facies are shown in Figures 3, 4 and 5 and descriptions and interpretations are summarised in Table 1.

Silt-dominated rhythmites

This facies reaches a total thickness of 0.9m(Kn) -1.9m(Ro) and is found at the base of both cores, immediately overlying diamicton. Couplets consist of a lower coarse (silt and some fine sand) unit, which is much thicker (20-120mm vs. 0.5-8mm) than the overlying fine unit (composed of silty clay and clay; Figs. 3, 4a). The coarse units show no overall grading in particle size, but consist of multiple ungraded or normally graded laminae between 0.5-40mm thick, with occasional thin, but distinct, laminae of clay-free, coarse silt and sand (Figs. 3, 5a). Normally graded laminae are composed of coarse to fine, clayey silt and are initially thin (<1.5mm), but then thicken towards the centre of each coarse unit; often laminae thin and fine again towards the top of the unit. Contacts between laminae are sharp, planar or irregular, and are frequently marked by soft sediment deformation, consisting of load casts and flame structures (Fig. 5a). Flame structures are 1-3mm high and may be tilted and oriented in one direction. They are often associated with small rip-up clasts in the overlying coarse lamina, indicating partial erosion of the underlying sediment. Occasional granules and fine pebbles have caused deflection downwards of the underlying beds and are interpreted as dropstones.

Thin, pale lamina of coarse silt and sand may be present at the base of the coarse unit, which is usually erosional on the underlying fine unit. The uppermost lamina in the coarse unit is always composed of pale coarse silt and sand, and is commonly between 0.5-1.2mm thick (Fig. 5b).

The upper fine unit is dark grey in colour, is composed of silty clay and clay and usually exhibits normal grading. Both the lower and upper contacts are sharp (Fig. 6a, b). The upper contact is frequently irregular, is often marked by flame structures c.1mm high and occasional rip-up clasts of clay are visible at the base of the overlying coarse unit. The fine unit may also contain thin, nearly white laminae of coarse silt and sand, similar to that seen at the top of the coarse unit (Fig. 5b).

Interpretation: Silt-dominated rhythmites are interpreted as annual varves, as they exhibit most of the characteristics suggested by Smith and Ashley (1985) and Ashley (1995), including: sharp contacts between summer and winter layers consistent with deposition after autumn overturning; fining upwards in the winter layer; and considerable variation in summer layer thickness reflecting variable rainfall and slumping of sediments, but very little in winter layer thickness, unless silt laminae are present. The sediments resemble descriptions of proximal varves deposited adjacent to the ice margin (Smith, 1978; Ringberg and Erlström, 1999).

Normally graded laminae containing coarser laminae within the summer layers are interpreted as turbidity current underflows. These are related to a variety of causes, including episodic increases in meltwater and sediment influx due to rainfall (Lambert and Hsü, 1979; Blass *et al.*, 2003; Hambley and Lamoureux, 2006) and surge currents generated by slumping along the lake margins (Smith and Ashley, 1985; Hambley and Lamoureux, 2006). Other normally graded units without internal lamination may represent deposition from underflows and interflows caused by meltwater inputs (Hambley and Lamoureux, 2006). The fine-coarse-fine variation in lamina thickness in many summer layers indicates that seasonal variation in meltwater generation was the dominant (but not the only) control on sedimentation here. Occasional thin laminae of clay-poor, coarse silt and sand may be associated with higher energy underflows where finer suspended sediments bypassed the core sites (Smith, 1981), or they may represent sporadic aeolian deposition within the lake. Similarly, the occurrence of a coarse lamina at the top of each summer layer may represent deposition by small-scale subaqueous slumps or increased runoff in early autumn (Hambley and Lamoureux, 2006), or reflect increased aeolian deposition at this time of year (Lamoureux and Gilbert, 2004). Evidence of deformation and erosion indicates that dewatering and autocompaction of sediments had not yet occurred. Silt laminae within winter layers are also interpreted as turbidity currents, again most likely due to periodic slumping of lake margins during winter low stage (Shaw *et al.*, 1978; Ashley 1995). However, it is possible that some of these are summer layers, deposited during a season where little or no melting occurred, or when meltwater was diverted to another site.

Silt-clay rhythmites

These rhythmites overlie the silt-dominated rhythmites and have a total thickness of c.0.3m. They are transitional between silt-dominated and clay-dominated rhythmites (see below), but are more are similar to silt-dominated rhythmites. They differ primarily in that the coarse unit is much thinner than in the silt-dominated rhythmites (<30mm, usually <20mm thick), and contains 1-5 massive and normally graded laminae between 0.2-10mm thick (Figs. 3b, 5b). Occasional laminae of coarse sand or clayey silt are also present. Possible evidence of bioturbation in the form of burrows is identifiable at the top of normally graded units. These consist of shallow (c.0.5mm thick), steep-sided pits cut into the underlying sediment and infilled with coarser overlying material (Fig. 5c). As in the silt-dominated rhythmites, the base of many units is marked by a strongly normally graded lamina which changes colour to dark grey upwards; again the coarsest sediment is at the top of each unit, and consists of a thin lamina of white sand or coarse silt (Fig. 5b). Fine units are similar to those the silt-dominated rhythmites, and may contain up to 3 laminae of white silt or sand (Fig. 5b).

Interpretation: Silt-clay rhythmites are also interpreted as varves, deposited further away from the ice margin than silt-dominated rhythmites. The number of laminae within each summer layer is much less than in silt-dominated rhythmites, indicating fewer depositional episodes. The absence of erosional surfaces and soft sediment deformation in summer layers indicates that sediment had time to settle and compact prior to the start of the next inflow. These sediments are discussed further below.

Clay-dominated rhythmites

Silt-clay rhythmites fine upwards into clay-dominated rhythmites, which reach a maximum thickness of 0.2m (Figs. 4c, 5c,d). They are much thinner than silt-dominated and silt-clay rhythmites (total couplet thickness 0.3-2.6mm), and the coarse unit is between 0.5-3 times the thickness of the fine unit. Coarse units are either internally structureless, in which case they consist of coarse silt, or they contain a thin lamina of silty clay within medium silt, usually followed by a thin lamina of coarse silt immediately below the fine unit (Fig. 5c). Structureless coarse units closely resemble the thin laminae of coarse material seen within the fine units of silt-dominated rhythmites. Fine units in the clay-dominated rhythmites are similar to fine units in the silt-clay rhythmites, and are composed of silty clay and clay, which is often normally graded. Rare examples of bioturbation occur in both coarse and fine units.

