Ellsworth Subglacial Lake, West Antarctica: A Review of Its History and Recent Field Campaigns

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Ellsworth Subglacial Lake, first observed in airborne radio echo sounding data acquired in 1978, is located within a long, deep subglacial trough within the Ellsworth Subglacial Highlands of West Antarctica. Geophysical surveys have characterized the lake, its subglacial catchment, and the thickness, structure, and flow of the overlying ice sheet. Covering 28.9 km^2, Ellsworth Subglacial Lake is located below 2.9 to 3.3 km of ice at depths of -1361 to -1030 m. Seismic reflection data have shown the lake to be up to 156 m deep and underlain by unconsolidated sediments. Ice sheet flow over the lake is characterized by low velocities (<6 m yr^{-1}), flow convergence, and longitudinal extension. The lake appears to be in steady state, although the hydrological balance may vary over glacial-interglacial cycles. Direct access, measurement, and sampling of Ellsworth Subglacial Lake are planned for the 2012/2013 Antarctic field season. The aims of this access experiment are to determine (1) the presence, character, and maintenance of microbial life in Antarctic subglacial lakes and (2) the Quaternary history of the West Antarctic ice sheet. Geophysical data have been used to define a preferred lake access site. The factors that make this location suitable for exploration are (1) a relatively thin overlying ice column (~3.1 km), (2) a significant measured water depth (~143 m), (3) >2 m of sediment below the lake floor,

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(4) water circulation modeling suggesting a melting ice-water interface, and (5) coring that can target the deepest point of the lake floor away from marginal, localized sediment sources.

1. INTRODUCTION

Deep continental Antarctic subglacial lakes are one of the few remaining unexplored environments on Earth. Found beneath both the East and West Antarctic ice sheets, it has been hypothesized that these lakes are extreme, yet viable habitats, which may host unique microbial assemblages that have been potentially isolated for millions of years [*Siegert et al.*, 2001]. Furthermore, the sediments that have accumulated at the bottom of subglacial lakes may contain important records of Antarctic ice sheet history.

Ellsworth Subglacial Lake (hereafter referred to as "Lake Ellsworth") is a small subglacial lake (14.7 km long by 3.05 km wide) in West Antarctica. The lake, which lies beneath 2.9 to 3.3 km of ice, is located within the catchment of Pine Island Glacier in a deep subglacial trench ~30 km northwest of the central ice divide of the West Antarctic Ice Sheet (WAIS), and some ~70 km west of the Ellsworth Mountains (Figure 1). Lake Ellsworth has been identified as a prime candidate for direct measurement and sampling [*Siegert et al.*, 2004; *Vaughan et al.*, 2007; *Lake Ellsworth Consortium*, 2007]. Recent geophysical surveys have demonstrated that the lake is up to 156 ± 1.5 m deep [*Woodward et al.*, 2010] and that the lake floor is draped with over 2 m of unconsolidated sediments [*Smith et al.*, 2008]. A new program, the "Lake Ellsworth Consortium," plans to sample Lake Ellsworth in the 2012/2013 Antarctic field season. This U.K.-led program involves scientists from 11 U.K. universities and research institutions, along with collaborators from Chile and the United States. The Lake Ellsworth experiment aims to determine (1) the presence, origin, evolution, and maintenance of life in an Antarctic subglacial lake through direct measurement, sampling, and analysis of this extreme environment and (2) the palaeoenvironment and glacial history of the WAIS including, potentially, the date of its last decay, by recovering a sedimentary record from the lake floor. The case for the exploration of Lake Ellsworth has been outlined previously [*Siegert et al.*, 2004; *Lake Ellsworth Consortium*, 2007]. This article reviews the history of Lake Ellsworth research and summarizes recent geophysical reconnaissance studies that underpin the lake access experiment.

2. LAKE ELLSWORTH: DISCOVERY AND REDISCOVERY

Lake Ellsworth was first observed in a single 60 MHz airborne radio echo sounding (RES) survey line acquired during the U.K. Scott Polar Research Institute, U.S. National Science Foundation, and the Technical University of Denmark (SPRI-NSF-TUD) 1977/1978 airborne campaign [*Jankowski and Drewry*, 1981; *Siegert et al.*, 2004]. Although the exact positions of the survey platform were uncertain owing to the navigational techniques available at the time, it is clear, on the basis of comparison with recent data sets, that these RES data were acquired directly over the center of Lake Ellsworth, in an orientation lying along the lake's long axis, subparallel to the direction of ice flow. However, it was not the first time an important scientific campaign had traveled over the lake; the route of the 1957/1958 Sentinel Range (Marie Byrd Land) traverse [*Bentley and Ostenso*, 1961] also crossed the lake in an orientation roughly perpendicular to the long axis and the later RES transect. Owing to the spacing of the seismic and gravity measurements and the small target body, however, no observations of the lake were made during the traverse. The position of Lake Ellsworth was first mapped by *McIntyre* [1983]. Despite this, the lake remained unrecognized in the broader literature and was not included in the first official inventory of subglacial lakes [*Siegert et al.*, 1996]. In 2003, the lake was "rediscovered" in McIntyre's thesis, and the original RES data were reexamined, revealing a typical lake-like reflector ~10 km long, in hydrostatic equilibrium with the overlying ice sheet. Lake Ellsworth was then identified as a suitable target for exploration [*Siegert et al.*, 2004] and was named and included in the updated subglacial lake inventory [*Siegert et al.*, 2005].

3. RECENT GEOPHYSICAL SURVEYS

As part of an extensive airborne geophysical survey of the Pine Island Glacier catchment in 2004/2005, the British Antarctic Survey (BAS) acquired ice thickness and surface elevation data over Lake Ellsworth. This was followed in January 2006 by a ground-based traverse from Patriot Hills to Lake Ellsworth, via the Institute Ice Stream, undertaken by researchers from the Centro de Estudios Científicos (CECS). Radio echo sounding and GPS measurements were made along the traverse route and over and around the lake. Both the CECS and BAS surveys acquired ice thickness data using radars with a frequency of 150 MHz. The combined results of these surveys were reported by *Vaughan et al.* [2007].

