High-resolution seismic imaging of a Younger Dryas and Holocene mass movement complex in glacial lake Windermere, UK

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ABSTRACT

The stratigraphy and sedimentological processes operating over the last 15,000 years within glacial lake Windermere (UK), at the mouth of Cunsey Beck, were imaged by a decimetre-resolution seismic reflection survey. A complex of fifteen mass movement deposits was identified as contemporaneous with the Younger Dryas, and two within the overlying Holocene drape. The high vertical resolution and dense grid of profiles allowed pseudo three-dimensional mapping of individual events, along with the determination of their relative temporal relationships. The size of the mass wasting deposits has been estimated to range between 2100 and >100,000 m$^3$. The geometry, structure and relationship to the existing stratigraphy suggest a rapid emplacement of the Younger Dryas mass movement deposits, facilitated by climatic changes making subaqueous slopes unstable, with possible triggering by seismic activity. Morphometric parameters, such as volume and planar surface area, indicate a greater mobility of the Younger Dryas mass movement deposits compared to the Holocene events. The sediments of all imaged mass movement deposits are believed to originate from the slope deposits of the lake. The age of two Holocene mass movement deposits, triggered by flooding or terrestrial debris flows, is estimated to be 2400 and 4400 years BP.

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1. Introduction

Lake deposits can provide a continuous, high-resolution record of sedimentation processes associated with environmental changes without the erosional unconformities usually found in sub-aerial deposits. Sediment provenance, environmental conditions, vegetation, fauna and changes due to anthropogenic influence are recorded within lacustrine sediments (Shen et al., 2008). Furthermore, catastrophic events such as seismic and volcanic activities, rockfalls, floods, extreme river discharges and mass movements, sourced onshore as well as below the lake level, leave their fingerprint in the sedimentary succession (Schnellmann et al., 2006). For glacigenic lakes the limiting boundary for tracing back these events is usually the last glaciation, during which ice related erosion removed all previous deposits.

High-resolution seismic reflection surveying is commonly used to study the large- and small-scale morphological and stratigraphic features associated with the depositional history (Scholz, 2001). For absolute dating purposes, core analysis is often combined with geophysical methods (Todd et al., 2008). Mass movements related to continental margins and in the marine realm are well studied due to their large size, geo-hazard potential and the availability of industrial 3D seismic data sets (e.g., Hafldason et al., 2004; Hühnerbach and Masson, 2004; Masson et al., 2006). Previous studies of Late Glacial and Holocene sediments in lacustrine and fjord environments have focused on general stratigraphic and morphological interpretation (Mullins and Halfman, 2001; Baster et al., 2003; Schnellmann et al., 2006; Vardy et al., 2010). Mass movement deposits have been imaged and linked to palaeoseismic events (Schnellmann et al., 2002; Waldmann et al., 2011). Depositional processes and mobility in weakly consolidated lacustrine sediments have been addressed (Schnellmann et al., 2005; Moernaut and De Batist, 2011), but are still not well understood.

Here we investigate the depositional history of Late Glacial and Holocene sediments in the south basin of glacial lake Windermere, UK, and the morphological characteristics of a series of subaqueous mass movements dating back to the Late Glacial and mid-Holocene times. Windermere has been investigated using Chirp and multi-channel boomer data in the past (Pinson, 2009; Vardy et al., 2010) to gain an understanding of the overall history of the lake deposits from active ice-retreat at the end of the last glaciation through to modern lakebed processes. As part of this, a decimetre-resolution 3D seismic volume was acquired to investigate a locally confined mass movement complex in the north basin of the lake (Vardy et al., 2010). In this study, we applied a parametric sub-bottom profiler to image a region in the south basin (which is less well studied) around two mass movements visible in swath bathymetry data at high lateral detail and with decimetre vertical resolution. The study area is located close to the mouth of Cunsey Beck, the major source of sediment flux into the south basin. The sub-bottom data revealed two events within the Holocene deposits and 15 nested events within the underlyng postglacial deposits in an area of approximately 600×800 m.
The high-resolution of the data set allowed a reconstruction of the spatial relationship of the individual events, their individual morphology, as well as an assessment of the likely sources, timing and processes for their emplacement. This study will contribute to the available morphological database of lacustrine mass movement deposits and will also address questions related to the timing and triggering of mass movements and their mobility.