Interpretation: Clay-dominated rhythmites differ considerably from silt-dominated and silt-clay rhythmites. The very thin coarse layers and the absence of massive or normally graded laminae of clay-silt indicate that sediment influx to the core sites is much lower than before. This may reflect the recession of the ice margin out of the basin, or the trapping of sediment within a newly formed proglacial or subglacial lake upstream (Smith 1981). Coarse units with a silt - clay-silt - silt pattern are similar to those described by Smith (1978), and are interpreted as summer deposits reflecting two separate inflow maxima, one from late spring/early summer snowpack melting and the second from late summer glacial melting. However, structureless coarse layers are less clearly associated with summer melting, and these laminae closely resemble the silt laminae found in many silt-dominated and silt-clay rhythmite winter layers. It is impossible to say whether these are full summer layers, turbidity current deposits within winter layers, or whether the coarse-fine couplets were formed due to some process other than annual variation in lake stratification and meltwater influx.

Microfabric Textures

S.E.M. images of sediments are shown in Figure 6. Fine units show a distinct change upwards. The basal part of the lamina consists of relatively poorly sorted prolate fine silt and platy clay particles (Fig. 6c). Clay particles are arranged in domains (stacks of particles; Bennett *et al.*, 1991) and exhibit dominantlyface-to-face contacts consistent with dispersed deposition. However, some edge-to-face and face-to-edge contacts are observed, and while these can be partly attributed to tilting of the clay domains against larger silt grains, some small flocs are observed (Fig. 6c).

As particle size reduces and sorting improves upwards through the laminae, preferred orientation is increasingly well-developed (Figs. 6a,d,e). The top 0.1mm of most laminae consists almost entirely of clay domains deposited face-to-face and displaying a strong parallel orientation; coarser grains are interpreted as dropstones (Fig. 6g). Where the upper contact exhibits soft sediment deformation structures, or is disturbed by emplacement of coarse grains, the fabric may be folded (Figs. 6f,g), or exhibit a wavy structure (Fig. 5h).

Coarse units in silt-dominated and silt-clay rhythmites are largely composed of relatively poorly sorted sediment, consisting of a combination of blocky and prolate single particles, and domains of platy clay particles (Figs. 6i,j). Sediment is generally unoriented (Fig. 6i), but poorly developed preferred orientation is seen towards the top of some normally graded units. Sediment is more porous than in fine units, edge-to-edge contacts between clay domains are common, and chains of linked domains occur, indicating flocculation (Fig. 6h,l; O'Brien and Pietraszek-Mattner, 1998). However, clay domains are absent from the very coarse laminae found immediately below and within fine units (Fig. 6k). Coarse units in clay-dominated rhythmites may contain clay domains, in which case flocs are identifiable, or resemble the very coarse laminae found in the fine units of silt-dominated and silt-clay rhythmites.

Laminae Thicknesses

Total thicknesses for all varves are shown in Figures 7a and b, together with variation in thickness across adjacent cores where that information is available. Varve thickness decreases upwards through each core, but with considerable variation from varve to varve. Variation in thickness of couplets also decreases upwards.

Comparisons of total varve thicknesses for each varve type are shown in Figures 7c-f. No correlation in thickness was found between the sites for silt-dominated rhythmites (varves) (7c,d). However, comparison of silt-clay and the lowermost clay-dominated rhythmites (varves) shows a clear correspondence in total thickness variation up-core between Kn varves 28-72 and Ro varves 30-70 (Figs. 7e,f). Four rhythmites present in the Knocknanool core are not seen in the Rooskagh core. The three lowest rhythmites (Kn varves 37, 40, 47) are very thin (<1mm), consist of a single normally graded silt layer with a clay cap, and the lack the coarse silt lamina seen at the base of the winter layer in other varves. Consequently, these rhythmites are considered to be false varves caused by single winter underflows. The winter layer of the fourth rhythmite (Kn varve 67) has evidence of soft sediment deformation and partial erosion along the upper contact; it is overlain by a thin lamina of coarse silt and then by a typical summer layer sequence. In the Rooskagh core the equivalent to Kn varve 66 (Ro varve 65) contains a silt lamina. In this case it appears likely that deposition of coarse silt from an underflow has caused disturbance of the underlying winter layer at Knocknanool, but almost entirely removed the varve at Rooskagh. Comparison between the cores indicates that deposition started at the Rooskagh site between 2-4 years before Knocknanool. No correlation was seen in rhythmite thicknesses for clay-dominated rhythmites.

INTERPRETATION AND DISCUSSION

Proximally deposited sediments within the proglacial lake at Knocknanool exhibit a clear annual control on their deposition, resulting in well-defined couplets. Summer deposits resemble those described elsewhere (e.g. Smith and Ashley, 1985; Ringberg and Erlström, 1999) and appear to have been deposited dominantly from underflows caused by pulses of meltwater entering the lake basin. Some of this sediment was deposited as flocs, although coarser laminae contain no evidence of flocculation. Fabrics consistent with deposition by flocculation were also identified by Long and O'Riordan (2001) in glaciolacustrine deposits at the southern end of Lough Ree.

Flocculation can be a significant process in cold freshwater environments where sediment organic content is low and can be caused either by bioflocculation due to the presence of bacteria (Droppo *et al*., 1998), or electrochemical flocculation (Woodward *et al*., 2002). Controls on the proportion of flocculated sediment and size of flocs include: suspended sediment concentration which can be a limiting factor if low (e.g. Malmaeus, 2004); shear stress, as higher shear stresses result in break-up of flocs; and dissolved ion concentration, particularly Ca^{2+} and Mg^{2+} ions (Tsai *et al*., 1987). As the bedrock throughout the Irish Midlands is predominantly limestone, ion concentrations and suspended sediment concentration are unlikely to have fallen below the limits needed to allow flocculation, and it appears that coarser, well-sorted laminae are likely to have formed from flows with higher shear values, so that flocs failed to deposit at this point in the lake basin.