These surveys indicated that Lake Ellsworth was located at the bottom of a long, deep subglacial trough, but that the lake was much narrower than previously estimated, with a maximum width of only ~2.7 km. This led to a reduction in

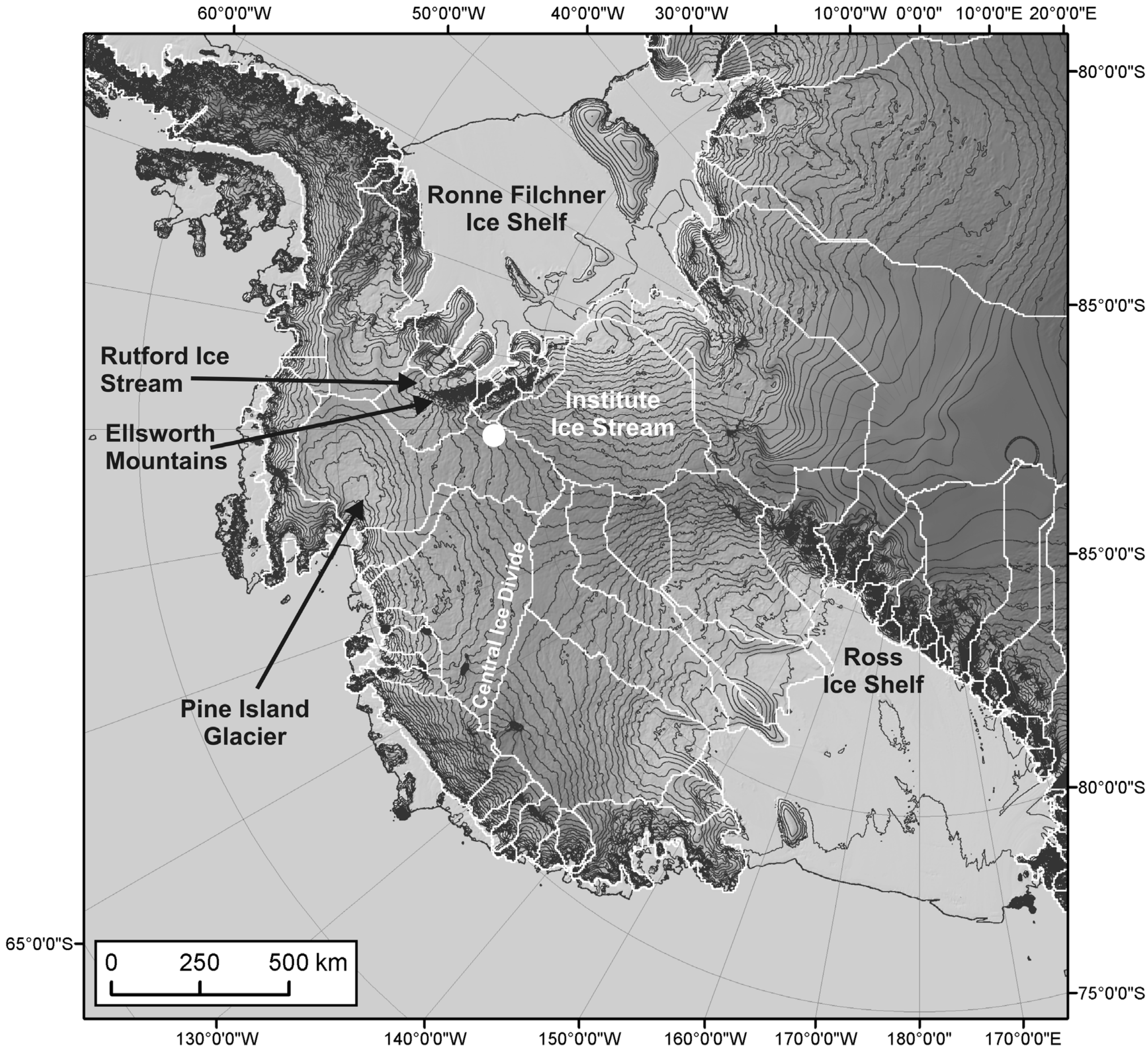


Figure 1. Location of Lake Ellsworth (white dot) in West Antarctica. Base map is the Bamber et al. (Antarctic 1 km Digital Elevation Model [DEM] from Combined ERS-1 Radar and ICESat Laser Satellite Altimetry, data set, National Snow and Ice Data Center, Boulder, Colorado, 2009, available at http://nsidc.org/data/nsidc-0422.html) satellite altimetry–derived DEM with contours at 100 m intervals. White lines mark major ice divides.

the estimated total area of the lake to ~18 km^2. This was rather less than the 100 km^2 suggested by *Siegert et al.* [2004] because the lake is constrained topographically, making it elongated rather than circular. Using the RMS variability of the hydrological head, derived from the uncertainty in ice thickness measurements, and assuming an ice density of 920 kg m^{-3}, *Vaughan et al.* [2007] isolated the possible density of fluid in the lake. They concluded that the fluid body of Lake Ellsworth has a density between 950 and 1013 kg m^{-3}, indicative of fresh water, with little likelihood of the lake containing substantial concentrations of materials that would result in a fluid body of greater density (e.g., acids, salts or heavy clathrates).

Data from the BAS airborne survey of Pine Island Glacier catchment revealed that Lake Ellsworth is one of a series of subglacial lakes located in deep, SE-NW trending, subglacial valleys within the Ellsworth Subglacial Highlands [*Vaughan et al.*, 2007]. These valleys are probably erosional features developed during periods of less extensive glaciation at some stage prior to the formation of the current ice sheet [*Vaughan et al.*, 2007]. Analysis of the regional hydrological regime indicated that these subglacial troughs act as conduits for subglacial water flow from the ice divide (between Pine Island Glacier and the Institute Ice Stream) to the Byrd Subglacial Basin. *Vaughan et al.* [2007] suggested that Lake Ellsworth was part of a well-connected drainage system, with well-defined upstream and downstream hydrological pathways through its deep subglacial catchment, making it effectively an "open system" in terms of its hydrology. From the RES data, they inferred there to be no hydrological barrier that could block water flow out of the bottom end of the lake and that the outflow probably drains into a second lake only 15 km downstream. Based on this, *Vaughan et al.* [2007] suggested that the likelihood of Lake Ellsworth hosting long-isolated microbiological life was reduced, but still recommended that Lake Ellsworth remained a "strong candidate for *in situ* exploration."

4. GEOPHYSICAL RESULTS

A full geophysical characterization of Lake Ellsworth was undertaken during the Austral summers of 2007/2008 and 2008/2009. The aims of this fieldwork were to (1) determine lake water depth and bathymetry, (2) map the outline of the lake and the topography of its catchment, (3) produce a detailed map of ice flow over the lake, (4) characterize the nature of the ice-water and water-bed interfaces, (5) establish sediment thickness beneath the lake floor, (6) map the geometry of englacial layering within the overlying ice sheet, and (7) measure any detectable tidal signatures.

4.1. Radio Echo Sounding Surveys

A detailed grid of RES survey lines was acquired over Lake Ellsworth and its surrounding area using the ground-based ~1.7 MHz pulsed DEep-Look-Radar-Echo-Sounder (DELORES) radar system (Figures 2 and 3a). Just over 1000 km of RES data (including BAS and CECS data) have now been acquired over, and in the vicinity of, Lake Ellsworth. The bed was identified in more than 95% of the survey line data, and an ice thickness map and digital elevation model (DEM) of the bed were constructed (Figures 3c and 3d). Roving GPS data acquired along the RES profile lines during the surveys were used to generate a DEM of the ice surface (Figure 3b).

