Basal melt over Subglacial Lake Ellsworth and it catchment: insights from englacial layering

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ABSTRACT. Deep-water 'stable' subglacial lakes are likely to contain microbial life adapted in isolation to the extreme conditions of pressure, temperature and darkness. Key to these conditions is the rate of water supply into the lake from above and upstream. Isochronous radio-echo layers have been used to infer melt rates above Lake Vostok and Lake Concordia in East Antarctica but have not be used more widely. Here, we examine internal ice-sheet layers above and around Lake Ellsworth in West Antarctica, to establish where the ice sheet has been 'drawn down' to the bed due to basal melting. We show that melting occurs predominantly across the long northwest edge of the lake as the ice sheet, flowing obliquely to the lake axis, becomes afloat. We also reveal melting southeast of the lake, within a second subglacial lake near the head of the hydrological catchment. It is likely these two sources of water will contain a subtly distinct hydrochemistry due to solute acquisition from basal sediments during subglacial flow. In Lake Vostok, water input to the lake is part-balanced by accreted ice. However, we see no evidence for this in the radio-echo sounding data. Instead, water may continually exit Lake Ellsworth at its downstream margin.

INTRODUCTION

The exploration, access and measurement of Antarctic subglacial lakes has the potential to address several significant scientific questions regarding Antarctic Ice Sheet history, life in extreme environments, and how subglacial hydrology can influence ice sheet flow (Siegert, 2016). Important to each of these questions is how water is supplied to, and released from, subglacial lakes. Considerable focus has been given to inputs and outputs associated with water flow across the ice sheet bed (e.g. Fricker and others, 2007; Wright and others, 2012; Fricker and others, 2016) but there has been relatively little investigation constraining basal melt of the overlying ice sheet at the ice-water interface. A characteristic of the ice sheet that can be exploited to constrain both the location and magnitude of basal melt is the englacial structure of the ice sheet, which can be imaged and characterised using radio-echo sounding (RES) (Siegert, 1999; Dowdeswell and Evans, 2004). Englacial layers, associated with variations in the density, conductivity and fabric structure of the ice sheet, are assumed to be isochronous and, in most cases, are associated with the burial of palaeo-ice sheet surfaces (Siegert, 1999). Over subglacial water bodies, and localised areas of high geothermal heat flux, englacial layers can be locally drawdown so that younger layers are found at greater than expected depths in the ice sheet column, indicative of high rates of subglacial melt (Siegert and others, 2000; Gudlaugsson and others 2016; Jordan and others, 2018).

The importance of direct melting of the overlying ice sheet into subglacial lakes is the role it can play in influencing: (i) the pattern and rate of circulation of the water body (Thoma and others 2009, 2011; Woodward and others, 2010), through determining where melt water is inputted; and (ii) sedimentary processes in subglacial lakes (Bentley and others, 2011; Smith and others, 2018), by influencing where sediments will melt out from the ice sheet column, rain out into the water column and be deposited on the lake floor. Whilst basal melt at the ice-water interface does not operate in isolation, i.e. in an open system it will interact with subglacial water flowing between the ice sheet and the bed, improved knowledge of the location and magnitude of basal melt will enhance understanding of the drivers of hydrological processes in subglacial lakes.

Numerical modelling of water circulation has been undertaken for three Antarctic subglacial lakes (Pattyn and others, 2016): Lake Vostok (e.g. Wüest and Carmack, 2000; Mayer and others, 2003; Thoma and others 2008a, 2008b), Lake Concordia (Thoma and others, 2009) and Subglacial Lake Ellsworth (SLE) (Woodward and others, 2010; Thoma and others, 2011). Input data for these models comprised lake bathymetry (i.e. water column thickness) determined from seismic reflection surveys or the inversion of gravity measurements, ice column thickness, assumed values of geothermal heatflux and the velocity of ice flow from GPS or InSAR measurements. For each lake a basal mass balance (i.e. predicting where basal melt, causing layer drawdown, and refreezing, causing layer uplift, occurs), the pattern and velocity of water flow, and the extent and thickness of accreted ice were determined. In comparison to Concordia and Vostok, water circulation modelling suggests that SLE has higher rates of basal melt, basal refreezing and a more vigorous water circulation (see: Table 1 of Pattyn and others, 2016). In addition, due to SLE being positioned at a depth that intersects the Line of Maximum Density, deeper parts of the lake may experience convective (ocean-type) circulation leading to mixing of the water column, whilst shallower parts may have limited convection and a stratified water column (Woodward and others, 2010; Pattyn and others, 2016).