Winter laminae also contain evidence of minor flocculation at their base, which is consistent with relatively high suspended sediment concentrations immediately after overturning. Subsequently, the upward-fining of sediment and the apparent absence of flocs is consistent with a reduction in suspended sediment concentration and maximum available particle size as sediment deposition progresses without the input of fresh material. Some caution is necessary in interpreting the development of a preferred orientation at the top of each lamina, as this type of fabric may be formed either by deposition of dispersed (non-flocculated) grains, by break-up of flocs during deposition due to high shear (Bennett *et al*., 1991; Partheniades, 1991), or by post-depositional alteration of fabric by bioturbation (O'Brien and Pietraszek-Mattner, 1998). However, there is no evidence for high shear during deposition, and the absence of burrows shows that bioturbation was unlikely to have been important, at least in silt-dominated rhythmites.

While finer layers exhibit most of the characteristics of typical winter varve layers, they are thinner than similar examples seen in Scandinavia and New England (O'Brien and Pietraszek-Mattner, 1998; Ringberg and Erlström,1999). This can be at least partly explained for silt-dominated rhythmites by partial erosion of the upper surface of the winter laminae, indicated by the presence of soft sediment deformation structures and rip-up clasts. However, winter layers remain thin as evidence of erosion disappears in silt-clay rhythmites. One possibility is that a relatively high proportion of fine silt and clay was removed from the water column by flocculation during the summer months, so that relatively little material remained to be deposited during winter. Alternatively, the winter freeze-up may have been relatively brief during ice recession in this area, compared to ice-marginal sites in Scandinavia and North America.

The occurrence of erosion surfaces in both summer and winter layers of silt-dominated rhythmites also explains why correlation of these varves is not possible. At the Rooskagh site in particular, comparison of adjacent cores indicates that winter layers present in one core have been completely removed in a second core taken less than 5m away (e.g. Fig. 7d, varves 2-5). Even where winter layers have been preserved in both cores, there can be considerable variation in both winter layer thickness and total varve thickness (e.g. Fig. 7d, varves 7-10), indicating that further erosion may have occurred, possibly removing other winter layers. Evidence for erosion is more frequently seen in the Rooskagh core, which probably reflects the closer proximity of this site to the point discharge which formed the Knocknanool delta.

Correlation was also not possible between the higher type 3 rhythmites, where coarse units were of similar thickness to fine units. This is probably because summer layers and winter turbidites are indistinguishable in these distal sediments. However, correlation of thicknesses is possible for those silt-clay and clay-dominated varves between 20-2mm in thickness which contain summer layers consisting of more than one lamina. Within a 30 varve sequence, 3 possible false varves were detected, indicating that the cores are between 1-4 years apart in age.   However, if erosional partings and evidence of soft sediment deformation in silt-dominated varves are considered, the error for each core is up to 43 years for Rooskagh and up to 9 years for Knocknanool. Nevertheless, despite the effect of erosion, it is noteworthy that the difference in the total number of rhythmites between sites is just 4 (166 at Knocknanool, 170 at Rooskagh).

CONCLUSIONS

Varved sediments are present in glaciolacustrine sediments underlying Knocknanool Bog, Co. Roscommon. Summer layers are characterised by deposition from underflows and interflows, partly due to flocculation, with thickness controlled by seasonal meltwater generation. Winter layers are deposited mostly as dispersed grains, but with minor flocculation at the base of layers. Occasional underflow deposition also occurs in winter. The varves exhibit proximal to distal fining up-core. Correlation between cores is possible if medial to distal varves between 20-0.5mm thick are used; local errors may be as high as 43 years per core.

A number of conclusions can be drawn about the use of similar sediments in the Irish Midlands to construct a varve chronology, based both on the work detailed here and previous work in Scandinavia (De Geer 1940). Core sites should be selected with reference to lake bottom topography and sediment thicknesses in order to select sites where the thickest possible sequences with the least likely disturbance are located and sites should also be located away from points where meltwater discharge is likely to have caused repeated scouring of the lake bottom (De Geer, 1940). In order to maximise the chances of locating erosional horizons, multiple cores (at least two, preferably more) should be taken at each core site. Core sites should be as close together as feasible – a maximum of 500m is suggested – so that visual correlation between cores is possible. Correlation between cores should be based on medial to distal varves only, where thickness variations clearly correspond; the age for each core site can then be calculated by adding on the number of proximal varves below the correlated part of the core. Finally, other dating means, including thermoluminescence dating (e.g. Berger, 1984) and tephrachronologies (where possible) should be used to check varve chronologies, once constructed.

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Figure Captions

Fig. 1. (a) Quaternary glacial landforms in Ireland, showing positions of eskers, drumlins, ice margins and the location of Fig. 1b (redrawn by P. Coxon, after McCabe, 1987). SIEM – Southern Ireland End Moraine. (b) Possible extent of proglacial lakes in Ireland. Maximum lake extent is after Van der Meer and Warren (1997) and is based on present extent of catchments; early post-glacial lake extent is after Mitchell (1986).

Fig. 2. (a) Map of the central Irish Midlands showing the extent of Glacial Lake Riada and glacifluvial and ice-marginal landforms. (b) Location of core sites and relationship with adjacent glacial features. K = Knocknanool core; R = Rooskagh core.

Fig. 3. Stratigraphic logs of Knocknanool and Rooskagh cores, with details of sedimentary structures. Grey bars beside detailed logs indicate thickness of individual couplets.

Fig. 4. Facies in the Knocknanool core, showing rhythmically laminated sediments. (a) Silt-dominated rhythmites. Red arrows indicate erosional horizons; white arrows indicate the position of fine units at the top of rhythmites. (b) Silt-clay rhythmites; white arrows indicate position of fine units at the top of rhythmites. (c) Clay-dominated rhythmites (base of core only). The green arrow marks the change to rhythmites without clay laminae.

