Location for direct access to subglacial Lake Ellsworth:
An assessment of geophysical data and modeling

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[1] Subglacial Lake Ellsworth has been proposed as a candidate for direct measurement and sampling, to identify microbial life and extract sedimentary climate records. We present a detailed characterization of the physiography of this subglacial lake from geophysical surveys, allowing bathymetry and geomorphic setting to be established. Lake Ellsworth is 14.7 km × 3.1 km with an area of 28.9 km^2. Lake depth increases downlake from 52 m to 156 m, with a water body volume of 1.37 km^3. The ice thickness suggests an unusual thermodynamic characteristic, with the critical pressure boundary intersecting the lake. Numerical modeling of water circulation has allowed accretion of basal ice to be estimated. We collate this physiographic and modeling information to confirm that Lake Ellsworth is ideal for direct access and propose an optimal drill site. The likelihood of dissolved gas exchange between the lake and the borehole is also assessed. **Citation:** Woodward, J., A. M. Smith, N. Ross, M. Thoma, H. F. J. Corr, E. C. King, M. A. King, K. Grosfeld, M. Tranter, and M. J. Siegert (2010), Location for direct access to subglacial Lake Ellsworth: An assessment of geophysical data and modeling, *Geophys. Res. Lett.*, *37*, L11501, doi:10.1029/2010GL042884.

1. Introduction

[2] Since the discovery that subglacial Lake Vostok possessed a water column of over 500 m [*Kapitsa et al.*, 1996], microbiologists have regarded subglacial lakes as viable habitats for life, which may involve unique adaptations. Additionally, palaeoclimatologists have suggested subglacial lakes may contain records of ice sheet and climate history within sediments on their floors. To identify life in subglacial lakes and to understand the climate history within their sediment records requires direct measurements and sampling. Recent gravity and seismic measurements over Lake Vostok have improved understanding of 3D bathym-

etry and sediment distribution [*Filina et al.*, 2008], but to date, no subglacial lake has been accessed.

[3] In 2003 the Subglacial Antarctic Lake Environments (SALE) programme of the Scientific Committee on Antarctic Research (SCAR) suggested an appropriate first access site would be one of the relatively small subglacial lakes [*Priscu et al.*, 2003]. As a consequence of this assessment, subglacial Lake Ellsworth in West Antarctica was offered as an excellent candidate for direct measurement and sampling [*Siegert et al.*, 2004; *Vaughan et al.*, 2007]. To evaluate the suitability of this lake and determine the prime location for direct access, information on the lake's bathymetry and the physical processes operating within the lake are necessary.

[4] During the 2007/8 and 2008/9 seasons subglacial Lake Ellsworth was subject to a detailed ground-based geophysics campaign, involving towed radar, seismics, GPS and stake measurements. Here we present results outlining the physiography of the lake and its subglacial surroundings. We then present model simulations of lake water circulation and model prediction of basal mass balance. This information is integrated to provide the most suitable location for lake access and to assess the potential risks associated with the concentration of dissolved gasses within the lake.

2. Geophysical Data Collection

2.1. Radar Surveys

[5] Radio-echo sounding (RES) lines totaling ~740 km were collected in a grid over Lake Ellsworth and the surrounding area (Figure 1) using a ground-based, 1.7 MHz pulsed radar. The ice sheet surface elevation was determined using kinematic GPS with differential correction from the Midlake GPS base station (Figure 1). Ice-bed reflection travel times were converted to ice thickness using a mean radio-velocity in the ice column of 0.168 m ns^{-1}. Estimated RMS errors in ice thickness based on crossover analysis of RES surveys over the lake are ±6.4 m. Surface elevation and ice thickness measurements were then used to construct a Digital Elevation Model (DEM) of the basal topography of the lake catchment (Figure 1).

2.2. Seismic Surveys

[6] Five seismic reflection lines, spaced ~1.4 km apart and aligned perpendicular to the long axis of the lake were completed (Figure 1). With the exception of Profile D, all lines covered the full lake width and part of the surrounding bed. Data were detected using 48 geophones at 10 m spacing. Shot spacing was 240 m, producing single-fold seismic reflection profiles. Data processing included a normal moveout correction and migration.

