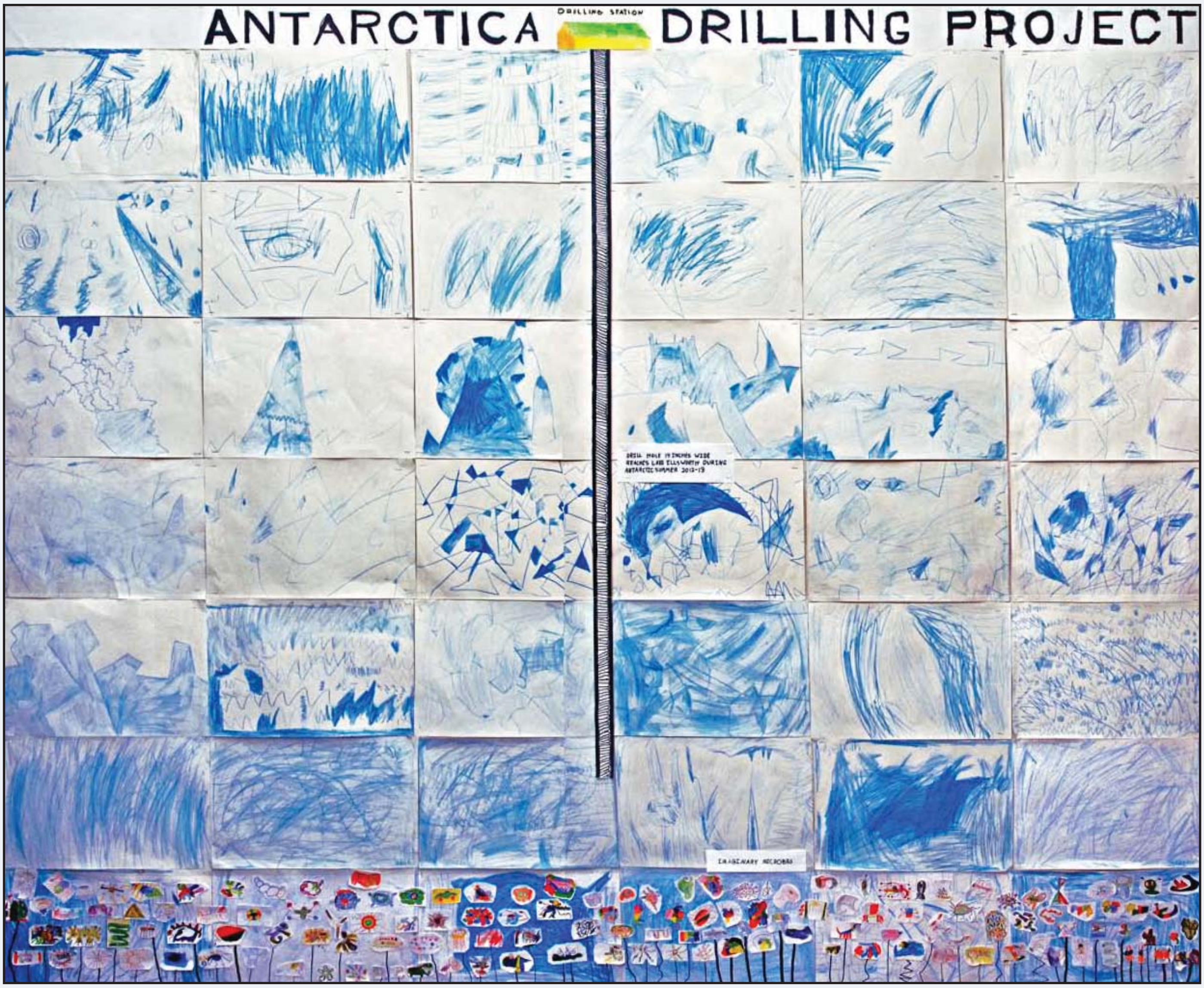
Proposed Exploration of Subglacial Lake Ellsworth Antarctica

Draft Comprehensive Environmental Evaluation



Subglacial
Lake
Ellsworth
Antarctica

February 2011

The cover art was created by first, second, and third grade students at The Village School, a Montessori school located in Waldwick, New Jersey.

Art instructor, Bob Fontaine asked his students to create an interpretation of the work being done on The Lake Ellsworth Project and to create over 200 of their own imaginary microbes. This art project was part of The Village School's art curriculum that links art with ongoing cultural work.

Contents

Non Technical Summary

Introduction

A draft Comprehensive Environmental Evaluation (CEE) has been carried out by the British Antarctic Survey (BAS) for the proposed investigation of Ellsworth Subglacial Lake in West Antarctica (referred to hereafter as Lake Ellsworth).

This draft CEE has been prepared in accordance with Annex I of the Protocol on Environmental Protection to the Antarctic Treaty (1998). The guidelines for Environmental Impact assessment in Antarctica (Resolution 4, ATCM XXVIII, 2005) were also consulted. This draft CEE describes the proposed activity, alternatives, the local environment and the likely environmental impact. It recommends preventative and mitigation measures and outlines gaps and uncertainties regarding the proposed exploration programme.

Description of the proposed activities

This programme proposes to undertake direct measurement and sampling of Lake Ellsworth to satisfy two fundamental scientific aims:

1. to determine the presence, origin, evolution and maintenance of life in an Antarctic subglacial lake through direct measurement, sampling and analysis of this extreme environment, establishing whether, and in what form, microbial life exists in Antarctic subglacial lakes, and
2. to reveal the palaeoenvironment and glacial history of the West Antarctic Ice Sheet (WAIS) including, potentially, the date of its last decay, by recovering a sedimentary record from the lake floor. This is critical to assessing the present-day risk of ice sheet collapse and consequent sea-level rise.

To meet these aims, the proposed exploration will involve accessing the lake using a hot water drill and deploying a sampling probe and sediment corer to allow sample collection. The proposed drilling and sampling exercise will likely last four days. (Following retrieval of the samples, there is an option to deploy a thermistor string which would remain *in situ* connected to the surface via a communication cable allowing ongoing measurements of the lake to be taken).

A field camp providing temporary accommodation and power for ten scientists and support staff will also be established for an estimated eight weeks.

The deployment of heavy equipment has been shown to be possible at this location based on several deep-field reconnaissance studies. This programme will build, test and deploy all the equipment necessary to complete the experiment in a clean and environmentally responsible manner.

Samples will be analysed and split in field laboratories and at the UK's Rothera Station, then distributed to laboratories across the UK.

To meet the scientific aims the programme has the following objectives:

- To produce a CEE describing the potential environmental impacts of the programme and how they can and will be mitigated by conforming with relevant best practice guidance (including the NAS guidelines on environmental stewardship when exploring subglacial lakes and the SCAR Code of Conduct on subglacial aquatic environment access).
- To build a hot water drill capable of drilling cleanly through up to 3.5 km ice.
- To construct a sampling probe capable of measuring and sampling the water column and surface sediment.
- To construct a sediment corer capable of retrieving a 1 m to 3 m sediment core.
- To develop a communications tether that can be used to lower the probe / corer and guide its measurement and sampling strategy.
- To design and deploy a field camp capable of supporting the programme and organise the logistics.
- To access the lake using the hot water drill.
- To deploy and recover the sampling probe into the lake, taking measurements and samples of water and lake floor sediment.
- To deploy and recover the sediment corer into the lake and recover a sediment core.
- To distribute the samples for analysis according to an agreed scientific protocol plan.
- To inform the science community and the wider population of the results.
- To inform future management and exploration of subglacial lakes in Antarctica.

Description of the environment

Lake Ellsworth is located at 78°58'34"S, 090°31'04"W in West Antarctica. It is positioned within the uppermost catchment of the Pine Island Glacier some 70 km west of the Ellsworth Mountains at an ice-surface elevation of 1895– 1930 m above sea level.

Extensive information on the baseline conditions has been gathered during previous non-intrusive site surveys. These indicate that the lake is located at the bottom of a deep, narrow, subglacial trough and that the lake lies approximately 3-3.25 km below the ice surface.

The lake volume is an approximate 1.4 km3 ±0.2 km3. It is likely, although not confirmed, that the lake forms part of an open hydrological system.

The lake bed is comprised of high porosity low density sediments at least 2 m thick.

No flora and fauna habitat is present at or near the drill site. Nor are there any protected areas in the region of the drill site. The microbial diversity within the lake is unknown.

Impact assessment and mitigation measures

A full assessment of potential environmental impacts is included in this draft CEE. This programme has been in a planning and design stage for six years, throughout which environmental protection has been a central and dominant feature.

The most significant impact predicted is the potential for contamination of the lake and subsequent impact on microbial function. The lake's microbial populations are currently unknown (and can only be determined through the exploration). This impact will be mitigated through the use of the hot water drill methodology (using melted ice water heated to 90 °C, filtered to 0.2 μm, and UV treated), and thorough microbial control contamination methods.

Other impacts result from the emissions generated through the combustion of fossil fuels during the logistics and drilling, potential local contamination from minor fuel spills, and from the wastes generated. These will be mitigated through good planning and management on site.

The potential for "blowout" resulting from dissolved gas build up has been rigorously assessed, and the overall risk confirmed as very low.

Alternatives

Alternatives examined include using different techniques for lake access, investigating alternative subglacial lakes, using different methods of microbial control and not proceeding with the project.

All alternative options have been ruled out as they would afford less protection to the environment or not satisfy the scientific goals of the programme. We are extremely confident that there are no realistic alternatives to that proposed in this draft CEE.

Environmental monitoring and management

The environmental monitoring proposes to assess the actual (rather than predicted) environmental impacts and involves reporting on completion of the fieldwork the resulting total emissions and wastes generated. Any environmental incidents (such as fuel or other spills, windblown equipment or wastes, breaches of the waste, fuel handling or bio security protocols) will be reported.

The microbial control methods will be tested during laboratory trials before the equipment is deployed in the field. However, the effectiveness of the microbial control methods can only be assessed after the fieldwork is complete, once the samples of drill fluid that will be collected during drilling have been analysed in UK Laboratories. The results of these analyses will give an indication of the efficiency of methods used and the potential for any contamination that has arisen. Preliminary analysis of potential contamination can be undertaken on-site using epifluorescence microscopy.

Gaps in knowledge and uncertainties

Given the exploratory nature of this scientific research, there remain unknowns, uncertainties and gaps in current knowledge. The most substantial relate to the following:

- The most sensitive receptor of Lake Ellsworth, the microbial bio-diversity, is unknown and can only be discovered through the execution of this project.
- While it is likely that Lake Ellsworth is part of an open hydrological system, we do not yet know this and there is a low likelihood that the system is closed. This has implications for dispersal of contamination introduced to the lake and for the risk of dissolved gas build-up that could lead under an extreme condition, to surface blowout.
- The microbial control methods proposed for use are subject to further development and trial to confirm they will meet the programme standards.
- Whilst the programme's primary scientific objectives are not dependant on deploying a thermistor string, such a deployment would provide an opportunity to obtain the first accurate depth-temperature record of the ice-lake-sediment column. No decision has yet been made on the use of a thermistor string, but if deployed it will meet the programme's rigorous microbial control criteria. However, unlike other equipment it will be left in situ.
- The final arrangements for transporting equipment to the site are yet to be decided, therefore the associated atmospheric emissions will be re- calculated with greater accuracy in the final CEE. The figures quoted in this draft represent the worse case scenario emissions.

Conclusion

Having prepared a full CEE and adopted rigorous preventative and mitigation measures, the UK considers that the exploration of Lake Ellsworth will have a less than minor or transitory impact on the Antarctic environment. However, due to the uncertainties inherent in such exploratory science, there is a risk of greater impacts (more than minor or transitory). As the actual impacts can only be assessed after they have already occurred, a precautionary approach has been taken reflecting this risk.

This precautionary approach meets the recommendation of the NAS – EASAE report that "all projects aiming to penetrate into a lake should be required to undertake a Comprehensive Environmental Evaluation".

The UK concludes that the global scientific importance and value to be gained by the exploration of Lake Ellsworth outweighs the impact the proposed programme is predicted to have on the environment and justifies the activity proceeding.

Acknowledgements and further information

This draft CEE has been prepared by the Lake Ellsworth Consortium and reviewed by the programme's Advisory Committee which is made up of internationally based independent scientists and experts.

Particular thanks are given to Peter Barrett, Neil Gilbert, Chuck Kennicutt, Martin Melles and Satoshi Imura for their constructive comments on a preliminary draft of this report.

The draft CEE is made available on www.antarctica.ac.uk/ellsworthcee

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Chapter 1: Introduction

It has long been speculated that Antarctic subglacial lakes house unique forms of microbial life adapted to these unique habitats, and that lake bed sediments have most likely recorded past climate change that may provide critical insights into the glacial history of Antarctica. Testing this hypothesis requires *in situ* exploration and sampling.

Over three hundred and fifty subglacial lakes are known to exist in Antarctica. One lake in West Antarctica, Lake Ellsworth, is an excellent candidate for exploration. The lake, at **78°58'34''S, 090°31'04''W** (Figure 1), has been shown to lie beneath 3 km of ice, is 12 km long, 3 km wide and up to 160 m deep.

This programme proposes to undertake direct measurements and sampling Lake Ellsworth to address two key scientific goals:

1. to determine the presence, origin, evolution and maintenance of life in an Antarctic subglacial lake through direct measurement, sampling and analysis and establishing whether, and in what form, microbial life exists in an Antarctic subglacial lake; and
2. to reveal the palaeoenvironment and glacial history of the West Antarctic Ice Sheet (WAIS) including, potentially, the date of its last decay, by recovering a sedimentary record from the lake floor, which is critical to assessing the present-day stability of the ice sheet and consequent sea-level rise.

To meet these goals, the proposed exploration will access the lake using a hot water drill and deploy a sampling probe and sediment corer to collect water and sediment samples. The proposed drilling and sampling exercise will take an estimated four days. Following retrieval of the samples, there is an option to deploy a thermistor string which would remain *in situ* connected to the surface via a communication cable to collect ongoing measurements of the lake's properties. We note while the thermistor string is not a requirement of the project, there is likely to be significant broader scientific interest in acquiring a depth temperature record of the ice-water-sediment column for the determination, for example, of the geothermal heat flux.

A field camp, providing temporary accommodation and power for around ten scientists and support staff will be established on-site for an estimated eight weeks.

The deployment of heavy equipment has been shown to be possible at this location, based on several deep-field reconnaissance studies. This programme will build, test and deploy all the equipment necessary to complete the experiment in a clean and environmentally responsible manner.

Samples will be analysed and split in field laboratories and at the UK's Rothera Station, then distributed to laboratories across the UK.

Previous non-intrusive geophysical investigative work was completed at Lake Ellsworth during the 07/08 and 08/09 seasons to aid the design of the programme and provide baseline data for this CEE. This included Radio Echo Sounding (RES) surveys to establish the base of the ice; seismic surveys of the lake floor and sediments; GPS measurements of the ice flow above the lake; and shallow ice cores to calculate accumulation rates; and preliminary analysis of microbiota and geochemistry in the overlying ice.

The proposed programme will be managed as a consortium led by Professor Martin Siegert of the University of Edinburgh. In 2004, the Lake Ellsworth Consortium was established as a multidisciplinary group to plan, coordinate and undertake the direct measurement and sampling of this lake. Planning has involved over thirty scientists and engineers from fifteen UK Universities and research institutions and has been incremental yet purposeful, open, inclusive and transparent. BAS are members of the consortium and its Environment Office are leading and managing the preparation and production of the CEE with input from other consortium members. The programme is funded by the UK's Natural Environment Research Council.

The programme will be conducted for 5 years in three phases:

Phase one (3 years, October 2009 to October 2012) will focus on setting up the lake access experiment. The hot water drill equipment and probe will be designed, built and tested, and the field camp will be established directly above Lake Ellsworth. The draft CEE will be submitted to the XXXIV Antarctic Treaty Consultative Meeting (ATCM) in 2011, for comment by Antarctic Treaty Consultative Parties (ATCPs). The final CEE will be completed by ATCM XXXV in 2012 and take into account comments received.

Phase two (5 months, November 2012 to March 2013) will be the lake access experiment. The field camp will be set up, the hot water drill will produce a hole down to the lake surface from which a sampling probe will be deployed to take measurements. Lake sediments will then be collected using a sediment corer. A thermistor string could then be deployed before the borehole refreezes. All water and sediment samples will be returned to the UK via the Bonner Laboratory at Rothera Research Station. Finally, the camp will be fully decommissioned and, along with all wastes, removed from Antarctica. All equipment will be returned to the UK with the exception of the thermistor string (if deployed), and the hot water drill system which will remain on the continent for use in future drilling programmes.

Phase three (1 year and 7 months, April 2013 to September 2014) will include data analysis, synthesis and dissemination of results.

This draft CEE is made available to the public via the programme website (www.antarctica.ac.uk/ellsworthcee). It was circulated by the UK Government to the Governments of the other ATCPs more than 120 days before ATCM XXXIV held in Buenos Aires in 2011.

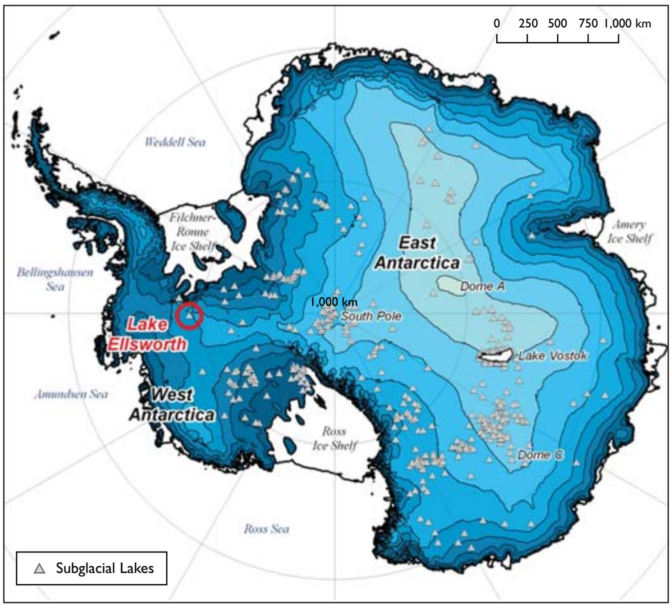

Figure 1. *The location of 386 Antarctic subglacial lakes (from Wright and Siegert, in press). Lake Ellsworth is circled.*

Chapter 2: Description of proposed activity

Background and justification

The notion of freshwater subglacial lakes in Antarctica led microbiologists to predict the presence of life forms adapted to the unique and isolated conditions (Ellis-Evans and Wynn-Williams, 1996; Priscu et al., 1999), and others to predict the likely presence of sedimentary records of ice and climate change deposited on the lakes' floors (Barrett, 1999).

In 1996 Siegert et al. presented evidence for over 70 subglacial lakes scattered widely beneath the Antarctic Ice Sheet. In updating the inventory of subglacial lakes (Siegert et al., 2005), Lake Ellsworth was identified as an ideal candidate for exploration (Siegert et al., 2004), because it is:

1. small and therefore easy to comprehend;
2. located near an ice divide where lake access is not complicated by ice flow (~5 m yr^{-1});
3. enclosed topographically, and therefore resistant to ice-sheet changes that might occur over glacial cycles; and
4. proximal to the logistical hub at Union Glacier, from which heavy loads can be input from South America to Antarctica and deployed to the lake site.

As a consequence of this assessment, NERC-funded geophysical surveys of the lake were carried out to better characterise the lake (Woodward et al., 2010). These results, described in Chapter 3, confirmed Lake Ellsworth's suitability for addressing the scientific aims as it has i) a relatively thin overlying ice column (~3.1 km); ii) a significant water depth (~143 m); iii) >2 m of sediment accumulated on the lake floor; iv) a melting ice-water interface at the proposed lake access site (as suggested by water circulation modelling); and v) likely very low sedimentation.

Lake Ellsworth has the potential to house microorganisms that have been isolated from the rest of the biosphere for several hundred thousand years; sufficient time for development of novel physiological and biochemical metabolic strategies.