The aims of this paper are to report the character and 3D form of the englacial layer package over SLE and its wider catchment, to: (i) assess whether the geometry of the englacial layers is consistent with existing numerical models of water circulation in SLE; (ii) improve understanding of the interactions between SLE and the overlying ice sheet (i.e. identifying the sources of meltwater); and (iii) make the englacial layer dataset accessible to the ice sheet modelling community. Our study is justified by the surprisingly few detailed observational investigations (3D or otherwise) of englacial layers over and around subglacial lakes (see: Siegert and others, 2000; Leonard and others, 2004; Siegert and others, 2004; Tikku and others, 2005; Carter and others, 2009), the unparalleled resolution, detail and tailored survey design of the SLE RES dataset, and the forthcoming exploration of Subglacial Lago CECs (Rivera and others, 2015), located not far from SLE, by a UK-Chilean research programme.

SUBGLACIAL LAKE ELLSWORTH

Between 2007-09 SLE was subject to a comprehensive ground-based geophysical characterisation, including RES, seismic reflection, GPS and shallow ice core measurements, and numerical modelling of water circulation patterns, in advance of an attempt at direct access and exploration in 2012 (Woodward and others, 2010; Ross and others, 2011a; Siegert and others 2012, 2014; Smith and others 2018). Whilst the basal topography, water column thickness, nature of the sediments on the lake floor and the subglacial hydrological flow paths have been constrained (Ross and others, 2011a; Siegert and others 2012; Smith and others, 2018), few details of the englacial layer form have been reported. Ross and others (2011b) reconstructed Holocene ice flow using englacial layer folding, but did not report or discuss the implications of the broader internal layer geometry for SLE. Here, we describe the RES survey of SLE and its ice surface and subglacial catchments, and detail the geometry and character of englacial layers in the SLE RES dataset, using these data to independently evaluate: (a) the validity of the output from the numerical models of water circulation in SLE; (b) conceptual models of sediment deposition in SLE; and (c) catchment-scale hydrological connectivity.

METHODS

The RES survey used the ground-based ∼1.7 MHz pulsed DEep-Look-Radar-Echo-Sounder (DELORES) RES system (King and others, 2016) towed by a snow mobile at an average rate of ∼12 km hr^{-1}. Traces, comprising the stacking of 1000 measurements, were acquired at an approximate along-track sampling resolution of 3-4 m. The survey (Figure 1d) was designed to characterise the physical system of the subglacial environment, from the ice divide to beyond the down-ice end of SLE, as well as the extent and form of the lake surface. A nested grid of closely-spaced (i.e. line-spacing of 300-350 m) RES lines were acquired at the down-flow end of the lake, with the aim of characterising the bed topography in high-resolution to measure any outlets of water and associated morphology. Nearly 1000 km of RES data were acquired, with the ice-bed identified and picked in more than 95% of the data (Ross and others, 2011a). Post-processing of the RES data in the software Reflexw comprised a typical processing scheme for low frequency impulse RES data (i.e. bandpass frequency filter, gain to compensate for geometrical divergence losses, Kirchhoff migration). Processed data are displayed, and picked layers assigned to ice thickness values, assuming a radio-wave velocity of 0.168 m ns^{-1}. A series of eight englacial layers were identified and picked; the uppermost seven of these layers could be traced continuously over a wide region allowing them to be gridded. Picking of layers was not possible, or was not continuous, where high-amplitude layer buckles, steep layer slopes and/or offline reflectors occurred. Digital elevation models (DEMs) were generated from the layer picks using the topo2raster algorithm (Hutchinson, 1988). Picks of the ice thickness and subglacial topography from the DELORES surveys, combined with existing ground and airborne RES surveys (e.g. Vaughan and others, 2007), were also gridded using the topo2raster algorithm, to produce DEMs of ice thickness and the glacier bed (Figures 1b, 3a and 5). These grids were used to calculate the hydropotential of the outlet zone of SLE, following the methods detailed in Jeofry and others (2018). The extent of the subglacial lake (Figure 1) was determined from the identification of a qualitatively bright smooth specular radar reflection in the base of the trough. Surface elevation was measured along the RES profile lines with