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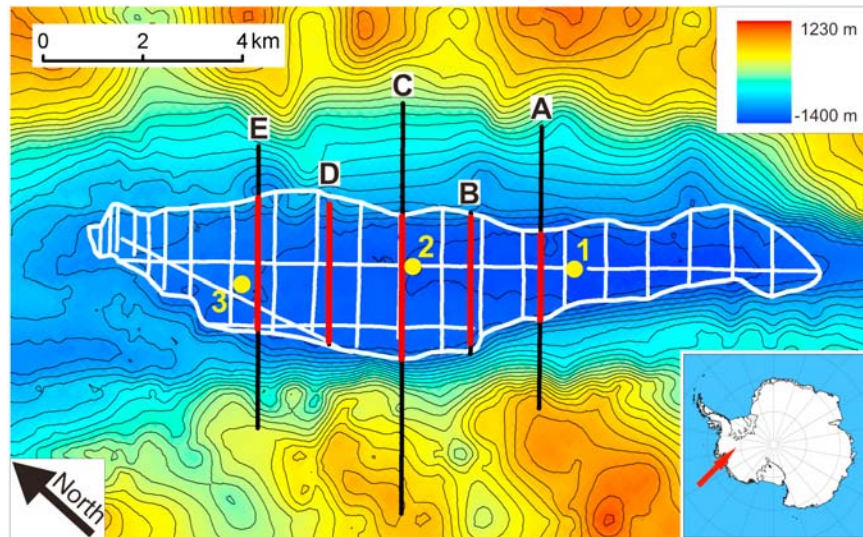
Figure 1. Location map, lake outline and surrounding subglacial topography for subglacial Lake Ellsworth (based on new RES data), with bed surface contour lines at 100 m intervals. Black lines represent the acquired seismic lines (labeled A–E), parts colored red represent sections with lake-like reflectors. White lines are RES lake-like reflectors. Yellow circles mark the locations of GPS base stations over the lake (1 = 'uplake', 2 = midlake; 3 = lowlake). Elevations are relative to WGS-84 ellipsoid.

[7] The ice-base reflection is clear (e.g., Figure 2a) and was picked continuously in all five processed sections. Although the lake-bed reflection could also be picked along most of the lines, short gaps, where the lake-bed reflection could not be picked clearly, were filled by linear interpolation. Similarly, linear interpolation was applied close to the lake edge as the lake-bed reflection could rarely be picked where the water depth is less than ~10 m.

[8] To convert travel-times to layer thickness, mean seismic velocities in the ice column of 2846 m s^{-1} (upper 100 m), and 3815 m s^{-1} (below 100 m) were used, determined from a short-offset seismic refraction experiment and temperature modeling. Water depths were calculated using a seismic velocity of 1437 m s^{-1}. Errors in the ice and water column thicknesses (±10 m and ±1.5 m respectively) arise from uncertainty in the seismic velocities and the travel-time picks. Comparing seismic and RES ice thickness calculations using crossover analysis produces a RMS error of ±6.3 m, showing excellent correspondence between the two data sets.

[9] A DEM of the lake surface was produced from the gridded RES data (Figure 2c). Water column depths calculated from the seismic datasets were then used to produce a DEM of the water column (Figure 2d). To produce this DEM, we interpolated a linear decrease in water depth between the deepest points on the outer seismic lines (A and E) and the corresponding lake end (up-lake or down-lake, respectively). The ice-base and water column DEMs were then combined to give a DEM of bed topography of the lake (Figures 2e).

2.3. Ice Flow Measurements

[10] Four GPS receivers were operated on the ice sheet surface to measure ice flow. Three were positioned over the lake (Figure 1) and the fourth was on the adjacent ice sheet ~11 km to the east. Data were recorded at a minimum sampling rate of 5s over a period of 60 days. The off-lake station was processed using a kinematic Precise Point Positioning approach implemented in the GIPSY software [*King and Aoki*, 2003]. The motions of the three on-lake stations were then determined relative to the base station. Henceforth, we will refer to the SE end as up-lake (or upstream) and the NW end as down-lake (or downstream).