The results of this proposed exploration will advance knowledge on how life functions in these ultra-oligotrophic systems, analogous to other Antarctic subglacial aquatic environments, the Earth's oceans during periods of global ice cover (e.g., the Snowball Earth hypothesis), and Europa, the Jovian moon that has a liquid ocean beneath a crust of ice. The findings will be of direct relevance to knowledge on the development, limitations on, and evolution of life on Earth and elsewhere in the Solar System.

The proposed recovery of a short (1-3 m) sediment core from the floor of Lake Ellsworth will help to evaluate WAIS history and therefore present-day stability. The history of the WAIS, and in particular the date when the ice sheet last decayed, is unknown and is critical to assessing the present-day risk of ice sheet collapse, and consequent sea-level rise.

Ice cores cannot provide this information as they are restricted to the age of the ice itself, which in West Antarctica is ~100,000 years. Diatoms in subglacial mud suggest central West Antarctica was ice-free less than 600,000 years ago (Scherer et al., 1998), whereas sedimentary records from a distal site close to the Transantarctic Mountains, ANDRILL

AND-1B, suggests the last time central West Antarctica was ice-free was ~1 m.y. ago (Naish et al., 2009). The best single location to address this issue is a sedimentary environment located on the interior flank of the Bentley Subglacial Trench. This is the area of early ice sheet decay according to the model of (DeConto et al., 2007) in the centre of the WAIS, and one that has a likely persistent ultra low rate of sedimentation

The floor of Lake Ellsworth is consequently well suited to contain a record of the WAIS since its last formation. The sediment will also likely contain a record of changes in the lake environment through time.

The direct measurement and sampling of Lake Ellsworth will be a benchmark in scientific discovery. The identification of life in Antarctic subglacial lakes and knowledge of West Antarctic glacial history are ambitious research aims that are achievable by the multidisciplinary consortium assembled, and the ambitious research and logistics plans proposed.

Outreach and knowledge exchange are important to this programme as well. The good track record of the team in outreach and media engagement will be enhanced by the programme, which will actively engage with media of all kinds. The excitement of exploration of the unknown will be shared with school children and university students and be used to demonstrate how basic scientific discovery and technology development is essential and inspiring.

The site

Lake Ellsworth is located in the centre of the West Antarctic Ice Sheet (WAIS) as shown in Figure 1. It lies at approximately 1900-1925 m elevation, only 30-35 km from the WAIS divide between Pine Island Glacier and the Institute Ice Stream.

The description of the lake setting is given in Chapter 3: Baseline conditions.

To meet the goals of the programme the following objectives are to be achieved:

- To produce a CEE describing the potential environmental impacts of the programme and how they can and will be mitigated by conforming with relevant best practice guidance (including the NAS guidelines on environmental stewardship when exploring sub glacial lakes and the SCAR Code of Conduct on subglacial aquatic environment access).
- To build a hot water drill capable of drilling cleanly through up to 3.5 km of ice.
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- To access the lake using the hot water drill.
- To deploy and recover the sampling probe into the lake, taking measurements and samples of water and lake floor sediment.
- To deploy and recover the sediment corer into the lake and recover a sediment core.
- To distribute the samples for analysis according to an agreed scientific protocol plan.
- To inform the science community and the wider population of the results.
- To inform future management and exploration of subglacial lakes in Antarctica.

Chapter 3: Baseline conditions of Lake Ellsworth

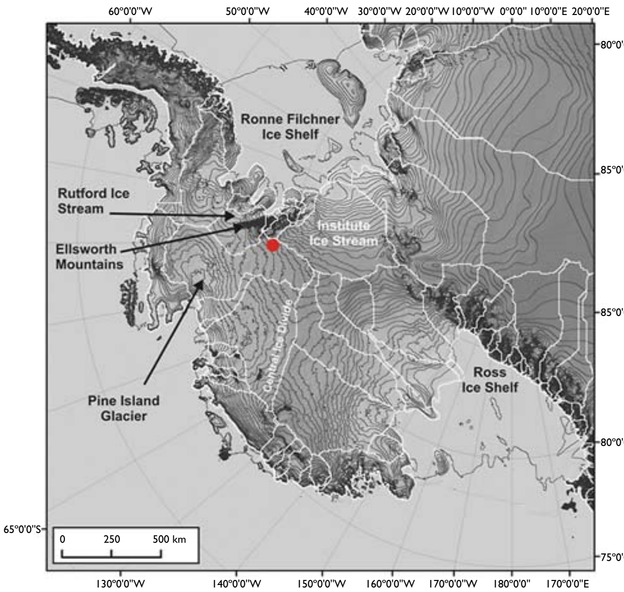

Figure 2. *Location of Lake Ellsworth (red dot) in West Antarctica. The base map is RAMP DEM (Antarctic Mapping Project Digital Elevation Model) with contours at 100 m intervals. White lines mark major ice divides.*

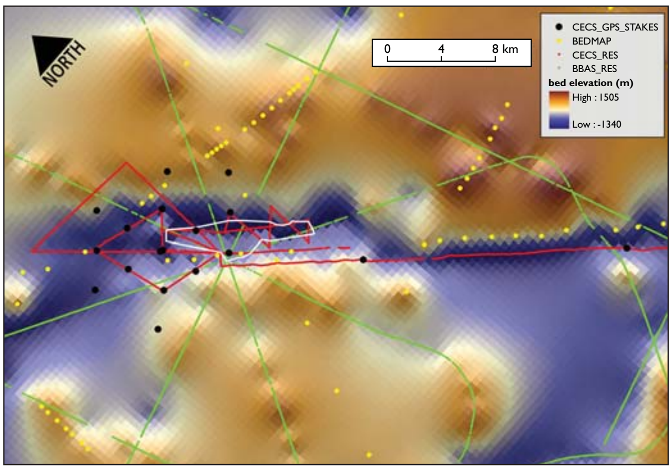

Figure 3. *Location of RES and GPS datasets pre-dating the Lake Ellsworth AFI project. Yellow dots = BEDMAP points (including original SPRI-NSF-TUD RES line and 1957 IGY traverse), red lines = CECS ground-based RES data, green lines = BAS airborne RES data. The gridded basal topography was constructed from these datasets. The white polygon represents the lake outline derived from these data (Vaughan et al., 2007), whilst the black dots represent the locations of stakes installed by CECS researchers for GPS ice flow measurements in Jan 2006.*

This chapter summarises the baseline conditions for Lake Ellsworth and its surrounds, as identified by previous non-intrusive work. Geophysical surveys of the lake were undertaken during the 07/08 and 08/09 seasons to aid the design of the lake access programme and to provide baseline data for this CEE. This comprised Radio Echo Sounding (RES) to establish the extent of the lake, the ice thickness and the basal topography; seismics to measure the depth of the lake floor and the nature of basal sediments; GPS to derive the ice flow velocity above the lake; and shallow ice cores for accumulation rates and provide preliminary analysis of microbiota and geochemistry of the overlying ice. The data revealed the lake dimensions, the basal morphology and likely subglacial hydrology related to the lake and its subglacial catchment (Woodward et al., 2010).

Location

Lake Ellsworth, at 78°58'34''S, 090°31'04''W, is located within the uppermost catchment of the Pine Island Glacier some 70 km west of the Ellsworth Mountains at an ice-surface elevation of 1895-1930 m above sea level, as shown in Fig. 2.

Geophysical surveys and available data

Prior to direct measurement and sampling of subglacial lakes, knowledge of their physical characteristics and topographic setting is necessary. Geophysical methods such as radio-echo sounding (RES) and seismic reflection are ideal for making these observations and providing data vital for constraining numerical modelling of the physical processes (melting, refreezing, water circulation) operating within the subglacial lake. These models, in turn, guide the selection of locations for access, sampling and measurement.

Lake Ellsworth was first observed in a single 60 MHz airborne radio-echo sounding survey line acquired during the SPRI-TUD-NSF 1977/78 airborne campaign (Jankowski and Drewry, 1981). Previous to that, it had been crossed by the 1957-58 Sentinel Range (Marie Byrd Land) traverse. However the lake was not documented until the mid 1980s when its position was mapped by (McIntyre, 1983). Since then it has been shown to be a suitable target for entry and study (Siegert et al., 2004), and a series of field campaigns to characterise the lake settings has been undertaken (Vaughan et al., 2007; Woodward et al., 2010).

As part of an extensive airborne geophysical survey of the Pine Island Glacier catchment in 2004/05, the British Antarctic Survey (BAS) acquired ice thickness and surface elevation data over Lake Ellsworth (Figure 3).

In field season 2005/06 researchers from the Centro de Estudios Científicos (CECS) undertook a ground-based traverse from Patriot Hills to SLE via the Institute Ice Stream, making radio-echo sounding (RES) and GPS measurements along the traverse route and over the lake (Figure 3). The combined results from the BAS and CECS surveys were reported by (Vaughan et al., 2007).

These data indicate that Lake Ellsworth is located at the bottom of a deep, narrow, subglacial trough approximately 3-3.25 km below the ice surface (Vaughan et al., 2007).

Hydrological analysis led Vaughan et al., (2007) to conclude the fluid body of Lake Ellsworth has a density indicative of fresh water, with little likelihood of substantial concentrations of material that would cause an increase in density (e.g. acid, salts or heavy clathrates). They suggested that subglacial drainage was the dominant water supply to the lake.

Data from the wider 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 (Figure 2). 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 Lake Ellsworth was part of a well-connected drainage system, with well-defined upstream and downstream hydrologic pathways through its deep subglacial catchment; effectively an 'open' hydrological system.

During the Austral summers of 2007-08 and 2008-09 a full geophysical characterisation of Lake Ellsworth was acquired. This survey provided most of the data reported here. The aims of the fieldwork were to: (i) determine lake water depth and bathymetry; (ii) map the outline of the lake and the topography of its catchment; (iii) produce a detailed map of ice flow over the lake; (iv) characterise the nature of the ice-water and water-bed interfaces; (v) establish sediment thickness beneath the lake floor; (vi) map the geometry of englacial layering within the overlying ice sheet; and (vii) measure any detectable tidal seiches.

Radio-echo sounding surveys

A detailed grid of radio-echo-sounding (RES) survey lines was acquired over Lake Ellsworth and its surrounding area using the ground-based 1.7 MHz pulsed DELORES radar system (Figures 4 & 5). The RES survey was designed to define: i) the outline of Lake Ellsworth ii) its glaciological and topographic setting; and iii) the geometry of internal layering within the overlying ice.

Just over 1000 km of RES data (including BAS and CECS data) were acquired over, and in the vicinity of, Lake Ellsworth. The bed is clearly identified in >95 % of the data and an ice thickness map and DEM of the bed have been constructed (Figure 5). Roving GPS data, acquired along the RES profile lines during the surveys, were used to generate a matching DEM of the ice surface (Figure 5).

The DELORES RES data are characterised by strong, well-defined intra-ice reflections in all profiles (e.g. Figure 4). 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' was also a characteristic of the SPRI-TUD-NSF, BAS and CECS RES datasets in the wider area around the lake (Siegert et al., 2004; Vaughan et al., 2007). It is not clear whether this is a property of the ice or simply a consequence of the absorption of electro-magnetic energy in the warmer parts of the ice at depth.

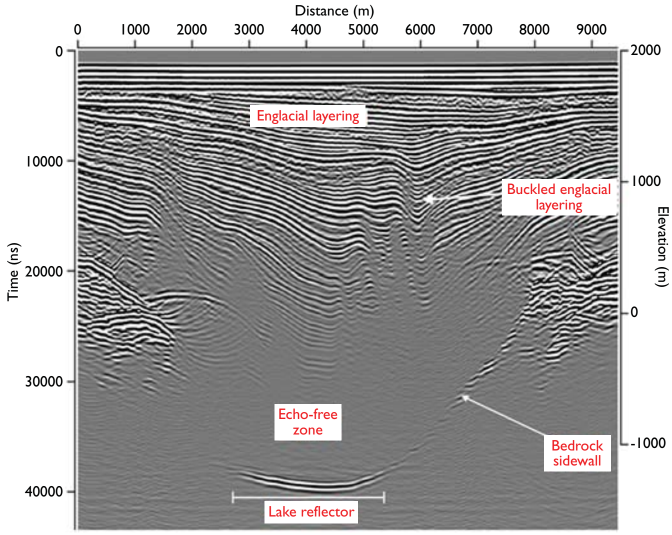

Figure 4. *DELORES radio-echo sounding data across Lake Ellsworth (Line D7.5). A prominent lake-like reflector is observed between 2600 and 5400 m along the profile at depths of ~3100 to ~3220 m. Buckled englacial layers generated by ice flow over a zone of pronounced subglacial topography southeast of Lake Ellsworth (see Figure 5) are annotated. Ice flow is approximately into the page. See figure 5 for location.*

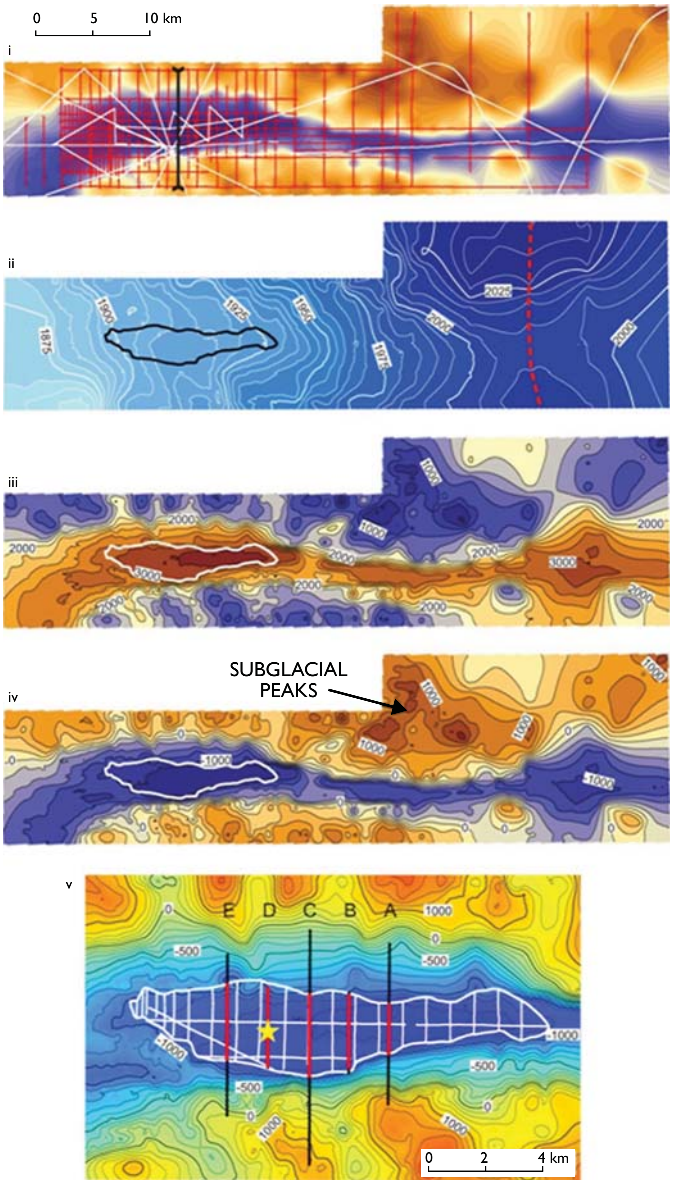

Figure 5. *Images produced from DELORES RES datasets: (i) map showing location of acquired RES data. Red lines represent DELORES data, white lines represent BAS and CECS 150 MHz data also used for the gridding of ice thickness and subglacial bed grids. Line D7-5 (Figure 4) is shown with a black line; (ii) GPS-derived ice sheet surface topography. Contours at intervals of 5 m. Red dashed line shows approximate position of ice divide. Black polygon is the outline of Lake Ellsworth; (iii) RES-derived ice thickness grid, contours at intervals of 200 m; (iv) RES-derived subglacial topography, contours at intervals of 200 m; (v) Outline of Lake Ellsworth mapped from 'lake-like' reflections identified in RES and seismic data (white and red lines respectively). Seismic lines are labelled A to E. The parts of the seismic lines coloured black show the extent of the acquired seismic data. The proposed lake access location is shown with a yellow star. Backdrop grid is subglacial topography with contours at intervals of 100 m. Images (i-iv) have a common scale. Ice flow is roughly right to left in all images.*

Ice sheet surface

The ice surface map (Figure 5) confirms the centre 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 West Antarctic Ice Sheet characterised by an ice surface 'saddle'. Directly above and upstream of Lake Ellsworth, the contours of the ice sheet surface are clearly influenced by the lake and the deep subglacial valley within which it sits. The ice sheet surface contours have a semi-amphitheatre-like morphology around the head of the lake that continues up-catchment directly above the long-axis of the subglacial trough. Over the lake, the gradient of the ice sheet surface is reduced compared with the surrounding 'grounded' ice, particularly over its central sector where, over a distance of 5 km, the ice sheet surface drops by <5 m (in contrast to areas up-catchment of the lake where the elevation of the ice sheet surface falls 30 m over the same distance). Downstream of the lake, the ice-sheet surface steepens once more with a gradient similar to that upstream of the lake.

Lake surface and extent

RES data allow the outline of Lake Ellsworth to be mapped with confidence (Figure 5). The total area of the lake is 28.9 $km^2 \pm 0.1$ km^2. Lake Ellsworth is located at the base of a broad overdeepening (see section 'Bed topography'), with the lake surface at elevations 1030 to 1361 m below sea level. The RES data confirm the previous observation that the lake has a marked lake surface gradient (~330 m over the ~11 km from its deepest to shallowest points). This is a very steep lake surface gradient along the direction of ice flow in comparison to some larger subglacial lakes, but is not unique among other lakes (Siegert et al., 2005; Wright, Siegert in press). This gradient is likely to result in differential melting and freezing across the lake, which would in turn drive enhanced water circulation within the water body (Siegert et al., 2004).

Bed topography

The map of basal topography (Figure 5), which integrates RES and seismic data, confirms Lake Ellsworth is located within a deep subglacial trough that runs for at least 45 km north-westward from the ice divide. The trough is constrained on either side by high, rugged subglacial topography. 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 800-950 m below sea level. Although impounded by high topography on both sides (generally >400 m above sea level), to the southeast of the lake there is a particularly pronounced area of subglacial mountains with peak elevations between 1200 to 1400 m asl. In the vicinity of Lake Ellsworth the trough widens and deepens, becoming 5.5-6.5 km across, with the valley floor attaining a depth of more than 1350 m below sea level.

Downstream of Lake Ellsworth the bed topography is marked by a pronounced ridge, which trends obliquely across the lake outlet zone and across the valley (Figure 5). This ridge, which rises ~200 m above the elevation of the water 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. Preliminary analysis of the RES data reveals reflections of greater amplitude than expected in the downstream region, across zone in which any lake water is likely to flow if it escapes the lake. The conclusion from this analysis is that lake water may issue on occasion from the lake, which is consistent with Vaughan et al. (2007) inference of an open hydrological system.

Englacial layering

Englacial layers within the RES profiles (Figure 4) have been picked and transformed into 3D surfaces. These data have been integrated with the DEM of the subglacial bed to facilitate 3D numerical modelling of ice flow and basal melting over Lake Ellsworth (Hindmarsh et al., in prep.). 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 from higher order mechanical effects as well as being caused by melt anomalies.

Buckled internal reflectors generated by ice flow over and around the subglacial mountains to the southeast of the lake demonstrate that ice flowing off this sector of the ice sheet (just downstream of the present ice divide) later traverses Lake Ellsworth, and that this flow configuration has been unchanged for at least the last 7,000 years and possibly much longer (Ross et al., submitted).