2. Regional setting and the study area

Windermere is located in the south eastern part of the Lake District, UK, and is a north–south trending ribbon lake, separated into the north and south basins by a bedrock high. The lake has an area of 14.8 km² and an overall length of about 17 km, with the north basin being significantly wider (up to 1.5 km) than the south basin (typically 0.5 km). The mean lake level is c. 35 m above present sea level and the maximum water depth is 62 m (northern end of the north basin).

Our study area is located at the mouth of Cunsey Beck (Fig. 1). This river delivers the main sediment flux into the south basin from a catchment area around Esthwaite Water to the west of the lake, with an approximate catchment size of 20.7 km² (Fig. 1). Esthwaite Water acts as a sediment trap for some of the coarse grained particles, but the majority of fines are transported further into the basin of Windermere. Maximum terrestrial slope angles at the lake shore are about 10°; however, the western lake shore around Cunsey Beck is more gently dipping (c. 5°). Where Cunsey Beck enters Windermere, the lake is 950 m wide, and has a maximum water depth of 35 m. The shore proximal parts of the lake have water depths of <20 m, with a major break of slope at c. 200 m from the western shore, and at >300 m from the eastern shore, giving rise to steep slopes (up to 17°) dipping down into the deeper basin.

The basement rocks of the region are of Silurian age (Lawrence et al., 1986). The entire southern lake basin is underlain by banded siltstones and mudstones with subordinate sandstone turbidites of the Bannisdale Formation of the Windermere Supergroup (Millward et al., 2000). Several major synclines and anticlines with a south west–north east trend are present at both southern lake shores.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Overview of acquisition parameters for the parametric sub-bottom profiler.</th>
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Served in the lake sediments (Pinson, 2009). This was followed by the mere valley left a complex sequence of BIIS glaciogenic landforms pre-Windermere Interstadial (more widely referred to as Bølling/Allerød 1977; Coope et al., 1977). Retreat of this ice mass from the Windermere area had thinned enough to expose the high peaks by 16 ka BP (16.5 ± 1.7 ka BP at New Close and 19.4 ± 2.6 ka BP at Warton Crag; Telfer et al., 2008) the whole region was ice-free (Pennington, 1943, 1977; Coope et al., 2008) the whole region was ice-free (Pennington, 1943, 1977; Mackereth, 1971). By the onset of the Holocene at about 11.7 ka BP (NGRIP event stratigraphy and GICC05 chronology, Lowe et al., 2008) the whole region was ice-free (Pennington, 1943, 1977; Coope et al., 1977).

3. Methods

A 2D seismic reflection data set was collected in April 2011, using an Innomar™ parametric sub-bottom profiler, side-mounted onto the vessel R/V The John Lund. Parametric profilers have the advantage of narrow focused beams, short pulses with wide frequency bandwidth, and convenient small transducer sizes (Wunderlich et al., 2005). Parametric systems produce two slightly different primary frequencies which generate new secondary frequencies (the sum and difference of the primary frequencies), which are received and analysed. The Innomar™ system used here transmits primary frequencies around a centre frequency of 100 kHz, which generate secondary frequencies between 5 and 15 kHz. For the small transducer size used (22×22 cm), the half-power beam width (at −3 dB) is very narrow (3.8°; Table 1). Regional survey lines were acquired at 50 m spacing, with a more densely spaced grid of 10 m lines over two debris flows (Fig. 2) identified in swath bathymetry data. A survey speed of around 2 m s\(^{-1}\) was used, together with a heave compensator to reduce vertical movements due to wave action, resulted in very good data quality. Positioning was identified by Differential GPS, and lake level data were recorded with a tide gauge. Variations of the lake level during the survey were in the range of ±5 cm, and therefore static corrections were not applied to the seismic reflection data. A sound velocity profile was performed daily, and indicated that there was no significant layering within water column. All seismic data were band-pass filtered (6–18 kHz), and an envelope function was applied to aid interpretation.

The parametric seismic profiles gave a penetration of up to 20 m below the lakebed. Due to the selected dominant frequency of 12 kHz and a bandwidth of c. 10 kHz, a vertical resolution better than 10 cm was achieved. In addition to the parametric data, a previously recorded
multi-channel boomer seismic profile was used to correlate these data with the wider stratigraphic context (Pinson, 2009; Fig. 3). The boomer system, with a frequency band between 0.4 and 4.0 kHz, imaged deeper and achieved a vertical resolution of about 30 cm. The ice retreat surface was imaged in the boomer data, at a depth of slightly more than 30 m below the lakebed. All parametric sub-bottom profiler sections were depth converted with a constant acoustic velocity of 1435 m s\(^{-1}\).