3. Physiography of Subglacial Lake Ellsworth

3.1. Lake Geometry

[11] Lake Ellsworth sits in the bottom of a narrow, steep-sided valley, is 14.7 km long, has a maximum width of 3.1 km, and a total surface area of 28.9 km^2. The RES data have clarified the shape of the lake's shoreline (Figure 1). Ice thickness decreases from 3280 m to 2930 m down the lake's long axis. In the same direction, the lake surface elevation rises from −1361 m to −1030 m (Figure 2c). The lake surface and bed profiles shown in Figure 2b reveal a broad, generally U-shaped, lake bed topography. Water depth (Table 1 and Figure 2d) progressively increases down-lake. Maximum water depth on the up-lake line (Line A) is 52 m, increasing to a maximum of 156 m on the down-lake line (Line E).

[12] From the water column DEM (Figure 2d), we calculated a lake volume of 1.37 ± 0.2 km^3. The likely uncertainty in this value will be influenced primarily by those parts of the lake where there are no seismic data, upstream of Line A and downstream of Line E. To quantify this uncertainty we considered two extreme situations. 1) The lake bed rises steeply within a short distance of the seismic surveys and the water column then remains shallow (<10 m) right up to the lake edge. 2) Water depth remains constant away from the seismic lines, with the bed only rising steeply close to the lake edge. These represent extreme, but not wholly unrealistic, possible configurations of lake bathymetry. The shallower case reduces the calcu-
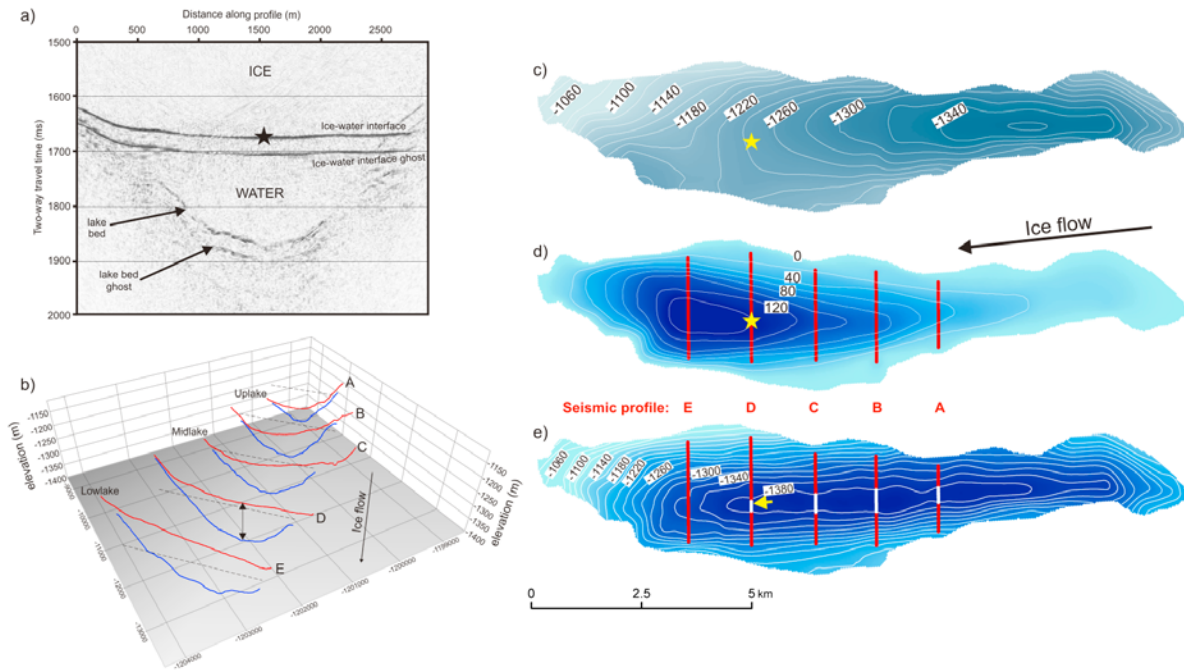
Figure 2. Seismic reflection data from Lake Ellsworth: (a) Example of seismic reflection data (profile D). Main reflections and corresponding ghosts (data acquisition artefacts) are identified. View is uplake with ice flow out of the page. The black star marks the proposed point of lake access. (b) A 3D visualisation of the lake surface (red lines) and lake bed (blue lines) identified from the five seismic profiles. Black dashed lines represent the critical pressure boundary (ice thickness of ~3170 m) for each seismic line. The proposed point of access is marked by the vertical arrowed line on profile D. View is uplake (into ice flow). (c) Ice-water interface (m relative to WGS-84 ellipsoid). (d) Water column thickness (m). (e) Lake bed topography (m relative to WGS-84 ellipsoid). Yellow stars and arrows indicate the proposed access location. Red lines in Figures 2d and 2e indicate the measured positions of the lake bed (and water column thickness) from the seismic data; the parts highlighted white in Figure 2e represent the areas of the lake bed below −1380 m. For Figures 2c–2e contours are at 20 m intervals.