4.1.1. Ice sheet surface. The center of Lake Ellsworth is located approximately 30 km from the ice divide between Pine Island Glacier and the Institute Ice Stream; a major divide of the WAIS (Figures 1 and 3b). The ice sheet surface around Lake Ellsworth is strongly influenced by the presence of the lake and the geomorphology of the lake's subglacial catchment. Owing to low basal shear stresses, the gradient of the ice sheet surface over the lake is low (<0.003) when compared to the surrounding ice surface (~0.006). Upstream of the lake, the ice sheet surface has a semiamphitheater-like morphology, the result of an abrupt transition in basal conditions as the ice sheet flows into the deep subglacial trough from the surrounding subglacial highlands. Subglacial morphology is also likely to play an important role in maintaining the ice surface saddle that characterizes the ice divide southeast of Lake Ellsworth (Figure 3b).

4.1.2. Bed topography and lake surface. The map of basal topography (Figure 3d) integrates the DELORES RES data with the BAS and CECS RES data and the five seismic reflection profiles. This map confirms that Lake Ellsworth is located within a deep, broad subglacial overdeepening in the Ellsworth Subglacial Highlands [*Siegert et al.*, 2004; *Vaughan et al.*, 2007], which runs for at least 45 km north-westward from the ice divide. This trough is constrained on either side by high, rugged subglacial topography, and the maximum peak-to-trough amplitude is of the order of 2300 m. In the upper reaches of the catchment, the trough is relatively narrow (2.5–3.5 km across), with the valley floor generally at elevations between −800 and −950 m. Although impounded by high topography on both sides (at elevations generally >400 m), to the southeast of the lake there is a particularly pronounced area of subglacial mountains with peak elevations between 1200 and 1400 m. In the vicinity of Lake Ellsworth, the trough widens and deepens, becoming 5.5 to 6.5 km across, with the valley floor attaining a minimum elevation of approximately −1360 m.

The new RES data show that the extent of Lake Ellsworth (Figure 4) is greater than that mapped by *Vaughan et al.* [2007], particularly in its northeast sector. The total area is now estimated to be ~28.9 km^2. The lake surface, between the minimum and maximum elevations of −1361 and −1030 m, has a pronounced along-flow lake surface gradient (~0.03), markedly steeper than other reported subglacial lake gradients (e.g., Vostok Subglacial Lake). Steep gradients are more likely to result in differential melting and freezing along the lake axis and therefore enhanced water circulation [*Siegert et al.*, 2001, 2004; *Woodward et al.*, 2010]. The lake surface is also twisted across its long axis; in the upstream half of the lake, the surface slopes toward the northeast, whereas in the downstream half, the slope is toward the southwest (Figure 5b). This lake surface morphology is probably caused by flexural support of the overlying ice by the steep bedrock walls that flank the lake.

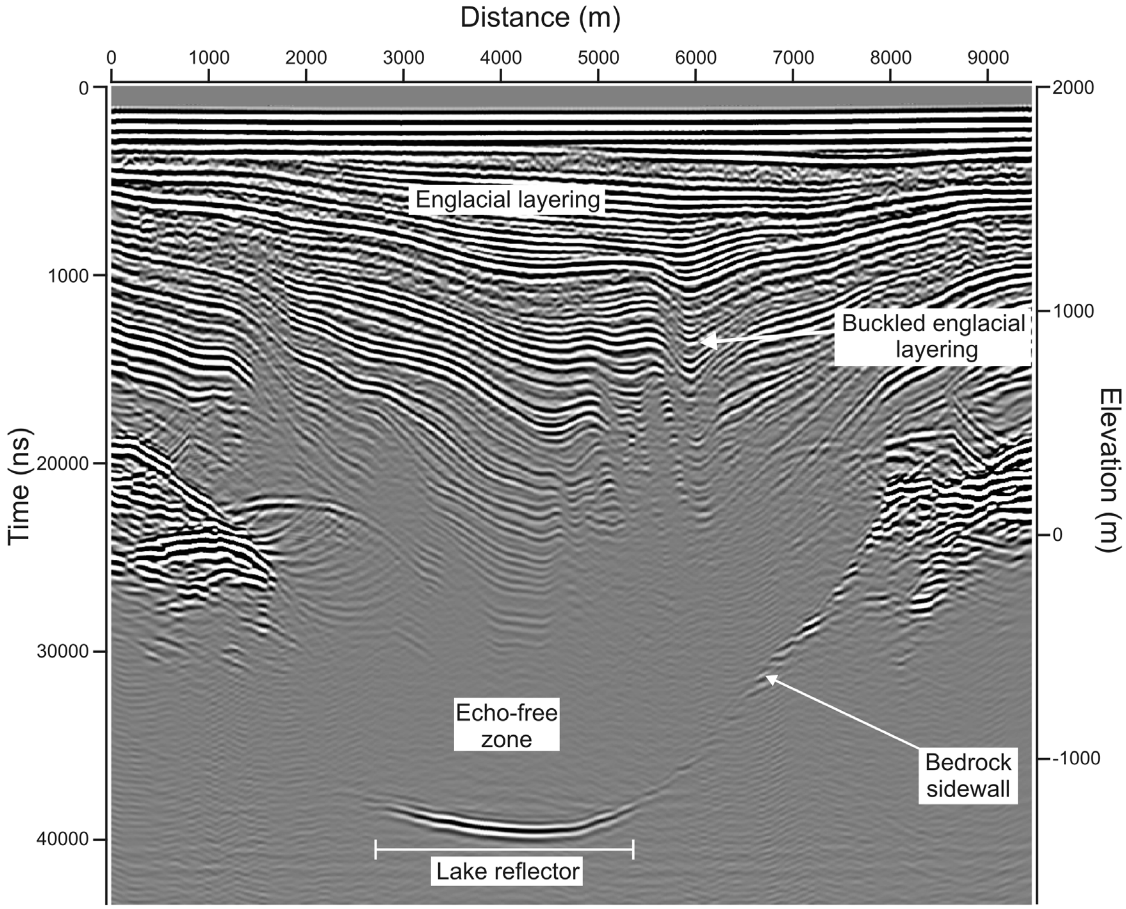
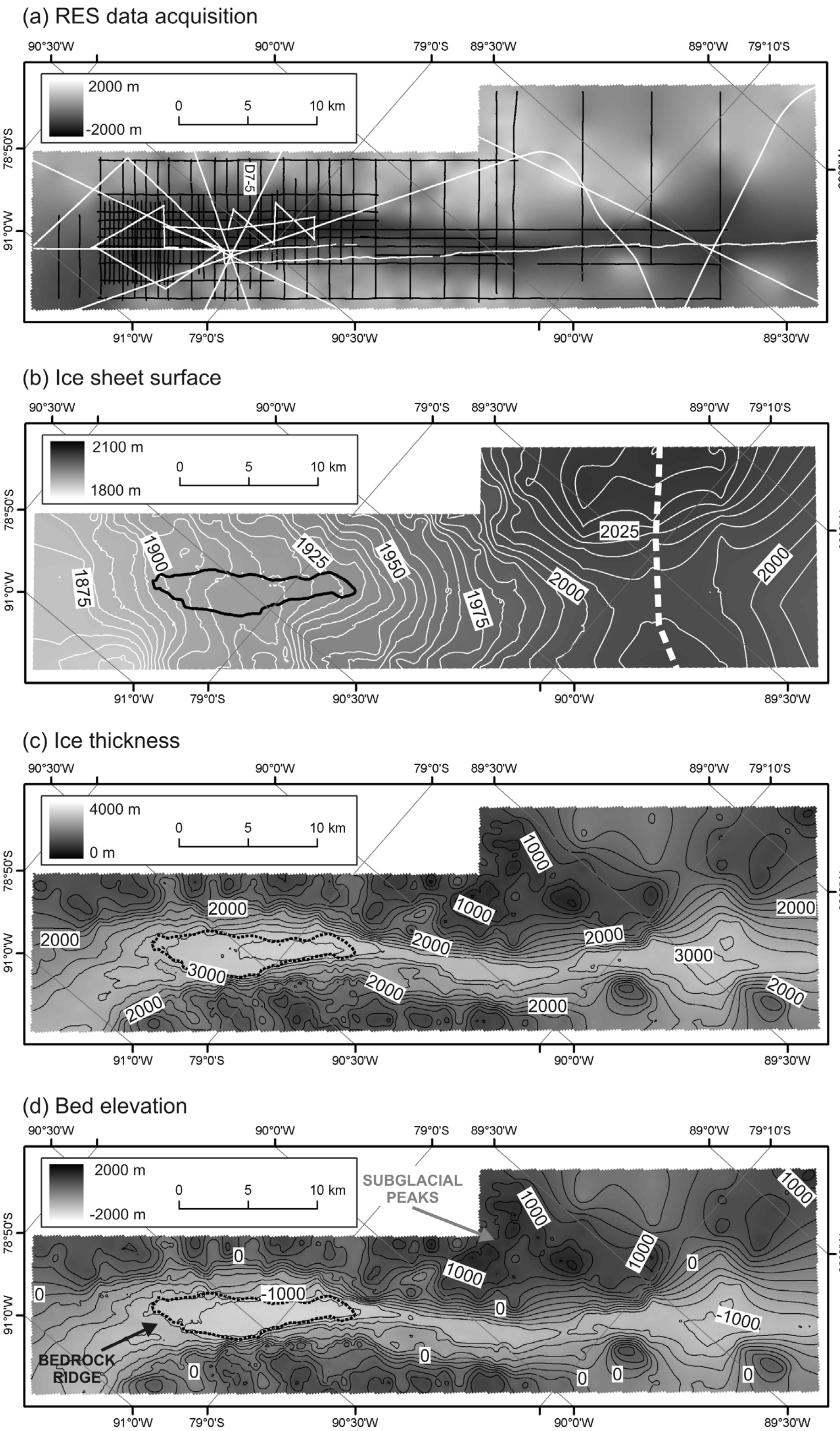