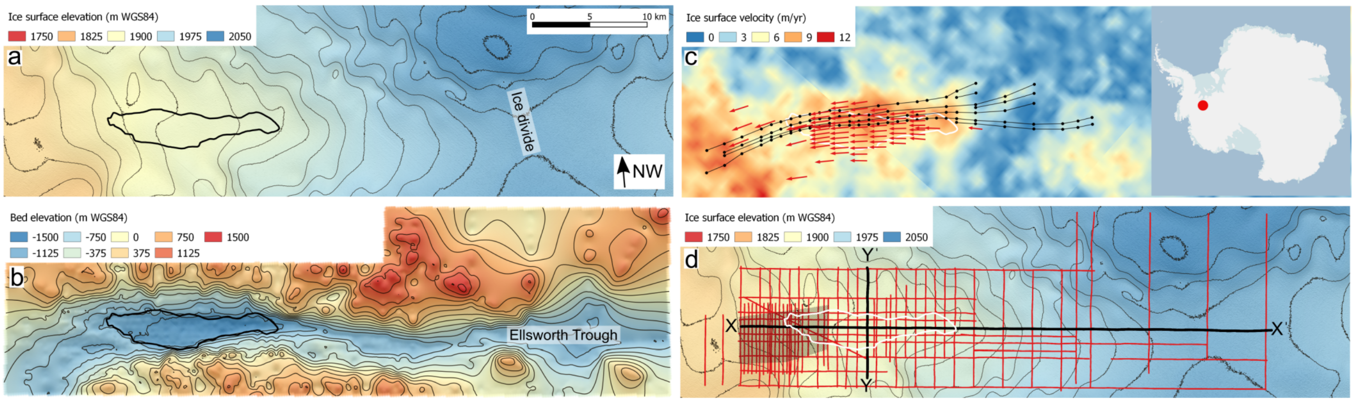

Fig. 1. Location and geography of Subglacial Lake Ellsworth (SLE), West Antarctica: (a) Ice surface topography (m WGS84) from Reference Elevation Model of Antarctica (REMA) (Howat and others, 2019), underlain by a hillshade of the same data (illuminated from azimuth of 315° and altitude of 30°, with Z factor of 100). Contours in 10 m intervals; (b) Subglacial topography (m WGS84) of the Ellsworth Trough (Ross et al., 2011a; Ross and others, 2014). Basal topography over SLE is the lake ice-water interface, not the lake floor. Contours in 200 m intervals; (c) ice flow velocity from MEaSUREs (Rignot and others, 2017), overlain by GPS measurements of ice flow (red arrows) and orientation of internal layer folds (black dots and thin black lines) (from Ross and others, 2011b); (d) Location of SLE DELORES ice-penetrating radar data (red lines) underlain by REMA ice surface DEM. Locations of radargrams in Fig. 2 are shown (black lines). Surface elevation contours are in 10 m intervals. Hatched area is extent of Figures 5b and 5c. Inset shows location of Figures 1a-1d. Figures 1a-d are rotated clockwise by 41.4°. Extent of SLE shown by black (a,b) and white polygons (c,d).

Leica (500 and 1200) GPS in rover mode, with processed observations gridded to generate a DEM of the ice surface. A horizontal offset between the GPS (on lead skidoo) and the midpoint of the radar antennas was corrected manually during post-processing. Four static Leica GPS base stations (three over the lake, one on slow flowing ice adjacent to it) were used to measure ice flow velocity and any possible vertical displacement during the 2007-08 field season, and to correct the position of the roving data. Two static Leica base stations were used in the 2008-09 season (one over the lake, one on slow flowing ice adjacent to it).

RESULTS

The RES stratigraphy across the survey area is characterised by a series of strong, bright, thick, discrete reflections to depths up to 2000 m below the ice surface (Figure 2). In large parts of the survey area (Figure 1), including areas below the ice divide, few if any layers are observed in the radargrams at depths greater