### 4. Results

#### 4.1. Seismo-stratigraphic framework

Previous high-resolution single- and multi-channel Boomer profiles acquired throughout the lake (Pinson, 2009; Vardy et al., 2010) defined five main seismo-stratigraphic units (SSS I to SSS V) for the Windermere sediments. Here we use a simplified version of this framework, combining SSS I and SSS II into a single seismo-stratigraphic unit (SSS I; Fig. 3), resulting in four main seismo-stratigraphic units (SSS I to SSS IV). The multi-channel boomer data achieved good penetration, allowing the construction of an interval velocity model using common-reflection point gathers, which identifies the oldest unit, SSS I, as a strongly attenuating deposit with high acoustic interval velocities between 1750 and 2000 m s\(^{-1}\). At multiple intersections throughout the lake (Fig. 4 and Table 2). The oldest facies, F IIa, is a 50 to 60 cm thick uniform layer with low amplitude internal reflections, traceable throughout the deeper parts of the lake basin. Facies F IIIb varies in thickness between less than one and a few metres, thins towards the basin centre and is often located close to break of slopes. This facies occasionally scour into older strata and usually demonstrates a transparent seismic characteristic. In places, F IIIb exhibits stacked packages, divided by high amplitude reflections, but without interbedding of other facies. F IIIc is an up to 1 m thick package of layered high and low amplitude reflections, similar to the seismic characteristic of unit SSS II. If F IIIb is present, F IIIc can be observed mostly above, but locally also below these deposits.

Furthermore, we also subdivide SSS IV into two separate sub-units (SSS IVa and IVb; Fig. 4 and Table 2). SSS IVa is an up to 4 m thick uniform deposit with some low amplitude, but continuous internal reflections. SSS IVb is a reflection free upper layer of 0 to 40 cm thick, mostly recognisable in the deeper basin and thinning out at water depths of <20 m. Within SSS IVa, there occasionally appear locally confined and scattering high amplitude reflections, with blanking of underlying strata.

#### 4.2. Correlation with core stratigraphy

Several short cores of 5–6 m in length have previously been collected and analysed in both lake basins (Pennington, 1943, 1977; Smith, 1959; Mackereth, 1971; Coope et al., 1977). The main seismo-stratigraphic units SSS I through IV can be correlated against these core stratigraphies at multiple intersections throughout the lake (Fig. 4 and Table 2; Pinson, 2009; Vardy et al., 2010). The closest to our study area, Core M (Fig. 2) in the south basin, is described by Mackereth (1971).

We correlate (Figs. 4 and 5):

- The coarsely layered seismo-stratigraphic unit SSS IV with the lower part of Core M (Fig. 4). Annual varves, up to 2 cm thick, are indicative of extremely high deposition rates after the LGM and ice...
retreat, when sedimentation in Windermere was dominated by inorganic glacial outwash (Pennington, 1943; Coope et al., 1977).

- The uniform facies F IIIa with the distinct organic detritus silt layer of about 30 cm thick deposited during the Windermere Interstadial (Mackereth, 1971; Coope et al., 1977).

- The usually transparent facies F IIIb with the 60 cm thick deposit of highly disturbed and disoriented material above the upper boundary of the glacial fines. In other cores, similar deposits are shown to comprise Younger Dryas age material (Pennington, 1947; Mackereth, 1971).

- The layered facies F IIIc with the thin layer of about 50 cm of organic-poor laminated clay (some 400 paired varves of glacial fine outwash deposits) of Younger Dryas age (Pennington, 1947; Mackereth, 1971).

- The layered sub-unit SSS IVa with organic-rich Holocene deposits, when sedimentation rates were in the range of 0.2 to 0.6 mm year\(^{-1}\) (Chiverrell, 2006).

- The reflection free sub-unit SSS IVb with recently deposited organic ooze.

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Fig. 4. Short seismic sections with and without interpretation: (A) close to the core location; (B) from the study area and c. 300 m north of the core location; (C) from the study area and c. 500 m north of the core location. (D) Core-M, described by Mackereth (1971). Note the comparable seismo-acoustic characteristic of the thin crème coloured (at 4.0 to 4.3 m in the core) and the thick yellow coloured (at 0.4 to 2.9 m in the core) reflection package. See Fig. 2 for profile locations. Vertical exaggeration: ×10.