Figure 2. DEep-Look-Radar-Echo-Sounder (DELORES) radio echo sounding (RES) data across Lake Ellsworth (Line D7.5). A prominent lake-like reflector is observed between 2600 and 5400 m along the profile between depths of approximately −1200 to −1310 m. Buckled englacial layers, generated by ice flow over and around subglacial mountains upstream of the lake (see Figure 3), are annotated. Ice flow is roughly into the page. Elevations are relative to WGS-84 ellipsoid. See Figure 3 for location.

Downstream of Lake Ellsworth, the bed topography is marked by a pronounced bedrock ridge, which trends obliquely across the lake outlet zone and across the valley (Figure 3d). This ridge, which rises ~150 to 200 m above the elevation of the lake surface, appears to determine the downstream boundary of Lake Ellsworth and is likely to play a key role in controlling the nature and timing of drainage from the lake. The subglacial hydrological implications of this landform are currently being explored [*Ross et al.*, 2009], but it is a distinct possibility that a hydrological sill exists. This would be contrary to the conclusions of *Vaughan et al.* [2007], who suggested that the lake was part of an open hydrological system.

4.1.3. Englacial layering and modeling. The DELORES RES data are characterized by strong, well-defined englacial reflections in all profiles (e.g., see Figure 2). Throughout the majority of the Lake Ellsworth catchment, however, imaged englacial layers are predominantly restricted to the upper 2000 m of the ice column. Below this depth, most of the radargrams are markedly free of internal reflections. This echo-free zone [*Drewry and Meldrum*, 1978] was also a characteristic of the SPRI-NSF-TUD, BAS, and CECS RES data sets in this part of West Antarctica [*Siegert et al.*, 2004; *Vaughan et al.*, 2007]. It is not clear whether the echo-free zone around Lake Ellsworth is a property of the ice or simply a consequence of the absorption of electromagnetic energy in the warmer parts of the ice at depth.

Englacial layers within the RES profiles (Figure 2) have been picked and transformed into three-dimensional (3-D) surfaces. These data have been integrated with the DEM of



(a) RES data acquisition
2000 m
-2000 m
0 5 10 km
D7-5
(b) Ice sheet surface
2100 m
1800 m
0 5 10 km
1875
1900
1925
1950
1975
2000
2025
2000
(c) Ice thickness
4000 m
0 m
0 5 10 km
1000
1000
2000
2000
2000
3000
2000
2000
3000
2000
2000
2000
2000
(d) Bed elevation
2000 m
-2000 m
0 5 10 km
SUBGLACIAL PEAKS
1000
1000
1000
1000
0
0
-1000
0
0
-1000
BEDROCK RIDGE
0
0
0
0
0
90°30'W
90°0'W
79°0'S
89°30'W
89°0'W
79°10'S
78°50'S
91°0'W
89°0'W
91°0'W
79°0'S
90°30'W
90°0'W
89°30'W

the subglacial bed to facilitate 3-D numerical modeling of ice flow and basal melting over Lake Ellsworth [*Ross et al.*, 2009]. Initial results show that, over the lake, some anomalies in the layering near the steeper bedrock wall can be understood in terms of perturbations to the velocity field caused by ice sheet flow into the deep subglacial trough from the surrounding subglacial highlands, as well as being caused by melt anomalies.