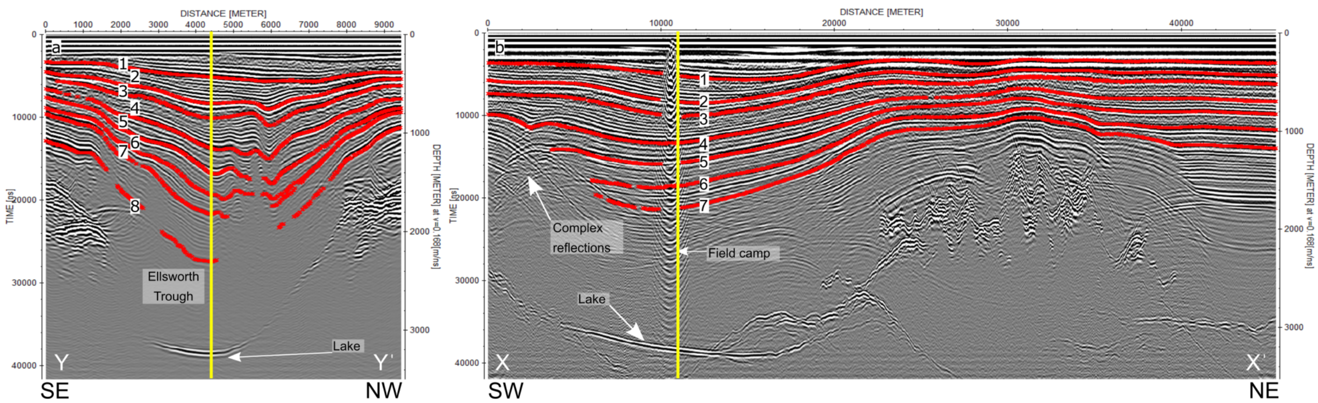

Fig. 2. Example radargrams of RES data and picked layers (1-8) over SLE and surroundings (see Fig. 1 for location): (a) Radargram from survey line D7.5 acquired across SLE, just up ice of its centre point. Ice flow is into page. 8 picked englacial layers are shown (red lines); (b) Radargram from survey line C5, acquired from just across the ice divide along the long axis of the Ellsworth Trough and SLE. Ice flow is approximately right to left (see Figure 1c). Note that the subglacial mountain range between 20-40 km is an offline reflection due to proximity of rugged relief. Complex reflections from a series of buckled layers intersecting obliquely with the survey line (see Figure 1c) and the 2007/08 field camp are indicated. Only 7 layers were pickable in line C5, as layer 8 was not readily identifiable in this orientation. Yellow lines show intersection point of radargrams. Location of data acquisition seen in Figure 1d

than 2000 m, suggesting a thick (up to 1 km) echo-free zone (Drewry and Meldrum, 1978). The englacial reflections are typically continuous within the survey area, although one or two layers (e.g. between picked layers 2 and 3) demonstrate bifurcation and pinch-out when ice thickness increases and decreases, respectively (Figure 2a). A prominent feature of the RES data over SLE are buckles generated by up-ice flow over rugged subglacial topography (Ross and others, 2011b), which disrupt the layer stratigraphy and geometry, and limit uninterrupted layer picking in ice >500 m below the ice surface in some areas (e.g. Figure 2b). The thickness of the englacial reflections (~10 m) is consistent with them representing the merged radar-response of multiple thinner discrete layers (Siegert, 1999; Dowdeswell and Evans, 2004).

Across ice flow, englacial reflections drape over the rugged topography with traceable layers over the Ellsworth Trough mapped at ice thicknesses up to double that observed over the topographic highs of the valley sidewalls and surrounding highlands and interfluves (Figures 2a and 3). This layer relief (i.e. of up to 1000 m) results in steep englacial layer slopes, which may account for the loss of radar returned power of some of the deeper layers (e.g. layer 8) proximal to the valley walls of the subglacial trough (Figure 2a).

It is apparent from both the radargrams and the gridded DEMs that subglacial topographic relief may