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5. Mass movement deposits

Interpretation of the data set has revealed 17 individual mass movement deposits (E-I through E-VXII), which were mapped between seismic profiles. Two mass movement deposits were emplaced within the Holocene sediments of SSS IV (Figs. 6 and 7). All other events were emplaced within the Younger Dryas sediments and identified as F IIIb, but in places scour into older strata.

The relative timing of emplacement for each event (E-I = oldest, E-XVII = youngest) has been determined based on the relative position of the bounding reflections within the seismic sections. For two events, no temporal relationship could be defined, because they are spatially isolated (E-I and E-II), while some events show frontal ramp features (e.g. E-VIII; Fig. 9). Occasionally, we recognised step-ups and step-downs in the proximal parts of the larger events (e.g. E-I and E-VIII; Fig. 9).

The two Holocene events exhibit a highly irregular upper boundary. The modern lakebed still shows a distinct relief, even though the deposits are now draped by younger Holocene sediments. The very high amplitude, lower boundary is less irregular, but shows signs of erosion into older strata (Figs. 6, 7, and 9). The two Holocene deposits have a generally reflection-free internal architecture. Occasionally, high amplitude diffraction hyperbolas appear within these deposits.

5.2. Deposit morphologies

The Younger Dryas mass movement deposits often exhibit lobed planiform shapes and even circular shapes can be recognised where material movement is unimpeded (e.g. E-VIII and E-XII; Figs. 7 and 9), but often shows a sheet-like, non-erosive characteristic (e.g. E-IV and E-XI; Fig. 7). Upper boundaries vary between slightly irregular to regular morphologies (Figs. 6, 7, and 9). E-I is the only event with evidence for thrust features, while some other events show frontal ramp features (e.g. E-VIII; Fig. 9). Occasionally, we recognised step-ups and step-downs in the proximal parts of the larger events (e.g. E-I and E-VIII; Fig. 9).

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5.1. Reflector geometries

We recognised two different styles of reflector geometries for the identified mass movement deposits in the study area (Fig. 9), which separate the Younger Dryas from the Holocene events. The majority of the Younger Dryas mass movement deposits show an almost transparent internal seismic characteristic. The lower boundary is sometimes irregular (e.g. E-VIII and E-XII; Figs. 7 and 9), but often shows a sheet-like, non-erosive characteristic (e.g. E-IV and E-XI; Fig. 7). Upper boundaries vary between slightly irregular to regular morphologies (Figs. 6, 7, and 9). E-I is the only event with evidence for thrust features, while some other events show frontal ramp features (e.g. E-VIII; Fig. 9). Occasionally, we recognised step-ups and step-downs in the proximal parts of the larger events (e.g. E-I and E-VIII; Fig. 9).

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5.2. Deposit morphologies

The Younger Dryas mass movement deposits often exhibit lobed planiform shapes and even circular shapes can be recognised where material movement is unimpeded (e.g. E-VI, E-VIII, and E-XIII; Fig. 10), but become irregular when confined by features in the pathway of emplacement. Such features are palaeo-bathymetric highs (e.g. E-VXII), basin borders (e.g. E-VI and E-VXVII), or pre-existing mass movement deposits (e.g. E-XIII). In addition, some unconfined deposits exhibit a highly irregular shape (e.g. E-XII and E-XIV), indicative of a high mobility and fluid-like deposition, which is controlled by minor palaeo-lakebed relief.

For example, E-XVII flows from an underlying morphological high in both directions (Fig. 10).
Both Holocene events have a lobed shape and material spreads out unidirectionally from the foot of the slope, thinning distally. E-XVI exhibits individual finger-like features at distal parts of deposition, which are not so apparent in the gridded surfaces, while E-XVII has a surface with blocks of relatively undisturbed material. These blocks are visible in the seismic sections (Fig. 9C, D).