4.2. Seismic Reflection Surveys and Water Circulation Modeling

At least 387 Antarctic subglacial lakes have now been identified using data from ground-based, airborne, and satellite platforms [*Wright and Siegert*, this volume], but water depth measurements from such lakes are few in number. Gravity data have been used to estimate the depth, and in some cases the bathymetry, of a series of lakes [*Studinger et al.*, 2004; *Bell et al.*, 2006; *Filina et al.*, 2008]. However, prior to the Lake Ellsworth field campaign in 2007/2008, seismic measurements had only been made at Vostok Subglacial Lake and South Pole Lake [*Masolov et al.*, 2006; *Peters et al.*, 2008].

Five seismic reflection lines spaced ~1.4 km apart were acquired across the long axis of Lake Ellsworth (Figures 4, 5) [*Woodward et al.*, 2010]. The ice base and lake bed reflections were identified and picked in all five of the processed seismic profiles. By applying seismic velocities to the reflection picks and combining the product with surface GPS data, reflector elevations were established. These data were gridded, along with picked RES data where appropriate, to produce 3-D surfaces of the ice-water interface, lake bed, and the water column thickness (Figures 5c–5e) [*Woodward et al.*, 2010].

The seismic data reveal that Lake Ellsworth has a broad, generally U-shaped, lake bed morphology (Figure 5e). The water column progressively increases down-lake (SE to NW) from a maximum thickness of 52 ± 1.5 m on line A to 156 ± 1.5 m on line E (Figure 5d) [*Woodward et al.*, 2010]. Based on the gridded data sets, the estimated volume of Lake Ellsworth is 1.37 km^3, although this figure is subject to an error margin of ±0.2 km^3 because of uncertainties in the gridding of the lake's bathymetry in the upstream and downstream parts of the lake beyond the end two seismic lines [*Woodward et al.*, 2010].

The 3-D numerical model Rombax [*Thoma et al.*, 2007], using the seismic and RES-derived gridded data sets as input data, has been used to describe water circulation in Lake Ellsworth and to evaluate the potential mass balance characteristics of the overlying basal ice [*Woodward et al.*, 2010]. This model assumes a closed hydrological system (i.e., no water flows into or out of the lake); any melt input into the lake is balanced by accretion ice formation elsewhere. The modeling suggests that the ice-water interface in the upstream half of the lake is characterized by basal melting (mean melt rate of 3.8 ± 0.7 cm yr^{-1}). However, in the downstream half of the lake, the model predicts basal freezing and the development of a thin layer of accretion ice (mean thickness of 12.5 ± 3.5 m) [*Woodward et al.*, 2010]. At this stage, no evidence for accretion ice has been observed in the RES data from Lake Ellsworth.

Because Lake Ellsworth is overlain by a range of ice thicknesses (3280–2930 m) (Figure 3c), it is characterized by an unusual thermodynamic regime [*Woodward et al.*, 2010]. The critical pressure (p_c) [*Wüest and Carmack*, 2000] occurs at the intersection between the freezing point of water (T_f) and the temperature of maximum density (T_{md}) [*Woodward et al.*, 2010]. When the overburden pressure (ice and water) is greater than p_c, warmed water will rise through buoyancy, but when the overburden pressure is less than p_c, warmed water will tend to sink. Because the critical pressure boundary intersects Lake Ellsworth [*Woodward et al.*, 2010] (Figure 5b), the water column straddles two thermodynamic states with the potential for the development of zones with distinct water circulation patterns (convective or stratified). Modeling, however, suggests that this does not occur. Driven by the steeply sloping ice-water interface, water circulation occurs throughout the lake irrespective of the presence of the critical pressure boundary [*Woodward et al.*, 2010].

Preliminary analysis, using the seismic reflection data to establish the acoustic impedance of the water-sediment interface, suggests that the lake bed is composed of high-porosity, low-density sediments [*Smith et al.*, 2008]. These sediments have acoustic properties very similar to material found on the deep ocean floor, indicative of deposition in a low-energy environment. Analysis suggests that this sedimentary sequence is a minimum of 2 m thick.

Figure 3. (opposite) (a) RES data acquired around Lake Ellsworth. Black lines represent DELORES data; white lines represent British Antarctic Survey and Centro de Estudios Cientificos 150 MHz data [*Vaughan et al.*, 2007] also used in the gridding of ice thickness and subglacial topography. RES line D7-5 (Figure 2) is indicated. Background layer is bed elevation (Figure 3d). (b) Ice sheet surface, with contours at 5 m intervals. White dashed line shows approximate position of ice divide between Pine Island Glacier (to left) and the Institute Ice Stream (to right). Black polygon is the outline of Lake Ellsworth. (c) Ice thickness, with contours at intervals of 200 m. (d) Subglacial topography, with contours at intervals of 200 m. Elevations in (a), (b), and (d) are all relative to WGS-84 ellipsoid. Ice flow across the lake is roughly right to left throughout Figure 3.

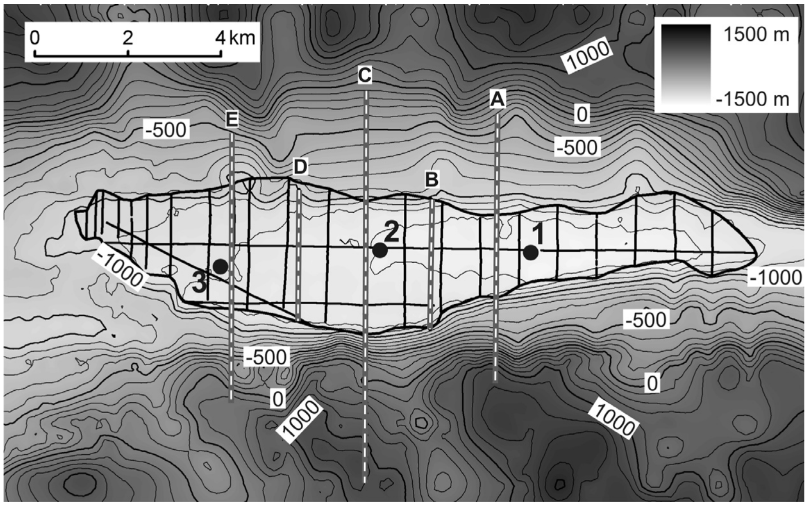


Figure 4. Outline of Lake Ellsworth mapped from "lake-like" reflectors identified in RES (thin black lines) and seismic data. Backdrop grid is subglacial topography with contour lines at 100 m intervals. White dashed lines represent acquired seismic lines (labeled A–E). Black numbered circles mark the locations of GPS base stations over the lake (1, uplake; 2, midlake; 3, lowlake). Elevations are relative to WGS-84 ellipsoid. Ice flow is roughly right to left.

