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Late Devensian to Holocene environmental change, Loch Lomond, UK: A seismic sedimentary record of deglaciation, paraglacial and postglacial landscape evolution

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ABSTRACT

We present an interpretation of two-dimensional sub-bottom profiling data from Loch Lomond, Scotland, UK. Sediments deposited during and following the last glacier advance have been investigated for decades around the shores of Loch Lomond. For the first time, this study presents an interpretation of the subsurface providing a window into the late Quaternary and Holocene history of Loch Lomond and its surrounding. The seismic stratigraphy records the infill of the loch during the final stages of the Loch Lomond Stadial (LLS, 12.9–11.7 ka BP), through the Holocene and into the present day. Results reveal the presence of distinct seismic facies (SF) identifying four principal seismic horizons; SF-I, SF-II, SF-III, and SF-IV. The SF-I horizon represents the glaciated surface, interpreted as subglacial till (locally forming drumlins), glacial moraines or bedrock. Ice retreat was accompanied by glaciolacustrine sedimentation in a proglacial lake setting, depositing up to 44 m of laminated sediments and ice marginal fans (SF-IIa, b). A period of landscape instability followed with extensive deposition of mass transport deposits (SF-III). These deposits, characterised by chaotic seismic facies with an erosional basal surface, are up to 43 m thick and may represent up to 50 % of the sediment fill. SF-IV comprises finely laminated sediments deposited during the Holocene and highlights slower sedimentation rates in comparison to earlier phases of sedimentation. This study reveals new insights into the deglaciation of Loch Lomond, including previously unrecognised extensive mass transport deposits buried in the subsurface, associated with a period of paraglacial adjustment.

1. Introduction

Throughout the Quaternary, Earth's climate has been punctuated by alternating cooler and warmer intervals resulting in the cyclical advance and retreat of ice sheets and glaciers over relatively short time scales, forming spectacular landscapes and landforms across the mid and high latitudes (Gordon and Ballantyne, 2021). Towards the end of the last (Late Devensian) glaciation the Northern Hemisphere experienced an abrupt period of renewed atmospheric cooling, known as the Younger Dryas (YD), which is broadly correlative to the Loch Lomond Stadial (LLS) in the British Isles, lasting from 12.9 ka to 11.7 ka (Sissons, 1979; Bakke et al., 2009; Macleod et al., 2011; Bickerdike et al., 2016; Lowe et al., 2019). The climatic shift at that time has been linked to weakening or disruption of the Atlantic Meridional Overturning Circulation (AMOC) arising from a rapid influx of fresh water to the Atlantic, possibly combined with negative radiative forcing and altered atmospheric circulation (Renssen et al., 2015). The resulting cooling impacted the high latitudes of Europe, Iceland, and Greenland (Liu et al., 2012; Carlson, 2013) by halting the retreat and causing renewed growth of ice masses. In upland areas of Britain, this phase was characterised by the expansion of an extensive mountain icefield across western Scotland as well as a number of separate mountain ice caps, ice fields and corrie glaciers, and is known as the Loch Lomond Readvance (LLR).

During the Loch Lomond Readvance, an outlet glacier of the West Highland icefield advanced down Loch Lomond and beyond its southern shore to deposit a sequence of landforms and sediments (Bickerdike et al., 2016; Lowe et al., 2019) that now form the type locality for the Loch Lomond Stadial (LLS) in Britain. The maximum advance of the outlet glacier is recorded by terminal moraines, shown in Figure 1A (Rose and Smith, 2008; Bickerdike et al., 2016). Due to the excellent preservation of glacial landforms and stratigraphical sequences, the landscape around southern Loch Lomond has received considerable attention from researchers investigating environmental change during and following the LLS (Rose, 1981; Browne and McMillan, 1989; Sutherland and Gordon, 1993; Phillips et al., 2002; Rose and Smith, 2008;

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Macleod et al., 2011; Bickerdike et al., 2018). However, despite the attention given to the sediments and landforms surrounding southern Loch Lomond (*e.g.*, Sutherland and Gordon, 1993; Evans, 2021), very few studies have investigated the sediments within the loch itself. Furthermore, none of these studies have investigated deeper than the uppermost sequence of organic Holocene sediments (*e.g.*, Dickson et al., 1978), and therefore the landscape processes affecting the loch during and following retreat of Loch Lomond glacier are relatively

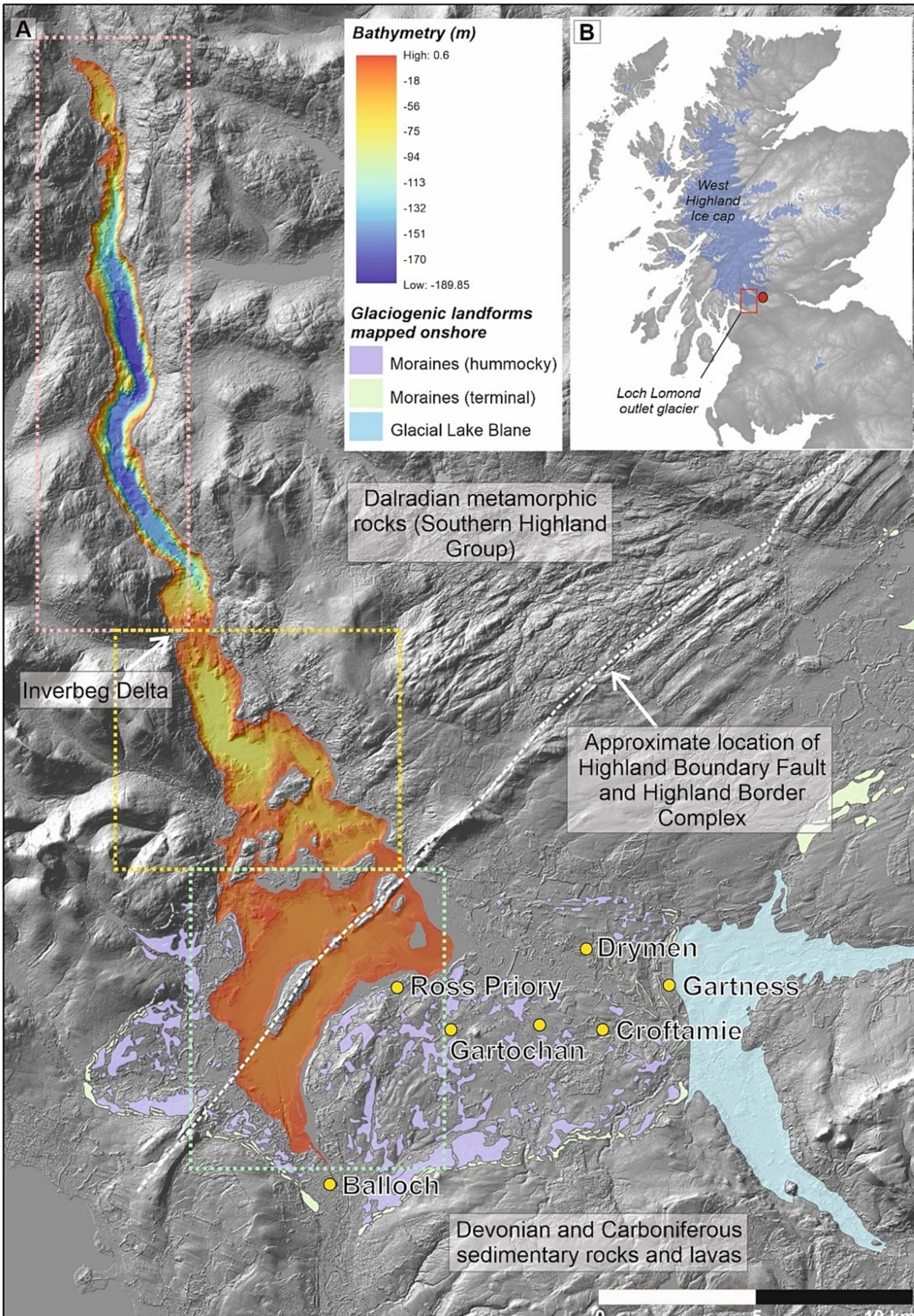

Table 1
Chronostratigraphy of the Late Devensian (Late Pleistocene) and Holocene periods from geological units identified around the southern basin of Loch Lomond.

Period	Event and age	MIS	Glacial till	Lacustrine and fluvial sand & gravel	Lacustrine and fluvial clay & silt	Marine clay & silt
Holocene	Holocene (11.7 ka–present)	1	n/a	Endrick and Law Formation: Fluvial deposits and fans/deltas around the margins of Loch Lomond	Kilmaronock Formation: Thinly bedded silt and clay with plant remains and organic rich bands (Loch bed deposits).	Erskine Formation: Typically very silty clay and contains sulphide. Includes shallow marine fauna indicating temporary brackish water conditions in Loch Lomond (only deposited in Loch Lomond between 6.9 and 5.4 ^{14}C ka)
Late Devensian	Loch Lomond Stadial (LLS) (12.9–11.7 ka)	2	Gartocharn Till: Loch Lomond readvance till, usually shelly, derived from glacially reworked Clyde Beds. Associated with radiating piedmont lobe of Loch Lomond outlet glacier.	Drumbeg Formation: Ice contact deltaic and glacioflucial deposits associated with Loch Lomond outlet glacier.	Blane Water Formation: Regularly interbedded clay and silt (forming varves in places). Proglacial lacustrine sedimentation associated with Loch Lomond outlet glacier.	n/a
	Windermere lateglacial Interstadial (14.7–12.9 ka)	2	n/a	n/a	n/a	Clyde Beds (Linwood and Paisley Formations): Laminated to homogenous silts and clays with arctic-boreal marine fauna
	Dimlington Stadial (~31–14.7 ka)	2	Wilderness Till Formation: Deposited by main Late Devensian ice sheet. Forms major component of the drumlinised till sheet to the south of the Loch Lomond Readvance limits.	n/a	n/a	n/a
Mid Devensian	(57–31 ka)	3	Balglass Burn: Lower weathered till and upper unweathered till (Wilderness Till Fm), separated by glaciotectonically deformed organic deposit of MIS 3 age.	n/a	n/a	n/a

unknown. The research presented here aims to address this significant knowledge gap by analysing high resolution 2D sub-bottom profiling data that were acquired by the British Geological Survey (BGS) in 2014. The results of this study are relevant beyond Loch Lomond as the sedimentary processes identified may be comparable to processes affecting lakes in modern deglaciating mountain catchments.

2. Study area

2.1. Regional setting

Loch Lomond is the largest body of freshwater by area in Britain (71 km^2) and forms a north–south trending glacially eroded basin with an average water level that currently sits at approximately 8 m above Ordnance Datum (OD). Approximately 36.4 km in length, Loch Lomond can be divided into three discrete basins: Northern, Central and Southern (*sensu stricto* Stewart et al., 1984; Linton and Moisely, 1960) (Fig. 1A). The Northern basin is long and narrow and has the deepest present-day water depth (16.2 km long, up to 1.3 km wide, 190 m deep). The Central basin is slightly wider (up to 1.5 km in width and 60 m deep) and is separated from the Northern basin by the Inverbeg delta and bathymetric high that spans the width of the Loch. The Southern basin forms the widest part of the loch (7.8 km) and has the shallowest present-day water depth (20 m). The distinction of the three basins in Loch Lomond allows ease of describing the location of various features observed in the seismic data (Fig. 1A). The NE–SW trending Highland Boundary Fault (HBF) crosscuts the Southern basin of Loch Lomond. To the north of this major tectonic boundary, the bedrock is dominated by mica-schist and schistose grit (the Beinn Bheula Schist and Ben Ledi Grit formations, respectively, of the Southern Highland Group) whereas to the south, the bedrock is comprised of Devonian and Carboniferous sandstones, marls and basalts (Stewart et al., 1984; BGS, 1987) (Fig. 1A).