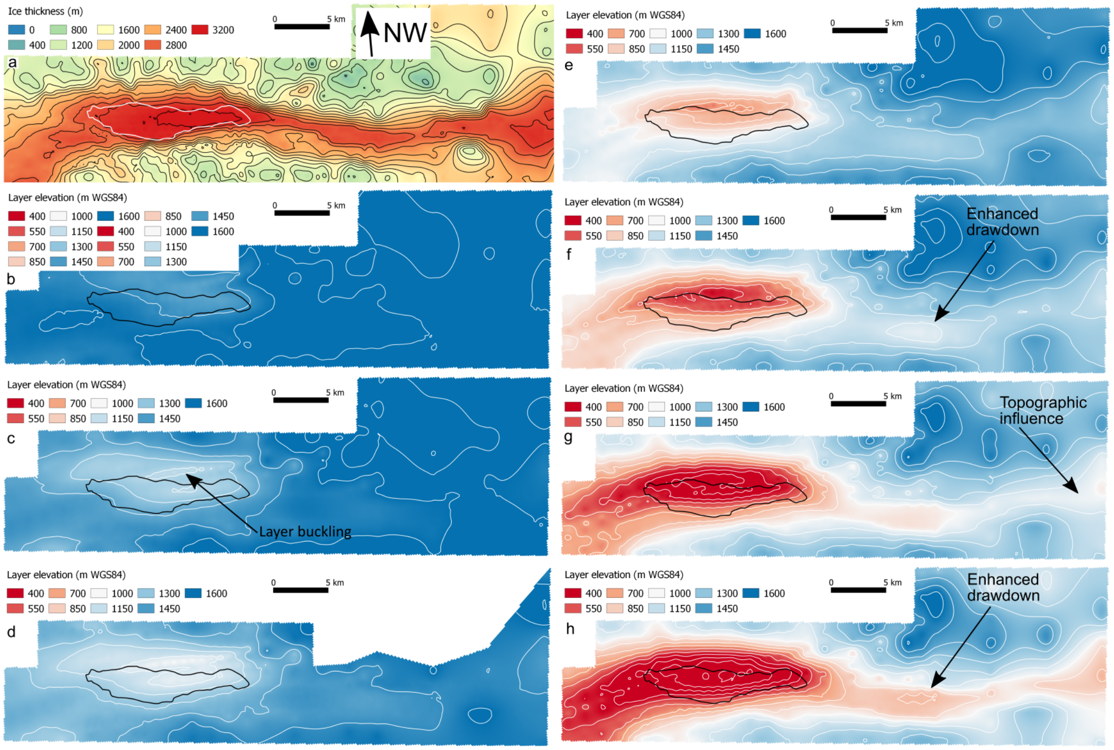

Fig. 3. Elevation (m WGS84) of gridded englacial layers 1-7 throughout the SLE catchment. (a) ice thickness (m) derived from RES surveys, with contours at 200 m intervals; (b) layer 1 elevation; (c) layer 2; (d) layer 2; (e) layer 4; (f) layer 5; (g) layer 6; (h) layer 7. All layers (Fig. 3b-3h) are shown with a common colour scale that is saturated below 400 m WGS84 and above 1600 m WGS84, to demonstrate layer evolution with depth through the ice column. All layer elevation contours are at 100 m intervals. Lake shoreline is white (a) and black (b-h) polygons. The orientation of Figures 3a-h have been rotated clockwise by 41.4° for display.

not be the only factor influencing englacial form and geometry, however. The maximum drawdown of layers is offset from the centre of the trough axis, with drawdown focused to grid NW of the trough long axis (e.g. right-hand side of Figure 2a). In gridded layers 2-7 the axis of maximum drawdown has a very strong spatial correspondence with the mapped grid-NW lateral edge (i.e. shoreline) of the lake (Figure 3). This is in direct contrast to the geometry of these layers over the grid-SE lateral lake margin, where the elevation of all these layers is observed to be rising in the ice located above the lake shoreline (Figure 2a and 3). As such, maximum drawdown is offset to grid-NW of the central axes of both the Ellsworth Trough and SLE.

Although there is some sagging of layers throughout the Ellsworth Trough, drawdown is much more pronounced along the length of the lake (Figure 2b and 3). In the deeper layers (i.e. layer 4 and below) a second zone of enhanced drawdown is apparent in the base of the Ellsworth Trough between SLE and