Lake-water depth

Five seismic reflection lines spaced ~1.4 km apart were acquired across the long axis of Lake Ellsworth in 2007/08 (Figures 5, 6 and 7). These data allow us to: i) map the lake bathymetry; and ii) investigate the thickness of sediments beneath the lake basin (Woodward et al., 2010). An example of seismic data is shown in Figure 6. The ice-base reflection can be clearly identified in all five of the processed seismic profiles. A well-defined reflection arriving at travel times greater than the ice base in all seismic profiles is consistent with a lake-bed reflector. By integrating reflection picks with surface GPS data, reflector elevations were established and then gridded to produce 3D surfaces of the ice-water interface, lake bed and the water column thickness (Figure 7).

The seismic data reveal Lake Ellsworth has a broad, generally U-shaped, lake-bed morphology (Figures 6 and 7). The thickness of the water column progressively increases down-lake (from SE to NW), with a maximum measured thickness of 156 m on the down-lake profile (Figure 7). The estimated volume of Lake Ellsworth is 1.4 km^3 ± 0.2 km^3 (Woodward et al., 2010).

Water circulation and lake hydrological balance

The hydrological balance of the lake is likely to be affected heavily by whether the system is open or closed. In an open system, melt water into the lake can be balanced by outflow without a need for accretion ice as has been found at Lake Vostok (Jouzel et al., 1999). In a closed system, however, water cannot escape, and so the hydrological balance must be maintained by accretion. Modelling is able to inform us of

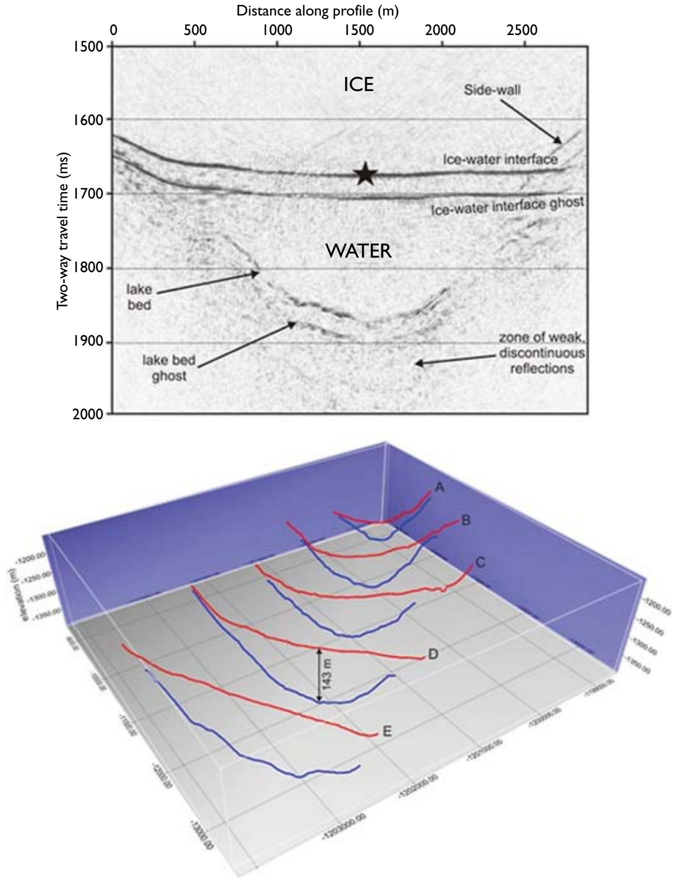

Figure 6. *Seismic reflection profile D. View is uplake with ice flow aligned roughly out of the page. Black star marks proposed point of lake access. Note that for visualisation purposes the uppermost 3000 m of the seismic profile has been removed; (ii) 3D visualisation of the lake surface and lake bed interfaces identified from the five seismic reflection profiles. The proposed point of access is marked by the vertical arrowed line on profile D. Red lines represent the lake surface and blue lines are the lake bed. View is towards the SE (approximately into ice flow).*

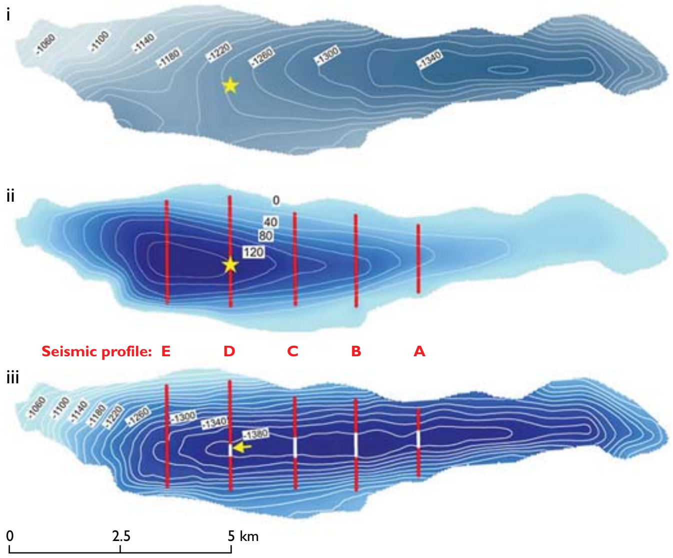

Figure 7. *Gridded seismic datasets: i) ice-water interface (integrated seismic and RES data); ii) water column thickness (seismic data only); iii) lake bed topography (ice-water interface minus water column thickness). Yellow stars and arrows indicate the proposed access location. Contours for all 3 parts are at 20 m intervals. The red lines in ii and iii represent the measured positions of the lake bed (and water column thickness). The parts highlighted white in iii represent the areas of the lake bed below -1380 m. Ice flow throughout the diagram is from right to left.*

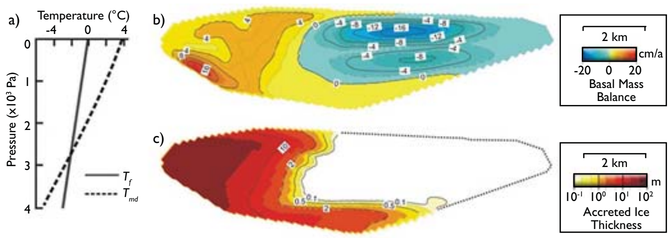

Figure 8. *Ice-base and lake water characteristics: (a) Depression of freezing point (T_f) and temperature of maximum density(T_{md}) with overburden pressure; (b) Modelled basal mass balance; (c) Modelled accreted ice thickness (in metres). Ice flow is roughly from right to left.*

the likely water circulation and accretion rates under a closed system (described below), but is currently unable to offer insights into the processes in an open system.

With this in mind, we used the 3D numerical fluid dynamics flow model Rombax (Thoma et al., 2007) to inform us about the lake's physical processes, as an end-member of the likely system to be encountered. The model assumes a closed hydrological system (i.e. no water flows into or out of the lake), which we reiterate may be inappropriate for Lake Ellsworth. Water enters the lake by melt from the overlying ice and exits by accretion of lake water to the base of the ice sheet. The modelling suggests basal melting is the dominant process acting at the ice-water interface in the upstream zone of the lake (Figure 8). However, downstream the model predicts basal freezing and the development of a thin (<40 m) layer of accretion ice for 50% of the lake surface (Figure 8). We note that RES data do not reveal an accretion ice layer like that seen at Lake Vostok (Bell et al., 2002).

A full description of the likelihood of Lake Ellsworth being either an open or closed system hydrologically is given in Appendix 1.

Basal sediments

Analysis of the seismic reflection data indicates the lake bed is composed of high-porosity, low-density sediments. These sediments have acoustic properties very similar to material found on the deep ocean floor, indicative of deposition in a low-energy environment (Smith et al., 2008). Analysis suggests that this sedimentary sequence is a minimum of 2 m thick, although deeper seismic reflections (e.g. Figure 6) may indicate that a much more substantial thickness of sediment lies under Lake Ellsworth.

Ice flow

During the 2007/08 field season four static GPS stations were deployed above, and in the vicinity of, Lake Ellsworth with the primary goals of detecting any tidal signal in the lake, determining the ice sheet flow regime (velocity) and to process other kinematic datasets (Figure 9). The off-lake and mid-lake stations were re-occupied during the 2008/09 field season.

In addition to these static base station data, surface 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 fifty eight aluminium 'glaciopoles' installed over the lake during the 2007/08 field season and eight wooden stakes installed downstream of Lake Ellsworth by CECS in January 2006. GPS measurements of both glaciopoles and wooden stakes were made during both field seasons.

From the measured changes in the positions of the markers in the stake network between the 2007/08 and 2008/09 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 9). The stake network shows: (1) convergent ice flow over the lake; (2) increasing ice flow velocity down the length of the lake; (3) greatest flow velocity over the middle of the lake, decreasing towards both its lateral margins; and (4) rotation of flow apparently associated with a change in the orientation of the subglacial trough downstream of the lake.

Ice cores and lake geochemistry

Three shallow (<20 m) ice cores were recovered from the ice sheet surface above Lake Ellsworth in the 2007/08 field season. One core was analysed in the field for measurements of snow and firn density (Figure 10), whilst the other two were returned to the UK for laboratory analysis (one for oxygen isotope derived accumulation rates and another for general 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).

From the ice core data we calculate the likely hydrochemistry of the lake assuming a closed system. By doing this, we reveal the likely maximum lake geochemistry (i.e. maximum likely chemical concentrations). In a perfectly open system, the water chemistry will resemble that of the ice, providing end-member scenarios.

The Lake Ellsworth Consortium (2007) estimated that the residence time of water was ~5,000 years if the lake was hydrologically closed, and that there had been ~80 renewals of lake water in the 400,000 years the lake has existed. This suggested that the chemical composition of the lake water might be up to 80 times that of the incoming ice melt if there were no other sources or sinks of ions within the lake, since only ~0.1% of solute from melt water is incorporated into accretion ice during freezing. The calculations were based on the lake dimensions assumed from the one RES line that was available at that time. However, the revised dimensions of the lake reported here, when coupled with average melt and accretion rates of 15 cm/yr, suggest that the maximum residence time of water in a closed lake is ~750 years suggesting that there might have been as many as ~530 water renewals over the last 400,000 years. This suggests that the chemical composition of the lake water might be up to 530 times that of the incoming ice melt if the lake was closed and there were no other sources or sinks of ions within the lake.

The Lake Ellsworth Consortium (2007) assumed that the chemistry of meteoric ice melt is equivalent to that of the average chemistry recorded in the Byrd Ice Core, giving the expected chemistry of lake water in Table 1. Provisional geochemical data for the average composition of firn and ice in the top 20 m of the recently acquired surface ice cores from above Lake Ellsworth (n = 11) are also given in Table 1. These surface ice core values are higher in most species, which may be a consequence of rock dust blown from the Patriot Hills and factors such as proximity to sources of sea salt aerosol and the relative amounts of sublimation of snow prior to deposition. The consequence of these higher concentrations is that the lake waters may be more solute rich than first estimated, assuming closed conditions, with overall solute concentrations being comparable with the more concentrated basal melt waters that have been sampled to date from beneath smaller warm- and polythermal-based glaciers in the Northern Hemisphere (Skidmore et al., 2010). The inferred concentrations of Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, SO_4^{2-} and HCO_3^{-} that we estimate are probably conservative, since these ions are generated from interactions between glacial flour and ice melt and so may be generated within the lake, or in hydrological flow paths en route to the lake. The inferred concentrations of H^{+}, NH_4^{+} and NO_3^{-} are probably too high, since glacial flour uses up H+ in chemical weathering actions, and microbial activity will remove NH_4^{+} and NO_3^{-}. Microbial activity may also change levels of SO_4^{2-} and HCO_3^{-}. We estimate that the pH of the lake water will be ~6 and that NO_3^{-} and NH_4^{+} concentrations will be around 1 µeq/l, similar to those in Lake Vostok (Siegert et al., 2003).

Surface accumulation

Surface accumulation (in ma^{-1}) in the vicinity of Lake Ellsworth is relatively high, as demonstrated by the inability of the 2007/08 field party to locate seven of the fifteen wooden Chilean stakes installed less than two years previously. Based on simple vertical measurements of the position of the snow

	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	*	*	8.9	0.65	2.8	0.57	*	5.3w	1.4	0.83	~8.2
Inferred Lake Ellsworth (from Byrd Core)	950	>3.0	530	210	800	27	<70	1100	530	<370	~640
Inferred Lake Ellsworth (from Provisional Surface Data)	*	*	4700	340	1500	300	*	2800	740	<440	~4300

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. Units are µeq/l. * indicates not measured so no data are available.

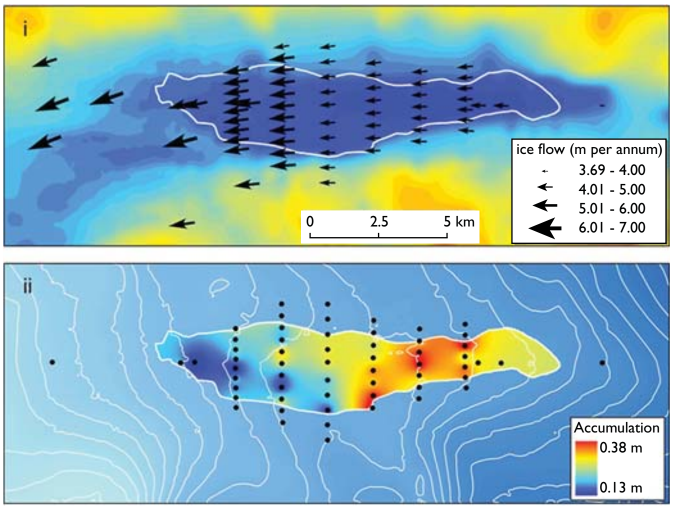

Figure 9. *(i) Direction and rate of present-day ice flow from GPS measurements of a network of surface markers. Size of arrows denotes rate of flow (larger arrows = faster flow); (ii) Surface accumulation (ma^{-1} ice equivalent) over Lake Ellsworth between 2008 and 2009. Black dots mark observation points. i and ii have a common scale with ice flow roughly from right to left.*

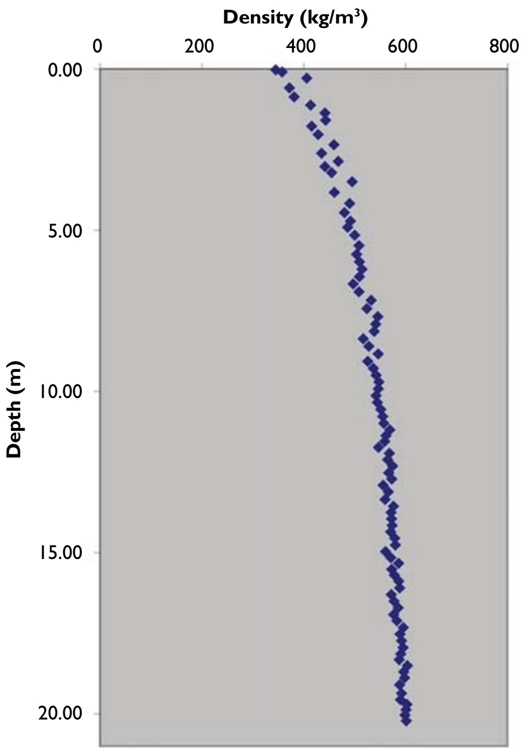

Figure 10. *Snow/firn density measurements from a 20 m deep borehole cored over the centre of Lake Ellsworth.*

surface at each of the 58 glaciopoles deployed in 2007/08 and re-measured in 2008/09, an approximation of the spatial distribution of accumulation around Lake Ellsworth has been established. Accumulation is greatest above the upstream half of the lake and there is a general decrease in the rate of accumulation downstream (Figure 9). Accumulation is within a range of 0.25 to 0.38 cm a^{-1} ice equivalent upstream of the lake's midpoint and within a range of 0.12 to 0.25 m a^{-1} ice equivalent downstream of this point (Figure 9). Despite the rather crude method of data collection, and some noticeably localised anomalies in these data, caused by the heavily sastrugied snow surface, the overall trend of decreasing accumulation downlake is evident.

Meteorological conditions

A lack of meteorological observations in the vicinity of Lake Ellsworth makes a description of the local climate difficult. However, an automatic weather station was deployed near the centre of the lake during the 2007-08 and 2008-09 Antarctic field seasons, which recorded air temperatures, atmospheric pressure, wind speed and direction. Winter meteorological observations have not yet been undertaken.

Average air temperatures during the summer (measured by a temporary, non-calibrated, automatic weather station) are ~ -19 °C. Measurements of borehole temperatures at depths of 20 m below the ice surface suggest that mean annual air temperatures are in the region of -32 °C, and show no significant change over the last 50 years.

Summary of lake access site

Geophysical data were collected over two full field seasons, to comprehend an accurate physiography for Lake Ellsworth. Radar was used to define the lake surface, its surrounding topography, englacial layering and basal conditions. Seismics were used to measure the water depths. GPS was used to understand the ice flow velocity and surface accumulation rate. Water circulation modelling was used to understand where regions of ice accretion may occur at the ice-water interface. In combination these data provide the most detailed assessment of any Antarctic subglacial lake, which allows us to identify the most appropriate site for direct lake access (Woodward et al., 2010). Lake access is chosen at the location marked in figures 5, 6 and 7 because:

- The lake is deepest at this point (although the water column, at 147 m, is less thick than that downstream, owing to the inclined ice roof), which means a full water column record will be recovered.
- The floor of the lake is flat at this point, meaning that lake floor sediments are likely to be unaffected by slope depositional and transport processes.
- Modelling and radar suggest the ice-water interface to be unaffected by the build up of accretion ice at this point, which is advantageous for lake access via hot water drilling.

Microbial content of the lake

One of the project's aims is to determine the presence of life in Lake Ellsworth. The microbiology of the lake is currently unknown. While the mere presence of life in itself would be a major scientific discovery, we might expect indigenous organisms to possess special or unique adaptations to this environment. Such unique environments are expected to support significant chemical gradients, including dissolved oxygen from gas hydrates released during the melting of ice. Microbial life, if present in Lake Ellsworth may, therefore, be pelagic and / or benthic, distributed along gradients in the water column, embedded in accretion ice or in the overlying meteoric ice. The identification of living organisms along with a determination of the essential element composition in the surrounding media will provide clues to potential biogeochemical activity and the sources of energy and carbon necessary to sustain metabolically active populations if present.

Microbial content of the snow

Preliminary analysis of the Ellsworth snow overlying the subglacial lake has been undertaken by filtering 1 l of melted snow through a sterile 0.2 µm filter, and staining with the fluorochrome DAPI (4', 6-diamidino-2-phenylindole), mounting onto glass slides and stored frozen at -20 °C, prior to enumeration by epifluorescence microscopy at x1250 (Porter and Feig 1980).

This analysis revealed a cell count of between 1.47 (±0.4 1) x 10^3 and 1.68 (±0.3 1) x 10^3 ml^{-1} snow melt (Pearce, unpublished). This is consistent with that identified at the South Pole in 2000, i.e. 200-5000 cells ml^{-1} (Carpenter, 2000).

Fauna and Flora

The area in the vicinity of the proposed drill site and camp is not a habitat for any native flora and fauna (Pers. Comm. Prof P Convey).

With the exception of a lone skua heard on the 28th December 2008, no macroscopic flora or fauna have been observed in the vicinity of the proposed Lake Ellsworth drill site during either of two recent field seasons (2007-08 duration approximately 3 months, and 2008-09 duration approximately 1 month).

Lichens (*Xanthoria spp* and possibly *Candelariella flava*) are distributed sparsely on rocky outcrops in the Ellsworth Mountains, and have been recorded in the Union Glacier area (where project staff and equipment will arrive in the Ellsworths and transit to the drill site).

Protected Areas

There are no Antarctic Specially Protected Areas, Antarctic Specially Managed Areas or Historic Sites and Monuments in the region of Lake Ellsworth.