Fig. 5. (a) Close-up of coarse unit in silt-dominated rhythmites showing soft sediment deformation structures and erosional surfaces overlain by paler coarse-grained silt and fine-grained sand. (b) Close-up of silt-clay rhythmites showing multiple normally graded laminae within coarse units and pale laminae of coarse-grained silt and fine-grained sand immediately below fine units. Fine units are marked by outlined arrows, normally graded laminae by triangles and coarse-grained laminae by open arrows. (c) Close-up of transition between silt-clay and clay-dominated rhythmites, showing coarse-fine-coarse grading within coarse units (closed-head arrows) and possible burrow cross-cutting two fine units (open arrow). Fine units indicated by outlined arrows. (d) Close-up of clay-dominated rhythmites overlain by non-varved rhythmites, showing coarse units consisting of single, non-graded laminae alternating with fine units of similar thickness. Boundary between clay-dominated rhythmites and non-varved sediments marked by arrow. Major units on scale bars are centimetres

Fig. 6. SEM images of fine units in rhythmically laminated facies . Top of unit is at top right of all photos. (a) Contact between fine clay unit and overlying coarse unit. (b) Contact between coarse unit and overlying fine unit. (c) Microfabric at base of fine unit. Note combination of platy clay grains and prolate silt grains and poorly developed preferential orientation of clay domains. (d) Microfabric at top of fine unit, showing dominantly clay sized material, with strongly developed preferred orientation. Coarse grains are interpreted as dropstones. (e) Close-up of top of fine unit, showing arrangement of grains in domains with face-to-face contacts. (f) Folding within clays at top of a fine unit. (g) Distortion of microfabric at the top of a fine unit due to emplacement of a

coarse grain. (h) Wavy distortion of clay microfabric at top of fine unit. Top of unit is to right of photo. (i) Microfabric at base of a normally graded lamina. Some preferred orientation is visible. (j) Close-up of the base of a normally graded lamina in a silt-clay rhythmite, showing multiple edge-to-edge contacts between clay domains. Outline of part of large floc is indicated by arrows. (k) Arrangement of grains in a coarse silt lamina in a clay-dominated rhythmite. No preferred orientation is seen. (l) Coarse unit, clay-dominated rhythmite, showing development of chains of clay domains consistent with flocculation.

Fig. 7. (a) Total varve thickness, all facies types, Knocknanool core. (b) Total varve thickness, all facies types, Rooskagh core. (c) Varve thicknesses, silt-dominated rhythmites and lower silt-clay rhythmites, Knocknanool core. Error bars indicate variation in thickness for individual varves. (d) Varve thicknesses, silt-dominated rhythmites and lower silt-clay rhythmites, Rooskagh core. Error bars indicate variation in thickness for individual varves. (e) Varve thickness, varves 28-85, Knocknanool core. Circled points are varves with no equivalent in the Rooskagh core. (f) Varve thickness, varves 30-85, Rooskagh core.

Table 1 Facies description and interpretation

Facies	Coarse unit characteristics	Fine unit characteristics	Interpretation
Silt-dominated rhythmites	Coarse- to fine- grained silt and clayey silt; multiple, usually normally graded laminae; frequent soft sediment deformation structures and erosion surfaces, dropstones, some flocculation	Sharp upper and lower contacts; Normally graded silty clay to clay; occasional coarse-grained silt laminae; always underlain by coarse-grained silt; soft sediment deformation structures common on upper contact	Annual varves, summer deposition from turbidity currents and interflows, winter deposition from suspension and occasional underflows
Silt-clay rhythmites	Coarse- to fine- grained silt and clayey silt; 2-5 normally graded laminae with occasional coarse-grained silt laminae; occasional soft sediment deformation structures and burrows; flocculation common	As in silt-dominated rhythmites, but soft sediment deformation structures rare on upper contact, silt laminae less common	Annual varves, as above, but erosional surfaces are uncommon
Clay-	Coarse- to fine- grained	As in silt-dominated	Coarse-fine-coarse

dominated rhythmites	silt and clayey silt; either 3 laminae coarse-fine-coarse, or a single lamina which may be graded. Rare burrows.	rhythmites, but without underlying coarse silt, and silt laminae within clay are 1-2 grains thick	sequences with clay cap are interpreted as annual varves; origin of couplets with unlaminated coarse layer is unclear

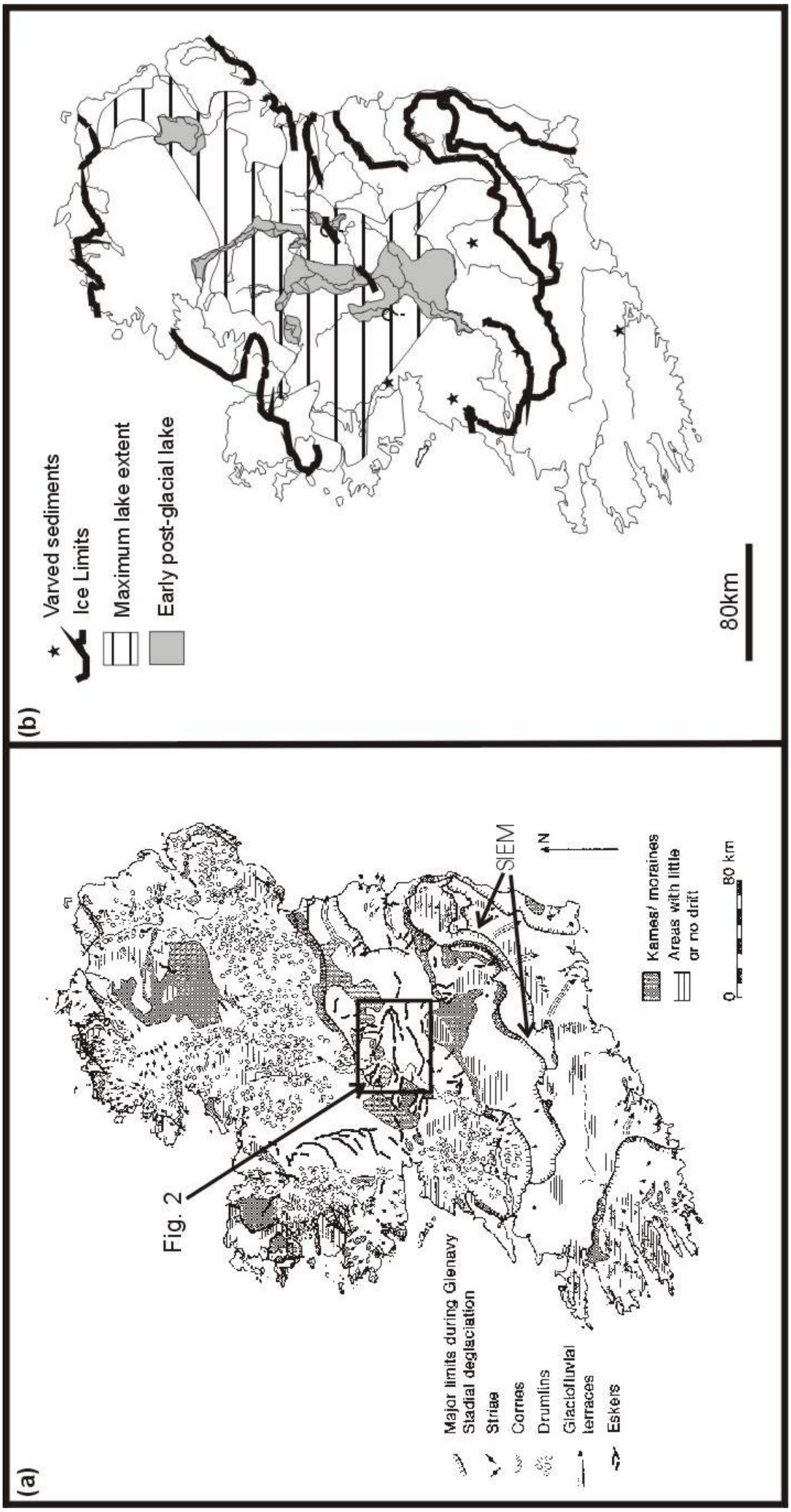
(a)
Major limits during Glenavy Stadial deglaciation
Striae
Corries
Drumlins
Glaciofluvial terraces
Eskers
Fig. 2
SIEM
N
Kames/ moraines
Areas with little or no drift
0
80 km
(b)
Varved sediments
Ice Limits
Maximum lake extent
Early post-glacial lake
80km