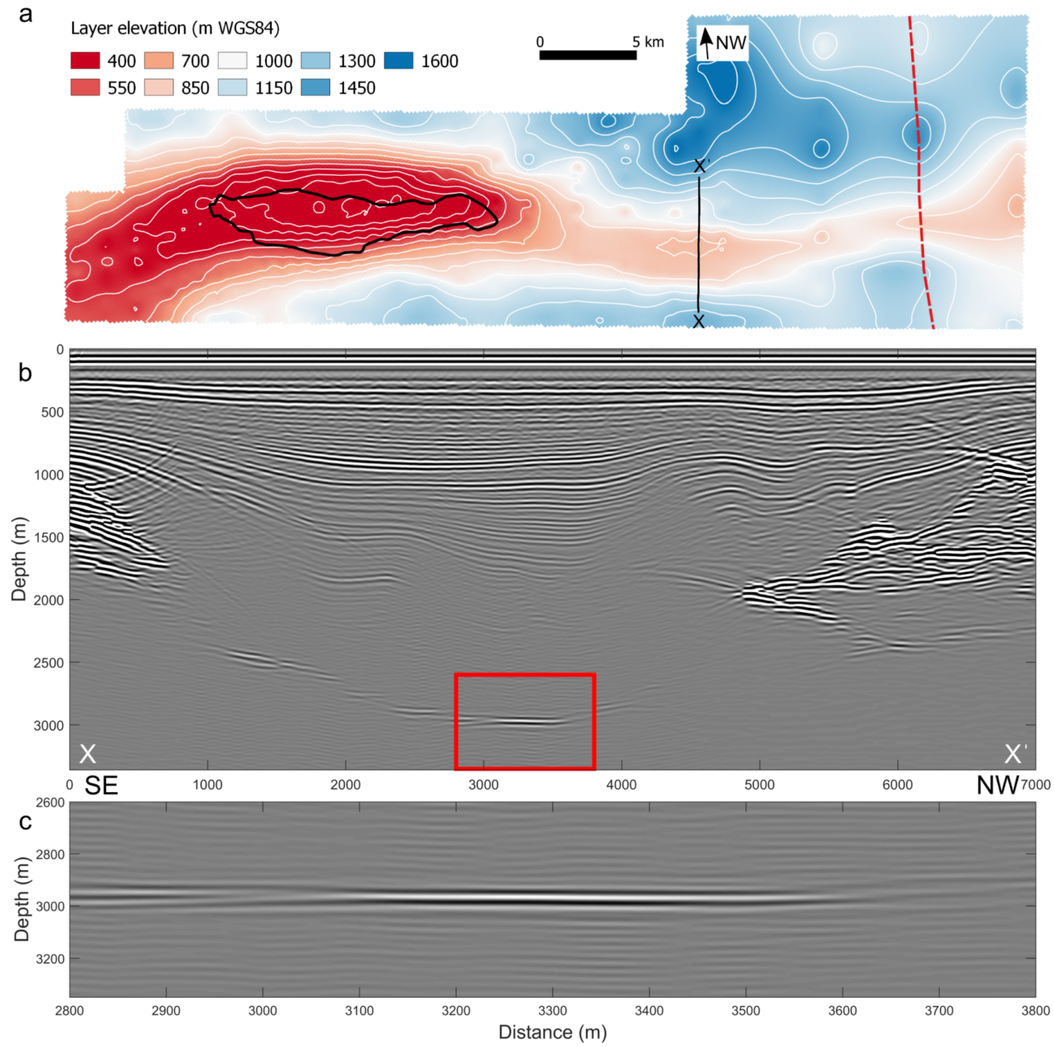

Fig. 4. Englacial layer geometry and basal reflection properties associated with a small water body in the upper Ellsworth Trough. (a) Layer drawdown of englacial layer 7. Location of RES line D18.25 is shown by black line, ice divide by dashed red line. Contours at 100 m intervals. The orientation of Figure 4a has been rotated clockwise by 41.4° for display; (b) Radargram from survey line D18-25 showing bed topography and englacial layers. Red box shows extent of 4c; (c) zoom-in of radargram D18.25 showing qualitatively bright flat specular reflection on the floor of the Ellsworth Trough at an ice thickness of nearly 3 km.

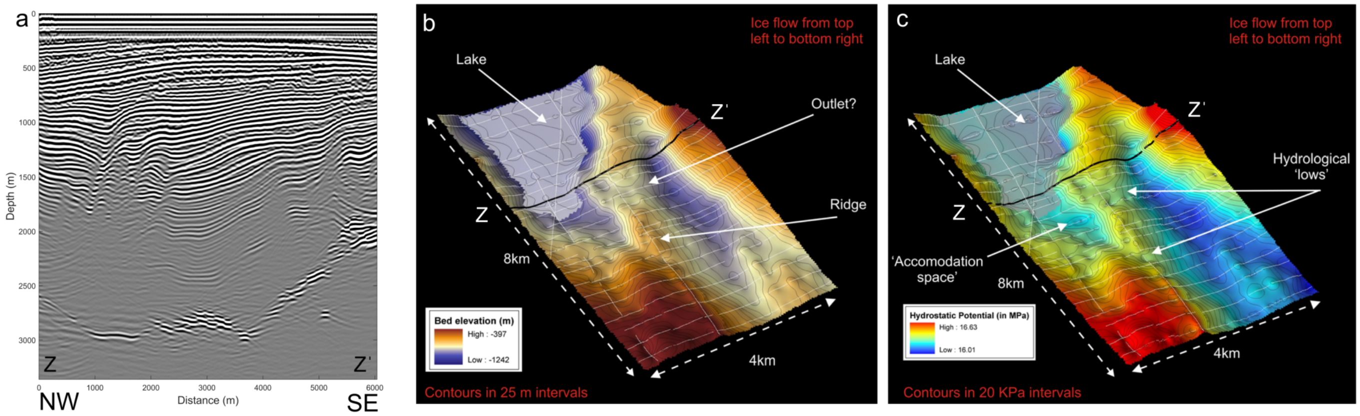

Fig. 5. High resolution topography and hydropotential of the outlet zone of SLE: (a) Radargram E2 displaying a narrow bright reflection from the down-ice most part of SLE, and the subglacial topography, including a 200 m high ridge that impounds the down-ice end of the lake; (b) RES-derived DEM of the topography at the outlet of SLE. Lake, ridge and possible lake outlets are annotated; (c) RES-derived hydropotential map of the outlet zone of SLE, showing the hydropotential high associated with the subglacial ridge. Potential hydrological lows, where water may discharge from SLE are shown. White lines on 5b and 5c are the location of RES data, with the location of radargram E2 (5a) represented by a black line. DEM cell size for 5b and 5c is 50 m. Extent of 5b and 5c shown in Figure 1d.

the ice divide (Figure 3). RES data perpendicular to this zone of layer drawdown are associated with a localised qualitatively bright flat basal reflection in the deepest part of the trough, where the ice is thick (Figure 3a), directly beneath the maximum layer drawdown (Figure 4). This is indicative of the presence of a secondary smaller water body in the Ellsworth Trough between SLE and the divide (Figure 4), and is consistent with the potential for a connected subglacial hydrological system along the base of the Ellsworth Trough (Vaughan and others, 2007; Siegert and others, 2012; Smith and others, 2018; Napoleoni and others, in prep).