From the interpreted seismic sections, we extracted upper and lower boundaries for all mass movement events. Data were gridded and values for area, volume and thickness of deposits were calculated (Table 3). We also measured the length of deposition, but due to uncertainties related to the position relative to the failure zone, we could not calculate accurate run-out values. We estimated the slope angles and basal dip angles for most of the events, using the apparent knickpoint in the cross-sectional shape of the mass movement events (Table 3, Fig. 11). Histograms showed widely distributed values and did not allow a clustering of the data set with confidence, other than clearly separating the Younger Dryas and Holocene events. The Younger Dryas events usually show shallower slope angles (i.e. <8°), shallower basal dip angles (i.e. <1°), greater length of deposition (i.e., a higher mobility) and less thick deposits. The statistical analysis of Moernaut and De Batist (2011) has shown a wide distribution of slope angles for frontally emergent slides, between 0° and 21°, and basal slope angles in toe regions were in the range of −0.2° to 1.6° (negative values denote upslope transport). This is in good agreement with our data set (e.g. E-III with \( \alpha_b = 0.3° \), \( \alpha_s = 4.7° \), where \( \alpha_b \) is basal dip angle and \( \alpha_s \) is adjacent slope angle, and E-VI with \( \alpha_b = 0.1° \), \( \alpha_s = 6.8° \); see also Table 3).

We analysed the ratio between volume \( (V) \) and depositional area \( (A) \). Moernaut and De Batist (2011) found strong correlations for both emergent \( (V = 0.0744A^{1.24}, R^2 = 0.939) \) and confined slides \( (V = 0.0727A^{1.30}, R^2 = 0.942) \) with very good fitness values to power functions. We found a similar strong correlation, but the power functions for our emergent slides are different: \( V = 0.209A^{1.16}, R^2 = 0.9365 \) for the Younger Dryas events and \( V = 0.2504A^{1.15}, R^2 = 0.8693 \) for all events, including the Holocene ones. The number of events in our study is not very high and the dimensional range of the events in our data set is smaller, but the lateral and vertical resolution should give well constrained dimensional values. Furthermore, the significant decrease of fit for the power functions when Holocene events are included demonstrates the obviously different behaviour...
of the mass movements in these sediments at similar dimensional scales. The Holocene mass movement deposits are more localised, and remain thicker than the Younger Dryas mass movement deposits. The higher mobility of the Younger Dryas mass movements is most likely related to different properties (e.g., cohesiveness) of the deposited sediments.

6. Discussion

6.1. Pre-Younger Dryas structure

Faults and scarps have been identified and mapped within SSS II (Figs. 6, 9 and 12). The general fault trend is NNW–SSE, parallel to the lake shores. However, some scarps and one fault have an E–W orientation (Fig. 12), which are probably related to underlying moraine ridges cross-cutting the lake basin (Pinson, 2009). The bathymetry also exhibits vertical steps of several metres at these two locations. The majority of faults are normal, down-throwing towards the centre of the lake basin, indicative of general downslope transport rather than basement tectonics. The identified scarps are better preserved at shallower depths than close to the main depositional centre, where subsequent failures have eroded the older scarps and failure zones. Alternatively, some of the mapped faulted blocks could be the result of uneven topography too steep for deposition, and therefore causing the impression of vertically translated blocks.

Fluid escape features, characterised by narrow chimney like structures widening with depth (from c. 5 m on top to c. 20 m on the bottom), disrupt the sediments around the failure zones. Typically, seismic reflection

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**Fig. 8.** Description of reflector geometries and properties for individual mass movement deposits. A legend summarises symbols used to describe the lower boundary, upper boundary, internal reflections and deposit shape. Events marked with (*) are cut by the boundaries of the data set or data are sparse. Events marked with (#) have no temporal constraints. Events marked with (ø) were emplaced at similar time intervals. In general, event relative age decreases from E–I to E–XVII.
amplitudes decrease within and below the chimneys (Fig. 6). When mapped in a planar view, the fluid escape features form distinct elongated and parallel zones in the central basin and show a NE–SW trend (Fig. 12), although there is also a scattered distribution of smaller features aligned closely to the major break of slope at the western side of the lake basin. Some of these features, which disrupt the sediments, exhibit high amplitude diffraction hyperbolas. The fluid escape structures ascend until they are trapped beneath the Holocene mass movement deposits (Figs. 6 and 7), explaining the high basal reflection amplitudes.

Chapron et al. (2004) demonstrated how fluid escape features in a French lake could be linked to the development of fractures and syn-sedimentary faults, eventually forming the head scarp of a large mass movement. The distinct chimneys observed in Windermere terminate below the Holocene deposits, i.e. no deformation of reflections occurs above. This suggests either an early development, which stopped before the Holocene deposition occurred or very recent features, which did not have time to ascend further. Fluid escape features are commonly associated with the dewatering of porous sediments in facies assemblages. Fluid escape features are also often linked to ground shaking due to seismogenic activity (Chapron et al., 2004; Moernaut et al., 2009). We link these features to a period of increased seismic activity after the deposition of the glacio-lacustrine infill, but before the Holocene period, probably caused by isostatic adjustment. Such adjustment may also have reactivated the inferred basement fault, running along the axis of the lake, which is inferred to have the same trend and location as the linear fluid escape features (Figs. 1 and 12).