Chapter 4: Description of the technologies

This chapter provides detailed information on the equipment and methodologies required to meet the scientific goals and objectives. It includes technical specification and drawings of the key scientific equipment to be deployed, plus descriptions on how the equipment will be used, the samples collected, and the subsequent laboratory analyses. Particular emphasis is given to the methods used to sterilise the equipment to ensure levels of cleanliness that will be crucial to the success of the science being conducted and for environmental protection (more detail on this is given in Chapter 6)

Hot Water Drill

Hot water drilling has been identified as the most effective means of obtaining rapid, clean access to Lake Ellsworth. The technique has been used successfully by the British Antarctic Survey (BAS) for over 20 years to access the water beneath ice shelves, with their present drill having penetrated over 2000 m of ice on Rutford Ice Stream. Readily available industrial equipment is to be used to build the drilling system for Lake Ellsworth.

The drilling concept is simple, as shown in Figure 11 above. Water is filtered then heated via a heat exchanger and pumped, at high pressure, through the drill hose to a nozzle that jets hot water to melt the ice. The hose and nozzle are lowered slowly to form a very straight hole, as gravity is used as the steering mechanism. The water from the nozzle uses the melted hole as the return conduit.

A submersible borehole pump installed near the surface, but below the lake's hydrological level (270 m below the ice surface, calculated from the ice density profile and the assumption that the ice column is floating), returns water to a number of large surface storage tanks, which are maintained at several degrees above freezing. The water is then reused by the hot water drill.

Several generators will provide electrical power for the drill. By using (and recycling) melted pre 1800 yr old ice as the drilling fluid, the hole created by the drill will meet the project's cleanliness criteria, minimising the potential for contamination of the lake by the drilling fluid. This is discussed further in Chapter 6.

During drilling, the water flow, pressure and temperature will remain fixed (3 l s^{-1}, 2000 psi, 90 °C), while the drilling speed is varied between 1.0 m s^{-1} and 0.5 m s^{-1} to create a hole that will have a uniform diameter of 36 cm at the end of the drilling process. Creating the lake access hole into the lake will take around 3 days. Before reaching the lake, the water level in the hole will be drawn down a few metres below the hydrological lake level. This drawdown will prevent water from entering the lake.

A filtration and UV system will be used to treat drill water to remove suspended solid particles, including bacteria and viruses. The water will pass through a five staged filtration system utilising spun bonded, pleated, and membrane filter elements with absolute micron ratings of 20, 5, 1 and 0.2, before being UV treated. This water is then heated to between 85 °C and 90 °C, and pumped down a single 3.4 km length of drill hose to a drill nozzle. During the initial stages of drilling, the hose on the winch reel and the drill nozzle will be

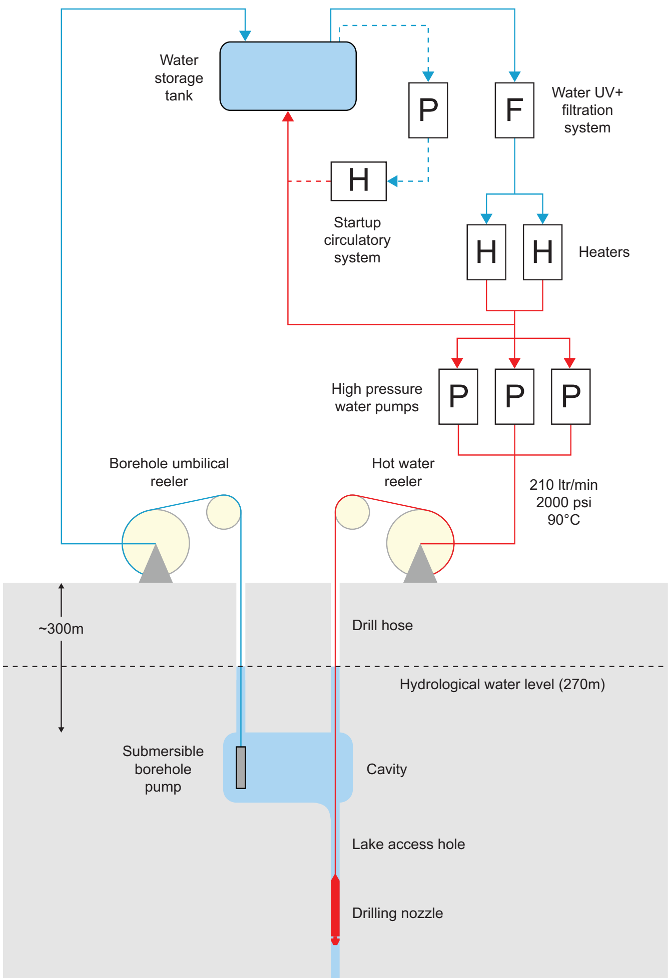

Figure 11. *Schematic diagram of the hot water drill system. H = heaters; P = pumps; F = filters.*

subjected to temperatures of 85 °C to 90 °C for at least 15 hours. During the entire drilling process, the smooth bore plastic lined drill hose will be continually flushed for at least 3 days by over 800 m^3 of hot filtered water, thus internally rinsing the hose and nozzle. After the initial high hose temperatures on the winch reel, the outer surface of the hose will be scrubbed using high pressure water jets and then passed through a UV collar just prior to the hose entering the hole. Once in the hole, the hose exterior is bathed in the admixture of filtered drill water and melt-water that flows up the hole at a rate of 1.8 m per minute to be reused by the drill, thus flushing any microorganisms released from the ice to the surface for filtration. Samples of drill fluid will be analysed to assess the quality of microbial control and to provide a comparator for lake samples.

Water will be passed through a number of filters and a dual UV unit. Each stage will be provided with tapping of points so that water samples may be collected and analysed. The final filter stage will be passed through a 0.2 micron filter. All filters will be provided with dual redundancy in order to allow new filters to be brought online without any interruption to the water flow.

Differential pressure across the filters will be monitored. Increases in these differential pressures will indicate the health of the individual filters. At a set differential pressure the filters will be changed out for new filters. All filters will be available for post operational analysis.

Detecting when the drill reaches the lake will be achieved using pressure sensors close to the submersible pumps; these will monitor the water level adjustment when the hydraulic connection between the hole and the lake is made.

Once the hole has been enlarged (by controlling the drill's rate of descent) at the ice/lake-water interface, the drill is recovered and the hole is available for water and sediment sampling. Closure of the hole, because of refreezing, reduces the diameter at a rate of ~ 0.6 cm per hour, resulting in a limited time when the hole will remain large enough to deploy equipment. If additional lake access time is required, the hole can be reamed for as long as fuel remains available.

Recent hot water drilling on Rutford Ice Stream, which twice drilled to a depth of 2000 m, demonstrated the following weaknesses in a previous version of the drilling system: drill hose coupling failure; periodic cessation of drilling to add lengths of drilling hose; and exposure to weather changes as a consequence of operating in open conditions. To eliminate the first two issues, we will use a single 3.4 km length of thermoplastic hose with double Kevlar braids to meet the pressure requirements and a single long pitch Vectran fibre outer braid strength member. To reduce the impact of weather conditions, the drill system will be housed in a covered container to offer protection.

Before shipping the hot water drill, testing of the entire system will, as far as is practicable, be undertaken to resolve any technical issues, provide valuable training for the engineers and scientists who will operate the drill at the field site, and ensure contamination controls can be demonstrated.

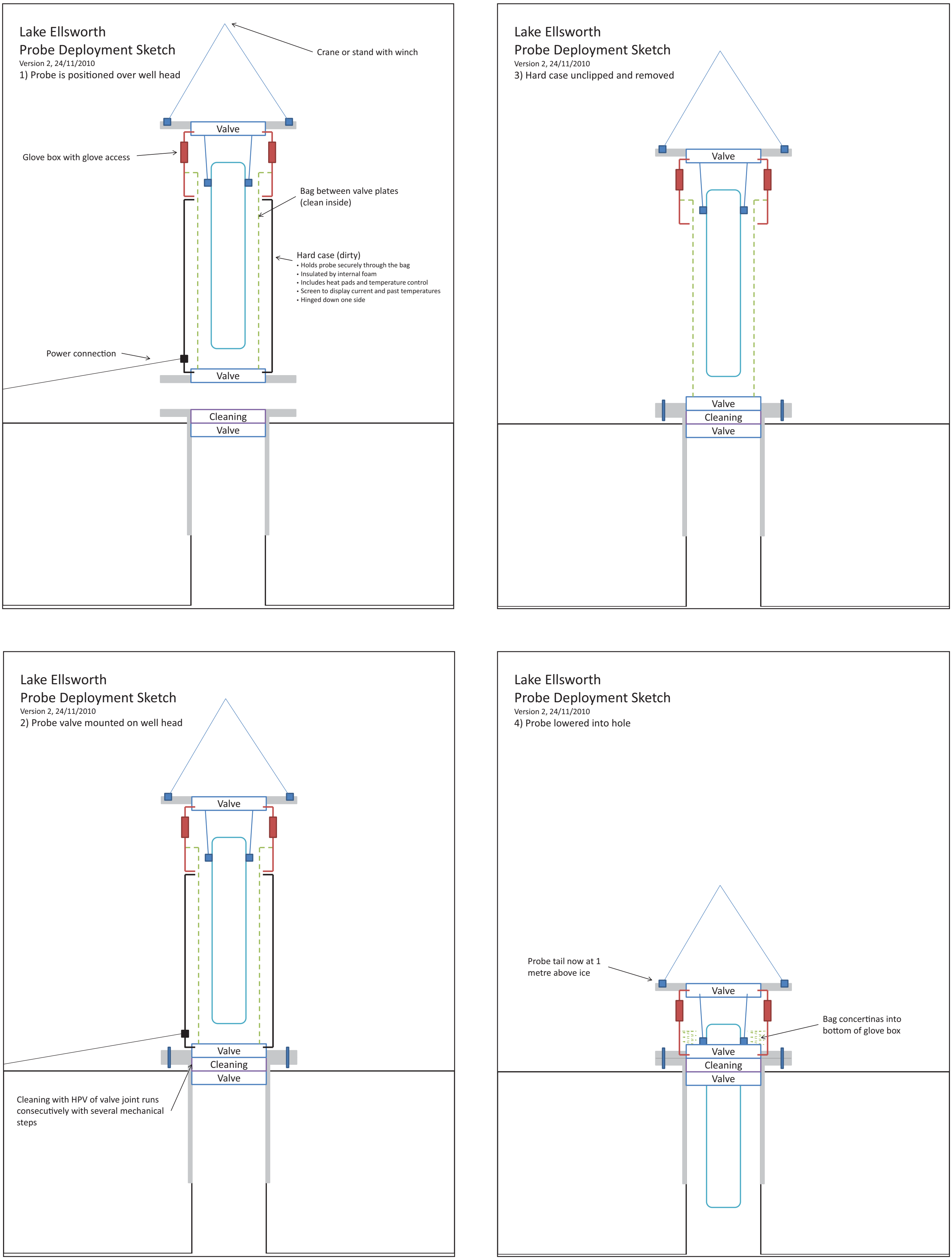

Figure 12. *Twelve stage sequence for deploying the scientific instruments.*

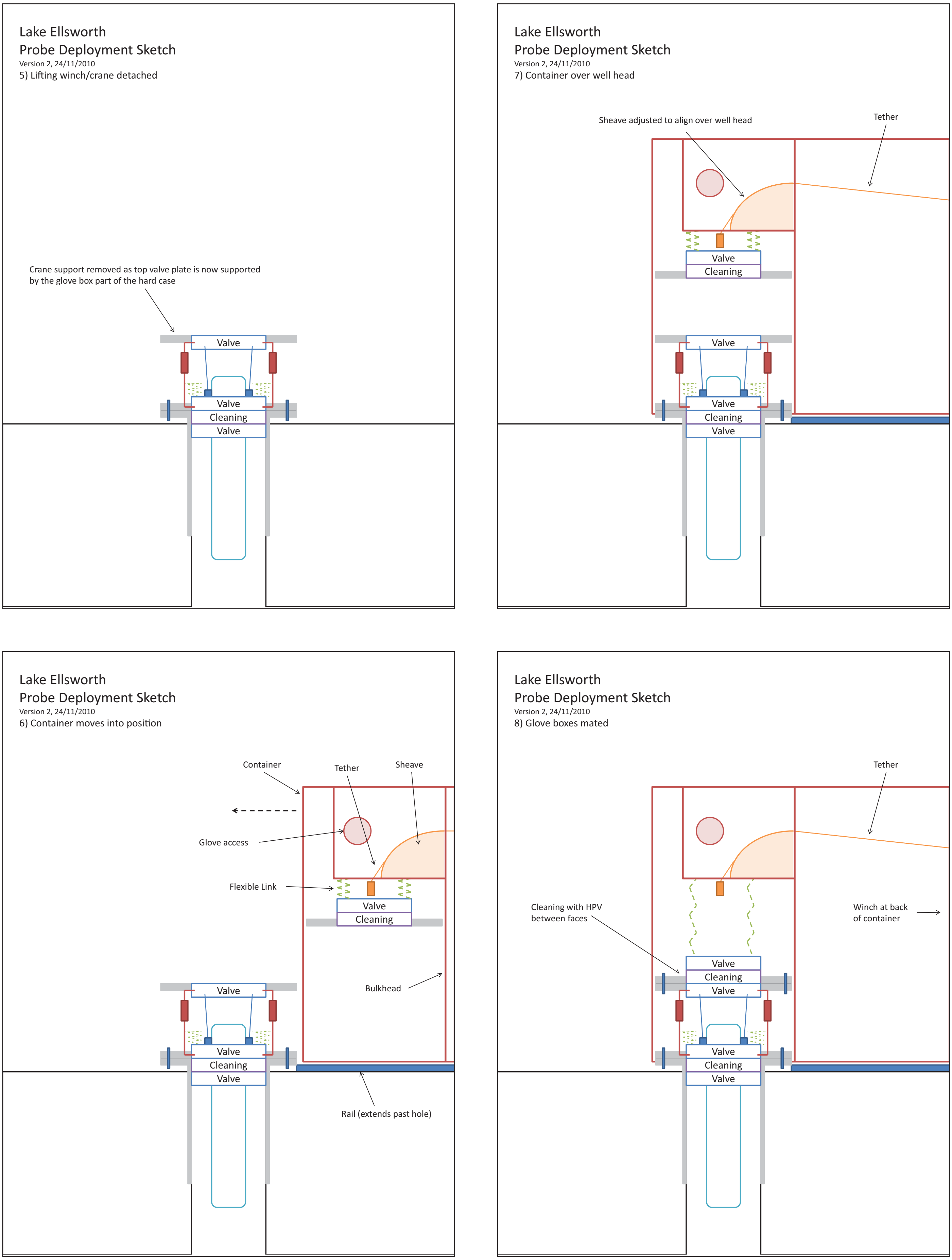

Figure 12. *Twelve stage sequence for deploying the scientific instruments.*

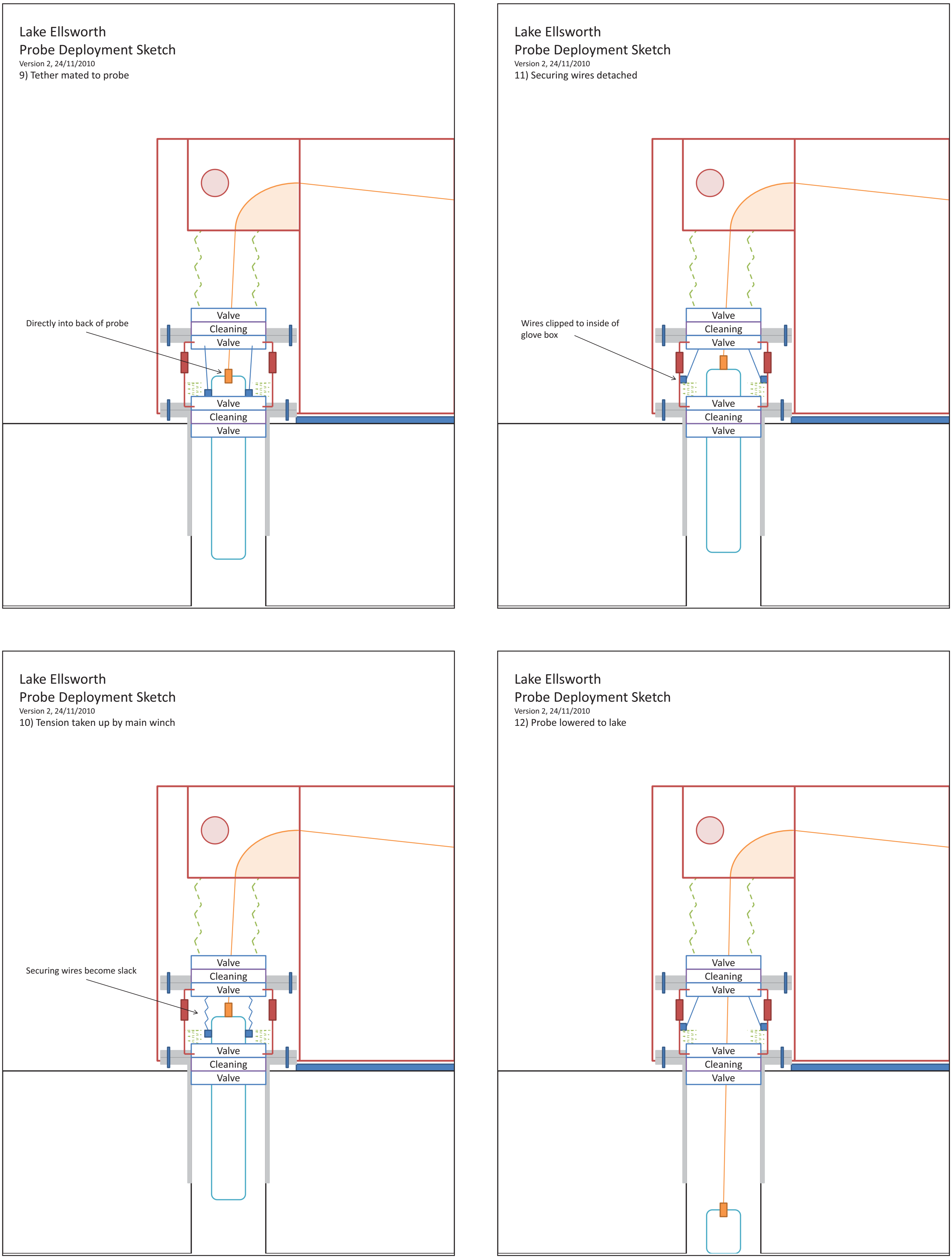

Figure 12. *Twelve stage sequence for deploying the scientific instruments.*

Vaughan et al., (2007) showed that the ice sheet around the drill site is floating on lake water, and that the lake-water pressure can be calculated with a high degree of certainty. This, with new data acquired in 2007/8, makes an assessment of the borehole liquid level needed to ensure minimal transfer between the lake and borehole relatively straightforward (270 m below the ice surface at the proposed drill site).

Deployment of instruments

The probe will be contained in a transit case for protection during transport and installation. The probe will be cleaned and sterilised inside a plastic bag suspended between valves. Detail on cleaning and sterilisation are given in Chapter 6. Deployment of the instrumentation is shown pictorially in Figure 12, and described as follows.

The Transit case will be suspended from a crane and connected to the head of the wellhead (2). While suspended the hard outer case will be removed (3). The probe is then lowered onto its glove box support (4). The crane support is then removed (5). The deployment container is wheeled into position (6 and 7). The glove box is then connected to the sheave within the container (8). The connecting valves are opened and the probe connector is connected to the tether (9). The tension is taken on the tether and probe support is removed (10 & 11). The probe is then lowered in to the hole (12).

The process is reversed to recover the instruments. The drill, probe and corer are all deployed and retrieved separately. The use of the cleaning collar (and other microbial control methods) reduces the risk of contamination being introduced during deployments.

Probe description

Preliminary designs for the probe and its systems have been completed by the National Oceanographic Centre (NOC) in collaboration with the Lake Ellsworth Consortium over the last four years. These designs are being refined by the proposed research programme (including design and testing in an oceanographic setting) prior to the production of two probes (for contingency).

The probes will consist of two pressure cases. The lower contains the majority of the instrumentation, and the upper the power and communications demodulation systems. These two vessels are separated by water samplers (see Figure 13). Data are returned in real-time, and water and sediment samples are recovered for post-retrieval analyses. This provides redundancy, and enables informed deployment of the sampler systems.