Figure 1.

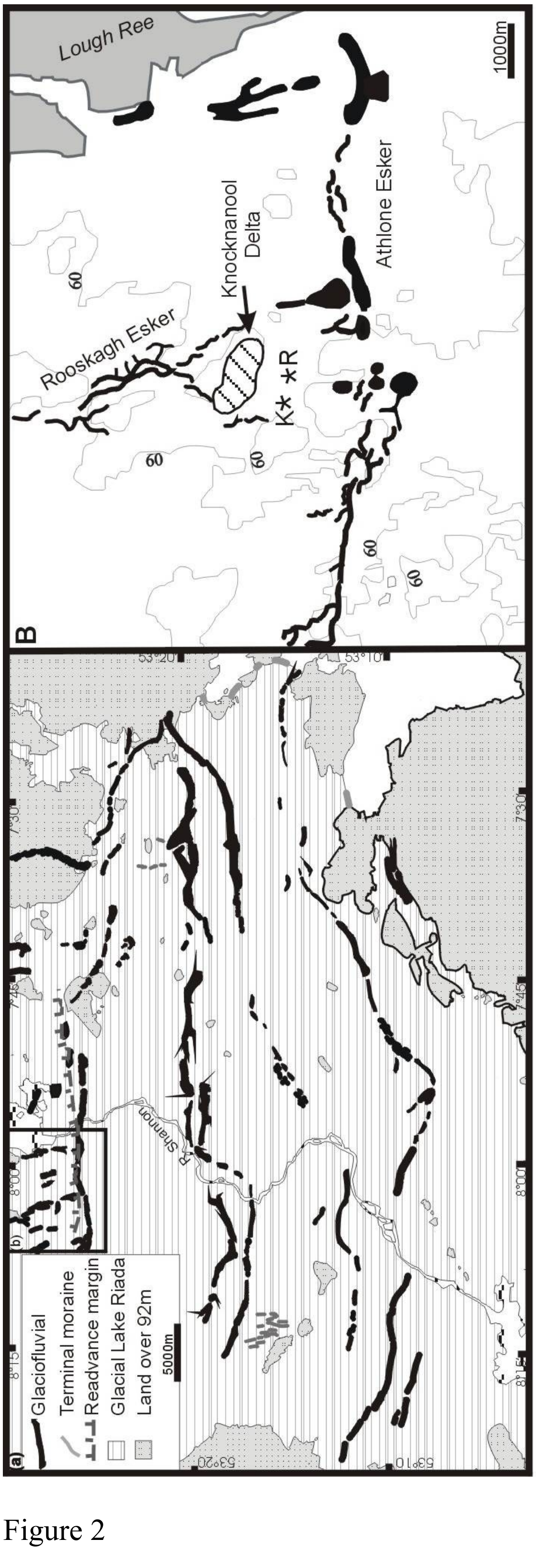
a)
Glaciofluvial
Terminal moraine
Readvance margin
Glacial Lake Riada
Land over 92m
5000m
(b)
R. Shannon
8°15
8°00
7°45
7°30
53°20
53°10
B
Lough Ree
1000m
Rooskagh Esker
Knocknanool Delta
Athlone Esker
K
R
60