lated lake volume by 0.2 km^3, the deeper one increases it by the same amount, giving a conservative error estimate of ±0.2 km^3.

3.2. Ice Sheet Flow Over the Lake

[13] Ice flow velocities measured with GPS receivers are given in Table 1. The flow speed increases from 4.5 m a^{-1} to 5.5 m a^{-1} from the up-lake GPS station to the down-lake one. Flow direction rotates slightly from 318.9° to 310.8° from up-lake to down-lake.

4. Thermodynamics of Subglacial Lake Ellsworth

[14] The bathymetry of Lake Ellsworth suggests an unusual coincidence of thermodynamic characteristics within the lake's water column. The freezing point of water (T_f) and its temperature of maximum density (T_{md}) depress at different rates with increasing overburden pressure. These relationships intersect at a critical pressure (p_c) of 2.84 × 10^7 Pa (Figure 3a) [*Wüest and Carmack*, 2000]. Where overburden pressure is less than p_c water warmed by geothermal heat flux or latent heat released during freezing is relatively dense and will sink. Conversely, where overburden pressure is greater than p_c warmed water is buoyant and will tend to rise.

[15] Figure 2b shows the location of this critical pressure boundary for each seismic line, converted to depth below the ice surface. For lines A–C, most of the water body sits below the critical pressure boundary. However, for much of the downstream half of the lake, including lines D and E, this boundary lies within the water column. 37% of the lake

Table 1. Measurements of Profile Widths, Maximum Depths, and Mean Depths For the Five Seismic Cross-Profiles[a]

GPS Station	Seismic Line	Width (km)	Maximum Depth (m)	Mean Depth (m)	Ice Flow (m yr^{-1})	Flow Direction (deg)
Offlake	n/a	n/a	n/a	n/a	1.9 ± 0.1	289.2 ± 2.0
Uplake	A	1.730	52	26	4.5 ± 0.2	318.9 ± 2.3
	B	2.560	91	43		
Midlake	C	2.900	109	56	4.9 ± 0.1	313.3 ± 0.9
	D	2.795[b]	143	83		
Lowlake	E	2.665	156	104	5.5 ± 0.1	310.8 ± 0.8

[a]Ice flow for the off-lake and three on-lake base stations is also shown.
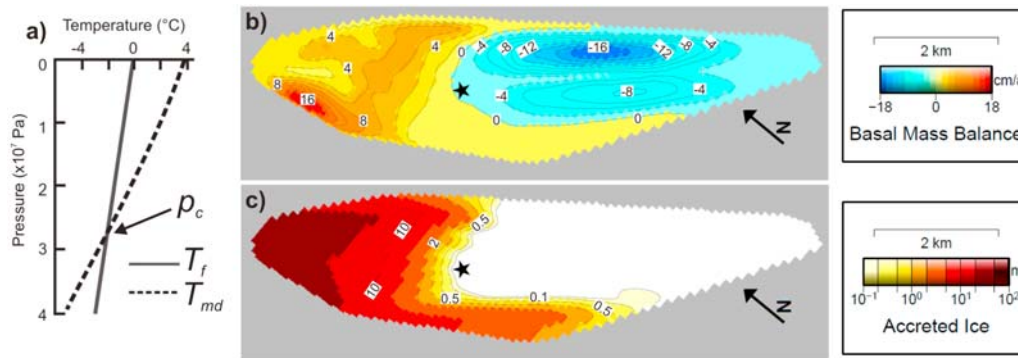[b]Seismic profile does not cover width of lake.