An onboard microprocessor and data logger will enable continued operation (e.g. sampling at predetermined intervals) and archiving of instrument data in case of communications failure.

Power will be supplied both through the tether and by onboard batteries, the latter being sufficient to complete the mission but with limited video footage. Probe-to-surface communications (two way) will be via an optical link and backup wire modem using commercial off the shelf (COTS) technology used in several deep sea remotely-operated vehicles.

A duplicate probe will be commissioned and deployed to the drilling site in case of failure or contamination.

Probe mounted corer

The tip of the probe will be equipped with a narrow-diameter push-corer. This will sample a few centimetres of sediment from the lake floor, including the crucial sediment-water interface. In ultra-oligotrophic lakes this interface is often the site of most life in the lake and so is a key target. Moreover, the use of a corer on the probe provides redundancy and, thus, greater assurance of recovering sediment if the main gravity corer were to fail. The probe mounted corer will be sterilised before deployment and samples capped in the sterile well head on retrieval.

Instrumentation

The probe will be equipped with >6000 m rated commercially available sensors to measure pressure, temperature, conductivity, oxygen concentration (electrode), redox potential and pH. A video camera and sonar will provide additional information on the lake environment. Redundant temperature, conductivity and oxygen (optode) sensors will also be installed. The instrumentation will be attached to the main body and at the front of the probe. A separate instrument housed in an 88 mm outer diameter cage will measure the sound velocity in the lake water.

Table 2 summarises the performances of the instrumentation package.

Sensor	Range	Accuracy	Resolution	Time constant
Pressure	0-10000 dbar	0.01% FS	0.001% FS	15 ms
Temperature	-5 – +45 °C	0.001 °C	0.0001 °C	50 ms
Conductivity	0-6400 µS/cm	5 µS/cm	0.1 µS/cm	50 ms
Oxygen	0-50 ppm	0.1 ppm	0.01 ppm	3 s
pH	0-14 pH	0.01 pH	0.001 pH	3 s
Redox	-1000 - +1000 mV	1 mV	0.1 mV	3 s
Sound velocity (SV)	1400-1600 m/s (extended on request)	0.03 m/s	0.001 m/s	NC
Temperature (SV)	-5 – +35 °C	0.01 °C	0.005 °C	NC
Pressure (SV)	0-600 bar	0.01% FS	0.001% FS	NC
Oxygen Optode	0-500 µM	<8 µM or 5% whichever is greater	<1 µM	25 s (63%)

Table 2. Probe instrumentation package performance.

A profiling sonar with an 80 m active radius will be mounted on the forward face of the probe. A second sonar on the rear end of the probe is under consideration (and will have no additional environmental impact in Antarctica if deployed). n. This would enable profiling of the underside of the ice. If profiling is not possible (possibly because of blind spots created by the tether and reinsertion guide) a ranging sonar will be used. Underwater video will be supplied with a video and light package. This will store data locally and transmit at high fidelity via the optical communications link.

Topside equipment

Sterilisation and cleaning will be achieved with on-site hydrogen peroxide plasma generation, and cleaning using double-filtered drill fluid (discussed further in chapter 6). This will include a system for sterilisation and cleaning of the probe (in its protective bag) and the tether immediately prior to insertion in the borehole.

A winch system suitable for both the probe and the corer will be developed. This will include: a spool, a top sheave, a render (clutch) system, a dipping top sheave mount (to enable fine control, and load relief if the probe becomes stuck), power converters and slip rings, optical and electrical communications pickup, and interface to the pre-insertion scrubber (as above).

The tether will be of synthetic composite construction and will include at least two copper conductors and at least two optical fibres. The tether will be sheathed in a flexible jacket to facilitate easier on-site sterilisation and cleaning. Command, control and data logging will be supplied by a dedicated and redundant computer-controlled system housed in a topside tent.

Sediment corer

Sediment coring at several kilometres water depth is a near-daily occurrence in the world's oceans. The technological challenge is to modify an existing design to enable sterilisation and cleaning, and diameter reduction for deployment down the borehole.

A percussion driven piston corer will be designed and manufactured by UWITEC (an established limnological engineering company based in Austria) and BAS. BAS and UWITEC have previously developed corers to successfully recover sediments from beneath the George VI Ice Shelf and the WAIS.

Key elements of the design are:

- Corer control unit at surface
- Corer interface housing
- Percussion housing
- Corer barrel (including fixed piston to retain core in a core liner making it possible to pull the corer out of the sediment from any penetration depth without loss of the core), and double core catchers to prevent sediment loss
- Spares and maintenance package

All aspects of the corer will be designed to facilitate cleaning and sterilisation (using the same procedures used for the probe). The pre-cleaned corer will be stored in a sterile bag that will be removed, prior to deployment, at a few meters depth in the borehole.

The corer and all its components will be cleaned in a similar manner to the probe. After probe retrieval the corer will immediately be deployed on the same tether as previously used for the probe. This will minimise costs, logistical effort and the changeover time between devices. The corer will be lowered to the lake floor and then hammered into the sediment by activating the percussion hammer. This operation will be controlled by the sensor package on the corer connected to a corer control unit on the surface located within a heated working space.

We anticipate penetration to ~1-3 m depth, but this will be dependent on composition (e.g. grain size) and water content of the sediment. The corer will be allowed to settle and then retrieved by winch to the surface. During retrieval the piston will be locked in place via the piston rod lock which, along with the core catcher at the lower end, will keep sediment in the core barrel. When the core reaches the surface it may be partly frozen. In advance of freezing cores will be handled vertically in order to preserve their palaeomagnetic signal.

Thermistor string

While the programme's primary science objectives are not dependent on deploying a thermistor string, such a deployment would provide an opportunity to measure time-dependent variability in the ice, lake and sediment temperature and other physical (and possibly chemical) properties. Information would be returned to a data logger on the ice surface, from where it will be collected and transmitted back to the UK via an Iridium link. The thermistor string, if deployed, will be subject to the same standard of microbial control as other equipment in contact with the lake, but it will not be recovered after use. Detailed plans for the deployment of the thermistor string have yet to be finalised and decisions on its construction and use will be reported in the final CEE.

Sampling strategy

The probe includes multiple rosettes of bespoke water samplers. These can collect samples at any time or depth (to be specified by the science programme or in response to *in situ* measurements). The initial plan for water sampling is based on 24×50 ml samples, collected by the probe in groups of four at each of six depths. We anticipate sampling at two levels in an upper dilute layer below the ice, two levels near the lake floor where sediment-water interaction may create a relatively concentrated layer, and two samples at intermediate depths. This strategy is illustrated in Figure 15.

The precise distribution of sampling will be influenced by real time data from the probe on the physico-chemical properties of the water column, and in particular on the degree of stratification determined during the probe descent. Sampling will be undertaken during ascent when sufficient information is available to determine the preferred sampling locations.

The method used maintains the pressure of the samples preventing outgassing on return to the surface. This means that the samples are pressurised on return to the surface allowing analysis of gas content. This will be completed using a bespoke degassing system (that will analyse the evolved gas as the samples are depressurised). Gas contamination

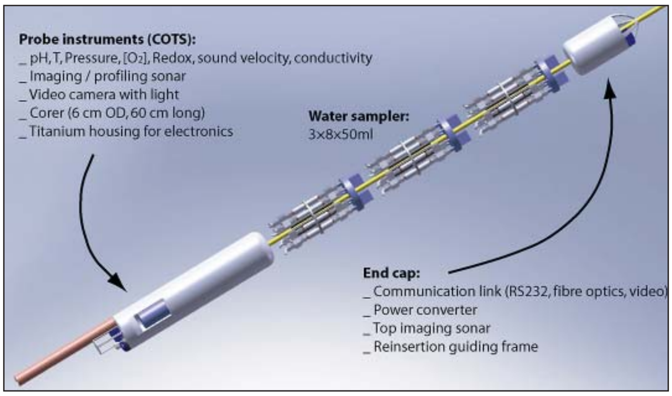

Figure 13. *Illustration of the probe concept and its instrument and sampling arrangement. The probe's dimensions are approx 4500 mm in length and 200 mm wide.*

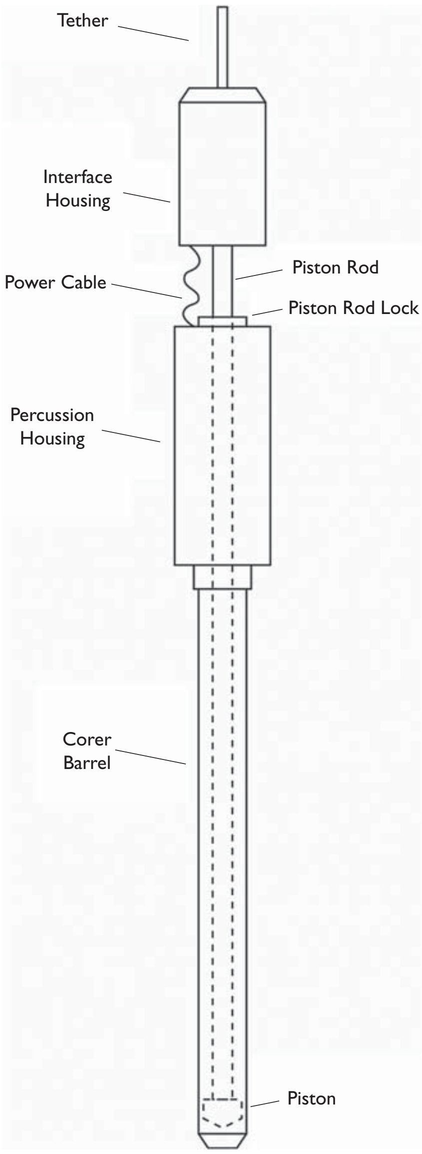

Figure 14. *The design and construction of the sediment coring system.*

will be minimised by purging / evacuation of valves and interconnecting pipes.

Each suite of four water samples will allow distribution of 100 ml for bioassay, 50 ml for hydrochemistry and 50 ml for organic geochemistry, without the necessity for movement of opened samples between laboratories, thereby reducing the chance of contamination. It also gives us flexibility for reallocation of samples if (i) some are contaminated during the collection process or later, (ii) first analyses indicate that the water is so dilute that samples must be combined to achieve detection, or (iii) unexpected results indicate the desirability of additional analyses.

The 50-100 ml samples also allow each analytical group the possibility of replicate analyses. The sampling strategy will remain flexible and responsive to measurements made during the first stages of the deployment programme.

In addition to the samples collected in the lake, control samples of the borehole water will be collected at intervals during the drilling programme to determine background levels of biological and chemical parameters.

The concept for the sampler is mechanically simple and can be cleaned and sterilised. Further design development is required to increase the sample volumes whilst minimising size. The current design consists of 8×3×50 ml individually triggered bottles (formed from commercial off the shelf technology tubing) and utilises commercial off the shelf valve technology with springs and magnetically-coupled release systems to open and then shut the valves. Samples are maintained at pressure, enabling quantitative analysis of dissolved gases. Each container with its two valves will be detachable from a carousel frame for processing and storage. Each of the carousels has two rotary pumps (providing an important level of redundancy) fitted to a manifold to flush the tubes with sample. Filters will be placed at the outlets of the sampling pumps to provide particulate samples.

Each bottle in the water sampler is initially filled with a sterile and clean solution a sample of which will be analysed for microbial content for quality control and to provide a comparator for lake samples. This is flushed on acquisition of a sample, which is then sealed from the environment. It will only be opened, after surface sterilization in a closed sterile microbiological cabinet. The current sampler design concept is shown in Figure 16.

Fieldwork analysis

The probe will deliver information concerning physical, chemical and biological properties of the lake's water column. Appropriate scientific expertise will be present in the field to (1) manage the probe's sampling strategy, and (2) interpret the probe's results to comprehend the environment of Lake Ellsworth. Data collected by the probe will be recorded on site and made available to project members in the first instance, and the international scientific community. If samples are recovered, it may be possible to undertake first analysis on site. The bulk of material recovered will be packaged into sterile containers and transferred to laboratories where detailed analysis can take place.

Laboratory analysis

The laboratory analyses of samples from Lake Ellsworth represent the vital scientific process by which the research aims will be met. The analyses comprise four distinct, compatible work packages set out below. Effective communication between these work packages will ensure excess sample material is utilised fully (Figure 17).

Microbiology

The objective of the microbiology work package is to use well-tested laboratory analyses to document the nature of microbial life in Lake Ellsworth. Lake samples, borehole samples (time series of drilling fluid) and surface ice samples will be studied, to investigate the variance of life and control the studies for potential contamination. We will measure life within Lake Ellsworth through: (a) microscopy; (b) molecular biology; and (c) physiology (Table 3).

Microbiology approach	Detection Methods
Microscopy	Specific stains (x5), SEM & TEM
Culture	10 x 384 well plate 10 l per inoculum
PCR	Clone library, RT-PCR, Q-PCR
FISH	10 group specific probes
Environmental Genomics	Metagenomics / Whole genome
Biomarkers	Radiotracer 2 ml x 5 per assay

Table 3. Microbiological analysis of Lake Ellsworth water samples.

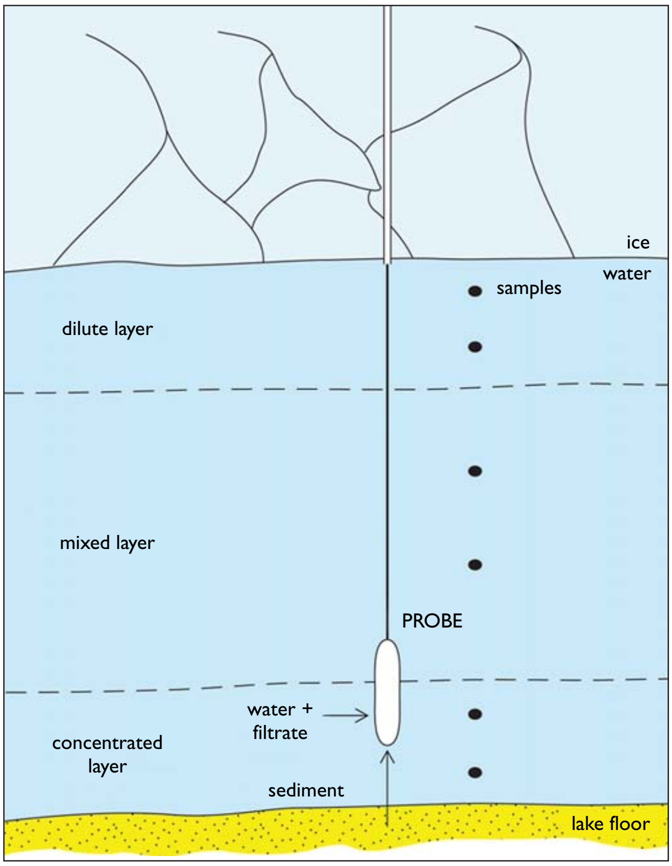

Figure 15. *Initial sampling strategy for the Lake Ellsworth probe.*

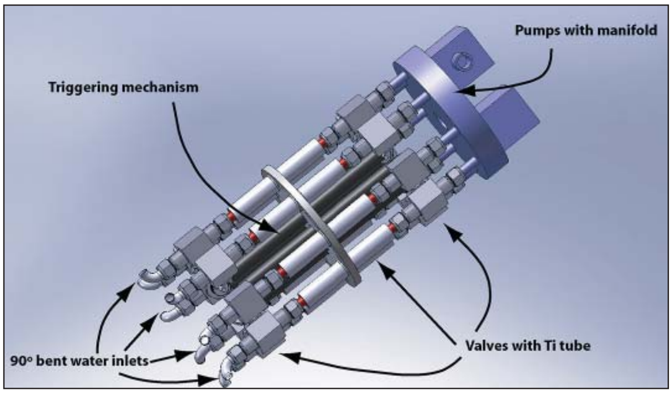

Figure 16. *3D representation of one carousel holding eight 50 ml sample containers. A full sampling unit will constitute of three carousels stacked together.*

Biological analysis

A combination of microscopy, biochemical and molecular biological techniques will be studied in 'clean' laboratory facilities to determine the abundance, distribution, and diversity of microorganisms in the lake. We will use standard microbial quantification techniques such as nucleic acid staining (SYTO 9, acridine orange) to obtain microbial numbers. Techniques such as FISH (Fluorescent In-situ Hybridisation) will be used to determine the phylogenetic groups of the organisms.

The following four laboratory techniques are available to investigate microorganisms within samples retrieved.

1. Microscopy; fluorescent and electron microscopy (used with specific gene probes).
2. Biochemistry (biogeochemical cycling). In the absence of light, the microorganisms within Ellsworth must be using either organics or inorganic redox couples to gather energy. We will use gene probes available for different biogeochemical activities to assay the water/samples for the presence of biogeochemical activity. This will include probes for iron cycling (reduction and oxidation), nitrate cycling, manganese reduction and other pathways of dissimilatory metal reduction and oxidation.

3. Molecular biology; genomic DNA (using gene probes coupled with FISH – Fluorescent *in situ* hybridisation) will be extracted from material obtained and used to construct a metagenomic library to screen for novel physiologies.
4. Infrared Raman (used to detect biomolecules); could reside at a surface station with the sensor head residing in the probe.

Organic geochemistry

The objectives of organic geochemical analysis are to characterize the organic chemistry of the water (i.e. what compounds are present, regardless of origin), to determine compounds indicative of, or capable of supporting, biological activity and to test for contamination. The restricted sample volumes from Lake Ellsworth will require different methods of analysis from more-typical experiments where sample volumes are unlimited.

The analytical techniques to be used include gas chromatography-mass spectrometry (GC-MS), and high performance liquid chromatography (HPLC).

The GC-MS will determine several different types of compound, including phenols, alkylphenols, polyaromatic hydrocarbons (PAHs), fatty acids and alcohols. Many organic compounds in natural waters reflect biological activity, but in very small samples we will focus on the more abundant types, especially fatty acids and fatty alcohols, including sterols. Amino acid concentrations will also be determined.

The HPLC work is best suited for water-soluble compounds (which are not suited for GC-MS). Using a unique coupling of HPLC to ICP-MS (inductively coupled plasma-MS), we will target compounds including heteroatoms that may reflect biological activity, especially organosulphur and organophosphorus compounds, variations in which can be compared against fluctuations of inorganic sulphate and phosphate in the same samples. The approach can also detect organometallic compounds such as porphyrins that are widely found in biological material (Raab et al., 2004).

Hydrochemistry

The objectives of this work package are to compare the water chemistry of Lake Ellsworth with that of the incoming ice melt to determine the following aspects of the physical, chemical and biological properties of the lake:

- the residence time of the water and the nature of circulation and stratification,
- the dominant geochemical processes,
- the nature of biogeochemical reactions and, hence,
- geochemical indicators of life.