### 6.2. Time frame for mass movements

We correlated the thin facies of F IIIa against the organic detritus silt layer in the core, which is interpreted as Windermere Interstadial deposits, dated to 13.4 ± 0.4 ka \(^{14}\)C BP (Mackereth, 1971). Facies F IIIc was correlated against the organic-poor glacial facies in the core, which are interpreted as resulting from deposition during the Younger Dryas cooling event (10.13 ± 0.35 ka \(^{14}\)C BP; Mackereth, 1971). These ages are bulk \(^{14}\)C ages, which do not provide a precise age control on the transition from the Interstadial to the Younger Dryas.

All mass movement deposits (facies F IIIb) that fill the basin of the study area are deposited above F IIIa, with the exception of localised scouring into older strata (e.g. E-I). In most cases, facies F IIIc can be observed above the most recent mass movement within the stack of events. Occasionally, F IIIc can be observed below a mass movement event (e.g. E-XII). This places the majority of the identified mass movement events within the Younger Dryas period. The large number of events for a relatively short time frame (i.e. 15 over a period of 1000 to 1200 years) suggests a rapid or catastrophic mode of deposition. The nature of possible triggering mechanisms is discussed further in Section 6.5.

While not directly sampled in existing core data, ages for the two Holocene events can be estimated based on their vertical position within the seismic unit and using an approximate sedimentation rate for Windermere during the Holocene (Figs. 6, 7 and 9). The upper boundary for these two deposits is very complex and therefore not possible to simply measure the thickness of the material on top. The horizon of emplacement for each event was selected as the approximate lower boundary of on-lapping deposits. Seismic sections from our data set show on-lapping Holocene sediments down to a depth of 125 cm for E-XVI and 70 cm for E-XVII. Chiverrell (2006) determined Holocene sediment accumulation rates for Windermere based on radiometric data, palaeomagnetic data and pollen marker horizons, finding a fairly constant value of 0.35 mm year\(^{-1}\) during this period. With the \(^{14}\)C age of 10,130 ± 350 ka BP at a depth of 290 cm in the core...
Fig. 10. Plan view geometry of all the mass movement events and the relationship to key surfaces: (A) basement and ice retreat surface (top of SSS I); (B) top of Interstadial layer of facies F IIIa; (C-I) individual events in temporal order as given in Fig. 8; (J) pre-Holocene palaeo-bathymetry (bottom of SSS IV); (K) two Holocene mass movement events; (L) current lakebed, gridded from sub-bottom profiler data. Striped patches on the western lake slope are areas with shallow biogenic gas within the Holocene sediments. The lakeshore and Cunsey Beck are indicated by bold lines. Coordinates: UTM Zone 30 (WGS-84).
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from the study site (Mackereth, 1971), we calculated a local value of
0.29 mm year\(^{-1}\) for the youngest event E-XVII, and 4400 years for E-XVI.
Although these age values are only estimates (being based on uncalibrated early \(^{14}\)C dates, sediment thicknesses, and local variations in accumulation rate) they raise two factors when relating to the Younger Dryas and Holocene events. Firstly, the estimated ages for the Holocene mass movements are too old for an anthropogenic triggering source. Secondly, the significant time lag between the rapidly deposited mass movements during the Younger Dryas and the two Holocene mass movements suggests a different trigger or process for their emplacement.

6.3. Classification of mass movements

Several classification schemes for subaqueous mass movements exist. Based on cohesiveness and turbulence of flow, Mulder and Cochonat (1996) suggest that a distinction can be made between mass slides (cohesive) and gravity flows (non-cohesive). We have not identified distinct large scale blocks within the Younger Dryas mass movement deposits, rather we observe a typically homogeneous and reflection-free seismic character that suggests matrix-supported motion. This, together with the absence of distinct large blocks, would place these events, following Mulder and Cochonat (1996), as gravity flows, with a sub-classification of mass flows and further sub-classification as debris flows. However, mass movements are able to evolve between types during deposition (Mulder and Alexander, 2001), and characterisation

Table 3

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Fig. 11. Cross sectional geometry of all the mass movement deposits with slope angle \(\alpha_s\) and basal dip angle \(\alpha_b\) (Table 3). Lower right shows a superposition of all the Younger Dryas and Holocene event geometries to enable comparison.
by seismic data alone is not always sufficient for a classification, particularly in lacustrine environments where the deposit morphologies are commonly affected by limited accommodation space (Tripsanas et al., 2008).