Figure 3. Ice-base and lake water characteristics: (a) Depression of freezing point (T_f) and temperature of maximum density (T_{md}) with overburden pressure. (b) Modeled basal mass balance (assuming a geothermal heat flux of 46 mW m^{-2}, and a heat flux into the ice of 20 mW m^{-2}). (c) Modeled accreted ice thickness (black star marks proposed access location).

volume exists above the critical pressure boundary. This has implications for the circulation model presented below.

5. Ice Water Interaction Within Lake Ellsworth

[16] To investigate the basal mass balance of the ice sheet over Lake Ellsworth we used the 3D numerical fluid-dynamics flow model Rombax [*Thoma et al.*, 2007] to simulate (i) water circulation in the lake; and (ii) the interaction between the water body and the overlying ice. The model has recently been improved by an updated equation of state and a revised equation for the freezing point temperature, according to the Gibbs thermodynamic potential [*Thoma et al.*, 2010]. We assumed that Lake Ellsworth contains fresh water [*Vaughan et al.*, 2007], that the geothermal heat flux is between 46 and 56 mW m^{-2}, and the heat flux into the ice is between 20 and 35 mW m^{-2}. We applied horizontal and vertical eddy-viscosities of 2×10^4 m^2 s^{-1} and 0.01 cm^2 s^{-1} respectively. The model assumes a closed hydrological system (i.e. no water flows into or out of the lake); water enters the lake by melt of the overlying ice and exits by accretion of lake water to the base of the ice sheet. The basal mass balance (Figure 3b) is a direct output of the numerical model. The distribution and thickness of the accreted ice (Figure 3c) however, needs additional information on ice flow at the lake-water interface. The model assumes a constant ice flow velocity of 4.5 m yr^{-1} at the lake surface equal to that measured at the ice surface (i.e. the ice sheet flows across the lake like a floating ice shelf) (Table 1).

[17] The dominant factor driving water circulation is the steep ice-water interface (Figure 2c). Because of this, model results suggest that water circulation occurs within the lake irrespective of the position of the critical pressure boundary. The mean melt rate is 3.8 ± 0.7 cm a^{-1} with maximum values of >16 cm a^{-1} (Figure 3b). Freezing is predicted for much of the down-lake area, with the highest accretion rates (also >16 cm a^{-1}) close to the NW shore. Figure 3c shows the steady-state accreted ice thickness, covering 13.3 ± 0.6 km^2 of the ice-base over the lake (51% of the total surface area). The mean accreted ice thickness is 12.5 ± 3.5 m, reaching a maximum of ~40 m.

[18] To quantify the model sensitivity to uncertainty in the interpolated water cavity we also ran the model using the two extreme bathymetry grids discussed in Section 3.1. Resulting changes to modeled melting and freezing rates were small (<4%), suggesting that the lack of measurements at the far ends of the lake does not lead to a major difference in the model output.

6. Implications for Direct Access to Lake Ellsworth

[19] The new bathymetry data lead to a number of conclusions regarding the in-situ exploration of Lake Ellsworth. Of primary interest among these is the choice of location where access should be made.

[20] Unlike the conditions found beneath some ice shelves, the basal freezing areas in Lake Ellsworth are unlikely to cause problems for lake access and instrumentation. As modeled freezing and water circulation rates are low, freezing will probably result in the formation of congelation ice (downward ice crystal growth from the ice water interface), rather than frazil ice formation (randomly orientated crystals forming a slush like-layer in the water directly beneath the ice water interface). Initial analysis of seismic reflection strengths shows no systematic difference between the up-lake and down-lake areas, which would be expected if the freezing mechanisms involved frazil ice. The seismic evidence is therefore in accordance with the modeling results. However, until the interpreted melt-freeze characteristics can be confirmed, it would be prudent to position the first entry hole outside our modeled basal freezing area, in case the ice-water interface proves less favorable to access than we interpret. This would suggest drilling should avoid the area downstream of seismic line D.