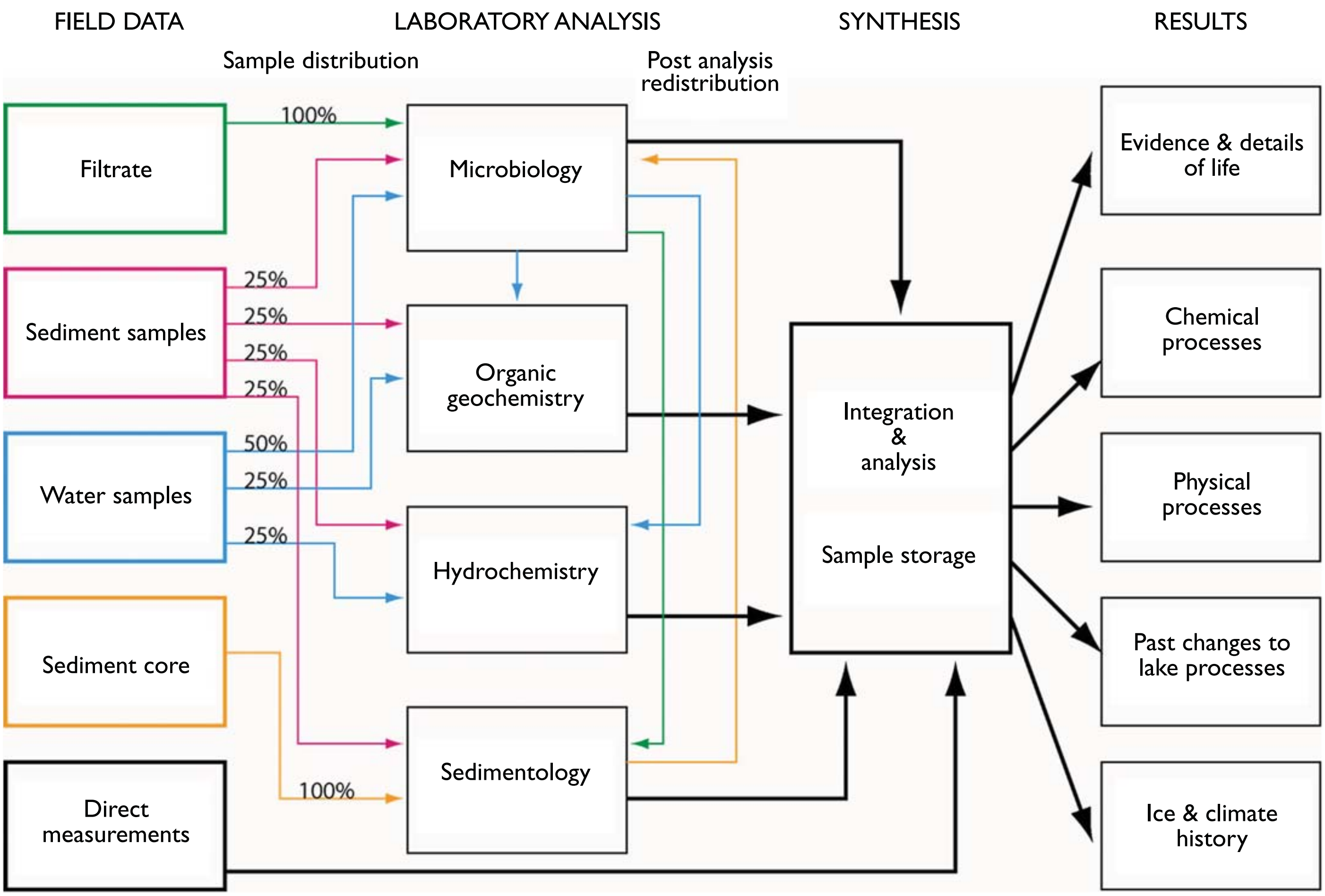

Figure 17. *Flow diagram of sample distribution and exchange, and analytical studies needed to meet the project aims.*

Sedimentology and palaeo-analysis

The sediment sequence beneath Lake Ellsworth is likely to contain an admixture of subglacially eroded sediment and dust from the ice above. Based on the seismic evidence that demonstrates sediment thicknesses of >2 m, it is likely that subglacially eroded sediment is the dominant component (estimates of aeolian dust concentrations in the overlying ice are too low to produce this order of sediment thickness). The array of sedimentological analyses that will be applied to the sediment core from Lake Ellsworth for life detection, core dating and palaeo-environmental reconstruction have recently been tested on Hodgson Lake, a subglacial lake that has recently emerged from a retreating margin of the Antarctic Peninsula Ice Sheet (Hodgson et al., 2009a, 2009b).

Integration of *in situ* and laboratory data

Direct measurements of the lake's water column (taken by the probe) will be compared with laboratory results from the water and sediment samples to form a comprehensive evaluation of the physical, chemical and biological conditions and processes within Lake Ellsworth. This integration will also involve analysis of the sediment core, to understand how modern conditions in the lake may have changed in the past.

Chapter 5: Description of the camp and the logistics

This chapter describes the camp equipment and personnel that will be deployed and the transport arrangements for deploying them.

Camp overview and location

The camp will be established during the 2012/2013 Antarctic season for a period of approximately eight weeks and will take the form of a static field operation camp (see Fig 18 for layout).

The camp will be located at **78°58'4.44''S 90°34'27.56''W**, well clear of any previous field camps.

Living and working environments will be achieved with a combination of tents used by the British Antarctic Survey as standard items at other field sites.

The majority of the drilling and sampling equipment will be housed in lightweight ISO 20' shipping containers, making transport and deployment relatively straightforward.

There will be one utility vehicle on site (envisaged to be a modified Tucker Sno-Cat with a hydraulic crane) which is essential to the operation.

Power will be provided by four standard generator sets running on AVTUR fuel (Jet A-1). They will provide 240 v 50H z 1Ø power to the domestic camp and 415 v 50 Hz 3Ø power to the drilling site.

Fuel will be transported and used in two ways:

- Drummed fuel will be used to supply the generator sets and vehicle.
- Bulk fuel (using flexible bladders) will be used to supply the hot water boiler.

There will be a communications link between the domestic camp and the drilling site allowing remote observation / operation of equipment.

Personnel

The on-site team for the 2012/2013 drilling season will be composed of ten people, covering the following roles:

- Programme Manager – responsible for overseeing the operation
- Drilling Engineers (x 2) – responsible for the drilling the hole
- Instrument Engineers (x 2) – responsible for deploying the instrumentation
- Plant Engineer – responsible for power generation, vehicles and fuel management
- Scientists (x 3) – responsible for directing and handling the samples
- Camp Manager – responsible for running the domestic camp and waste managemnt

All team members will attend the Antarctic Briefing Conference held annually by BAS and will undertake Antarctic Medical Preparation Training and Field Training prior to deployment. In addition, many of the team will double up on roles receiving training in each other's areas to ensure maximum efficiency and redundancy within the team.

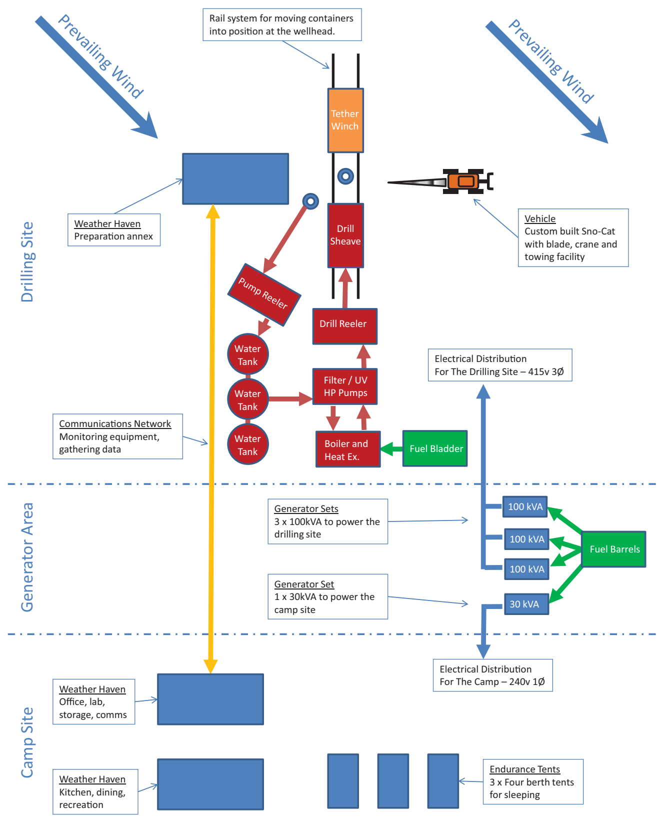

Figure 18. *Schematic layout of the camp.*

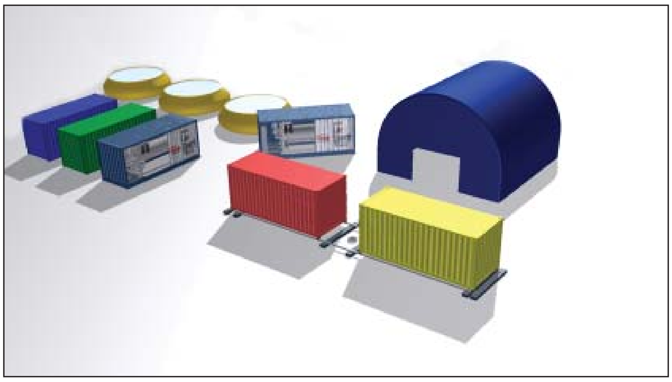

Figure 19. *3D Model of the drilling site as per the layout in Figure 18.*

Power generation and fuel calculations

The generators will be standard off-the-shelf units housed in acoustic cabinets and mounted on a skid base. They will have integral day-fuel tanks.

There will be 1 x 30 kVA unit to run the domestic camp and 3 x 100 kVA units which will have a combined output capable of running the drilling operation.

30 kVA utility set (Generator 1)
Allowing de-rating for altitude and using AVTUR fuel = **25 kVA**

100 kVA main sets (Generator 2, 3 and 4)
Option 1 – 3 sets running @ 80% = 240 / de-rate – 10% AVTUR & 8% altitude = **177 kVA**

Option 2 – 2 sets running @ 95% = 190 / de-rate – 10% AVTUR & 8% altitude = **156 kVA**

These two options make provision for redundancy.

Honda portable sets (PETROL) x 2 for charging, welding, starting engines, emergencies, etc.

The running hours for the units are as follows:

The plan is for an 8 week season = 56 days (**1,300 hrs**)

Main drilling = 2.5 days / Total drilling = 4.5 days (**100 hrs**)

Generator 1 = **650 hrs**

Generator 2 = 100 + 30 = 130hrs + 72 pre drill ramp-up = **202 hrs**

Generator 3 = 100 + 30 = 130hrs + 48 pre drill ramp-up = **178 hrs**

Generator 4 = 100 + 30 = **130 hrs**

Boilers = 100 + 30 = **130 hrs**

Sno-Cat = **250 hrs**

Generator 1 @ 7 lph = 4,550 l (**22 drums**)

Generator 2 @ 22 lph = 4,444 l (**22 drums**)

Generator 3 @ 22 lph = 3,916 l (**19 drums**)

Generator 4 @ 22 lph = 2,860 l (**14 drums**)

Boilers = 15,000 l (73 drums) + 4,500 l (22 drums) = 19,500 l (**95 drums**)

Sno-Cat = (Full load 30 lph / no load 20 lph / site 5-10 lph) = 2,460 l (**12 drums**)

Re-fuel planes = 6 flights @ 5 drums = 6,150 l (**30 drums**)

Contingency (approx 15%) = 7,380 l (**36 drums**)

Total AVTUR = 51,250 l (250 drums)

Total PETROL = 1,025 l (5 drums)

The fuel required on site for drilling, power generation and other logistics will amount to approximately **51,250 l** of **AVTUR** and **1,025 l** of **unleaded petroleum** spirit for generators, power tools, etc. This will fuel all equipment and vehicles directly associated with the programme including the refuelling of the BAS Twin Otter. This does not include fuel for the tractor train or IL-76 flights provided by Antarctic Logistics & Expeditions LLC (subsequently referred to as ALE).

Fuel is to be transported to site by ALE using sledges in a combination of 205 l drums and bulk fuel flexible bladders (5,800 l or 1,500 US gallons each bladder). Four of these bladders will be required to provide a sufficient, uninterrupted fuel supply for the hot water boiler.

This bulk fuel system has been used extensively by the US Antarctic Programme to transport fuel to the South Pole station. It is a well tried and tested method providing a high degree of confidence. Fuel handling, spill prevention and spill response procedures will be in place, as discussed further in Chapter 6.

Vehicles

The only vehicle used on site will be a Tucker Sno-Cat (or similar) modified specifically for this programme. It will provide a towing facility, a snow clearing blade and a 7.2 m reach hydraulic crane. The vehicle will be modified to run on AVTUR fuel, reducing the number of different fuels required on site.

The vehicle will be fully serviced and optimised prior to deployment and a "scrubber" will be fitted to the breather and exhaust to further reduce emissions. The vehicle will be maintained on site by an experienced plant technician.

The vehicle will be driven efficiently by trained operators and will not be left idling unnecessarily.

Water and waste

Water for the domestic camp and the drilling operation will be produced from melted snow.

It is anticipated that the drilling operation will use a maximum of **90,000 l** and the domestic camp will use a maximum of **10,000 l** of water.

The wastes generated throughout the duration of the programme will include human wastes (sewage), food wastes, food packaging, grey water, fuel drums and batteries. There will also be a small amount of waste oil (circa 15 l) from the 30 kVA generator which will require a service mid season.

All waste materials will be stored on site in appropriate containers pending removal at the end of the field season for appropriate disposal outside Antarctica.

Communications

There will be a comprehensive communications infrastructure on site consisting of an Iridium satellite system providing voice and data capability, high frequency (HF) radio providing long range voice capability and very high frequency (VHF) hand held radios providing local communications around the site.

There will be a local area network providing a method of storing and accessing data and e-mail, as well as providing a method of remote monitoring of the drilling equipment and generator plant.

Transport of equipment and personnel

The science equipment (including the hot water drill, winch, drilling hose, etc) and the auxiliary equipment (such as the generators, vehicle, domestic camp, etc) will have a total combined weight of 60 tonnes (approx) and the fuel supplies a further 55 tonnes (approx).

The majority of this equipment will be shipped to Punta Arenas, Chile, on the RRS James Clark Ross. From there, it will be moved to the ALE base camp by Ilyushin IL-76 heavy lift aircraft. Five rotations of aircraft will be required to transport the equipment into Antarctica over a period of two Antarctic seasons.

Onward transport will then be via a tractor train to the Lake Ellsworth site, via the Ellsworth Mountains, using up to two tractor and sledge units, each towing circa 18 tonnes of cargo. Between ten and twelve tractor traverses will be required to transport equipment and fuel to the drill site.

The proposed tractor route is as shown in Figure 21 and is estimated to be 295 km long.

Reconnaissance work carried out during the 2010/2011 season by ALE confirmed this route from the Union Glacier to the Lake Ellsworth drill site is crevasse-free and workable.

Personnel and some field support and light science equipment will be transported by BAS Twin Otter aircraft from Rothera over a number of flights through the programme duration.

Equipment and personnel removal

At the end of the 2012/2013 field season, the camp and equipment will be de-rigged and packaged for transport. All science samples and personnel will be transported off site at this time, along with some waste. This will be done using a combination of BAS Twin Otter through Rothera and ALE tractor train through the Union Glacier base camp.

The camp, the remaining waste and some field equipment will be moved off site during the 2013/2014 season by ALE. No equipment will be left at the Lake Ellsworth drilling site. The area will be groomed after the removal of all the equipment so that the site is returned, as far as possible, to its original condition.

The hot water drilling system will be transported by ALE to another location as it is due to be used by a science project during the 2014/2015 season.

Contingency plans

The programme team recognise the need for support from an established forward camp in the event of operational or serious health and safety incident. Such support will be provided by ALE from their base camp, and by BAS from Rothera.

In the event of an incident on site leading to the need for external support, there will be communication with BAS at Rothera Station and ALE at their Antarctic base. On site at Lake Ellsworth will be an Iridium satellite based system, high frequency (HF) and very high frequency (VHF) radio

Figure 20. *shows an image of the proposed flexible bulk fuel container on a skid base.*

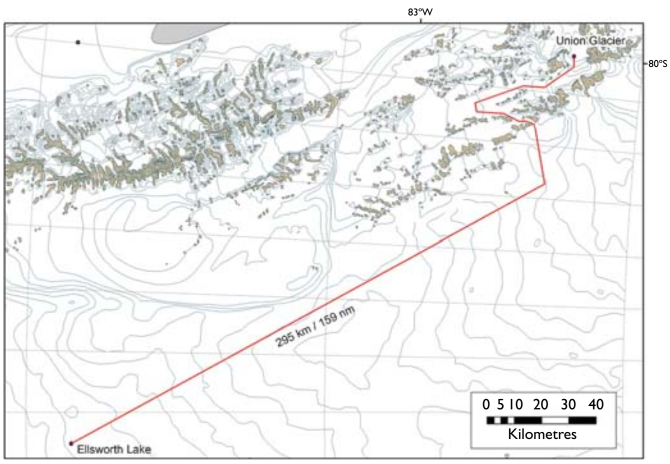

Figure 21. *The transport route for equipment and fuel from the ALE base camp at Union Glacier to the proposed drill site.*

Figure 22. *The tractor and sledge used to transport equipment and fuel to the drill site.*

communications. Both Rothera and ALE have a 24 hour emergency communication and listening service.

The BAS Twin Otter aircraft will provide search and rescue capability.

Safe Site Procedures

All work on site will be governed by a comprehensive set of safe working procedures backed up by many months of training prior to the commencement of the field season. All risks will be identified and safe procedures will mitigate these as far as possible. The Programme Manager on site will be responsible for ensuring that these procedures are followed at all times.

Where the consequence of a risk is unknown but facing it is unavoidable, e.g. the risk of a clathrate reaction whilst drilling at the point of breaking through to the lake, the safe site procedures will ensure that all personnel are clear of a pre-defined exclusion zone and that the equipment can be operated remotely from outside of this zone.

Chapter 6: Identification or prediction of impacts, including preventative or mitigating measures

Methods and data used to predict impacts and mitigation measures

To allow the assessment of the environmental impacts associated with this proposed exploration programme, relevant information on the nature of the programme (scope and duration) and the environment in which the proposed programme will take place, have been gathered. This chapter builds upon this information to discuss how the programme might alter the baseline environmental conditions (i.e. the potential environmental impacts), and how such impacts will be mitigated.

In addition to site and programme specific data, special consideration has been given to relevant guidance and codes of conduct documents. These include:

- *The Guidelines for Environmental Impact Assessment in Antarctica* (COMNAP, 1999) which gives advice on methods, procedures, and processes involved in writing EIAs in Antarctica.
- *Exploration of Antarctic Subglacial Aquatic Environments, Environmental and Scientific Stewardship* (National Research Council, 2007) (referred after as NAS – EASAE) which sets out principles for environmental protection and includes guidance on sterility and cleanliness.
- *Code of Conduct for the exploration and research of subglacial aquatic environments* (SCAR 2010) which summarises proposed best practice principles, in drilling and lake entry and sampling and instrument deployment.

The environmental impacts of this proposed programme are predicted on the basis of professional opinion and judgement, using the knowledge described above. Direct, indirect, cumulative and unavoidable impacts are examined. An impact matrix has been prepared to assess the predicted impacts of the exploration programme. Impacts are ranked according to their extent, probability, duration, intensity and significance.

Where impacts are predicted, measures to mitigate or to prevent those impacts are identified and discussed.

All activities will be carried out in strict compliance with the Environmental Protocol, and will be subject to a permit issued by the UK Foreign & Commonwealth Office under the Antarctic Act (1994).

Impact on native flora and fauna within Lake Ellsworth

Lake Ellsworth is a pristine aquatic environment and it is imperative that possible damage and contamination during its exploration be minimised or eliminated. There is currently no knowledge on the presence and type of any life forms within Lake Ellsworth but it is hypothesised that the lake contains unique microorganisms adapted to the extreme environment.

Microbial communities and naturally occurring mechanisms of introduction are discussed in the NAS-EASAE report which states that *"Many potential mechanisms exist for bacterial dispersion… about 10^{18} viable microbes annually are transported through the atmosphere between continents (Griffin et al., 2002)… Of particular importance to the study of subglacial aquatic environments is their potential connectivity, which may allow the movement of microbes beneath the ice sheet...The surface of the Antarctic ice sheet acts as vast collector for microbiota deposited from the atmosphere (Vincent, 1988) global ocean currents [and] birds… a subset of this microflora may retain viability and even metabolize within the snow and glacial ice (Price and Sowers 2004; Price 2007). These communities of viable cells and spores may ultimately reach the subglacial aquatic environments to provide a continuous inoculum at the melting glacier ice-lake water interface"*. This statement is significant as it indicates that the endogenous microflora in the overlying ice will have wide geographic origin and will be entering the lake through natural processes.