Down-ice of SLE, the englacial layers rise in elevation as the bed rises, and ice flows over a prominent ridge that impounds the bottom end of SLE (Figure 5) (Siegert and others, 2012; Ross and others, 2014; Smith and others, 2018). In these 'down-ice' most parts of the survey area (i.e. grid-SW) englacial reflections are observed much nearer to the (on average slightly shallower) bed, with a very thin, or perhaps no, echo-free zone in this area (Figure 5a). No evidence for englacial reflections associated with accretion ice have been observed in any of the DELORES data over the down-ice parts and outlet zone of SLE. The detailed geomorphology of the SLE outlet zone is presented here for the first time (Figure 5) and reveals a clear relationship between the 200 m high basal ridge that trends obliquely across the valley, and the down-ice shoreline of SLE. The DEM and hydropotential analysis (Figure 5) also reveals that, down-ice of the ridge, there is a second smaller basin, and hydropotential low, between the ridge and the grid-SE valley wall. Two possible hydrological connections, associated with low-lying channels that appear to cut across the ridge, may connect SLE with this basin during lake highstands associated with either periods of enhanced basal melt, or changes in the steepness of the ice surface (Siegert, 2005). 15-20 km beyond SLE another large subglacial lake has been observed with airborne RES (Vaughan and others, 2007; Napoleoni and others, in prep), and it is possible that episodic connection between SLE and this down-ice lake occurs during such highstands.

DISCUSSION

We have demonstrated that englacial layer drawdown over SLE is focused on the lateral NW shoreline of the lake. This initially appears to be a surprising finding, as intuitively we would anticipate basal melt, and therefore englacial layer drawdown, to be focused at the up-ice end of any subglacial lake, where the ice-water interface is lowest; and basal refreezing, with potential accretion ice formation and uplift of layers at the down-ice end of a lake, where the ice-water interface elevation is high.

GPS observations at SLE show that ice flow (Fig. 1c) is slightly oblique to the axis of the Ellsworth Trough (Ross and others, 2011b). This means that the ice does not flow straight down the trough, but instead flows north of grid NE to south of grid SW (i.e. obliquely across the trough and the lake). When combined with the elongate and slightly crescent shaped NW lateral shoreline of SLE, this results in the grounded ice to the NNE of the trough becoming afloat not at the narrow up-ice end of the lake, but instead across a much greater length of shoreline at the NE edge of the lake. Consequently, lake shoreline melt (Siegert and others, 2000, 2004; Tikku et al., 2005) is not confined just to the narrow (<1.5 km) up-ice tip of the lake shoreline, as it would be if ice flow was directly along the trough and lake axis, but instead occurs along a shoreline of 5 km, or more, in length. This has the potential to significantly increase the total amount of basal melt, even if the rate at which the ice base melts is unchanged.

Additional factors that may also contribute to the geometry of the internal layers over the lake are the significant relief (>2 km) between the floor of the Ellsworth Trough and the high elevation topography surrounding it, and the shift at the lake shoreline from a no-slip bed to a bed with zero basal resistance (first described by Weertman, 1976). Combined with the oblique ice flow direction, it could be that the drawdown of the internal layering is at least partly a result of mechanical effects of ice flow off the subglacial high and into the deep trough, combined with the 'Weertman effect'. Disentangling the relative importance of basal melt vs. mechanical effects is beyond the scope of this paper, however, and would potentially require significant 3D modelling work. From the 3D geometry of the englacial layers it is apparent that internal layer drawdown has a very clear spatial relationship with the extent of the subglacial lake (i.e. it is not so pronounced up-ice or down-ice of SLE), suggesting that basal melt is the predominant process controlling englacial layer form.

The drawdown of the englacial layers has a strong spatial consistency with the pattern of basal mass balance derived from numerical modelling of water circulation in SLE (Woodward and others, 2010). Using an idealised lake geometry and assuming a closed system, this modelling work suggests very high basal melt of 16 cm a^{-1} in a linear localised zone proximal to the NW side of SLE. This rate of high basal melt is 2-4 times greater than the melt rate over the centre of the lake, and elsewhere in the up-ice half of the lake. The spatial correspondence between this pattern of modelled melt and the englacial layer drawdown, the latter being a dataset entirely independent of any input data used in the modelling work, suggests that despite its limitations and assumptions the water circulation modelling is robust and produces a relatively realistic representation of the pattern of melt and, therefore, the pattern of refreezing and the water circulation in SLE. We note that no evidence for accretion ice (e.g. Bell and others 2002) has been observed in any RES data acquired over SLE to date, however.