Figure 2

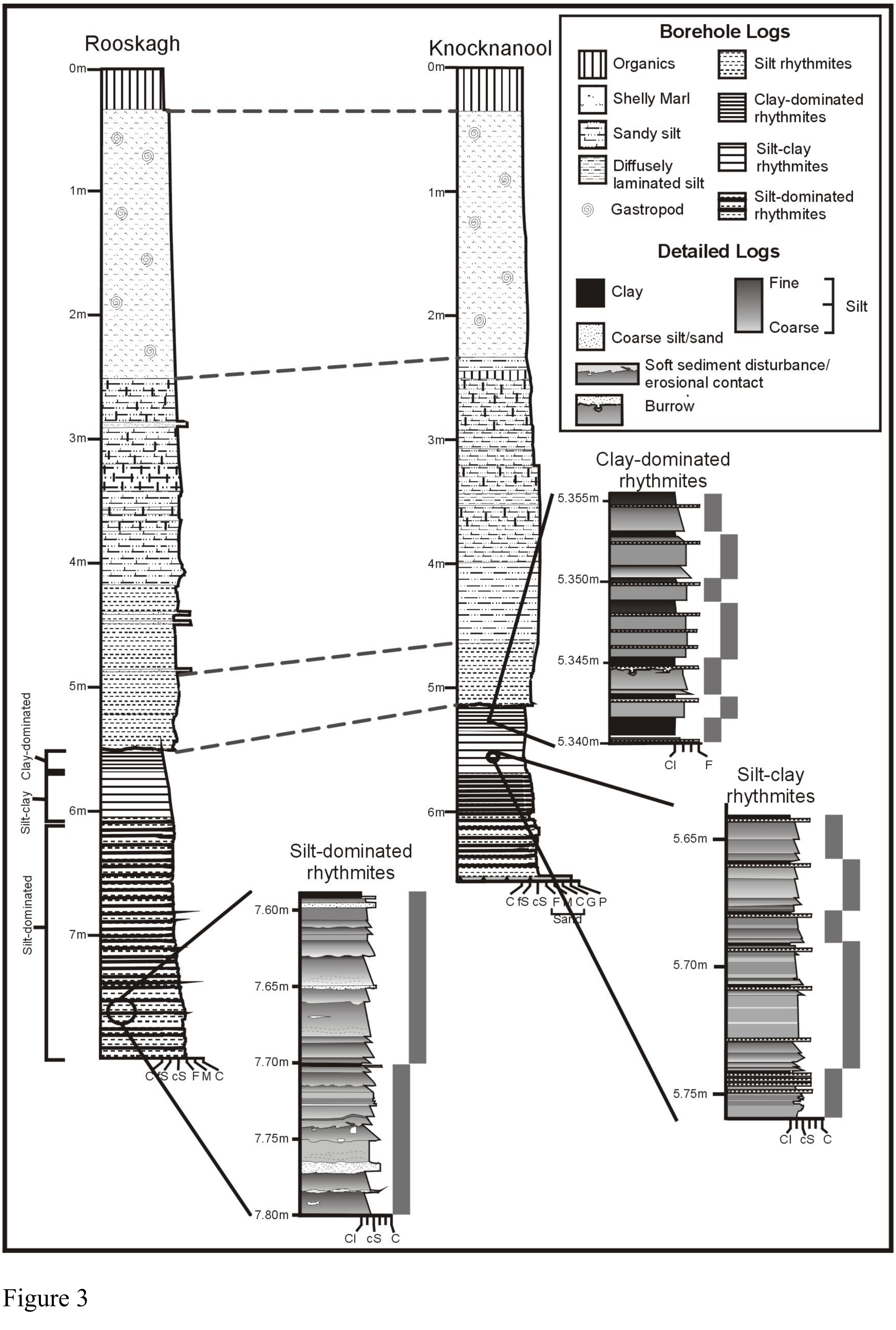
Rooskagh
Knocknanool
0m
1m
2m
3m
4m
5m
6m
7m
Clay-dominated
Silt-clay
Silt-dominated
C fS cS F M C
C fS cS F M C G P
Sand
Borehole Logs
Organics
Shelly Marl
Sandy silt
Diffusely laminated silt
Gastropod
Silt rhythmites
Clay-dominated rhythmites
Silt-clay rhythmites
Silt-dominated rhythmites
Detailed Logs
Clay
Coarse silt/sand
Fine
Coarse
Silt
Soft sediment disturbance/ erosional contact
Burrow
Clay-dominated rhythmites
5.355m
5.350m
5.345m
5.340m
Cl F
Silt-clay rhythmites
5.65m
5.70m
5.75m
Cl cS C
Silt-dominated rhythmites
7.60m
7.65m
7.70m
7.75m
7.80m
Cl cS C

Figure 3

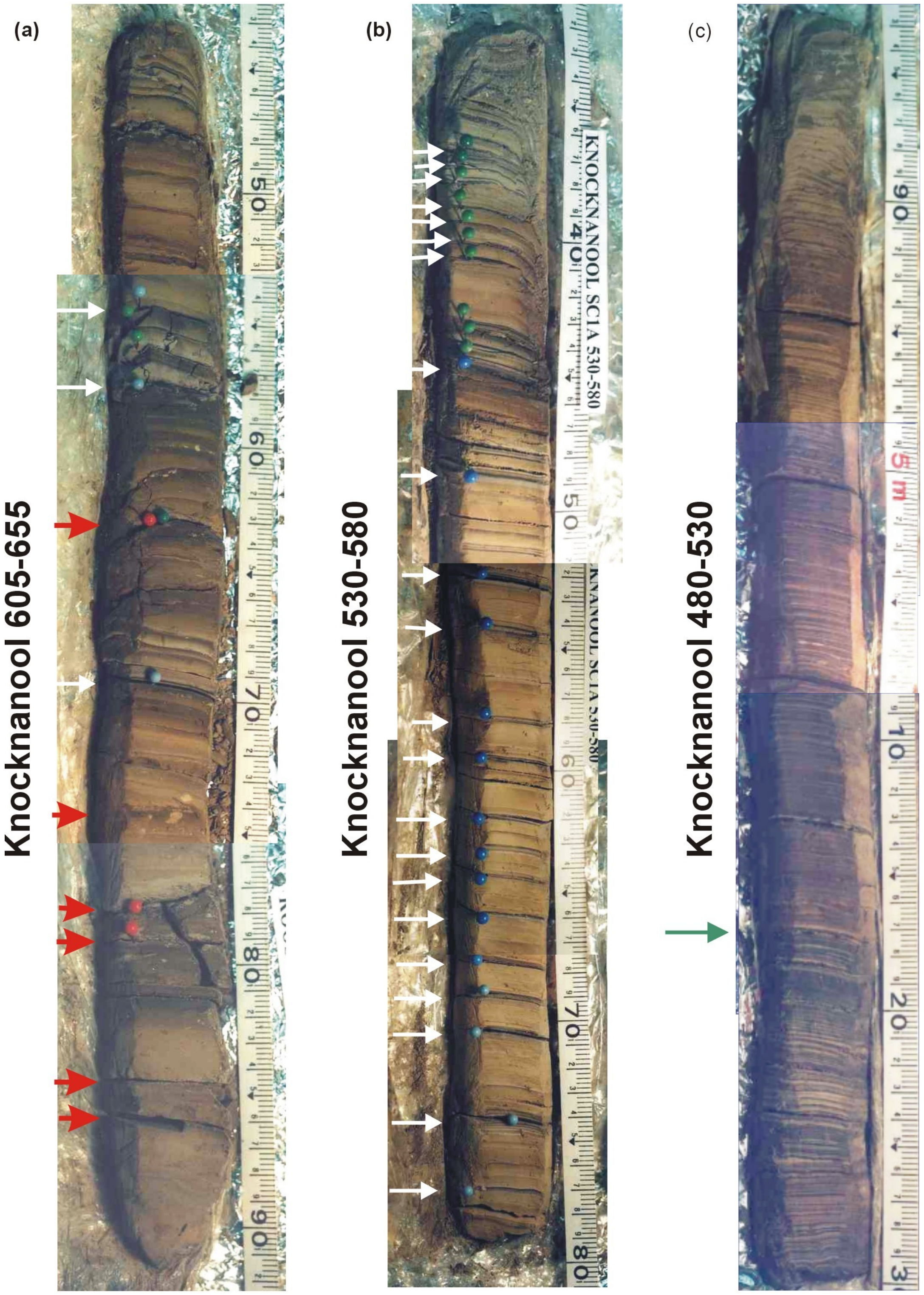
(a)
Knocknanool 605-655
(b)
Knocknanool 530-580
KNOCKNANOOL SC1A 530-580
(c)
Knocknanool 480-530