2.2. Late Quaternary glacial history

Linton and Moisely (1960) suggested that the north–south alignment of Loch Lomond cuts across three pre-glacial drainage basins that flowed towards the east, with two former west–east aligned interfluves previously having spanned across the Northern basin. Southwards directed ice flow during successive Quaternary glacial episodes breached these interfluves, creating the over-steepened rock slopes and truncated spurs that now border the loch, and focused erosion along the present line of the loch to shape the basins into their current form.

Little detail is known of the earlier Quaternary glaciations of Loch Lomond and the surrounding terrain because evidence has been removed by successively younger glaciations (Evans and Rea, 2003). However, there is an excellent geological record that relates to the end of the last (Late Devensian) glaciation and transition into the Holocene interglacial (Table 1). The Late Devensian (Late Weichselian in Europe) is equivalent to Marine Isotope Stage 2 (MIS 2) and is subdivided into the Dimlington Stadial (~31–14.7 ka), the Lateglacial or Windermere (Bølling/Allerød) Interstadial (~14.7–12.9 ka) and the Loch Lomond Stadial (~12.9–11.7 ka). The Dimlington Stadial was characterised by expansion of the Last British Ice Sheet and includes the period of maximum ice sheet extent (broadly between 30 and 22 ka, as different sectors reached their maximum position at different times) (Clark et al., 2022). The timing of Late Devensian glacier expansion in the wider Loch Lomond area is constrained by a till overlying glaciotectonised organic deposits dated to approximately 40–32 ka in

Fig. 1. A) Base map showing hill-shaded Digital Elevation Model of surrounding topography of Loch Lomond in greyscale (derived from: Intermap Technologies (2007): NEXTMap Britain elevation data from Intermap Technologies. NERC Earth Observation Data Centre, 2022). Multibeam bathymetry echo sound image of Loch Lomond showing water depth shown in colour scale. Three sub-basins are identified: Northern basin = dashed pink polygon; Central basin = yellow dashed polygon; Southern basin = mint green dashed polygon. Approximate location of the Highland Boundary Fault is highlighted by the white dashed line. Towns and villages have been highlighted where onshore sediments relating to the Loch Lomond Readvance have been described in the literature. Onshore glaciogenic landforms compiled by Bickerdike et al. (2016). Glacial Lake Blane limits from Macleod et al., 2011. B) Location of West Highland Ice Cap in Scotland during LLS and maximum extend of Lomond Glacier during LLS. Location of Loch Lomond study area in larger red box. MIS 3 age deposit highlighted at Balglass Burn to east of study area (red dot on inset map).

Balglass Burn, to the SE of Loch Lomond (Fig. 1B), indicating ice advance occurred after that date (Brown et al., 2007).

Warming at the end of the Dimlington Stadial and into the Windermere Interstadial was accompanied by rapid melting and complete (or near complete) deglaciation in Scotland (Ballantyne et al., 2021). Higher relative sea levels at that time (Fig. 2) temporarily turned Loch Lomond into a sea loch and deposited marine sediments (known as Clyde Beds, or Linwood Formation and Paisley Formation) around its southern shore (Sutherland and Gordon, 1993). Renewed cooling during the LLS caused regrowth of a mountain ice cap over the western Highlands and the southwards advance of an outlet glacier into and down Loch Lomond. Tills incorporating broken marine shells (from reworked Clyde Beds) and overlying dated organic deposits provide strong chronological constraint for the readvance, making the Loch Lomond area the type site for the LLS in Britain (Sutherland and Gordon, 1993). The extent of the Loch Lomond glacier outlet lobe is well defined by moraines and ice marginal glaciofluvial landforms around the southern margins of the loch (Bickerdike et al., 2016; shown in Fig. 1A); however, to date limited landform evidence has been described which documents how the glacier responded during deglaciation (*e.g.*, Bickerdike et al., 2018). A varve chronology derived from lake sediments from Glacial Lake Blane (outlined in Fig. 1A) has been used to suggest that ice reached its maximum position very late in the stadial, with final retreat occurring between 11.8 ka and 11.5 ka, close to the time of the LLS to Holocene transition (Macleod et al., 2011).

Rock slope adjustment and accelerated sediment transfer processes (*e.g.*, debris flows) are recognised to have accompanied final deglaciation in Scotland, during a phase of paraglacial landscape modification (Ballantyne, 2008, 2019). Within the Loch Lomond basin, landforms relating to post-glacial rock slope adjustment have been described (BGS, 1987; Jarman, 2006). However, relatively little evidence has been described so far documenting the impact of paraglacial sediment transfer processes, such as debris flows, in and around the loch.

Modelled relative sea level spanning this time period (Fig. 2) shows a fall from ~35 m OD at the onset of the Lateglacial (Windermere) Interstadial to ~0 m OD in the earliest Holocene, over a period of ~4000 years (Shennan et al., 2018a, 2018b). During the early- to mid-Holocene a short-lived rise in relative sea level to approximately 12 m OD once again temporarily connected Loch Lomond to the sea (Dickson et al., 1978). However, continued isostatic rebound restored the loch to its current freshwater condition from the mid-Holocene onwards.

2.3. Outcrop and core data

Within Loch Lomond itself, only one core located in the Southern basin, LLRD1, has a published subsurface lithological record and provides an important insight into the upper stratigraphy, which is otherwise unproven (Fig. 3). The core from LLRD1 was recovered between 0 and 5 m below the loch bed with radiocarbon ages dating to the early Holocene (Dickson et al., 1978; Turner and Thompson, 1979). Sediments recovered from the core revealed five discrete units, including (base to top): a green–grey clay transitioning to a finely-banded clay, black silty clay, and dark yellowish brown silty clay (gyttja) at the top of the core. An important discovery from the LLRD1 core was the black silty unit between 3.05 and 3.75 m, where marine plankton, abundant bivalves, an absence of freshwater plants and a higher carbon content suggested that Loch Lomond was connected to the sea in the early–middle Holocene between ~6108 and 7808 cal ^{14}C years BP. During this marine highstand, beaches and deltas were formed above the current water level and cliff lines were cut into glacial deposits, as discussed in Dickson et al. (1978). Several very short sediment cores have also been collected from locations throughout the loch by Farmer and Lovell (1986), who described the top 20 cm to range from highly porous brown muds to black micaceous oozes.

Outcrops identified in the surrounding area of Loch Lomond provide further evidence that helps piece together parts of the Late Devensian

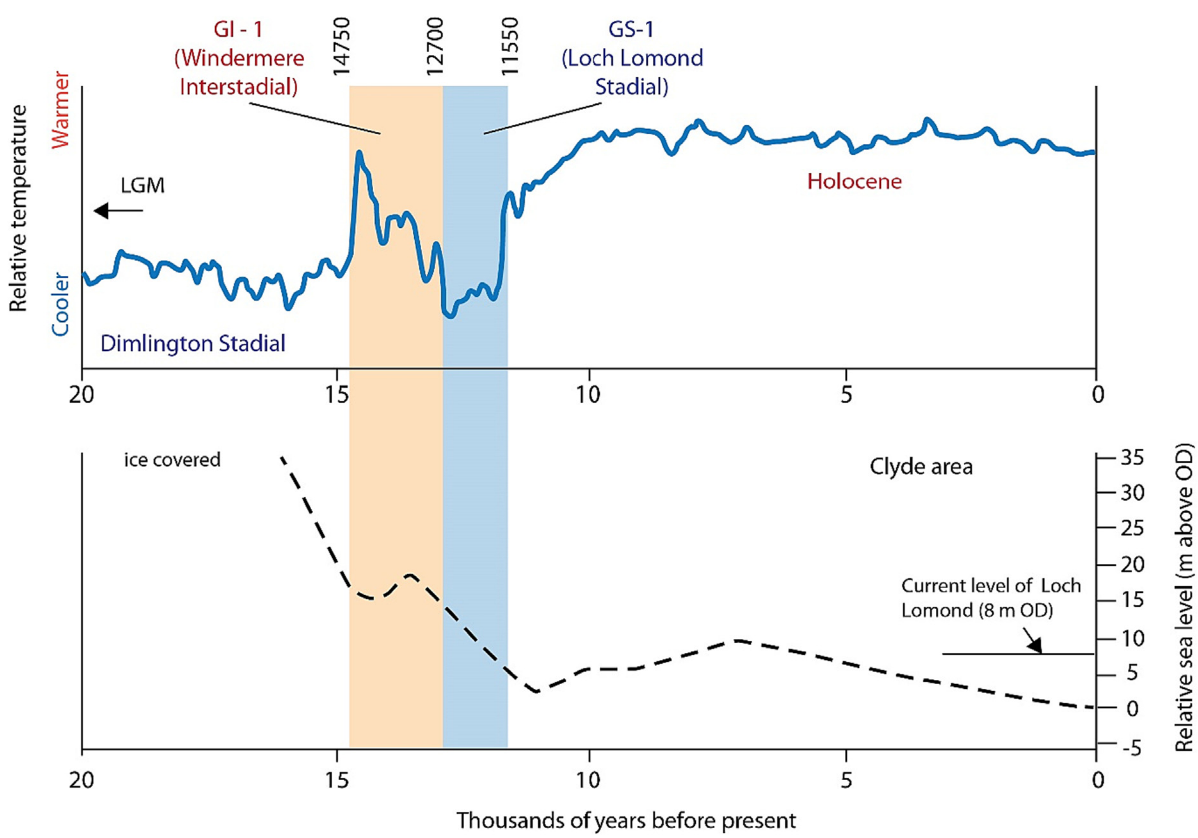

Fig. 2. Glacial to Holocene transition. Upper panel shows temperature trends around the North Atlantic region based on GISP 2 Greenland ice core data (modified from Platt et al., 2017). Lower panel shows modelled relative sea level around the Clyde area modified from Shennan et al. (2018a, 2018b).