A more general classification based on the frontal emplacement style of sub-marine mass movements has been proposed by Frey-Martinez et al. (2006). According to this, all the Younger Dryas events can be classified as ‘frontally emergent slides’, which ramp up from their basal shear surface and translate in an unconfined way over the palaeo-lakebed (Figs. 6, 7 and 9). The apparent thrust features of E-I would be indicative of a ‘frontally confined slide’, but the features are located close to the basin slope and not in a clear toe region which therefore differs from a typical frontally confined morphology (Schnellmann et al., 2005; Frey-Martinez et al., 2006).

The two Holocene events exhibit a more irregular boundary morphology, indicative of a higher degree of material cohesiveness compared to the Younger Dryas events. The Holocene events are not sampled by cores and we can only broadly classify them as gravity flows (mass flows), deposited in a frontally emergent mode.

6.4. Distribution of events

Using the temporal relationship between all mass movement events, a series of three-dimensional models with all events, key horizons and inferred flow directions was produced (Fig. 10). Generally, the direction of flow is controlled by the underlying morphology. We inferred the direction of flow from the basal slope angle, the general shape and cross-sectional profile of the individual events, identified toe regions and the position of the deposit relative to existing scarps at adjacent slopes. The direction of flow for E-I and E-II is of low confidence because major parts are not covered by the sub-bottom profiler data set. The point of origin for E-I (i.e. the adjacent slope) needs a large accommodation space to source the largest volume of transported deposits (>100,000 m³). The position of some observed thrust features would

Fig. 12. Plan view map showing stacked series of mass movement events which: (A) occurred during the Younger Dryas period (grey); (B) occurred during the Holocene (stippled). Faults (with tick marks on the downthrown side), scarps (with arrows towards the failure zone), areas with discrete chimneys of ascending fluids (white polygons), and 10 m contour lines of the underlying ice retreat surface (thin black lines) are indicated. The positions of the lake shore and Conwy Beck are shown. Coordinates: UTM Zone 30 (WGS-84).
indicate a direction of flow along a N–S axis. Scars are not only present around the northern outline, but also at the north-western side of this event (Fig. 12), close to an apparent sediment pathway source from a palaeo Cunsey Beck. The number of Younger Dryas mass movement deposits sourced from the western side of the lake is higher than from the east (9:6). However, several large Younger Dryas events are sourced from the eastern lake shore (E-V and E-VI). The estimated volume of Younger Dryas mass movement deposits sourced from the western side (>218,300 m$^3$) is two times greater than from the east (c. 104,800 m$^3$). The two Holocene events add c. 47,300 m$^3$ of deposited material sourced from the western side (Table 3), and throughout the stratigraphic sequence imaged, the locus of sediment deposition is to the west, where Cunsey Beck delivers the major sediment flux into the south basin. Both slopes have shown evidence for scars and normal faults with a downthrown side towards the lake basin, indicative of mass wasting and mass transport processes. Mobilised sediments of SSS II from shallow sections of the slope were deposited entirely above F IIIa within the central lake basin, except for some scouring deposits. The biggest scarp with an approximate height of 4 m is located at the western side (Figs. 7 and 9), close to the point with the highest number of identified events (Fig. 12). Up to five Younger Dryas events are stacked above each other at this location, whereas the eastern side shows a maximum of only two stacked events. Both Holocene mass movement events have left some deposits at shallower parts of the slope and although the two lobes slightly overlap, they are separated vertically by undisturbed deposits of SSS IV.

6.5. Trigger mechanism

Various trigger mechanisms for subaqueous mass movements have been postulated for lacustrine settings including: overloading of steep slopes due to rapid sedimentation; ground shaking due to seismogenic activity; regional flooding with related catastrophic river discharge; initiation of sub-aerial debris flows; lake level variations; surface wave activity; rock falls from adjacent slopes; and human activities.
Fig. 14. Plan view map of area around Holocene mass movement events with: (A) shaded relief bathymetry, gridded from sub-bottom profiler data with overlay of mass movement deposits (red/orange outlines), sediment source areas (red/orange shaded), and untransported sediment slab (yellow shaded). The positions of two profiles illustrated in Fig. 13 are also shown. (B) Holocene Isopach map with the same overlay as for (A). Coordinates: UTM Zone 30 (WGS-84).