Figure 4

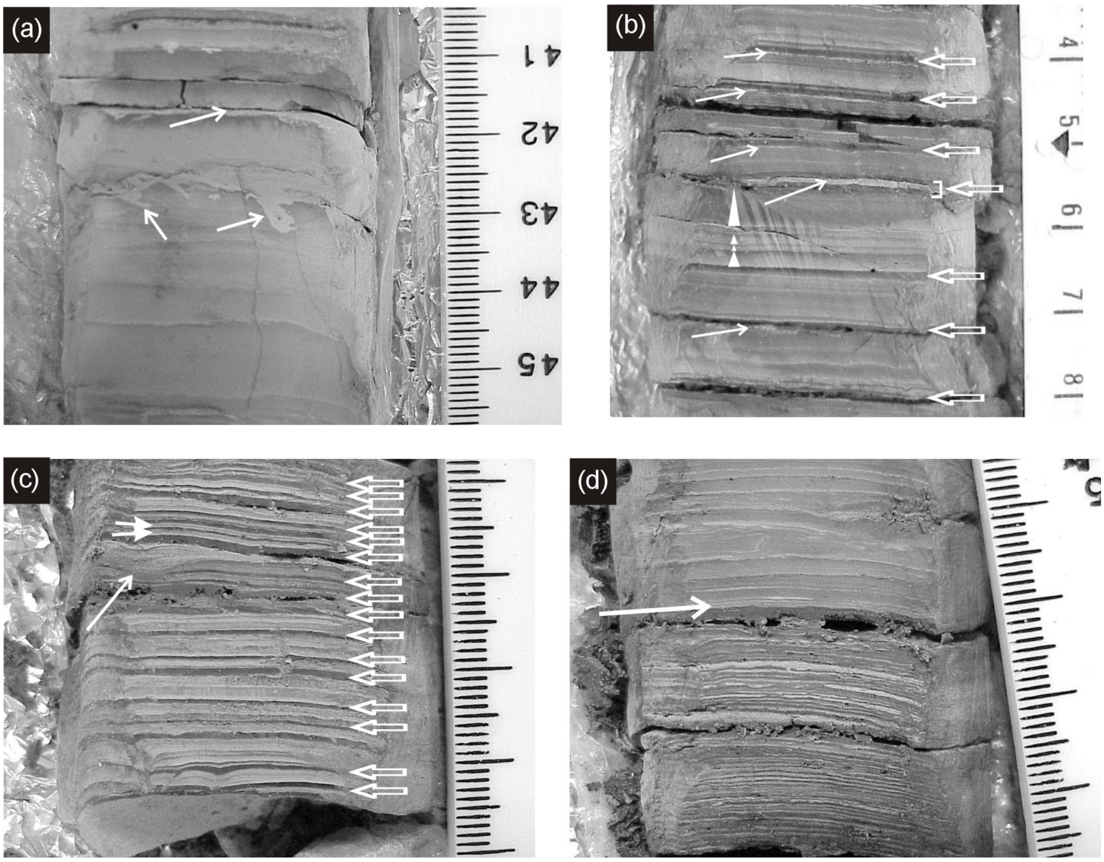

Figure 5

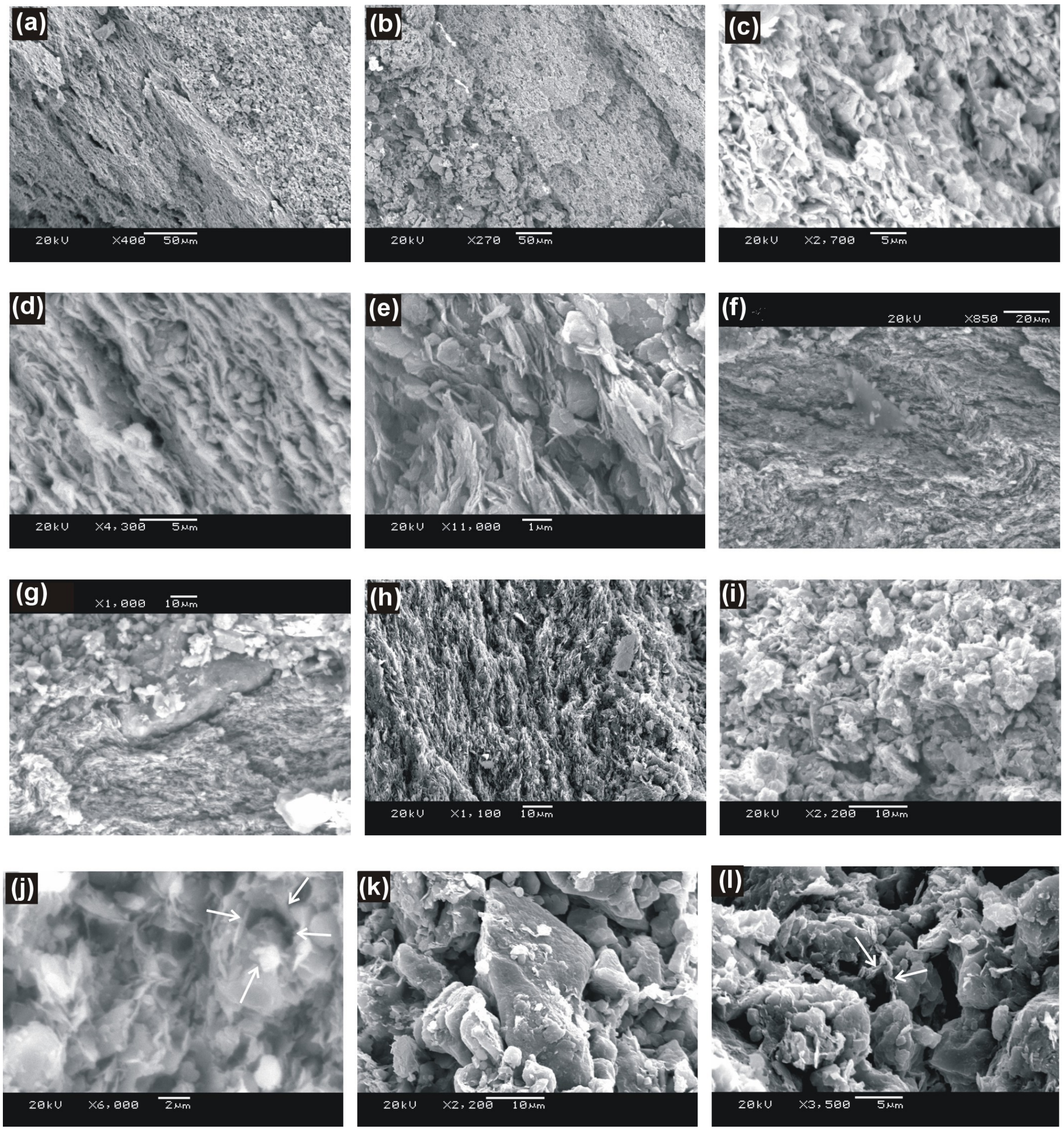
(a)
20kV X400 50µm
(b)
20kV X270 50µm
(c)
20kV X2,700 5µm
(d)
20kV X4,300 5µm
(e)
20kV X11,000 1µm
(f)
20kV X850 20µm
(g)
X1,000 10µm
(h)
20kV X1,100 10µm
(i)
20kV X2,200 10µm
(j)
20kV X6,000 2µm
(k)
20kV X2,200 10µm
(l)
20kV X3,500 5µm