[21] The hydrologic potential over Lake Ellsworth and its catchment basin [*Vaughan et al.*, 2007] suggests that if there is water through-flow, it will be towards the NW. Accumulation of any terrigenous sediments washed in by subglacial drainage is most likely to occur in the up-lake area where water may enter the lake and deposit its sediment load. These sediments could contaminate or disturb any sedimentary record coming from the ice sheet above the lake, especially if associated with high-energy flood events, so a down-lake location somewhere in the deeper part of the lake is preferred for acquiring a sediment core. Due to lower sedimentation rates, core recovery from a location remote from the source of sediment input is also likely to increase the probability of a longer time series of ice sheet history being recovered.

[22] The ideal location to sample the lake bed sediments would be within a wide, flat bed area, well away from the sides or other steep slopes. The deepest part of the lake basin, where a deep sedimentary record is most likely to be found, is defined by the −1380 m contour in Figure 2e. The deepest part of the basin sits upstream of the deepest water column and is crossed by seismic lines A to D.

[23] Based on these factors, we propose that the scientific goals for subglacial exploratory research are best achieved at 78°58′4.44″S 90°34′27.56″W (Figures 2 and 3). This location is outside the modeled zone of accretion ice formation, overlies the deepest part of the basin, has deep water (about 143 m), and is away from the up-stream end of the lake where inflow of sediment with basal meltwater may dominate the sedimentary environment.

7. Potential for Gas Build-Up Within the Lake

[24] If we assume that the lake is hydrologically closed there is a potential, over sufficient time, for dissolved gas and clathrates to build up within the lake [*McKay et al.*, 2003]. There is a danger that, during access, this gas may enter the borehole, either as enhanced dissolved gas or as clathrates, and expand to gas as it rises up the borehole, thus causing blowout at the ice surface. Previous experiments that have penetrated subglacial environments in Antarctica e.g. hot water access to the bed of Whillans Ice Stream [*Engelhardt et al.*, 1990] did not report an issue of gasses within the borehole. Subglacial sediments removed from the bed of Whillans Ice Stream did show evidence of degassing [*Tulaczyk et al.*, 2001] suggesting non-hazardous concentrations of dissolved gas.

[25] Furthermore, if SLE was a closed system, dissolved gas concentrations would take ~100,000 years to reach saturation in the lake water at a concentration of ~3.1cm^3/g at 0°C and 1 atms (assuming that ice melt in equals ice loss out as accretion ice, with an average melt and freezing rate of 4 cm per year over half the lake, and that accretion ice contains no gas). In this time, the West Antarctic Ice Sheet would have been subject to a full glacial-interglacial cycle, with expansion to a maximum glacial configuration followed by retreat to the present interglacial state. The likelihood of the lake remaining unchanged in size, and in hydrological isolation during this transition is low given the bulk of the ice sheet base is at the pressure melting temperature. We therefore believe the potential of borehole 'blowout' is extremely low.

8. Conclusions

[26] Subglacial Lake Ellsworth reaches a maximum depth of 156 m, has a surface area of 28.9 km^2 and a volume of 1.37 km^3. The combined effects of ice thickness and water column depths suggest an unusual thermodynamic regime, with a change in the sign of thermal expansivity of water occurring within the water column. The steeply sloping ice-water interface determines that water circulation will occur within the lake irrespective of the position of this critical pressure boundary. Assuming the lake to be hydrologically isolated we have modeled the maximum rates of subglacial melting and basal freezing at the ice water interface; both exceed about 16 cm a^{-1}; and the accreted ice reaches a steady-state thickness of ~40 m.

[27] We conclude that the optimum location to access Lake Ellsworth lies at 78°58′4.44″S 90°34′27.56″W. This reduces the risk from possible basal freezing mechanisms and optimizes the chances of recovering an undisturbed, continuous sedimentary sequence from the lake floor. This lake access location should allow sampling of the water column to search for microbial life and sampling of the sub-lake sediments to investigate West Antarctic Ice Sheet history.

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