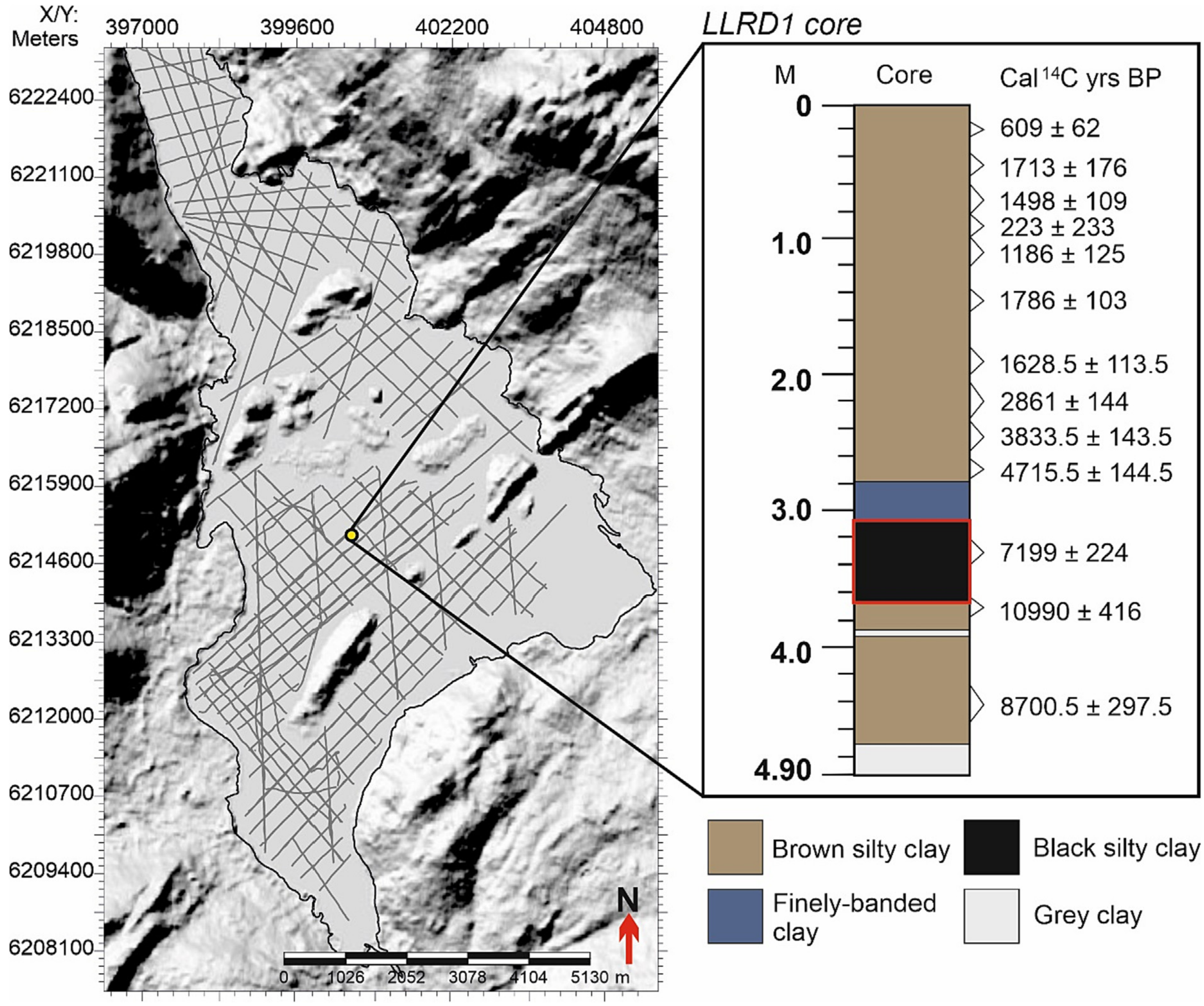

Fig. 3. Base map showing hill-shaded Digital Elevation Model of surrounding topography of Loch Lomond in greyscale (NEXTMap Britain elevation data from Intermap Technologies). Grey lines indicate seismic profile locations (acquired by BGS, 2014). Location of core LLDR1 recovered from the Southern basin of Loch Lomond (Dickson et al., 1978). The main lithologies and reported radiocarbon ages (calibrated to calendar years) are shown. The red box in the core image highlights the black silty clay lithological unit where marine plankton was identified between 3 and 4 m depths below the loch bed. Core lithology depth and age data from Stewart (2010a, 2010b).

and early Holocene history (Rose, 1981; Rose et al., 1988; Phillips et al., 2002; Lowe et al., 2019). Balloch, Croftamie, Gartness and Drymen are among a few locations, highlighted in Figure 1A, where sediments in exposures and excavations record changing environments during the Late Devensian to Holocene transition (see Sutherland and Gordon (1993) for details). In the absence of deeper core data within Loch Lomond, these outcrops provide evidence of the types of sediments, including tills, gravels and sands, and fine lacustrine sediments that were deposited during and following the last ice advance into the area (Table 1).

3. Methods

A lacustrine geophysical survey was undertaken by the British Geological Survey in Loch Lomond on board the BGS RV White Ribbon during 2014. The survey took place over three periods using three different sound source acquisition systems to allow comparison of different datasets (Fig. 4A, B, C). Phase 1 took place on 28–30 May 2014 using the Knudsen Pinger system (3.5 kHz or 15 kHz chirped array). Phase 2 took place on 10–16 July 2014 using the EdgeTech 3100 216s Chirp system (2 to 16 kHz, providing slightly less resolution but greater penetration) and Phase 3 took place on 21–23 July 2014 using a surface tow boomer. The surface tow boomer data was run at 200 J for the entirety of the survey with a 300 ms trigger, 250 ms sweep time and a band pass with a low pass of 1000 Hz and a high pass of 2200 Hz. Navigation was recorded using a Trimble 461 GPS unit and the SEGY files were recorded in the field and then imported into the IHS Kingdom Suite software to visualise and interpret the data. The three sub-bottom profiling datasets (Chirp, Pinger and Surface Tow Boomer acquisitions) complement each other for geophysical mapping as there is a compromise between resolution and acoustic penetration. Lower frequencies, such as the Surface Tow Boomer sub-profiling system, typically penetrate deeper into the stratigraphy enabling the acoustic basement to be detected and mapped. This dataset was only acquired in the Central and Southern basins, and so limits deeper sedimentary interpretation of the Northern basin. The higher frequency Pinger and EdgeTech Chirp data typically reveal high resolution data (*e.g.*, 0.2 m to 6–10 cm, respectively) in shallow stratigraphy (Fig. 4D, E), and were recorded across the Northern, Central and Southern basins.

Regional interpretation of the Loch Lomond high-resolution 2D seismic data was undertaken using the IHS Kingdom Suite software. Over 400 km of seismic lines were interpreted and then gridded to create regional maps that reveal the presence and distribution of major stratigraphical units. With no boreholes or associated data that penetrate deeper than 5 m below the loch bed in Loch Lomond, there is uncertainty in the interval velocities per unit to permit accurate depth conversion. However, regional studies from other lochs or lakes that

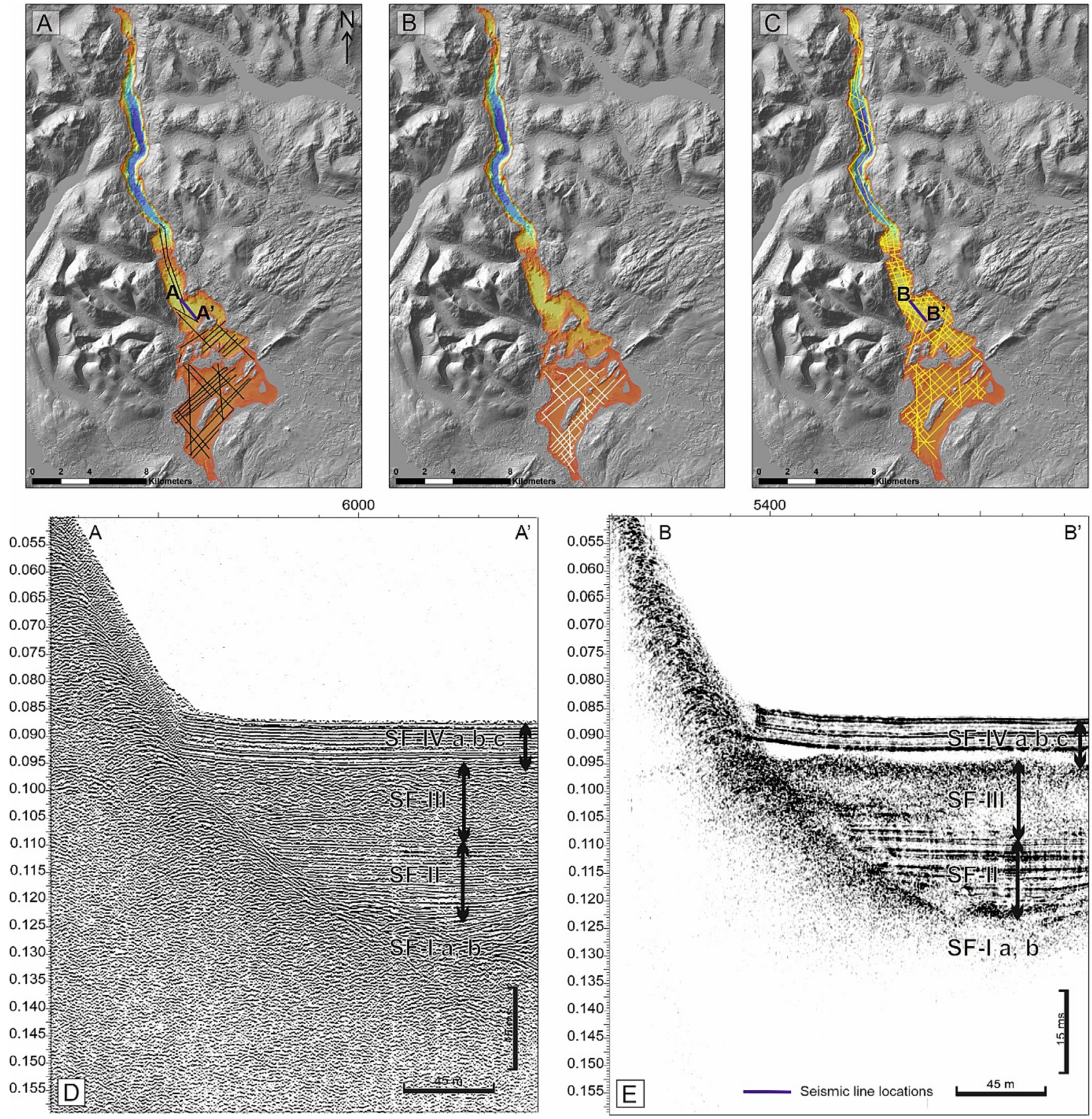

Fig. 4. Base maps showing hill-shaded relief (NEXTMap Britain elevation data from Intermap Technologies) of onshore area around Loch Lomond surrounding Loch Lomond. Location of surveys interpreted for gridding: (A) Surface Tow Boomer — acquired in Central and Southern basins; (B) Knudsen Pinger data — acquired in Southern basin; (C) EdgeTech 3100 216s Chirp data — acquired in Northern, Central and Southern basins. (D) Boomer data and (E) EdgeTech taken along the same transect in the Central basin of Loch Lomond enabling a comparison of the imaging quality from acoustic properties.

contain similar glacial to post-glacial sediments, such as Lake Windermere in the Lake District of the UK, have both 3D seismic data and borehole data that have enabled velocity values to be determined (summarised in Table 2) (Lowag et al., 2012; Pinson et al., 2013). This information was used as a proxy to the sedimentary units in Loch Lomond to determine the thickness of specific units, where a simple depth conversion can be calculated by:

$$\text{Depth} = \text{Two Way Time}/2*(\text{average velocity})$$

Table 2
Summary of main four stratigraphical units and associated velocities, Lake Windermere UK. Modified from Pinson et al. (2013).

Approximate age of unit (interpreted depositional setting)	Average velocity (m s^{-1})
Holocene (organic lake muds)	1490
LLS to Early Holocene (mass transport deposits)	1500
Late Devensian, LLS (glaciolacustrine)	1500 + 6 s^{-1} (velocity gradient 6 m s^{-1} per metre)
Late Devensian, Dimlington Stadial (melt out tills to overconsolidated tills)	2300–3500

Previously collected multibeam bathymetry data were used to help provide context for interpretation of seismic profiles in the Southern basin. These data were collected by BGS during a swath bathymetry survey of Loch Lomond carried out in November 2007 and February 2008, using a Kongsberg 300 kHz EM3002D dual head system mounted on the Loch Lomond and Trossachs National Park's solar powered catamaran, the *Bata Greine*. The bathymetric data output in the form of xyz grid data at 2 m horizontal resolution was converted into ascii files for visualisation in ArcGIS.