The NAS-EASAE report also refers to the microbiology in Lake Vostok, where *"Reporting on the microflora in ice cores from Lake Vostok, (Abyzov ,1993) points out that in the deepest ice he examined (2405 m) only spore-forming bacteria remained."* This implies that whilst the microflora in surface ice may be global in origin, the community structure has changed during transition to deep ice.

The introduction of non-native micro organisms which have the potential to alter the lake's native populations must therefore be prevented to protect both the environment and the scientific value of the exploration. This is especially important not only to protect the native microbial biodiversity of Lake Ellsworth, but also that of any subglacial aquatic habitat down gradient of the lake.

The Lake Ellsworth consortium recognises that the greatest environmental impact associated with this programme is the potential to introduce microbial life into the subglacial environment, or disrupt the communities present, and has integrated environmentally protective measures throughout the design of the programme. Microbial control is central and dominant in the design process. Protective measures include the selection of the drilling method with the least potential for contamination, the use of melted ice in the drill fluid and by cleanliness in all engineered systems. These work in addition to the naturally occurring sterilisation and cleaning action of the extreme environmental changes that the structures will encounter.

The hot water drilling system, using melted ice water as a drill fluid, heated to at least 90 °C, filtered to 0.2 μm, and UV treated, minimises the potential for contamination. Further protection is given by the cleaning and sterility methods i.e. microbial control applied to engineered equipment, and is discussed further below.

It is noted that the ideal programme design would involve achieving complete sterility for all equipment and drilling water. However, it is accepted that sterility, as an absolute value, is not always possible or verifiable.

Currently, there are no detailed, published cleaning protocols for microbial control that could be directly applied to the programme and so a task group was formed within the programme to discuss and decide on an appropriate set of standards to adopt within the Lake Ellsworth Programme.

This task group reviewed and recommended applicable protocols (e.g. from space and pharmaceutical industries, and the UK's National Health Service for surgical procedures) for cleaning that could be applied to the programme, and devised working standards and microbial control methods to be deployed that would enable the principles recommended by SCAR and NAS to be met.

The following standards will be applied:

1. Our general principle is a target of no measurable microbial populations to be present on any engineered structures in contact or communication (i.e. the probe, tether, sediment corer, and thermistor string if deployed) with the sub aquatic environment.
2. All engineered structures will be checked after manufacture and once ready for shipping to determine any presence of microbial populations (i.e. that the principle above is being met).
3. In addition to the above, once the engineered structures are in the field, they will be subject to a method of microbial control that has been proven to work on Ellsworth samples (through previous UK based laboratory trials).

These standards will be met through the application of a range of microbial control methods which, when coupled with the hot water drilling method described in Chapter 4 reduces the risk of contamination of Lake Ellsworth significantly.

Different categories of microbial control will be used in the different stages of programme, from programme design, construction and deployment of the equipment, and microbial population reduction methods (i.e. removal and destruction of organisms on experimental apparatus).

Our effort is focused on equipment that is in direct communication with the lake through the ice borehole. These are 1) the wellhead (consisting of a borehole liner, UV collar for sterilisation, and gate valves to provide an air-lock), 2) the sheaves used to lower equipment into the borehole, 3) the hot water drill hose and head for creation of the borehole, 4) the probe used to make measurements and take samples and its tether, 5) a sediment corer, and 6) a thermistor string (if deployed).

Microbial control at design stage

To improve the efficacy and extent of application of these methods there are a number of steps that can be taken during engineering design of the sampling equipment used. These are primarily:

1. Materials selection of probe and sampling equipment. In general, hard materials (e.g. titanium) are easier to clean than those with thick oxides (Aluminium) or soft materials (elastomers and rubbers which may be porous). Titanium will be used extensively on the probe. This simplifies microbial control and also enables trace iron analysis, (see Table 4) and reduction of the thickness of load bearing structures giving more room for ancillary equipment. Samples of all candidate materials have been exposed to cleaning and the population control measures to identify any material degradation and the efficacy of these treatments.
2. Minimisation of recesses. Recesses and intricate surface topography has been shown to promote microbial growth (Ploux et al., 2009). Autoclaving is the only procedure that can reliably kill organisms in blind recesses but cannot be used for all materials, components and subsystems. We have therefore limited the number and extent of recesses through design. Where a recess cannot be avoided we will use sterile liquids (for pressure communication and compensation) and elastomeric capping (potting) to provide a recess free and cleanable surface. All fluidic systems (e.g. the valve and pump system for the water sampler) are designed to enable flushing to enable cleaning with HPV and/or chemical wash.
3. Limited handling. The design should facilitate operation whilst requiring minimal handling. This requires simplicity, durability and reliability. For example the probe is designed to operate without being touched after final assembly, cleaning and bagging. Targeted reliability design has and will be used to ensure the sterile bagging is not opened to affect repairs or adjustments.
4. Containment. Once the engineered systems are assembled and cleaned they must be protected against recontamination. All the systems are designed to be placed within protective environments such as sterile bags which protect them against unavoidable handling.

Microbial control during construction, transport and deployment on site

In the construction phase, a combination of post manufacture cleaning and population reduction methods will be used to ensure components are clean. The population reduction methods selected (from the shortlist below) will depend on the material and design of the component. Assessment and verification will be undertaken at a process level in all cases and at a component level where required. The components will be assembled where necessary (e.g. where an inaccessible void is created such as in a gas filled pressure case) in a clean room environment to ISO 14644 (Cleanliness for equipment used in clean rooms) working to Class 100,000 (ISO 8) of this standard[1]. Terminal cleaning (i.e. at the end of the assembly) will be used in all cases and may be sufficient for simple structures and subsystems. Subsequent to final terminal cleaning equipment will be bagged and placed in a protective environment (e.g. heat sealed bagging or hard case).

The **sheaves**, **hot water drill head, probe tether** and **sediment corer mechanical systems** will all be sterilised using a combination of chemical wash, autoclaving, HPV and UV (see below) post construction and assessed prior to being placed in a protective environment for transport to site. These items are manufactured from robust materials that can withstand harsh cleaning and population reduction methods (such as autoclaving). They are also simple in design and do not have enclosed recesses or voids, making them amenable to HPV treatment. The latter can be applied through ports in the protective case or bagging (see below for a discussion of efficacy). This approach is both economic and effective.

The **probe** and **sediment corer electronics modules** will be cleaned and sterilised using HPV and in more robust areas also by UV at a subsystem level assembled in an ISO 14644 class 8 clean room environment, re-sterilised post construction and assessed prior to being placed in a protective environment for transport. This more complex preparation is required to assure protection of the environment and that scientific samples are not compromised with exogenous populations

[1] *Pharmaceutical industry permissible limits for cleanliness of equipment in clean rooms as per ISO 14644*

brought in on sampling equipment. It is also required for these more complex systems where recesses and enclosed voids (e.g. seals and sealed pressure cases) cannot be avoided.

The **hot water drill hose** will be cleaned internally by HPV and cleaned externally through the production line bath prior to being capped for transport. The hose interior will be used to transport hot water down to the base of the borehole and requires a greater sterility standard than the exterior which is too large to place in a protective environment. Before use it will be jet washed with the drill water (at a minimum temperature of 90 °C, filtered to 2 µm, and UV treated) and will then be continuously flushed with (the filtered and heated) water returning to the surface during pump operation during use.

For transport all equipment (including items in a protective environment) will be placed in 20' ISO shipping containers. The **probe** and **sediment corer** will be placed in containers as will the probe sheave, winch, and tether. The containers will be sealed with a combination of elastomeric compression seals and heat sealed (EVA) bagging. The integrity of the seal will be assessed using a positive pressure provided by filtered air and watching the pressure drop rate to assess leaks. The sealed containers will be shipped to site without breach of access and are designed to enable operation of the probe and corer without contact with the environment outside of the borehole. This is achieved by the use of flexible sterile links (tubes) and an air lock arrangement at the wellhead (see below). Sterilisation apparatus (HPV or UV see below) will be included in the sealed winch container to mitigate the risk of seal breach.

A mechanical drill will be used to create the top few meters of the borehole. The hole created will be further sterilised using a UV source lowered into the hole. The **wellhead** will be placed into this predrilled shallow borehole.

UV exposure will be used to sterilise the drill hose sheave and well head exterior. The drill hose will be mounted onto a winch and passed over its sheave and uncapped prior to commencing drilling.

The deployment procedure does not include assessment to provide data for control or verification of the processes once these are underway i.e. there will be no testing done in the field before use of the equipment. This would not be practical as access of sealed engineering structures by Antarctic personnel would be a source of contamination, and the analytical techniques (see below) with the required limits of detection take too long to provide meaningful feedback during the short duration of the experiment.

Prior to the commencement of drilling operations the well head UV collar (0.5 m diameter, 254 nm, 30 W) will be activated and the gate valves opened prior to lowering a UV source (254 nm, 30 W providing > 10^4 reduction (requires >16 mJ/cm^2 as per ANSI/NSF Standard 55-1991)) into the pre drilled borehole. In the widest part of the borehole (0.5 m diameter) this source may pass at approximately 2 m/s and still meet the ANSI/NSF standard. This provides a sterile top section to the borehole. During drilling the exterior of the drill head and hose will be jet washed with drill fluid (which is filtered, heat sterilised (90 °C), and UV treated) and will pass through the UV collar included in the well head. The function of the jet washing is to remove any remaining dirt and extraneous material from engineering surfaces. The efficacy of UV sterilisation treatment (see below) increases with the energy density applied to the exposed surface. The hose moves slowly (0.5-1.0 m min^{-1}) enabling efficient coupling of UV energy onto its surface. A UV dose of 2.2 J/cm^2 is theoretically possible. The drill hose interior will be flushed with water generated from local melt (3 l s^{-1}, 90 °C at the surface), filtered to remove particles > 0.2 m, and UV treated. The exterior of the hose will be flushed with a combination of this drill water and melt-water generated from the borehole drilling. This flushing enables significant dilution and removal of remaining microbes on the drill surface.

On completion of the hot water drilling the hose and drill head will be removed from the borehole. The hydrostatic level (i.e. the level of water in the borehole following breakthrough into the lake) is predicted to be approximately 270 m below the ice surface. The air filled section of the borehole will be sterilised again using a UV source passed up and down this region. During this procedure the UV collar in the wellhead will be used to sterilise the tether for the UV source. On removal of the UV source the wellhead gate valves will be shut.

The procedure for microbial control during deployment is identical for the probe and corer systems. Each is attached to a sealed container containing the tether and winch systems via flexible links (tubes) down which the tether can pass without coming into contact with the external environment.

The protective case (or bag) for the probe (and subsequently the corer) will be connected to the top of the wellhead. The upper gate valve is then opened and the UV collar used to sterilise the connection. This system will be prototyped and tested before deployment. If UV is not able to sterilise this link (in this air-lock) then HPV will be considered. This could be generated by the system included in the probe / corer / tether transport container. The probe (or corer) will then be lowered through an orifice (either a gate valve or a burst valve / weak point) in its protective casing into the wellhead. Once the top of the device is at the level of the top of the wellhead (approximately at the surface of the surrounding ice) the connection to the tether will be made through a glove box included in the flexible link. The sheave for the probe / corer tether is integral to this flexible link. The tether is then tensioned and used to lower the probe / corer into the borehole and lake. On recovery the probe / corer returns to its protective case for further handling and sample extraction under controlled conditions

Population Reduction Methods

Hydrogen Peroxide Vapour (HPV) will be used in the construction of many of the instruments and structures prior to shipping to Antarctica. HPV will also be an option at the field site to reduce exogenous micro organism populations if UV light alone is not shown to be sufficiently effective. It is the preferred method for planetary protection used by NASA (Chung et al., 2008), and is widely used for decontamination of equipment and facilities including hospitals and large laboratories, (French et al., 2004; Boyce et al., 2008; Otter et al., 2009).

Despite requiring a dedicated machine (to generate the vapour), heat and ventilation for a significant duration (~2 hrs to enable the peroxide to degrade to harmless water and oxygen) this technique is attractive because: systems are available commercially (e.g from Bioquell, Andover, Hampshire, UK and Steris, Basingstoke, Hampshire, UK); it enables treatment of engineered structures with complex topography and small recesses; it can be used on a wide range of polymers and all electronic components (Rogers et al., 2008), it has high and proven efficacy (typically 10^6 reduction, (Rogers et al., 2008; Otter 2009; Pottage et al., 2010; Otter and French 2009; Rogers et al., 2005) ,and does not result in a toxic end product requiring disposal (Rogers et al., 2005; Johnston et al., 2005; Klapes and Vesley, 1990). HPV is effective against a wide range of organisms including endospore forming bacteria such as; *Clostridium difficile* (Otter et al., 2009; Otter and French, 2009; Barbut et al., 2009; Johnston et al., 2005; Khadre and Yousef, 2001), *Bacillus anthracis* (Rogers et al., 2005), *Bacillus cereus* (Khadre and Yousef, 2001), *Bacillus subtilis* (Rogers et al., 2005; Klapes and Vesley, 1990; Wardle and Renninger, 1975),and biofilm forming bacteria, including; *Pseudomonas putid* (Antoniou and Frank, 2005; Silva et al., 2008), *Staphylococcus aureus* (French et al., 2004; Silva et al., 2008), *Staphylococcus epidermidis* (Wardle and Renninger, 1975), *Yersinia pestis* (Rogers et al., 2008). It is also effective against fungi (Hall et al., 2008), viruses (Pottage et al., 2010), and prions (proteinaceous infectious particles) (Fichet et al., 2007). After a thorough assessment of portability, ease of use and adaptability to the Antarctic environment a Clarus (TM) L2 hydrogen peroxide vapour generator has been purchased. The instrument will be used locally in the UK during manufacture and assembly.

However, in some implementations it does require modest volumes of hydrogen peroxide (typically 30% w/w, 100 ml would be sufficient to sterilise 30 m^3). We will take 2 l of Hydrogen Peroxide to the drill site which is more than sufficient to sterilise all equipment should contamination occur (e.g. in transit). There is evidence that efficacy is increased at decreased temperatures (-11 °C to 4 °C), (Klapes and Vesley, 1990). A full risk assessment and procedure for use will be in place in accordance with the standard practice of the British Antarctic Survey.

Ultra Violet Illumination will be used at the field site for treatment of the probe, the drill hose, and well head structures (including the air filled section of the borehole). UV has high efficacy (>10^4 reduction), is portable, requires modest infrastructure and is fast acting (Wong et al., 1998), (Bak et al., 2010; Gardner and Shama, 1998; Halfmann et al., 2007). However efficacy is dependent on the energy coupled into the surface which may be limited by surface topography, (Warriner et al., 2000). It may be used (e.g. on the moving drill hose) in applications where other methods are impractical. This motivates the widespread use in the access of Lake Ellsworth particularly where topography is limited or where sufficient exposure can be achieved with modest infrastructure. The tether will be exposed to UV through the collar at the wellhead. However in operation the tether can move quickly (<2 m s^{-1}) reducing the energy that can be coupled into the surface which may mean that the efficacy of this treatment may be insufficient. This is under investigation by the Lake Ellsworth consortium. The procedures outlined above ensure sufficient microbial control even if UV illumination of the tether proves impractical.

Autoclaving will be used in the construction and preparation of the probe (and the water sampler in particular). This method offers a proven and convenient method of treating resistant structures and is effective for closed volumes (e.g. water retained within a sample bottle). Autoclaving still remains the most popular method for sterilisation of healthcare surgical equipment, (Agency, 2007), and glass and elastomeric components used in the pharmaceutical industry, (Agalloco, 2004). This method is problematic for electronics, water sensitive, or temperature intolerant materials which are used on the Lake Ellsworth probe preventing use on all systems. However, autoclaving is attractive for robust subsystems (e.g. the water sampler bottle).

Chemical wash will be used in preparation of equipment where persistent micro-organisms are encountered. We will not use this method extensively on site to reduce the complexity of environmental protection and site cleanup. Only 70% ethanol will be used in Antarctica (total 10 l) for laboratory sterilisation and preparation of small items.

It has been found that chlorine-based compounds kill or inhibit a greater range of micro-organisms than any other reagents, (Pap and Kisko, 2008; Aarnisalo et al., 2007; Wirtanen et al., 2001). However, penetration of biofilms is more problematic than action on cells in suspension (Wirtanen, 2001). Hydrogen peroxide, (Wirtanen et al., 2001), and particularly peracetic acid-based treatments have been shown to be more effective against biofilms (Silva et al., 2008; Wirtanen et al., 2001; Fatemi and Frank, 1999). Peracetic acid has proven sporicidal, bactericidal, viricidal and fungicidal activity (Holah et al., 1990; Kruse et al., 1964). The Lake Ellsworth consortium will evaluate the efficacy and materials compatibility of the most promising of these treatments with the materials used in the construction of engineered structures (see below).

HPV and UV treatment may be combined (Gardner and Shama, 1998; Bayliss and Waites, 1979; Bayliss and Waites, 1980; Arrage et al., 1993; McDonald et al., 2000), to increase efficacy up to one hundred fold, (Bayliss and Waites, 1979: Bayliss and Waites, 1980). This technique will be used if sufficient standards are not achieved using other methods.

The synergistic effects of UV and hydrogen peroxide lead to a generation of hydroxyl radicals that have lethal effects on vegetative bacteria and spores, (Warriner et al., 2000). This is because hydrogen peroxide is a photo-sensitizer which produces OH, peroxy and hydroperoxy radicals, (Sosnin et al., 2004).

Verification and assessment

The efficacy of each of the microbial control methods described above will be verified in UK laboratory trials.

We will use positive control contamination by adherent bacteria *Pseudomonas fluorescens* to contaminate engineered surfaces and components. This species is commonly used as model system and is representative of likely contamination of engineered structures. The level of contamination will be assessed (see below), population reduction methods applied and repeated measurement of population used to calculate the reduction achieved. This method allows accurate efficacy assessment whilst minimising error by raising the number of cells well above the limit of detection.

The analytical methods proposed will also be used for assessment of the standards achieved in the preparation of engineered systems. As stated above the final assessment should generate a result at or below the detection limit of the analytical method and will be followed by a final population reduction step. This final step will not be assessed as the breach of protective environments required for assessment is a frequent cause of recontamination. However, the method used will have been qualified using the positive control method described above.

Analytical methods

Visualisation of cells with fluorescence microscopy post staining with 4,6-diamidino-2-phenylindole dihydrochloride (DAPI), 5-cyano-2,3-di(p-tolyl)tetrazolium chloride (CTC), Light GreenSF Yellowish (Acid Green) or LIVE/DEAD® BacLight™ Bacterial Viability Kit (Invitrogen). Fluorescence microscopy, (Kepner and Pratt, 1994), is advantageous as it has a low limit of detection (one cell per field of view), requires modest infrastructure and allows discrimination of live/dead cells (Boulos et al., LIVE/DEAD (R) BacLight (TM): 1999).

A qPCR enumeration using domain specific primers (archaea, bacteria, and eukaryota). qPCR is a robust (if experimental contamination is controlled) and quick analytical technique with very low detection limits, (Burns and Valdivia, 2008). The technique could also be employed in the field with modest infrastructure. We will also combine qPCR with fluorescent staining for positive contaminant live/dead discrimination (Rawsthorne and Dock et al., 2009)

Adenosine Triphosphate (ATP) will also be used as a marker of cell presence on probe components and will be measured using the bioluminescence luciferin-luciferase assay, (Lin and Cohen, 1968). The concentration of ATP found in solution in environmental samples is subject to processing and matrix effects as ATP binds efficiently to surfaces (Webster et al., 1984) and requires optimisation for the specific materials and geometries used in the Lake Ellsworth experiment.

Each of these techniques will be used in the preparation of engineered systems. Microscopy facilities will also be available on site at a minimum.