4.3. GPS Measurements

During the 2007/2008 field season, four continuously recording Global Positioning System (GPS) base stations were deployed above, and in the vicinity of, Lake Ellsworth [*Woodward et al.*, 2010], with the primary role of monitoring any tidal signal in the lake, determining the ice sheet flow regime (velocity and direction), and for use as base stations when processing kinematic GPS data (Figure 6a). Two of the base stations ("offlake" and "midlake") were reoccupied during the 2008/2009 field season. Owing to proximity to the ice divide, ice flow velocities around Lake Ellsworth are low (<10 m yr^{-1}). During the 2007/2008 season, measured ice flow at the offlake base station, situated over relatively thin (~1 km) ice beyond the limits of the lake, was 1.9 ± 0.1 m yr^{-1}. Measurements over the lake, where the ice was thicker and subject to zero basal shear stresses, showed higher velocities, between 4.5 ± 0.2 m yr^{-1} ("uplake" station) and 5.5 ± 0.1 m yr^{-1} ("lowlake" station) [*Woodward et al.*, 2010].

In addition to these base station data, ice flow data were also acquired from measurements of the positions of a series of temporary stakes installed on the snow surface. This "stake network" consisted of 58 aluminum poles installed over the lake during the 2007/2008 field season and 8 wooden stakes installed downstream of Lake Ellsworth in January 2006. GPS measurements of all stakes were made during both field seasons. From the measured changes in the positions of the markers in the stake network between the 2007/2008 and 2008/2009 field seasons, the direction and rate of ice flow at the ice surface were calculated. This has been used to produce a map of the rate and direction of ice flow over the lake (Figure 6a). The GPS data show that ice flow in the vicinity of Lake Ellsworth is characterized by the following:

1. There is convergent ice flow over the lake as the ice flows into the depression in the underlying topography. Convergence is greatest at the top end of Lake Ellsworth, with a noticeable decrease apparent down-lake. Data from GPS stake lines D6 and D5 (Figure 6a) show a shift from convergent flow (D10-D6) to a normal flow regime (D5) near the downstream end of the lake.

2. Ice flow velocity increases down the length of the lake (extensional flow). The measured rate of ice flow over Lake Ellsworth increases linearly from 4.09 m yr^{-1} near the head of the lake to 5.98 m yr^{-1} at its downstream end (Figure 6a). The maximum flow velocity measured was 6.60 m yr^{-1}, some 4.5 km downstream of the lake.

3. Ice flow is faster over the central axis of the lake (relative to other measurements in this survey). Rates of flow decrease toward both lateral lake margins (GPS stake lines D9 to D6) (Figure 6a).

4. There is westward rotation of ice flow in the lower parts of, and downstream of, the lake. Comparison between the GPS measurements in the area downstream of Lake Ellsworth with the GPS data over the lake clearly shows a pronounced local westward rotation of flow (Figure 6a).

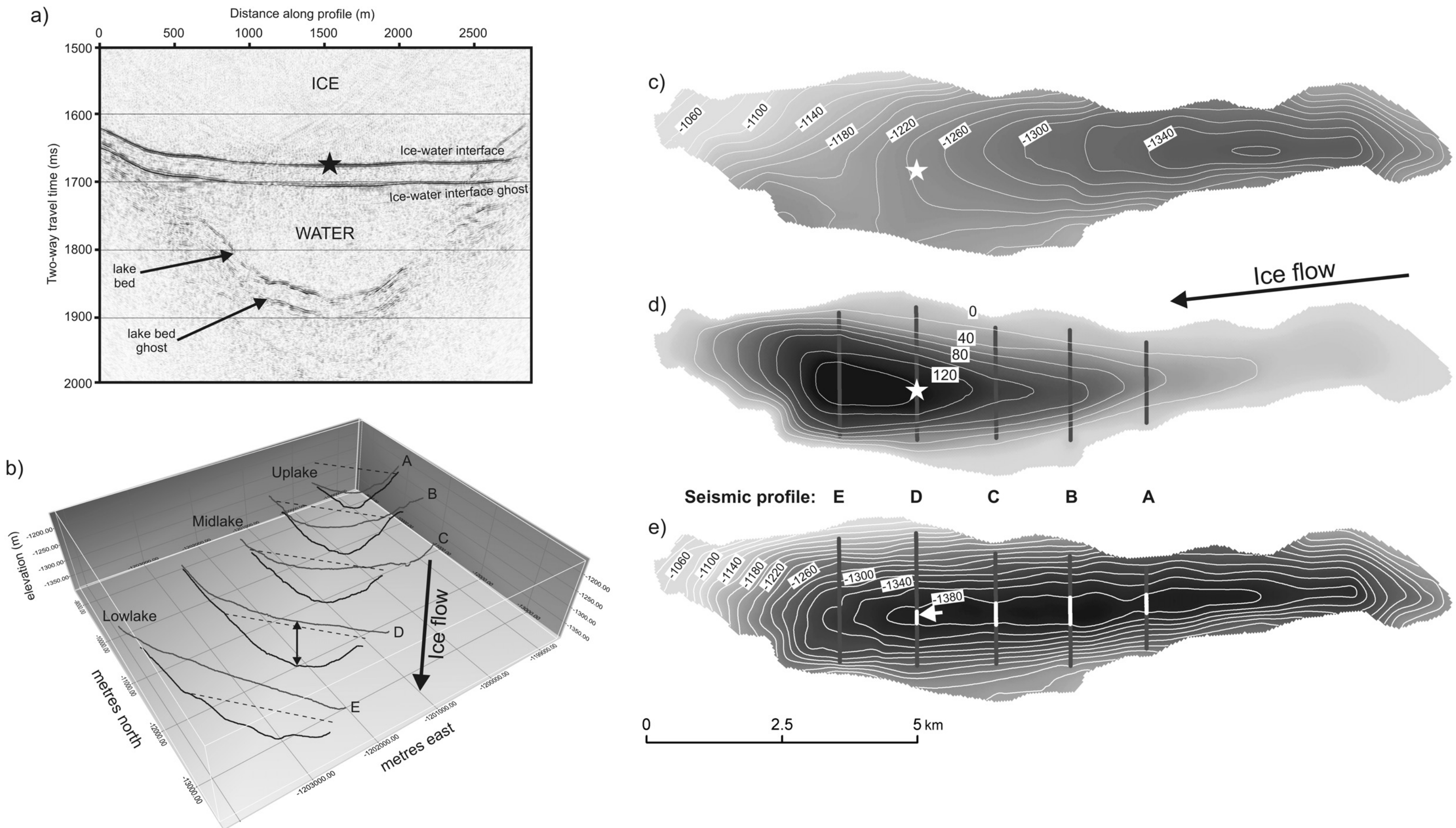


Figure 5. Seismic reflection data from Lake Ellsworth [from *Woodward et al.*, 2010]. (a) Example of seismic reflection data (profile D). Main reflections and corresponding ghosts (data acquisition artifacts) are identified. View is uplake with ice flow out of the page. The black star marks the proposed point of lake access. (b) A three-dimensional visualization of the lake surface (light gray lines) and lake bed (dark gray lines) identified from the five seismic reflection profiles. 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). Coordinates are meters polar-stereographic with a true scale at –71S. (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). White stars and arrows indicate the proposed access location. Gray lines across the lake in (d) and (e) indicate the measured positions of the lake bed (and water column thickness) from the seismic data; the parts highlighted white in (e) represent the areas of the bed below −1380 m. For (c) to (e), contours are at 20 m intervals.