4. Results

4.1. Bathymetry data

The high-resolution multibeam echosounder (MBES) bathymetry data is briefly described below for the Southern basin where observed depositional landforms give context to key features in the seismic data (detailed description of the wider loch bed geomorphology will be presented in a separate paper). The MBES data reveals the presence of an irregular topography of the present-day loch bed of Loch Lomond, particularly towards the margins of the present-day shoreline (Fig. 5A). To the southeast of the Southern basin, a series of elongated northwest to southeast landforms are identified. One exceptionally preserved landform, with an orientation of 135° to the southeast, is 400 m long and 60 m wide, as measured in the multibeam data. With a maximum slope of 10.5° on the eastern margin, a seismic cross-section shows it is ~7.5 m in height and reveals a wider base, where up to 66 m is measured (Fig. 5B, cross section A to A′). Towards the north-western shore of the Southern basin, the MBES data reveals flat-topped isolated bathymetric highs (~11 to 18 m high and up to 700 m across), separated by an elongate ridge (Fig. 5C, cross section B to B′). In the south of the Central basin, a rugged bathymetric surface shows broad (150 to 400 m) NNW to SSE trending features approximately 15 m high in ~30 m water depth (visible near the northern edge of the map shown in Fig. 5A).

4.2. Seismo-stratigraphical framework

Seismic facies represent sedimentary packages with differences in seismic amplitude, frequency and continuity relating to geological factors in the subsurface, including bedding continuity, layering and textures observed (Sangree and Widmier, 1979). Analysis of high-resolution geophysical seismic data has enabled the general character of subsurface sediments in Loch Lomond to be examined, including the internal geometry and depositional features of different sedimentary packages. Based on distinct acoustic differences within the seismic data, four principal seismic units have been mapped regionally across the Northern, Central and Southern basins (Fig. 6).

The nomenclature of 'Seismic Facies', or 'SF' is adopted as per Pinson et al. (2013) to highlight the similarities between facies of Loch Lomond and Lake Windermere. In places, the four principal units can be split into eight sub-units based on: 1) integrating LLRD1 core data (Dickson et al., 1978; Turner and Thompson, 1979), which enables subdivision of the youngest Holocene unit (SF-IV) into three discrete sub-units (SF-IVa, b and c, younging respectively); (2) subdividing glacial retreat into two sedimentary processes (proglacial lacustrine deposition, SF-IIa *versus* ice-contact fan deposition, SF-IIb), and; (3) subdividing SF-I into 'basement' (bedrock, SF-Ia) and a glacial landform (SF-Ib) (Figs. 5B, C and 7B). The regional depth converted grids for these four principal seismic units: SF-I, SF-II, SF-III, and SF-IV, are shown in Figure 8.

SF-I is the deepest stratigraphical unit identified in Loch Lomond. Its upper surface is characterised by a major acoustic reflector that separates it from the overlying SF-II. For the purpose of this study, three subdivisions of SF-I have been identified. *SF-I 'undifferentiated'* is characterised by dense reflectivity with a highly irregular upper surface that forms ridges, local topographic highs and basins. It is not possible to resolve deeper reflectors for SF-I 'undifferentiated', and the upper surface therefore represents acoustic basement for the imaged loch sediment succession. In other areas two sub-units, *SF-Ia* (lowermost) and *SF-Ib* (uppermost), are present (Figs. 5B, C, and 7B). SF-Ia is represented by a high impedance surface that is somewhat muted — likely due to

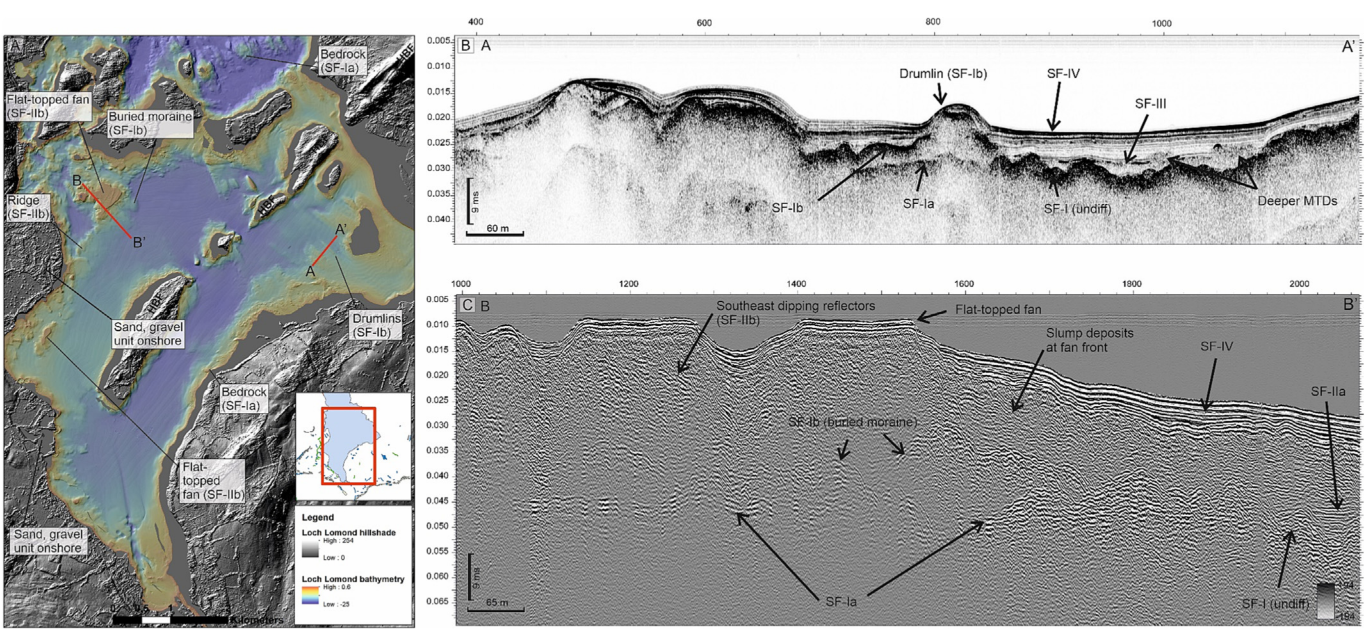

Fig. 5. A) Base map showing hill-shaded relief (NEXTMap Britain elevation data from Intermap Technologies) of onshore area around Loch Lomond and high resolution multibeam echosounder (MBES) bathymetry of the Southern basin of Loch Lomond. MBES data showing bathymetric expression of buried glaciogenic features typically associated with ice oscillation and/or advance (SF-Ib) and ice retreat (SF-IIb) on the loch bed. Red colours identify shallow water and blue colours show deeper water. The Highland Boundary Fault (HBF) is identified across the centre of the Southern basin. B) Section A–A′ = Northeast–southwest oriented drumlin identified on the seismic line (pinger), mapped as part of SF-Ib. C) Section B–B′ = Flat-topped features (fans) with southeast dipping reflectors joined by a ridge, mapped as part of SF-IIb on surface tow boomer data.

Seismic Facies unit	Seismic Faices sub-unit	Seismic Facies (seismic and/or core)
SF-IV Upper laminated unit Up to 8 m thickness	c	Boomer, EdgeTech & Chirp: well-laminated, continuous parallel reflections with alternating high/low impedance. Unit drapes onto topographic highs and thins at basin margins. Conformable base. LLRD1 core: Uniform, fine-grained laminated dark yelllow-brown muds (gyttja)
	b	LLRD1 core: 0.8 m black silty clay. Dark in colour, high carbon content, low magnetic susceptibility and intensity, presence of marine plankton, absence of freshwater plants
	a	Boomer & Chirp): Well-laminated, continuous parallel reflections. Undulating to flat basal contact. EdgeTech data shows unit as transparent. LLRD1 core: unknown if penetrated by core
SF-III Chaotic unit Up to 20 m thickness	n/a	Seismically transparent/chaotic package. Some high amplitude internal reflections. Erosive base in places cutting into underlying laminated unit. Not penetrated by core.
SF-II Glaciolacustrine/ marine unit Up to 44 m thickness	b	Isolated dipping reflectors with flat-topped topographic expression on MBES. Mapped as sands onshore. Not penetrated by core.
	a	Laminated unit. Vertical to near-vertical faulting and potential fluid escape features cross-cutting stratigraphy. Not penetrated by core.
SF-I Undifferentiated = acoustic basement	b (up to 25 m thickness)	Glacially sourced deposits, typically rugose topography and transparent acoustic imaging. Not penetrated by core.
	a	High impedance surface. Represents bedrock surface. Not penetrated by core.

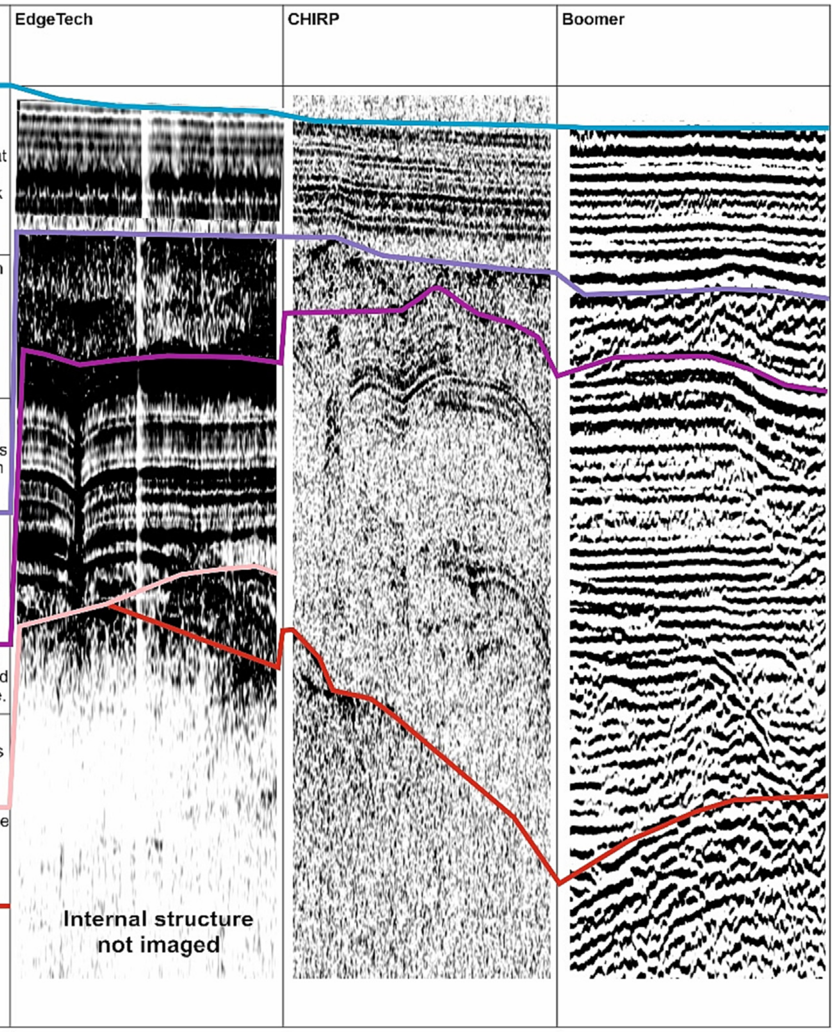

Fig. 6. Figure identifying four main stratigraphical units and eight sub-units (SF-I = oldest to SF-IV = youngest). Variations in acoustic properties between seismic datasets identified between EdgeTech, Pinger, Chirp and Boomer data, collected by BGS.

signal attenuation resulting from the overlying high reflectivity SF-Ib layer. SF-Ib typically displays a rugose topography locally including ridges and mounds characterised by strong irregular upper reflectors with increasing transparency at depth. Such features are up to ~25 m relief in the Southern basin where they are well imaged on the surface tow boomer data (Figs. 7D and 8D).