(Vardy et al., 2010) postulated that an increasingly warmer and wetter climate at the end of the Younger Dryas caused an increase in terrestrial sediment run-off that, together with large volumes of rapidly deposited fine-grained glacial outwash, led to an overloading of the steep lake slopes, triggering sediment failures. However, it is difficult to see how this increase in sedimentation alone can be enough to trigger so many observed events. Additionally, in our survey we observe undeformed Younger Dryas outwash material (Fillc) overlying the deformed, mass transport deposits of F Illb, which implies that reworking was ongoing throughout the Younger Dryas period rather than being concentrated into a single period of intense activity during climatic amelioration.

Similarly, other common triggers for lacustrine mass wasting can be ruled out. Catastrophic river discharge is an unlikely trigger for the mass movement events on the eastern shore because there is no fluvial input. Rock falls are not possible in the area (particularly to the west, which is low lying), but regional flooding may have produced sub-aerial debris flows that entered the lake. However, most of the observed scarpss are found in deeper water beyond the major breaks in slope, and therefore are unlikely to be formed by sub-aerial debris flows.

Surface wave action as a trigger can be excluded by calculating the wave base, which is ca. 17 m for a fetch length of 3000 m, an average water depth of 30 m and constant wind speeds of 40 m s\(^{-1}\) (Sorensen, 1993). However, seismogenic activity remains a possible scenario for the triggering of the mass movements in this area. Windermere is located within the seismic forebulge zone of the BISL (Muir-Wood, 2000) and experiences a modern uplift rate of c. 0.4 mm year\(^{-1}\) (Main et al., 1999), which may be the source for recent local seismogenic activity (Musson, 1998; BGS, 2011).

The two Holocene mass movement events are separated in time by several thousand years from the Younger Dryas complex and are likely to have been triggered by a process different from the Younger Dryas events. No clear failure scarpss are observed, although seismic sections show much thinner Holocene deposits nearer the shore (Fig. 13), while bathymetry and Holocene Isopach maps indicate the removal of Holocene sediments from some parts of the upper slope (Fig. 14). The possible source area is large enough to accommodate the volume of the two mass movement deposits, and adjacent to the expected position of Cunsey Beck based on hydrological analysis of the catchment area (Fig. 1). Although the present river position is south of this location, the flood plain shows evidence for various changes in river course, possibly driven by recent anthropogenic activity (e.g., farming practice). Another possible scenario is that the deposited material originated from a terrestrial source, such as a landslide, and would therefore not comprise lacustrine gyttja.

The basal shear surface of E-XVII can be recognised (Fig. 13) together with a distinct block of sediment which was not transported down the entire slope (Figs. 13 and 14). A block of undisturbed material suggests a mass wasting of existing slope sediments. However, the surface depression and source area of E-XVII appear to continue towards the shore, which suggest a terrestrial influence for this event. A flood event is a likely scenario for the triggering of this mass movement, mobilising unstable organic rich sediments, fluorally deposited directly at the mouth of Cunsey Beck.

7. Conclusions

The interpretation of a high-resolution parametric sub-bottom profiler data set allowed the identification of 17 individual mass movement deposits in a lacustrine environment. The high density of the data allowed detailed geomorphological mapping of the individual events including determination of their temporal relationship. We also identified post-depositional features within the sedimentary succession, such as fluid escape structures and rotational faulting. We reconstructed a depositional history for the stratigraphic units identified in the seismic sections. Based on this seismo-stratigraphic framework, and on the distribution and interaction of the mass movement events with previous deposits, we related 15 of the mass movement events to the Younger Dryas and two of the events to the Holocene period. We conclude that:

- At the end of the Younger Dryas, climatic changes to warmer and wetter conditions would have made subaqueous slopes unstable. Similarly, larger sediment discharge rates during ice retreat would result in the rapid deposition of poorly consolidated material in the lake, effectively preconditioning sediment deposited on the steepest lake slopes for failure. Seismic activity, related to isostatic rebound, is a possible triggering mechanism for individual events.
- For the two Holocene events, which are temporally unrelated, the spatial relationship between their origins and the predicted catchment input suggests a fluvial trigger, possibly related to flood events.
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References