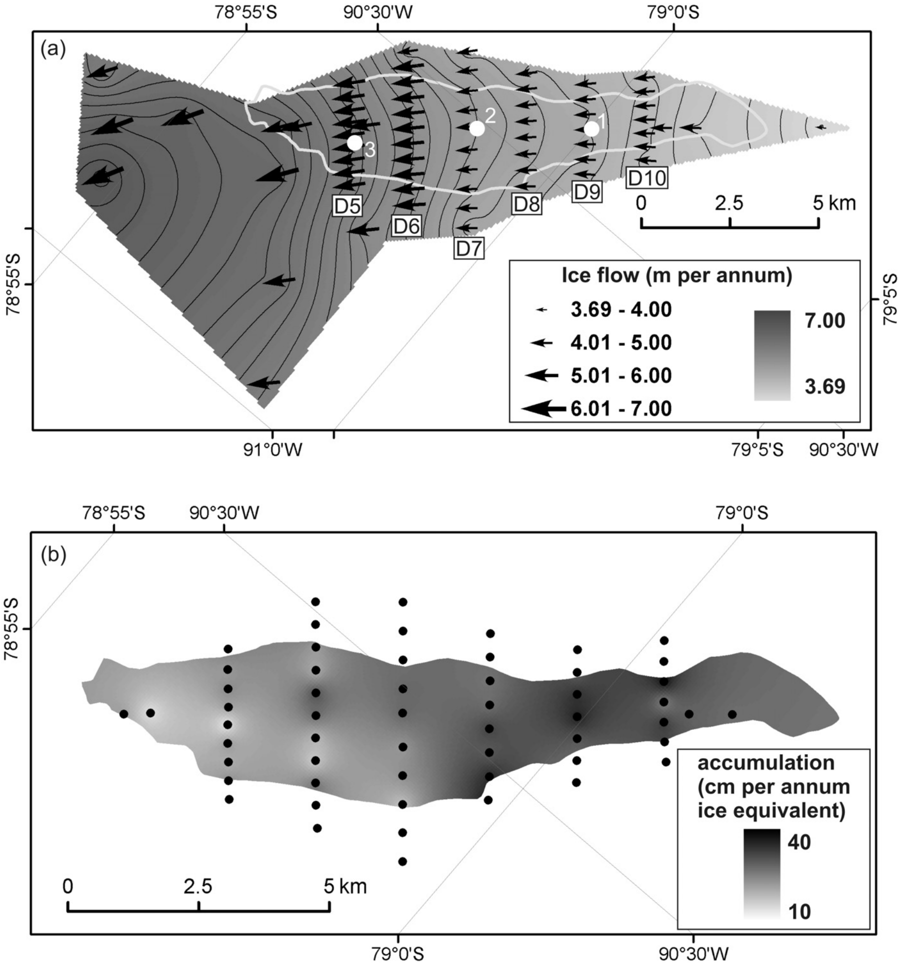


Figure 6. (a) Direction and rate of present-day ice flow from GPS measurements of a network of surface markers. Size of arrows denotes rate of flow (larger arrows equal faster flow). Base image is the gridded ice flow velocity with contours at 10 cm yr^{-1} intervals. White circles mark the locations of GPS base stations over the lake (1, uplake; 2, midlake; 3, lowlake). A fourth base station (off lake) was positioned 11 km northeast of the lake. (b) Surface accumulation (cm yr^{-1} ice equivalent) over Lake Ellsworth between 2008 and 2009. Black dots mark observation points.

4.4. Ice Cores and Lake Geochemistry

Three shallow (<20 m) ice cores were recovered from the ice sheet surface above Lake Ellsworth in the 2007/2008 field season. One core was analyzed in the field for measurements of snow and firn density, whereas the other two were returned to U.K. for laboratory analysis (one for oxygen isotope-derived accumulation rates and the other for biogeochemistry). A temperature of −31.9°C ±0.2°C was measured at a depth of 20 m at the base of one of these core holes [*Barrett et al.*, 2009].

Provisional geochemical data for the average composition of firn and ice in the top 20 m of one of the recently acquired surface ice cores from above Lake Ellsworth (n = 11) are given in Table 1. The *Lake Ellsworth Consortium* [2007] assumed that the chemistry of meteoric ice melt into Lake Ellsworth is equivalent to that of the average chemistry recorded in the Byrd Ice Core and used the ice core chemistry to calculate the expected chemistry of the lake waters (Table 1). The near-surface ice core values from Lake Ellsworth are higher in most species than the average chemistry of the Byrd core, which may be a consequence of aeolian inputs of crustal debris from the nearby Ellsworth Mountains and factors such as proximity to sources of sea salt aerosol and the relative amounts of sublimation of snow prior to deposition. The provisional geochemical data from the Lake Ellsworth ice core have been combined with the revised dimensions of the lake [*Woodward et al.*, 2010], melt and accretion rates of 4 cm yr^{-1}, and a residence time of 2370 years to calculate revised values of inferred water chemistry in the lake (Table 1). These figures suggest that given closed conditions, the lake waters may be more solute-rich than first estimated, with overall solute concentrations being comparable to basal meltwaters sampled to date from beneath smaller warm- and polythermal-based glaciers in the Northern Hemisphere [*Skidmore et al.*, 2010]. It is important to note that these calculations assume a closed system with no input from basal meltwaters derived from the subglacial hydrological catchment. Inflow of such water, which *Vaughan et al.* [2007] suggested may be the dominant input source for Lake Ellsworth, could alter the lake water composition significantly. Under such a scenario, the chemical composition of the lake would be strongly influenced by (1) any input of meltwater derived from sediment porewaters with high solute concentrations [*Skidmore et al.*, 2010]; (2) the degree of stratification of the lake (particularly in relation to how much denser solute-rich water may accumulate beneath the surface layer); and (3) the extent of mixing of inflow with preexisting lake water.