The SF-II seismic horizon picks the top of Seismic Facies IIa and b sub-units (SF-IIa, b), located stratigraphically above the irregular topography of SF-I (acoustic basement) (Fig. 4). The total preserved thickness of SF-II is calculated to range between 2 and 43 m, and it is present in the Northern, Central and Southern basins. Although SF-IIa is identified on the different seismic surveys available, it is particularly well imaged on the EdgeTech data (Fig. 4E). The internal reflectors in SF-IIa form a well-bedded to laminated sedimentary package, showing alternating high and low amplitudes, that typically onlaps onto the underlying SF-I surface. Although dominantly undeformed and layer-parallel, subtle faults and broad concave structures (up to 25 m width by <2 m in depth) are present (*e.g.*, Fig. 7B). From the seismic lines available in the western Southern basin, the axes of such features are mapped approximately NW–SE. The presence and distribution of SF-IIa is primarily confined within central parts of the basins. SF-IIa is calculated up to 44 m in thickness along the western margin of Loch Lomond and becomes thinner (<4 m) or absent towards the eastern margin and around present-day loch shorelines (Fig. 7C). The overlying SF-III unit often truncates the upper surface of this unit, however in places can also appear planar. In areas around the Southern basin, the SF-IIa unit can be crudely subdivided as two discrete units: towards the basin margin, a slightly more chaotic lower unit is observed with a well-laminated and onlapping section deposited above (Fig. 7B, C). Towards the Southern basin centre, such distinctions between these two SF-IIa sedimentary packages are less well-defined. Seismic horizon *SF-IIb* is laterally equivalent to SF-IIa, and forms part of the planar-topped features identified in the MBES data to the northwest of the Southern basin. In seismic data, the SF-IIa package is up to 20 m thick and contains dipping internal reflectors that dip approximately 20° towards the southeast (Fig. 5C, cross section B–B′).

The *SF-III* seismic horizon picks the top of the Seismic Facies III unit (SF-III) and is characteristically located above the laminated SF-II unit. SF-III is identified as a chaotic to structureless sedimentary package and is present across much of Loch Lomond. SF-III is calculated to up to 40 m in thickness with maximum values in the Central basin, where the present-day loch slopes are steeper relative to the Southern basin. In the Southern basin, thicknesses are calculated up to 15 m. The basal surface of SF-III can be erosive and is often observed cutting decicentimetres to several metres into the underlying lower laminated SF-II unit, forming terraces and channel-like features. The upper surface is often rugose; however, in many places it can also be observed as relatively horizontal. Although the internal seismic facies are identified as

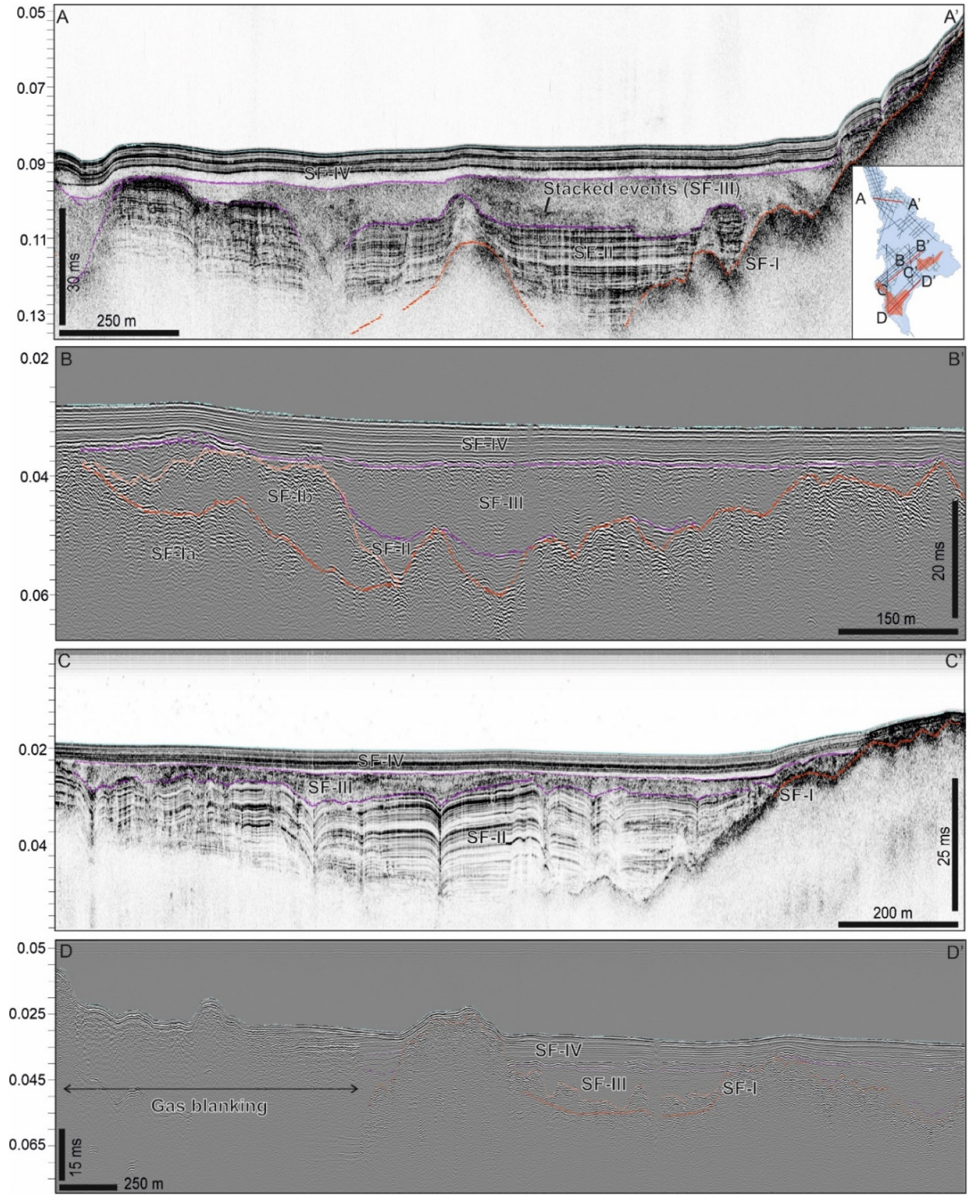

Fig. 7. Seismic sections in seconds TWT. Horizon colours indicate: Blue = loch bed; light purple = Top SF-III; dark purple = Top SF-IIa; peach = Top SF-Ib, and red = SF-I or a. A–A′ Northwest to southeast line across the Central basin (pinger data). Thick SF-IIa unit in depocenter. Shows thick SF-III unit with erosive base, appearing channelised in places. Onlapping of SF-IIa unit onto basement. B–B′ Southwest to northeast line across central Southern basin (Surface Tow Boomer data with psuedorelief seismic attribute). Shows subdivision of SF-Ia and SF-Ib where possibly differentiated, otherwise, acoustic basement is marked as SF-I. Very thin to absent SF-IIa unit present in the central part of the Southern basin. SF-IV shows no amplitude changes in Surface Tow Boomer data. C–C′ Southwest to northeast line across the western Southern basin (pinger data). Thick section of SF-IIa unit identified. SF-III unit is relatively thin in the western part of the Southern basin. SF-IV unit in pinger data shows variations in amplitude, which potentially marks changes between SF-IVa, b and c units. D–D′ Southwest to northeast line across the southern section of the Southern basin (gas area highlighted by red polygon in location map). The western margin identifies an area of gas blanking within the seismic profile. Approximately ×4 vertical exaggeration on seismic sections.

structureless, there are many examples where distinct, often stacked events, can be identified by high amplitude tops within the SF-III sedimentary sequence (Fig. 7C).

The *SF-IV* seismic horizon picks the top of the Seismic Facies IV unit (SF-IV), which is the loch bed. SF-IV is the youngest laminated sedimentary package identified in Loch Lomond and is mapped across the entire basin. It is typically located above the SF-III unit and drapes across topographic highs in the Central and Southern basins. In the Northern basin, SF-IV is observed to sit unconformably above SF-II in some areas. In the basin centres, the SF-IV unit has an estimated thickness of 5–8 m, however, across topographic highs, and towards basin margins, this decreases to <1–3 m thickness. By integrating the seismic data with the LLRD1 core data (Turner and Thompson, 1979), SF-IV is divided into three sub-units. SF-IVa represents the oldest and lowermost laminated sedimentary package (*e.g.*, Fig. 7C). The EdgeTech data shows this lower sub-unit as transparent to very faintly laminated, whereas the Boomer data shows the unit as well-laminated (Fig. 6). SF-IVb aligns with the marine layer observed in the core and could be associated with a high amplitude seismic expression. Finally, SF-IVc represents the youngest laminated sedimentary package, identified as yellowish-brown silty clay (gyttja) in the LLRD1 core.

4.2.1. Seismostratigraphical isopachs

An isopach of the loch sedimentary fill (where the acoustic basement grid is subtracted from the loch bed grid, *i.e.*, SF-I subtracted from the top of S-IV, respectively) shows the basinal architecture of