Figure 6

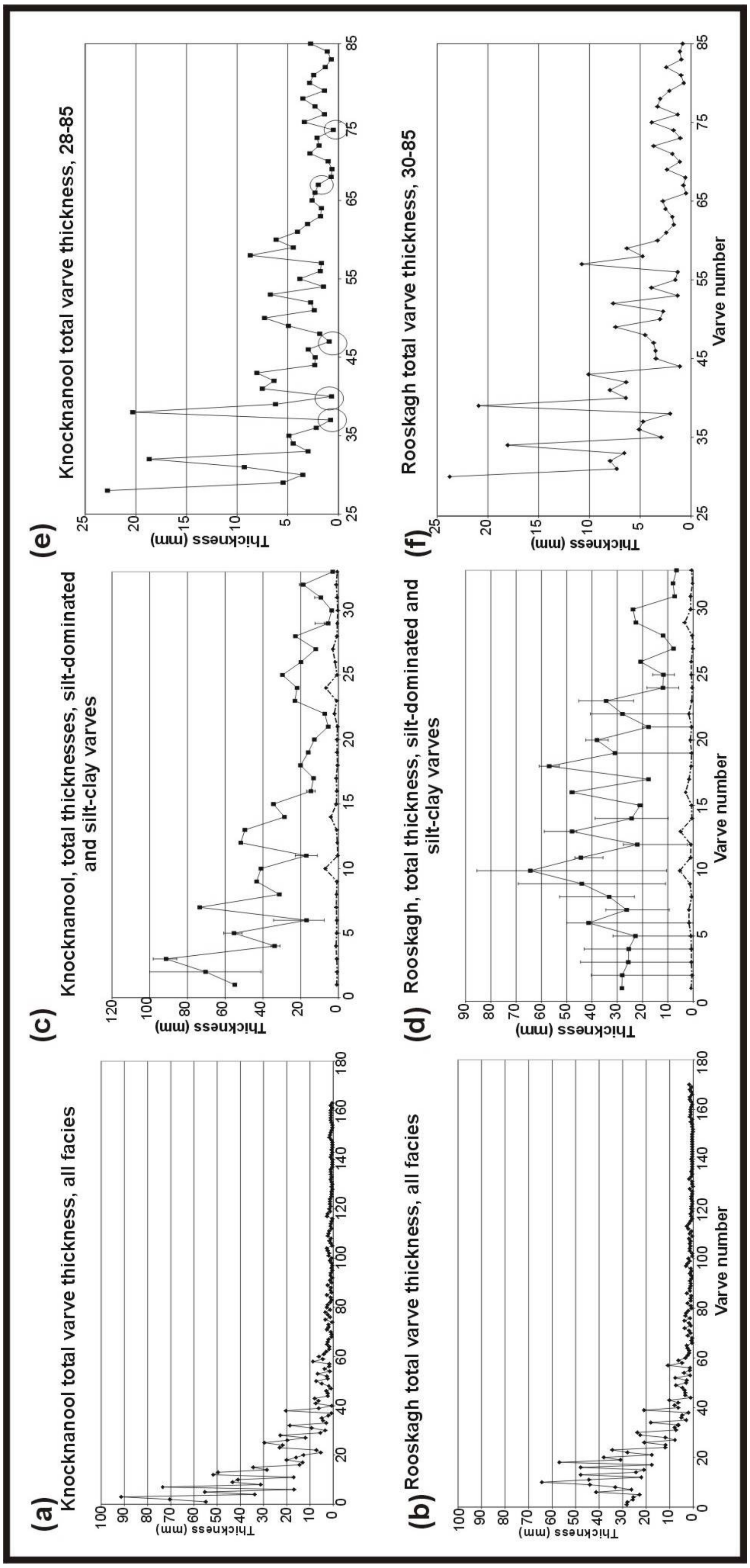
(a)
Knocknanool total varve thickness, all facies
Thickness (mm)
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
120
140
160
180
(b)
Rooskagh total varve thickness, all facies
Thickness (mm)
Varve number
(c)
Knocknanool, total thicknesses, silt-dominated and silt-clay varves
Thickness (mm)
120
100
80
60
40
20
0
5
10
15
20
25
30
(d)
Rooskagh, total thickness, silt-dominated and silt-clay varves
Thickness (mm)
Varve number
(e)
Knocknanool total varve thickness, 28-85
Thickness (mm)
25
20
15
10
5
0
25
35
45
55
65
75
85
(f)
Rooskagh total varve thickness, 30-85
Thickness (mm)
Varve number

Figure 7