4.5. Surface Accumulation

Surface accumulation (in m yr^{-1}) in the vicinity of Lake Ellsworth is relatively high, as demonstrated by the inability of the 2007/2008 field party to locate 7 of the 15 wooden stakes installed less than 2 years previously. Based on simple vertical measurements of the position of the snow surface at each of the 58 aluminum poles in 2007/2008 and 2008/2009, a rough approximation of the spatial distribution of accumulation around Lake Ellsworth has been established (Figure 6b). Despite localized anomalies caused by the heavily sastrugied snow surface, it is clear that the overall trend is for decreasing accumulation over the lake in the downstream direction (Figure 6b). Accumulation is generally within a range of 0.25 to 0.38 m yr^{-1} ice equivalent upstream of the lake's midpoint and within a range of 0.12 to 0.25 m yr^{-1} ice equivalent downstream of this point (Figure 6b).

4.6. Implications for Lake Access

The results of the geophysical investigations are critical for determining the location best suited to access and direct measurement of Lake Ellsworth. On the basis of the geophysical surveys and water circulation modeling, a preferred lake access location (78°58.1′S 90°34.5′W) (Figure 5) has now been established [*Woodward et al.*, 2010]. This site has been chosen because at this location, (1) the ice column (~3155 m) is thin relative to the majority of the lake; (2) the measured water depth is significant (~143 m), providing an opportunity to acquire a comprehensive profile of the water column; (3) more than 2 m of sediment is present on the lake floor; (4) modeling suggests a melting ice-water interface; (5) coring activities can target a deep point of the lake floor (−1386 m), near to the depositional center of the lake (coring further downstream would occur on the upslope to the lake margin); and (6) the sedimentation rate is likely lowest, given it is distal from the likely input sources of sediment upstream (the sediments are therefore likely to get older with depth more rapidly than in other places, increasing the chance of a longer record of ice sheet history, and are more likely to contain an undisturbed, continuous sedimentary sequence).

One factor that has important implications for the lake access experiment is whether the lake is an open or closed system. At this stage, the analyzed data do not allow us to make unequivocal statements concerning this issue. So far, however, no recognizable signal of ice sheet surface elevation change (indicative of subglacial water movement) has been reported over Lake Ellsworth in studies using ICESat data [*Smith et al.*, 2009; *Pritchard et al.*, 2009]. Although small-scale ice surface elevation changes can be identified within the GPS data, these are believed to lie within the uncertainties associated with snowpack compaction, accumulation, and base station movement. The lack of evidence for significant (i.e., >1 m) changes in ice surface elevation would tend to suggest that the lake is currently in hydrological steady state, which is possible in either a closed or an

Table 1. Estimates of the Chemical Composition of Water in Lake Ellsworth Making the Simple Assumption That the Lake Is a Closed System and That All Solute From Melting Meteoric Ice Accumulates in the Lake[a]

	H^+	pH	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	Cl^-	SO_4^{2-}	NO_3^-	HCO_3^-
Average Byrd ice core	1.8	5.7	~1.0	0.4	1.5	0.05	0.13	2.0	1.0	0.7	~1.2
Provisional surface firn and ice concentrations	NA	NA	8.9	0.65	2.8	0.57	NA	5.3	1.4	0.83	~8.2
Inferred Lake Ellsworth (from Byrd Core)	300	>3.52	170	68	250	8.5	<22	340	170	<120	~200
Inferred Lake Ellsworth (from provisional surface data)	NA	NA	1500	110	470	96	NA	900	240	<140	~1400

[a]Estimates are rounded to two significant figures and assume that the lake has been in existence for 400,000 years, with a residence time of 2370 years. Units are μeq/L. NA, data are not available.

open system configuration (input from melt of the overlying ice and basal water flow is matched by accretion ice formation and/or outflow). Preliminary analysis of the geomorphology of the area immediately downstream of Lake Ellsworth [*Ross et al.*, 2009] indicates that a prominent bedrock ridge impounds the lake. Such a feature is very likely to inhibit water outflow, at least to some degree. However, even if it is unable to exit the lake by overflow, subglacial water could exploit groundwater pathways (e.g., fractures, bedding planes, substrate permeability). Moreover, the gross hydrology of the lake may well change during periods when the ice sheet was thicker in this area (e.g., during the Last Glacial Maximum); thicker ice increases the likelihood of an open system so that an open system configuration may well be the predominant, i.e., glacial state, configuration for Lake Ellsworth.

5. PLANS FOR EXPLORATION

Direct access, measurement, and sampling of lake water and sediment from Lake Ellsworth are planned for the 2012–2013 field season. The most effective means of obtaining rapid, clean access to Lake Ellsworth through more than 3 km of overlying ice is by hot water drilling. Measurement and sampling of the water column and the upper lake bed sediments will be undertaken using a probe deployed and instructed from the ice sheet surface. Once in the lake, the probe will have the capability to directly measure pressure, temperature, conductivity, oxygen concentration, redox potential, acoustic velocity, and pH of the lake's water body. Underwater imagery will also be acquired, while the lake floor will be mapped using a profiling sonar mounted on the forward face of the probe; equipment for profiling the underside of the ice is also under consideration. Sampling will be initiated once the probe reaches the water-lake bed interface. Here a narrow-diameter push corer on the tip of the probe will sample a key target for microbiological life, the first few centimeters of sediment below the lake floor. The probe will then acquire lake water samples and filtrate at various points through the water column as it is winched back up to the access hole in the overlying ice. After retrieval of the probe at the ice surface, the access hole will be used to deploy the sediment corer. Current designs suggest that the corer will be lowered to the sediment surface and hammered into the sediment using a remote percussion hammer operated from the surface. Anticipated penetration depths are in the order of ~1 to 3 m, but this will be dependent on the physical properties of the sediment (e.g., grain size and water content).

Following recovery, water and sediment samples will initially be transferred to Rothera Research Station on Adelaide Island, Antarctic Peninsula for preliminary analysis and sample splitting. Water and sediment samples will then be transferred to U.K. laboratories for analysis of their (1) microbiology (lake water and sediment), (2) organic geochemistry (lake water and sediment), (3) hydrogeochemistry (lake water and sediment), and (4) sedimentology and palaeoenvironmental reconstruction (sediment core only). These laboratory analyses will be integrated with the direct measurements of the lake's water column (made by the probe) to determine the biological, chemical, and physical processes in the lake. The sediment core analyses will reveal how environmental conditions in the lake have changed through time, potentially providing important new information regarding the glacial history of West Antarctica. The exploration of Ellsworth Subglacial Lake may therefore produce profound scientific discoveries regarding both the life in extreme environments and WAIS history.

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