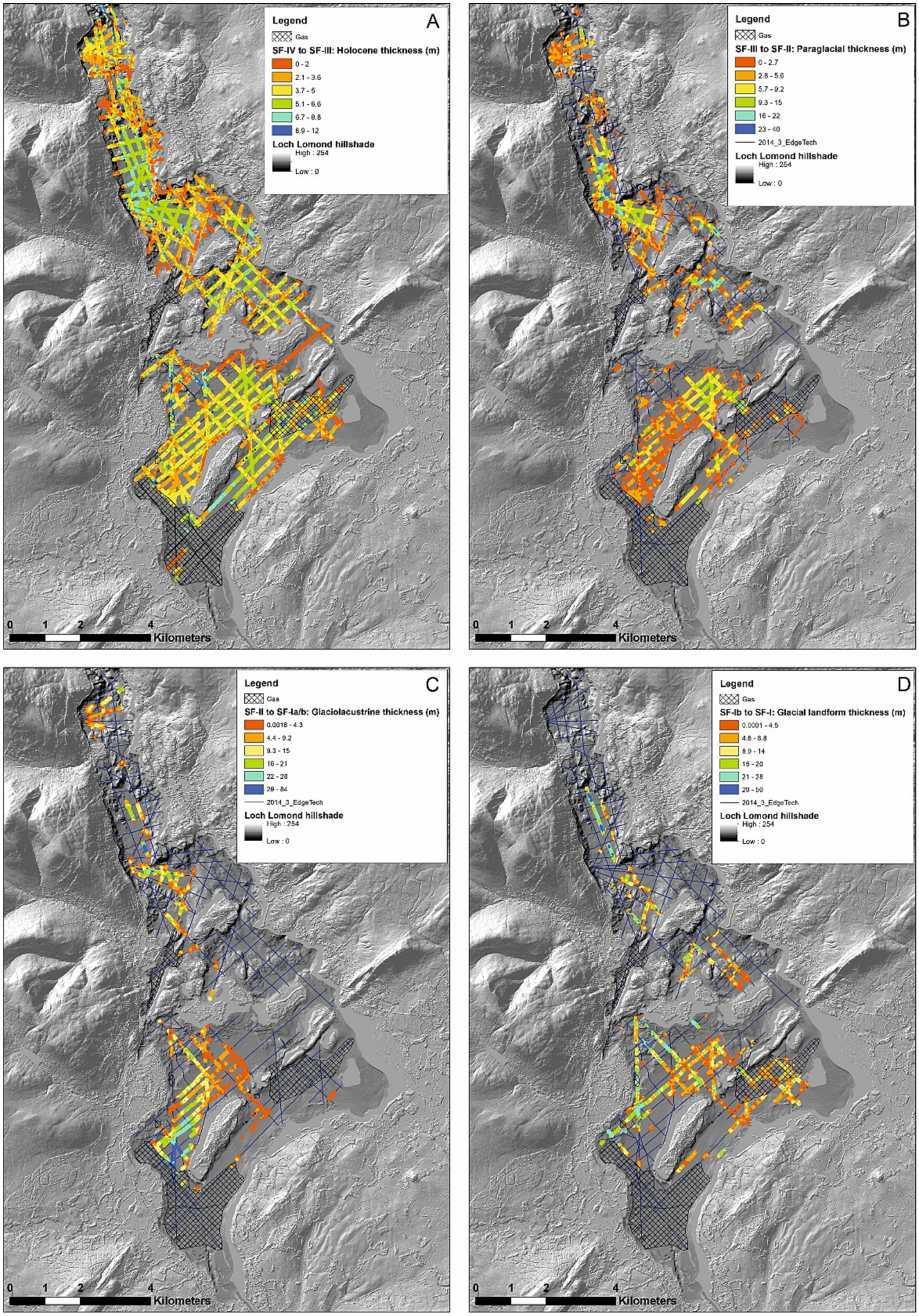

Fig. 8. Maps showing hill-shaded relief (NEXTMap Britain elevation data from Intermap Technologies) of onshore area around Loch Lomond, hill-shaded relief of Loch Lomond bathymetry data, and isopachs of mapped seismic units within Loch Lomond. (A) Unit IV — Holocene isopach thickness in metres across the Central and Southern basins. (B) Unit III — Paraglacial mass transport thickness in metres across the Central and Southern basins. (C) Unit II — Glaciolacustrine thickness in metres across the Central and Southern basins. (D) Unit Ib — Glacial landform thickness in metres across the Central and Southern basins. Note, this is a minimum sediment thickness due to some areas having poor bedrock imaging, typically relating to the presence of glacial deposits and landforms. Areas of gas are indicated by cross hatching.

Loch Lomond and reveals a series of deep depocenters and shallow basins in the subsurface separated by undulating ridges. Where both SF-Ia and SF-Ib were identified, the top of SF-Ib was taken as the base of the loch infill for thickness calculations. Imaging of acoustic basement in the Northern basin is poorly constrained due to the lack of surface tow boomer data, therefore sedimentary thickness has not been calculated for this area. Imaging to the west of the Southern basin is also obscured due to the presence of shallow gas resulting in acoustic masking of the seismic data (Figs. 7D and 8A–D), *e.g.*, Duck and Herbert, 2006.

Where data quality permits, depocentres are identified as thicker sedimentary packages (blue colours), which correspond to deeper basin centres (Fig. 8C), whereas thinner sedimentary packages (red colours) represent topographic highs and are typically draped by the youngest laminated SF-IV unit. An isopach of the Central basin reveals a depocenter ~3 km long by 0.6 km wide and up to 46–58 m deep, which curves around an underlying topographic spur on the eastern edge of the Loch. To the north of this spur, the depocenter trends north–south whereas to the south, the depocenter trends northwest–southeast. An isopach of the Southern basin reveals a northeast–southwest trending depocentrer ~3.8 km by 0.76 km and up to 42 m deep. These deeper depocenters have a close relationship to where the older laminated SF-IIa unit is identified. Shallower areas of infill up to 120 m by 160 m and 7 m deep, are located towards the margins of Loch Lomond; however, they typically only contain SF-III (chaotic) and SF-IV (youngest Holocene) sediments.

4.3. Interpretation of seismic facies and bathymetry data

4.3.1. Glaciogenic features identified on MBES data

Multibeam echo sound bathymetry data reveal the presence of topographic highs on the present-day loch bed and are typically identified towards the margins of Loch Lomond where the post-glacial sedimentary infill of the loch is thinner (Figs. 1A and 5). On the south-eastern shore of Loch Lomond around Gartochan (Fig. 1A), Rose and Smith (2008) mapped a series of elongate glacial landforms as drumlins. The elongated southeast-trending loch bed landforms identified in the south-eastern corner of the Southern basin in this study align with the glaciogenic landforms mapped by Rose and Smith (2008). This suggests that these loch bed features are also drumlins, and their presence supports the direction of ice flow in the south-eastern corner of the Loch Lomond outlet glacier towards the southeast (Fig. 1A). The flat-topped features identified to the northwest of the Southern basin are adjacent to an onshore unit of sands and gravels, mapped by Rose and Smith (2008), as fans. The prograding nature of this unit, as identified in seismic data (Section B to B′, Fig. 5C), suggests a glaciogenic ice-contact deposit, forming at the southern margin of the Loch Lomond outlet glacier as it was retreating (Fig. 9). Analogous prograding units, such as ice-contact deltas, are reported in similar ice retreat glacial lake settings. For example, the Porta Delta, northwest Germany, formed during retreat of the Scandinavian ice sheet and deposited as a subaqueous fan and delta complex, approximately 6.2 km long, 5.3 km width and up to 40 m thick (Winsemann et al., 2004).

4.3.2. SF-1 glaciated surface

SF-I 'undifferentiated' generally corresponds to the deepest acoustic reflector picked in the 2D seismic data. The data identifies a continuous, rugose, and high impedance reflector, resulting from a strong density contrast between the overlying units. In places, there is insufficient information from the seismic data to distinguish where SF-I 'undifferentiated' represents a bedrock surface or a surface comprising dense or stiff subglacially deposited sediments (*e.g.*, Lowag et al., 2012). Therefore collectively, it is interpreted here simply as a glaciated surface (which may comprise bedrock, till or moraines). In some locations both the SF-Ia and SF-Ib units are recognised, and further distinctions can be made. For example, in the Southern basin, SF-Ib is identified forming mounds and ridges (up to ~25 m in height) that overlie a lower (SF-Ia) reflector. To the southeast of the Southern basin, SF-Ib forms similarly aligned cross-profiles to drumlins mapped on adjacent onshore areas (Rose and Letzer, 1977; Rose and Smith, 2008) (Fig. 5A, B). SF-Ib is interpreted as glacial sediments (subglacial till or moraines). In these instances, the underlying SF-Ia is interpreted as the bedrock surface.

It is not always possible to calculate true sediment thickness from loch bed to bedrock due to moraines and other glacial landforms preserved at the bottom of the loch, which can prevent imaging the base of the sediment succession. Therefore, sediment thickness is considered a minimum thickness in this study and could provide approximate sedimentation rates following deglaciation to the present-day.

4.3.3. Glaciolacustrine sedimentation

4.3.3.1. SF-IIa proglacial lake sedimentation. SF-IIa is typically confined to deeper depocentres identified in the sedimentary isopach map, where up to 44 m thickness is calculated (Fig. 8C, Central basin). It is noted where SF-IIa is thinner or not present, SF-III may have partially or fully eroded the unit, however where present, much of the sedimentary package of SF-IIa comprises thin-bedded acoustic layering, suggesting a regular supply of sediment throughout deposition, such as in a glaciolacustrine or glaciomarine setting (*e.g.*, Vardy et al., 2010; Pinson et al., 2013; Lowag et al., 2012). Lacustrine environments act as a sink for water and sediment, commonly associated with glacial processes (Fitzsimons and Howarth, 2018). It is likely that thin bodies of sediment, such as turbidites, are bound by laterally persistent surfaces, which form the continuous acoustic layering observed in the seismic data. Such semi-regional surfaces are likely related to a reduction in sediment supply or energy regime. In places such as basin margins, the lower unit of SF-IIa can exhibit a more chaotic character. Such sedimentary processes are likely related to more energic processes, or rapid accumulation, including mass flows or prograding sandy sequences. SF-IIa facies are not present in the shallow basins located on the margins of Loch Lomond (Fig. 8C), suggesting that the conditions favouring settling and preservation of thick sequences of SF-IIa were restricted to the deeper central basins.

4.3.3.2. SF-IIb glaciofluvial sedimentation. On the western side of the Southern basin, a boomer profile reveals SF-IIb comprising a submerged ridge and planar-topped features with dipping internal reflectors approximately to the southeast, interpreted as an ice-contact subaqueous fan or delta (Figs. 5C, 9). Landforms formed by glaciofluvial processes (*e.g.*, deltas, delta moraines or fans) are identified in similar settings (Carrivick and Tweed, 2013). Such an interpretation is again consistent with sand and gravel features mapped on adjacent onshore areas around the margins of Loch Lomond (Rose and Smith, 2008), highlighted on the western margin of the Southern basin (Fig. 5A).

4.3.4. SF-III mass transport deposits

Mass transport deposits (MTDs) are sedimentary deposits of gravity-driven mass flows (*i.e.*, submarine landslides), that translate downslope to areas of lower gradient due to gravity-induced mass failure (Nwoko et al., 2020). The term MTD includes several deformation processes including creep, slump, slides, and debris flows (Dott, 1963; Middleton and Hampton, 1973). SF-III is characterised by homogenous to transparent or chaotic seismic facies, typically associated with MTDs due to the lack of internal stratification (*e.g.*, Sammartini et al., 2019; Carter et al., 2020). Seismic evidence in Loch Lomond suggests this unit could represent a time of significant reworking of material, as the base of the unit is often erosive, a common feature observed in the deposition of mass transport deposits (*e.g.*, Frey-Martínez et al., 2006; Garziglia et al., 2008; Posamentier and Martinsen, 2011; Dakin et al., 2013), as observed in Figure 7A. The distribution of these facies is relatively widespread across the basin (Fig. 8B), suggesting SF-III was deposited rapidly associated with large volumes of material. Where stacked events are observed, it is likely that multiple MTDs form mass