The geometry of the englacial layering, combined with the basal mass balance output from the water circulation modelling has implications for the pattern and rate of sediment deposition in SLE. The 2D conceptual models produced to date (Bentley and others, 2011; Smith and others, 2018) have neglected the 3D implications of basal melt along the long grid-NW shoreline of the lake, instead assuming a relatively constant rate of rainout from the ice column across the up-ice parts of the lake, focused on the narrower up-valley (i.e. NE) grounding zone. The englacial layers and the modelling instead point to a more complex pattern of sediment rainout from the ice base, with greater flux of sediment likely along the parts of the lake proximal to the longer grid-NW shoreline. Whether all rained-out sediment is deposited directly without further transport via overflows or underflows in the lake is unknown at present, and is potentially complicated by the presence of the Line of Maximum Density within the lake (Woodward and others, 2010; Bentley and others, 2011; Pattyn and others, 2016). However, we can assume that coarser material will be deposited directly by gravity, meaning that greater rates of sediment deposition are possible beneath the zone of significant englacial layer drawdown, and that there is the potential for occasional coarser material to be present nearer to the proposed access location (Woodward and others, 2010) than previously considered. Low acoustic impedance values, indicating a clay- to silt-rich matrix, do dominate the lake floor sediments, however (Smith and others, 2018).

The DEM and derived hydropotential of the SLE outlet zone further emphasises the geomorphic and structural geological controls on the location, extent and geometry of SLE (Ross and others, 2014), and most likely other subglacial lakes in the Ellsworth Subglacial Highlands (Vaughan and others, 2007; Rivera and others, 2015). They also hint at geomorphic evidence for hydrological connections between SLE and other lakes in the Ellsworth Trough hydrological catchment during periods of lake highstand. It is clear from RES evidence that there is abundant subglacial water within this catchment both up and down ice of SLE (e.g. Figure 4). As such, hydraulic connectivity, even if only episodic, is a very distinct possibility, particularly over glacial-interglacial cycles, when ice divide migration may occur, with potential subsequent implications for ice surface slope gradients. Any changes in ice-flow configuration (e.g. from ice divide migration over geological timescales) could also lead to variability in the location, rate and pattern of sediment influx and deposition into SLE by altering the distribution and pattern of basal melting. Such changes are unlikely to have occurred over the Holocene, however (Ross and others, 2011b). The chemistry of water emanating from melted ice directly over the lake will be distinct from that derived from the upstream lake (Figure 4), given the opportunity for solute acquisition when in contact with basal sediment during basal water flow from one lake to the other. This may also vary over time.

One aspect that our current dataset does not allow us to evaluate is the relative importance of basal melt or the input of water into SLE from these subglacial hydrological pathways. However, our study does demonstrate the potential variability in the spatial pattern of basal melt across a subglacial lake. Were future investigations of subglacial lakes in areas of significant subglacial relief (e.g. Lago CECs or SLE) to attempt to determine basal melt rates (e.g. using ApRES), then those investigations cannot assume that basal melt rates will be greatest over the centre of the water body. As such, detailed characterisation of the geometry of englacial layers over target lakes is necessary prior to site selection for measurements of basal melt.

CONCLUSIONS

1. We characterise the geometry of englacial layers over and around Subglacial Lake Ellsworth (SLE) using low frequency RES data.

2. Englacial layers are drawdown in a zone that is located along the grid NW shoreline of SLE.

3. Drawdown is interpreted to be predominantly the result of a zone of enhanced basal melt along the length of the 'grounding line' of the lake's grid-NW shoreline caused by ice flow oblique to the lake. However, we cannot entirely rule out the influence of mechanical effects associated with significant subglacial relief and the transition to a zero-resistance bed at the lake shoreline.

4. The pattern of drawdown inferred from the englacial layers is spatially consistent with basal mass balance output from models of water circulation in SLE, suggesting that these models may provide a reasonably realistic characterisation of water circulation in subglacial lakes.

5. Enhanced basal melt along the NW shoreline of the lake has implications for the rate and pattern of sedimentation in SLE, and for future measurement of basal melt over subglacial lakes in areas of significant subglacial relief.

6. Our data do not permit us to determine the relative importance of basal melt compared to inputs from subglacial water. However, the RES data and derived products (e.g. DEMs and maps of hydropotential), do suggest that hydrologic connectivity of the cascade of lakes within the Ellsworth Trough is possible, at least episodically. Both direct basal melt (i.e. over the lake), and basal hydrological inputs from the wider catchment will influence physical conditions within SLE.

7. No current evidence exists for the presence of englacial reflections associated with accretion ice over SLE.

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DATA AVAILABILITY

Shapefiles and gridded surfaces of the picked englacial layers will be made available via the Newcastle University research data repository (https://data.ncl.ac.uk/).

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