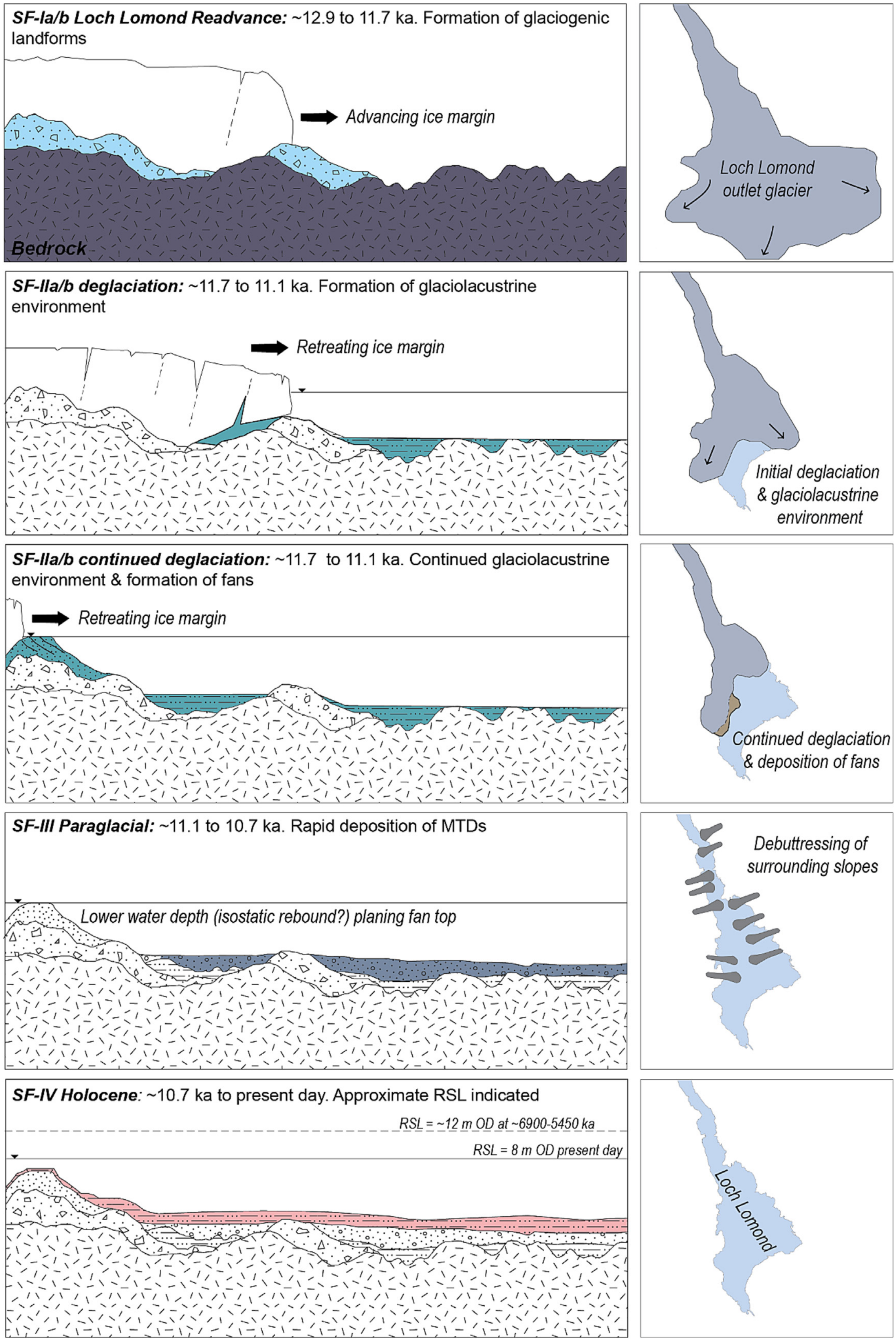

Fig. 9. Schematic depositional model showing the formation of sediments deposited in Loch Lomond, as identified from seismic facies, from the Late Devensian Loch Lomond Stadial.

transport complexes (MTCs) resulting from multiple failure events (Fig. 7A). Research presented by Sammartini et al. (2019) shows MTDs are common features in glaciogenic lacustrine environments (*e.g.*, Lake Ellery, New Zealand; Lake Constance, Switzerland; Lake Bergsee, Germany; Lake Ledro, Italy; Lake Botn, Norway; Lake Bohinj, Slovenia). Their study identifies mass-movement processes by the initiation of four major mechanisms: (1) lateral slope landslides, (2) margin collapses, (3) delta collapses, and (4) rockfalls. Such mechanisms of failure can evolve downslope as sediment density flows, resulting in various types of deposits within lacustrine settings. It is possible that the potential MTDs associated with SF-III identified in Loch Lomond reflect the phase of paraglacial response of the landscape to deglaciation, and the mass-wastage of glacially deposited materials in and adjacent to the Loch Lomond basin due to the wide exposure of sediment in an unstable state (*e.g.*, Ballantyne, 2002, 2008, 2014).

4.3.5. SF-IV Holocene lacustrine and marine sedimentation

SF-IV is characterised as a thin-bedded to laminated sedimentary package draped across the entire Loch Lomond basin. The SF-IV Group is divided into 3 discrete sub-units. The oldest unit (SF-IVa) appears as transparent on the EdgeTech dataset and well-laminated on the surface tow boomer profiles and is likely due to sediments having a homogenous composition. A 'grey clay' unit is penetrated at the very base of the LLRD1 core (Fig. 3), and likely corresponds with low sediment supply in a quiet environment, typical of lacustrine sedimentation. The middle unit, SF-IVb, characterised by a 70 cm-thick black silty clay unit identified in the LLRD1 core, possibly relates to the high amplitude event approximately in the middle of the seismic package. This sedimentary unit is likely related to dense, silty clays deposited from suspension settling during establishment of a marine incursion during the Holocene (*e.g.*, Dickson et al., 1978). Finally, the thinly laminated silty–clay gyttja in the upper part of the LLRD1 core (Fig. 3), correlating with the upper SF-IVc unit, is consistent with low sediment supply in a quiet environment, typical of lacustrine sedimentation, similar to SF-IVa prior to the marine incursion. The presence of mass transport deposits, as identified throughout the SF-IV-unit in the seismic data, likely result from the steep glaciated terrain and continued slope failures into the loch; however, mass transport deposition can also be triggered from anthropogenic sources (*e.g.*, Finlayson et al., 2023).

5. Discussion

5.1. Reconstructing the evolution of Loch Lomond's sedimentary infill

The four principal facies units identified in seismic data represent distinct phases of sedimentation that resulted from the glacial and post-glacial history of the landscape processes around Loch Lomond. Understanding the regional Quaternary history of Loch Lomond has culminated in a chronostratigraphical model correlating the four major acoustic units identified and a depositional model (Fig. 9) and associated chronological framework tying the surrounding environmental changes to the subsurface geology of Loch Lomond (Fig. 10).

5.1.1. Glaciogenic deposits

The sedimentary record of the last glacial maximum in the Dimlington Stadial (~30 to 14.7 ka) is supported by the relative stratigraphical position of the Wilderness Till, so-called from type sections identified in the Wilderness Planation area, north of Bishopshriggs, Glasgow (Browne and McMillan, 1989). Depositional elements relating to older ice advance and retreat oscillations are unlikely to have survived as widespread traceable units due to the later ice advance associated with the most recent, LLR (12.9–11.7 ka), glacial episode. Unlike the continental expansion of ice associated with the LGM of the Dimlington Stadial, the LLR was predominantly confined to the Highlands of Scotland Britain. In Loch Lomond, glacier ice advanced ~6 km beyond the south-eastern shores of the loch (Fig. 1A). The regional SF-I 'undifferentiated' horizon is interpreted as an amalgamation of both erosional and depositional elements, associated with the glacial occupation of Loch Lomond during the LLR. The bedrock surface represents the cumulative effect of erosion through repeated glacial cycles, whilst the dense subglacial sediments are interpreted as till (SF-Ib). Ice advance during the LLR formed glaciogenic deposits including drumlins and moraines composed of the Gartocharn Till Formation. The orientation of the drumlins within Loch Lomond supports interpretation of the south-eastwards extension of ice as it flowed across the landscape, and therefore we assign sediments of the SF-Ib unit to the Gartocharn Till Formation (Table 1) (Browne and McMillan, 1989).

5.1.2. Glaciolacustrine sedimentation

As the climate warmed at the start of the Holocene, the Loch Lomond outlet glacier started to retreat, resulting in environmental and depositional changes across the landscape. Proglacial lake development is a major component of deglaciation, which can influence meltwater, sediment flux and the formation of landforms along glacier margins as they retreat (Carrivick and Tweed, 2013). The thinly bedded acoustic layering of the SF-II unit, which immediately overlies the glacial till and glacially eroded bedrock, is interpreted as the deposition of glaciolacustrine sediments relating to large volumes of meltwater that would have been made available in a warming climate. The SF-II isopach (combined SF-IIa and b), shows the distribution of this unit and has implications on the occurrence of ice retreat as deglaciation occurred. The deposition (and preservation) of the SF-IIa and b units likely records an ice-marginal setting with sufficient accommodation space. Where SF-IIa is not present, such as in the shallow basins on the eastern margin of Loch Lomond, there may have been insufficient accommodation space to deposit sedimentary sequences. It is also possible that mass transport events associated with the overlying SF-III unit or nearshore processes completely eroded SF-IIa. The lower SF-IIa facies with discontinuous to transparent reflectors, may relate to a more proximal ice-marginal proglacial lake setting, attributed to higher energy and coarser grained facies deposition (*e.g.*, Fitzsimons and Howarth, 2018). The upper SF-IIa facies, containing laterally continuous reflectors may have been related to ice-distal conditions at a time when the ice margin had retreated further northwards up Loch Lomond. Both proximal and distal glaciolacustrine sediments have been recorded in excavations and cores from the Blane and Endrick valleys beyond the south-eastern shore of Loch Lomond (Browne and McMillan, 1989; Macleod et al., 2011). These relate to the ice-dammed Lake Blane which existed when the Loch Lomond glacier reached its maximum extent (Fig. 1A). We suggest that SF-IIa relates to deposition in a similar glaciolacustrine environment, but at a later stage once the ice margin had retreated away from the southern Loch Lomond shoreline allowing the area occupied by Lake Blane to drain. In this sense, SF-IIa is similar to the Blane Water Formation (Table 1); however, it is recorded here within the current extent of Loch Lomond rather than in the Blane Valley. Sedimentation rates during deposition of the SF-IIa unit are interpreted to have been rapid, potentially controlled by proximity to the ice-margin and lake water density stratification (*e.g.*, Carrivick and Tweed, 2013). The SF-IIb facies, interpreted as an ice-marginal fan, is thought to reflect a temporarily stable position of the ice margin as the ice was retreating. The onset of progradation represents a time of high sediment supply, with the height of the prograding unit limited by the water depth (*e.g.*, Winsemann et al., 2004).

5.1.3. Mass transport deposits

Continued melting and the ultimate withdrawal of glacier ice in the Loch Lomond valley resulted in a new environmental and depositional regime associated with paraglacial landscape response. Ice retreat likely resulted in exposure of loose valley side sediments, susceptible to slope failure and erosion, depositing directly into the glacial trough. The SF-III unit is interpreted to represent mass transport deposits (*e.g.*, subaqueous debris flows), which directly overlie and erode down into the underlying glaciolacustrine sediments. They appear to represent a marked phase involving the reworking of sediment within and around the loch. Paraglacial reworking of sediment by slope gravitational processes is recognised to be most active in the decades and centuries following glacier retreat (Ballantyne, 2002). We therefore attribute SF-III to a paraglacial phase whereby sediment that had been newly exposed by ice retreat was most susceptible to mass transport processes. No

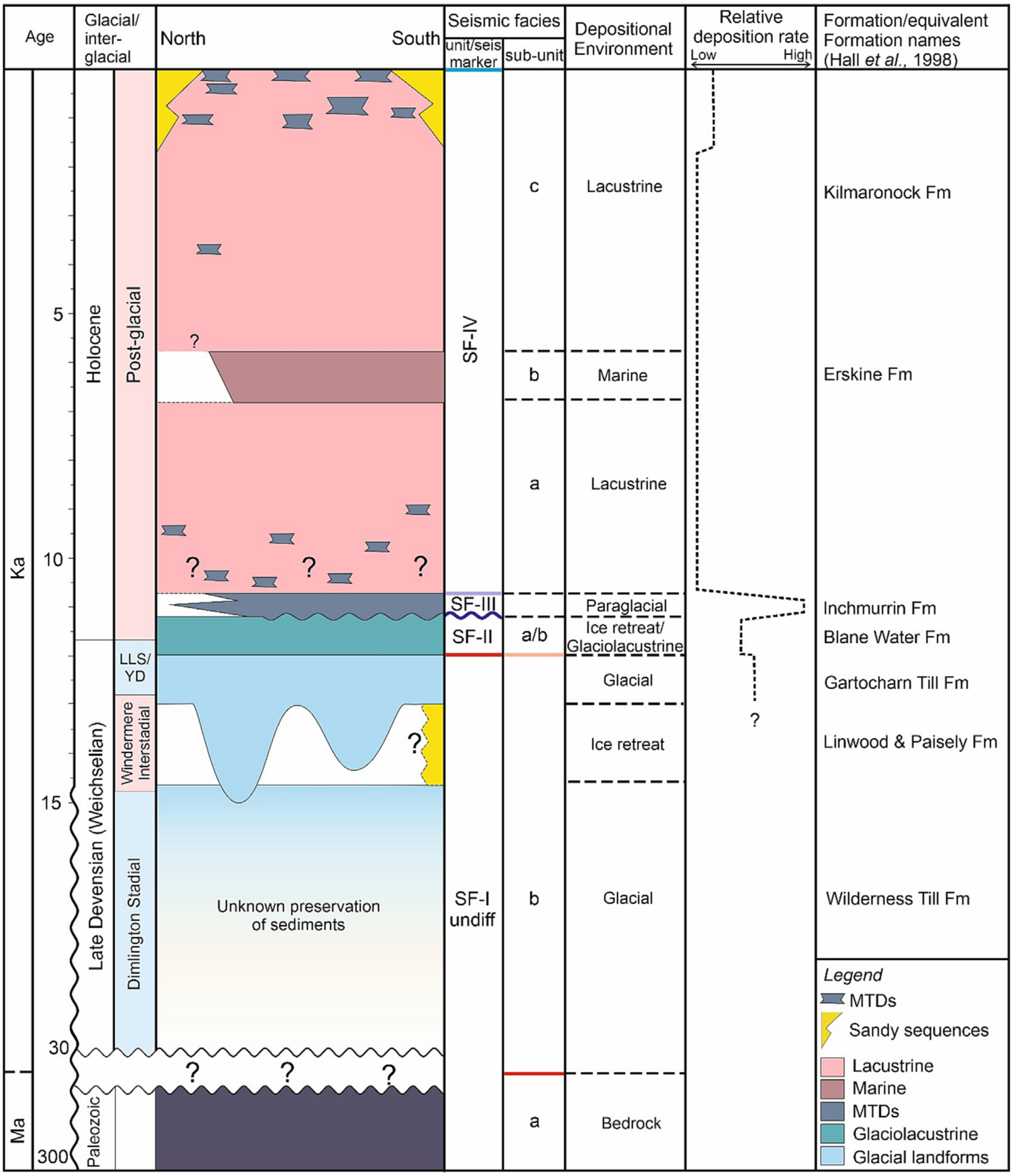

Fig. 10. Loch Lomond chronostratigraphical diagram identifying main sedimentary and associated seismic facies, depositional environment, relative deposition rates and formation names. Note 'Inchmurrin Formation' relates to the newly identified subsurface paraglacial formation. Chronostratigraphical framework is referenced to recent dating work undertaken in Scotland (*e.g.*, Lowe et al., 2019; Palmer et al., 2020).

stratigraphical units relating to this phase have previously been recorded around Loch Lomond; however, the significant impact of paraglacial sediment redistribution has been described in the wider area (*e.g.*, Finlayson, 2020). To complement the existing Late Devensian to Holocene stratigraphy in the area (Table 1), we have called this newly identified unit the 'Inchmurrin Formation', relating to the island of Inchmurrin where the SF-III unit is well imaged in nearby seismic profiles. Vardy et al. (2010) suggest a broadly equivalent chaotic unit in Lake Windermere to cover an estimated area of 130,000 m^2 with a total volume of *c.* 500,000 m^3 (average thickness of *c.* 3.8 m). These findings from Lake Windermere, Loch Lomond and other recently investigated water bodies (*e.g.*, Stoker et al., 2010) provide insight into the potentially significant presence of mass transport deposits that may be buried beneath other loch beds and lake beds in steep deglaciated environments.

5.1.4. *Holocene/lacustrine sedimentation*

As the landscape stabilised mass transport processes became less dominant with more gradual lacustrine sedimentation ensuing. The SF-IV facies are identified across the entire Loch Lomond basin. Different sedimentary processes are interpreted for sub-units of SF-IV, including widespread lacustrine deposition and a temporary marine incursion during the early-to-mid Holocene between 6900 and 5450 ^{14}C ka BP (Dickson et al., 1978), where the relative sea level is modelled as up to 12 m above OD (Fig. 2). The lacustrine sedimentation (SF-IVa and SF-IVc) can be assigned to the Kilmaronock Formation whilst sediments from the marine incursion (tentatively SF-IVb) are assigned to the Erskine Formation (Table 1). Isolated mass transport deposits are also identified within the SF-IV facies. These are ongoing processes, albeit at far lower rates than during the main paraglacial phase and may be triggered naturally or by human-related activities (Howison and Macdonald, 1988; Finlayson et al., 2023). Overall, sedimentation rates during the deposition of the SF-IV unit were very low, relating to low-energy conditions, dominantly from the settling of suspended sediment derived from fluvial systems that flow into the lake, and established vegetation, stabilising slopes, and sediment around the loch (Figs. 9, 10).

5.2. Comparison with regional lakes, lochs and fjords

A disadvantage of this seismographic investigation is the absence of deep borehole data to validate the acoustic interpretation of sediment fill, however the results of this investigation complement studies from different lochs around Scotland, lakes in England and fjord systems in Norway and Canada where sediment cores are available (Pennington et al., 1943; Audsley et al., 2016; Baltzer et al., 2010; Bellwald et al., 2016; 2019; Boulton et al., 1981; Howe et al., 2002; Lowag et al., 2012; Lowe et al., 2019; Macleod et al., 2011; Mokeddem et al., 2010; Pinson et al., 2013; Stoker et al., 2010; Trottier et al., 2021; Vardy et al., 2010).

The hummocky features identified in the mapped SF-Ib facies within the Loch Lomond dataset are likely to represent morainic features due to their stratigraphical position and similar reflection characteristics (*e.g.*, hummocky upper surface and chaotic, high amplitude internal reflectors) to those identified in other studies, such as the 'SF-I a to e' facies mapped in seismic data from Lake Windemere, Lake District, UK (Pinson et al., 2013). Their study shows a comparable structureless unit, comprised of a slumped and folded material unit above layered glaciolacustrine/lacustrine sediment. The Pinson et al. (2013) study also provided an exceptional insight into the nature of the glaciogenic landforms that exist at the base of the stratigraphy including interpretation of De Geer moraines, recessional moraines, and ice-front fans.

Unit SF-IIa in Loch Lomond is similar to other units described in several case studies from seismic datasets in lochs and lakes across Britain. The age of this unit is likely to vary between sites, as the timing of glacier retreat (giving way to glaciolacustrine conditions) was different across Britain (*e.g.*, Lake Windermere, Pinson et al., 2013). Although absolute dates for deposition are not available in Loch Lomond, similarities of the SF-IIa unit across different sites in the UK are discussed here. Loch Sunart is a sea loch situated on the southern shores of the Ardnamurchan Peninsula, Scotland. Pollen analysis and radiocarbon-dating from a 12 m long piston core enabled a chronological framework to be established for the site (Baltzer et al., 2010; Mokeddem et al., 2010). In Loch Sunart, the fine acoustic layering of Unit 2, SF-II in this study, is interpreted as incorporating the LLS age glaciomarine sediments, interpreted as the Muck Formation. Another example is from Loch Etive on the west coast Scotland, where Howe et al. (2002) attribute an equivalent 'deep' laminated seismic facies to the LLS and into the early Holocene, similar to Baltzer et al. (2010). Here, the deep laminated unit is interpreted to have been deposited in a glaciolacustrine to glaciomarine environment. In Lake Windermere, shallow sediment cores penetrated the equivalent facies of SF-IIa, identifying very fine laminated pink clay, with alternating layers of coarser and finer material (Pennington et al., 1943; Holmes, 1964). Pinson et al. (2013) assigned this equivalent unit slightly earlier, interpreting it as a glaciolacustrine facies deposited between 17.6 and 12.9 ka BP following the retreat of Dimlington Stadial ice in the area.

The chaotic to transparent unit representing SF-III in this study has not been identified in all lakes and lochs previously investigated in northern Britain. For example, such a unit was not detected in Loch Etive (Howe et al., 2002). However, an equivalent unit was identified in Lake Windermere (Lowag et al. 2012; Vardy et al., 2010; Pinson et al., 2013), Loch Sunart (Baltzer et al., 2010), and Little Loch Broom (Stoker et al., 2010). Baltzer et al. (2010) suggested that this thick transparent to semi-transparent unit is related to the rapid deposition of a huge supply of sediment when significant reworking was taking place during phases of unstable climate in the early and mid-Holocene. Pinson et al. (2013) suggest this facies (SF-III in this study) represents slumped deposits of Younger Dryas age. The shallow sediment cores collected in Lake Windermere (Pennington et al., 1943; Holmes, 1964) penetrated the equivalent facies of SF-III, identifying clay-rich facies with variable structure; with some cores having preserved laminations, whilst others showing heavy deformation and/or overturned laminae (Pinson et al., 2013). The common factor across all the sites where the transparent and chaotic unit has been recognised is that it has been attributed to a phase that follows local deglaciation. The presence of thick paraglacial deposits in Loch Lomond provides evidence for the large-scale impact of deglaciation on slope stability and the generation of landslides within and around recently deglaciated lake systems. In modern landscapes undergoing deglaciation this can represent a potential geohazard, inducing severe damage to population and infrastructure (Sepúlveda et al., 2023).

Thinly laminated lacustrine muds (SF-IV) have been deposited across the bed of Loch Lomond during the Holocene and into the present day. Similar seismic facies represent the Holocene sequence in other deglaciated lakes in upland settings, such as Lake Windermere (*e.g.*, Pinson et al., 2013), with sedimentation rates being characteristically lower that the preceding glaciolacustrine and paraglacial phases. For example, Schaller et al. (2022) estimate ~0.88 m/ka for Holocene sedimentation rates (from ~9.4 ka BP) in Lake Constance, Switzerland. In Loch Lomond, the maximum interpreted thickness of Holocene sediments is 8 m in the Central basin, suggesting comparable slower sedimentation rates (Fig. 10). This contrasts starkly with the earlier deglacial/paraglacial phase where up to 40 m of sediment was likely to have been deposited over a few centuries.

6. Conclusions

Historically, much research has been undertaken to understand landscape evolution and environmental change during the last glacial–interglacial cycle in Britain. High resolution multibeam and two-dimensional sub-bottom profiling data from Loch Lomond UK, provide new insights into the sedimentary sequences relating to the deglaciation, paraglacial and postglacial landscape change associated with the end of the last glaciation and transition into the Holocene in Loch Lomond. This study offers a unique insight into a key piece of evidence that has not yet been studied in the sedimentary record. The seismic data described in this report have revealed complete sequences of up to 58 m of sediment preserved in Loch Lomond, representing: (i) a subglacial surface; (ii) glaciolacustrine and ice-contact fan sedimentation; (iii) mass transport process; and (iv) lacustrine sedimentation. Of particular note are rapid sedimentation rates during deglaciation and a phase of paraglacial landscape adjustment that have been interpreted from the characteristics of SF-IIa/b (glaciolacustrine) and SF-III (mass transport deposits) facies.

The seismic facies representing mass transport deposits (SF-III) in Loch Lomond provides important analogous information for the potential scale of landslides into lakes in deglaciated lake basins. Although the signature of paraglacial sediment reworking has not been widely documented in previous studies from the Loch Lomond basin, this research suggests that it represents a substantial proportion (up to approximately 50 % in the Central basin) of the sediment fill within the loch, potentially offering new insight into the extent and rates of landscape adjustment that accompanied the transition from glacial to non-glacial conditions in the Loch Lomond area. These findings are of fundamental importance when considering landscape stability and potential future geohazards in regions that are undergoing rapid deglaciation (*e.g.*, mountainous areas around the Alps, Himalayas, and New Zealand).

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Declaration of competing interest

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

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