Developments planned by the Lake Ellsworth Consortium

Each of the population reduction methods and analytical methods requires validation, and in some cases optimisation or adaptation when used with the materials and systems used in the Lake Ellsworth experiment. There will also be a degree of feedback from these results into the design of engineered systems and the procedures used in the experiment.
To this end the Lake Ellsworth consortium is currently engaged in a comprehensive study of population control and analysis techniques. This includes the use of *Pseudomonas fluorescens* as positive control both for inter-comparison of analytical techniques and for efficacy evaluations. These will be completed versus a panel of materials used in the Lake Ellsworth equipment including titanium (used for many mechanical systems and specifically the critical sampling equipment), PTFE (used for seals and pipes) and polyurethane (tether and cable sheathing, potting of recesses and unions). This will enable the selection and widespread use of the most appropriate reduction and analysis methods for the Lake Ellsworth experiment. A preliminary list of the reduction methods is in shown in Table 4. Material degradation has been assessed by scanning electron microscopy of the surfaces) and log-6 microbial population reduction has been tested using an ATP-luciferase assay.

Type of Material	Lake Ellsworth equipment component	Acceptable Microbial Reduction Method
Titanium (grade 5)	Sampling bottles	70% (v/v) ethanol, HPV, UV
PTFE	Seals and pipes	70% (v/v) ethanol, HPV
Polyurethane	Probe tether and hot water drill sheathing	70% (v/v) ethanol, HPV
Ethylene propylene diene monomer	O-rings of sensors and sampling bottles	70% (v/v) ethanol, HPV, UV, autoclave

Table 4. Microbial reduction methods for selected materials used in Lake Ellsworth. The list includes methods that achieved log-6 microbial population reduction and did not cause material degradation.

This study of population control methods is on-going and the Lake Ellsworth Consortium plan to provide further updates (by submission of an Information Paper to the CEP 2011) and include the final selection of method in the final CEE.

Impact to air

The combustion of fossil fuels from the aircraft and tractor trains used in the logistics, and in the running of generators and vehicles at the drill site will produce carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), sulphur dioxide (SO_2) and particulates PM10.

The logistical arrangements are described in Chapter 5 of this report.

It is currently envisaged that 250 No. 205 l drums of AVTUR, and 5 No. 205 l drums of unleaded petrol will be required for powering the vehicles, generators and all the equipment at the drill site. The tractor supply vehicles require additional 32000 litres of AVTUR.

The predicted atmospheric emissions associated with the fuel used on site are presented in the table below. These emissions are spread over the four month period the field camp is operational but will peak during the three days of drilling. This will result in localised air pollution, but this is considered to be of very low significance.

Fuel emissions related to aircraft transport will be dispersed over a wide area en route and within Antarctica, but will be rapidly dispersed and will not affect ambient air quality. They will however contribute to the cumulative impact of operations in Antarctica.

The emissions associated with the programme are calculated in accordance with the methodology set out in 2010 Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting (see http://www.defra.gov.uk/environment/business/reporting/conversion-factors.htm), and are summarised in Table 5. An approximate total of 1745 tonnes of CO2e will be emitted throughout the duration of this programmes Antarctic field work. This estimate represents worse case scenario as it includes a significant amount of emissions related to shipping which has yet to be confirmed. The emissions will be re-calculated when the logistics have been finalised and will be presented in the final CEE report.

Whilst is it acknowledged that the emissions resulting from the logistics, running the field camp and drilling all contribute to a reduction in air quality, the impacts are minor and unavoidable. The programme will plan operations and logistics with maximum efficiency e.g. by minimising the number of journeys. All equipment (such as generators and vehicles) used on site will be new and maintained to the highest standard. Vehicles will not be left idling when not required to further reduce emissions.

Impact to ice

The drill site and camp will be situated on the ice, which could be impacted by loss of equipment, fuel spills and waste disposal.

Any equipment depoted at the drill site will be clearly marked with wands and the locations marked with a GPS to prevent the loss of the depot.

Only light refined fuels such as AVTUR will be used at the field camp. A maximum of 51250 l or AVTUR and 1025 l unleaded petrol will be stored on site in either UN Approved 205 l drums or flexible bulk fuel container ("bladder"). Small quantities of lubricating oils and hydraulic oils will also be used.

The bladders have been selected for use to provide an uninterrupted supply of fuel to the hot water boiler, and also because they are more lightweight than drums and therefore require less fuel to transport them to site. They are constructed from high-tenacity woven fabrics which are coated and impregnated with specialty synthetic rubber compounds. They are manufactured with heat and pressure seams, heavy-duty flange connections and reinforcements at all corners and openings. They exhibit excellent resistance to sun light (UV), temperature extremes, abrasion, corrosion, ozone checking and longterm storage and have been successfully deployed in the Antarctic for a number of years. The bladders will be positioned on site within a berm and secondary containment liner which would accommodate any fuel spilt should a bladder fail.

Fuel spills and leaks are most likely to occur through overfilling and splashes when transferring from the drum or bladder to the equipment, or as a result of the equipment leaking through faults. The likely spill volumes, should they occur, would be around 5 litres. Should a drum split then the maximum that could be lost is the 205 l drum volume, and in the unlikely event a bladder splits then the maximum volume would be 5800 l.

The volume and impact of any spills will be minimised through the robust nature of the bladders, secondary containment (of the bladders), the use of 'drip trays' or similar when refuelling, and the swift implementation of the oil spill contingency plan including the use of spill response equipment such as absorbents, repair kits (for both bladders and drums) and spare (empty) bladders and drums in which to transfer fuel from any damaged container. Spill response equipment will be available at all times on site and also in transit from ALE basecamp.

All operatives will be trained in fuel handling, refuelling, containment measures and in the use of the spill kits to reduce the occurrence and impact of spills.

Any spills that do occur will be reported immediately to the on-site Programme Manager and ultimately to the UK FCO.

Unless recovered quickly spills would be partially absorbed by the surface snow, although most will pass quickly through the surface layer to hard ice. At this depth, fuel spilt will remain within the ice for decades.

A range of waste materials will be generated during the programme, which unless properly managed, could negatively impact the environment. The programme will operate a Waste Management Plan, setting out how each waste stream will be stored before disposal, and full awareness training given to all site staff. Particular attention will be given to the need to secure wastes to avoid windblown litter. The waste streams generated will include:

- Hazardous wastes such as empty fuel drums, oils, oily rags (from generator maintenance), batteries etc.
- Sewage
- Grey water
- Waste food
- Non-hazardous packaging wastes

All of the wastes described above with will be stored appropriately before transporting back to the ALE base camp (by the end of the 2012-13 season) and from there out of the Antarctic. Where possible all wastes will be reused or recycled.

Scientific equipment will remain at the ALE base camp for reuse in planned science projects in later field seasons.

Removal of the wastes from Antarctica reduces the impact in Antarctica, however a low risk remains from windblown wastes becoming lost and having a low to negligible impact on the receiving environment. Whilst lightweight materials are most likely to be lost in this manner all materials including fuel drums are at risk. This will be mitigated by waste management procedures including the need to secure all waste.

Table 5: Summary of predicted atmospheric emissions from the field camp and drilling operations.

Converting fuel types by unit volume					CO_2	CH_4	N_2O	Total Direct GHG	Total Indirect GHG	Grand Total GHG	CO_2	CH_4	N_2O	Total Direct GHG	Total Indirect GHG	Grand Total GHG
Fuel Type	used for	Amount used	Units	x	kg CO_2 per unit	kg CO_2e per unit	kg CO_2e per unit	kg CO_2e per unit	kg CO_2e per unit	kg CO_2e per unit	Total kg CO_2	Total kg CO_2e	Total kg CO_2e	Total kg CO_2e	Total kg CO_2e	Total kg CO_2e
Gas oil	supply ship transporting equipment*	100000	litres		2.7667	0.0028	0.2517	3.0212	0.5265	3.5477	276670	280	25170	302120	52650	354770
AVTUR	site activities	51250	litres	x	2.5218	0.0012	0.0248	2.5478	0.4687	3.0165	129242.25	61.5	1271	130574.8	24020.88	154595.6
AVTUR	BAS Twin Otter flights deploying equipment and staff	29600	litres	x	2.5218	0.0012	0.0248	2.5478	0.4687	3.0165	74645.28	35.52	734.08	75414.88	13873.52	89288.4
AVTUR	ALE Ilyushin flights	347000	litres	x	2.5218	0.0012	0.0248	2.5478	0.4687	3.0165	875064.6	416.4	8605.6	884086.6	162638.9	1046726
AVTUR	ALE tractor train	32000	litres	x	2.5218	0.0012	0.0248	2.5478	0.4687	3.0165	80697.6	38.4	793.6	81529.6	14998.4	96528
Petrol	site activities	4100	litres	x	2.3018	0.0046	0.0156	2.322	0.4109	2.7329	2359.345	4.715	15.99	2380.05	421.1725	2801.223
Total	-	-	-		-	-	-	-	-	-	1438679	837	36590	1476106	268603	1744709

* *Figure estimated for ship fuel use associated with this project is worse case scenario assuming 5 days ship time at 20,000 litres per day. This will be refined prior to presentation of the final CEE.*

Impact to native flora and fauna (on the ice surface)

High intensity visitation may lead to trampling of vegetation and soils and disruption of animal behaviour and breeding activities; however, there is no known flora and fauna at or in the vicinity of the drill site surface that could be affected by this programme.

Inter and intra-continental transport provides the opportunity for the introduction of non-native species associated with importation contaminated cargo, scientific equipment, fresh food, clothing and personal possessions. Of increasing concern is the homogenisation of spatially distinct biodiversity through redistribution of Antarctic biota associated with human activities.

All staff will be briefed on environmental matters, informed of 'SCAR's environmental code of conduct for terrestrial scientific field research in Antarctica' and told to avoid entering ice-free areas whilst in transit through ALE base camp in an attempt to prevent impacts from trampling and avoid the potential deposition of non-native species.

The survival of any species inadvertently introduced to the Ellsworth site or along the transportation route is unlikely given the severe climate and lack of appropriate habitat for colonization. Nevertheless strict bio security procedures will be followed in line with best practice to avoid the potential for introducing non-native species (see 'SCAR's environmental code of conduct for terrestrial scientific field research in Antarctica'). All equipment will be cleaned before importation to Antarctica and only dried food rations will be imported to the field camp. All pre-used clothing shall be washed at the maximum temperature permissible immediately before departure for Antarctica. All technologies and equipment used during lake exploration will either be cleaned by the methods previously described (hot water, UV and HPV) or in the case of the probe, sterile bagged, before leaving the drill site to reduce the already very low risk of microbes from the lake being transferred to other locations whilst being transported out of Antarctica.

With these measures in place, the potential impacts of this programme to native flora and fauna is considered therefore to be low to negligible.

Non recovery of equipment

When drilling to the depths required to penetrate the lake, and collecting water and sediments samples, there is a risk of equipment loss. Whilst the environmental consequences of such an occurrence would be minor, the programme design has reduced its probability.

The hot water drilling method allows the hole to be re-reamed allowing melting around potential stick points in a clean and efficient way. Such additional ice melting would release equipment effectively (i.e. in a matter of hours), far faster than the alternative of mechanical coring that would also require the use of antifreeze fluid.

Were any equipment to be lost in the lake it could not be recovered easily. However, all mechanical connections meet standards developed in deep-sea exploration, which seldom experiences such loss of equipment.

Importantly, one hose and one tether will be employed, thereby avoiding the multiple connection issues that would otherwise be faced. Hence, the only weak point will be the connection between the hose and the nozzle, and the tether and the probe/corer.

A mechanic will be available to repair the winch if required.

Impact on wilderness and aesthetics

The timeframe of the field activities is eight weeks allowing for the mobilisation and demobilisation of all equipment, materials, wastes etc. During this time a small field camp will be established for a maximum of 10 staff. This will have a negligible visual and noise impact due to the minor nature and short duration of the activity.

The requirement for water will result in disturbance and removal of the snow surface. This will be mitigated during demobilisation when the site area will be regraded to prevent unnatural snow drifts from occurring.

The thermistor, if deployed, would be left *in situ* permanently, and whilst not visible, would have a low impact on wilderness values.

Cumulative impacts

A cumulative impact is the combined impact of past, present and future activities. These impacts can be cumulative over time or space.

Previous field work has been carried out in the area to gather data to aid the design of this exploration programme and this report. Their impacts were less than minor or transitory as assessed by a preliminary environmental assessment. The Lake Ellsworth Consortium has expressed a wish to carry out further scientific fieldwork at Lake Ellsworth in the future after this proposed exploration programme, although no plans have yet been prepared. Any future science proposals will be subject to an Environmental Impact Assessment.

Emissions to air from the combustion of fossil fuels used in the supply aircraft, track based transport, generators etc are cumulative and all contribute (however slight) to local and regional levels of pollution in Antarctica, as well as global atmospheric pollution.

Programme and site management

The Lake Ellsworth exploration programme has a management structure in place to ensure that the mitigation measures described in this chapter will be followed.

The programme team includes a Programme Manager who will be tracking all the individual tasks within the programme plan, including the requirements to gather the outstanding data, trial the equipment and any other task referred to in this report that is required for the final CEE or before the exploration can proceed.

All programme staff have a job description for all the roles in the programme, which includes their requirements and responsibilities applicable to environmental protection at all stages of the programme.

The programme operates to PRINCE2 and MSP programme management methodologies[2], so that if anyone leaves (for whatever reason) their responsibilities do not. For that reason, we can be confident that the programme management is robust.

The Programme Manager will be in the field, and will ensure – with the appointed field operations manager – that the exploration will be carried out in accordance with the CEE and any permit conditions. Full documentation will be written post fieldwork for submission to the FCO.

ALE, the contractors appointed for the logistical arrangements including fuel provision and the removal of wastes from Antarctica, are aware of the environmental requirements of the input they will provide. ALE have a multi-year IEE, approved to by the US Environmental Protection Agency. They have a Waste Management Permit granted by the US National Science Foundation for the "use of fuel and supplies for aircraft support, cache positioning, camp and field support and resupply". They operate to their own environmental policy which is consistent to that required by the Lake Ellsworth programme team.

The programme has, throughout its duration, been counselled and scrutinised by an Advisory Committee made up of independent scientists and experts. The members of this international committee are listed in Appendix 2.

Impact matrices

Table 6 summarises the environmental impacts associated with this exploration programme. The output and resulting environmental impact of each activity is identified. The probability, extent, duration and significance of these impacts are then ranked according to the criteria below, and finally measures that the programme team will use to mitigate or prevent those impacts from occurring are shown.

Criteria for ranking impacts are as follows:

Probability	Unlikely	
	Low	
	Medium	
	High	
	Certain	
Extent	Local	The drill site or the traverse route between ALE base camp and the drill site
	Regional	The Ellsworth Subglacial Highlands and the Byrd Subglacial Basin
	Continental	Antarctica and Southern Ocean south of 60°S
	Global	Earth and atmosphere
Duration	Very short	Minutes to days
	Short	Weeks to months
	Medium	Years
	Long	Decades
	Very long	Centuries to millennia
Significance	Very low	Ecosystems or natural processes or scientific research not directly affected
	Low	Changes to ecosystems or natural processes or scientific research are less than minor or transitory
	Medium	Changes to ecosystems or natural processes or scientific research are minor or transitory.
	High	Changes to ecosystems or natural processes or scientific research are greater than minor or transitory.
	Very high	Major changes to ecosystem or natural processes or scientific research are significant and irreversible.

[2] *PRINCE2 and MSP are Office of Government Commerce (OGC) standards for project and programme management. They are formal methodologies and are recognised throughout industry as best practice.*

Table 6: Impact Matrix for the exploration of Lake Ellsworth

Activity	Output	Predicted Impact	Probability	Extent	Duration	Significance/ severity	Mitigating or Preventative Measure
Use of aircraft, and tracked vehicles, for transport of equipment and staff.	Atmospheric emissions	Minor but cumulative contribution to atmospheric pollution including greenhouse gas emissions.	Certain	Local to global	Very Long	Low	Emissions are inevitable but will be minimised by well planned logistics to reduce flight and tracked vehicle rotations. Well maintained vehicles will be used, and driven at most efficient speed and not left idling unnecessarily. The shortest crevasse free route will be identified prior to field work to reduce fuel consumption when transiting from ALE basecamp to the Lake Ellsworth drill camp.
	Minor fuel spills during refuelling and operations	Contamination of snow.	High	Local	Long	Very low	Due care and attention, and the use of 'drip trays' or similar when refuelling, reinforced by education and training. Spill response equipment to be kept on site. Some fuel spilt will be absorbed by snow and recovered.
	Introduction of non-native species	Transfer of non-native species into, and around, Antarctica.	Low	Local	Short (if species dies), long (if microbes divide)	Very low (no non native species likely to survive the harsh conditions at the Ellsworth site.	All equipment to be cleaned before importing to Antarctica.

Table 6: Impact Matrix for the exploration of Lake Ellsworth

Activity	Output	Predicted Impact	Probability	Extent	Duration	Significance/ severity	Mitigating or Preventative Measure
Operating the science camp	Atmospheric emissions from the generators and boiler	Minor but cumulative contribution to atmospheric pollution including greenhouse gas emissions. Local fallout of particulates	Certain	Local to global	Very long	Very low	Generators and boiler will be new and maintained to the highest possible standards. The short duration of the fieldwork means they will only be running for approximately 8 weeks. If not needed, equipment to be switched off where practicable.
	Generation of liquid and solid wastes	Contamination of ice	Certain that wastes will be produced, unlikely that contamination will arise	Local	Medium	Low	Site to be checked for litter at the end of everyday. The project will operate a waste Management Plan ensuring that awareness training is given to all staff and that all wastes are stored correctly. All wastes (including grey water and sewage) will be transported back to the ALE Basecamp and ultimately out of Antarctica where it will be reused or recycled wherever practicable.
	Presence of tented camp	Affect on wilderness and Aesthetics	Certain	Local	Short	Very Low	The project will only involve a small field camp over a short duration (2 months), with a maximum of 10 people, in an area where science activities have already been conducted.
	Use of water	Affect on wilderness and Aesthetics	Certain	Local	Short	Very low	During demobilisation the site area will be regraded to prevent unnatural snow drifts and the landscape will be returned to baseline conditions.
	Impact on Native Flora and Fauna	Trampling of vegetation and soils and disruption of animal behaviour and breeding	Medium	Local	Short	Very Low to Low	There are no known flora and fauna at, or in the vicinity of the drill site surface that could be affected by this project. All staff are to be briefed on environmental matters. In addition they will be told to avoid entering ice-free areas whilst in transit through ALE Basecamp in an attempt to prevent impacts from trampling and avoid the potential deposition of non-native species.

Table 6: Impact Matrix for the exploration of Lake Ellsworth

Activity	Output	Predicted Impact	Probability	Extent	Duration	Significance/ severity	Mitigating or Preventative Measure
Lake Ellsworth Exploration	Impact on microbial biodiversity within Lake Ellsworth	Possible contamination of the pristine aquatic environment and ecosystem disruption	Medium	Regional	Short to very long	Low to high	Environmentally protective measures have been integrated throughout the design of the project. These include: • the selection of the hot water drilling method with the least potential for contamination • use of melted ice as the drill fluid which is filtered to 0.2 μm and UV treated • cleanliness in all engineered systems • strict microbial control though the use of HPV and UV • Sterilisation and cleaning action of the extreme environmental changes that these structures will encounter. The project's aims for microbial control is for no exogenous microflora populations to be detectable on any equipment in contact with the subglacial lake environment (including the thermistor string, if deployed). A thorough risk analysis has been conducted and concluded that the potential for blowout is very low
	Non Recovery of Equipment	Risk of loss of equipment in the Lake (or certain if the thermistor string is deployed)	Unlikely	Regional	Very long	Low	The project has been designed to ensure that the risk of equipment loss is unlikely. • The hot water drilling method allows the hole to be re-reamed the hole allowing melting around potential stick points in a clean and efficient way • all mechanical connections meet standards developed in deep-sea exploration • One hose and one tether will be employed. The only weak point will be the connection between the hose and the nozzle, and the tether and the probe/corer. • A mechanic will be available for repairing the winch if needed.

Chapter 7: Alternatives

Consideration of alternative methods, locations, timings, and logistical arrangements of the project are a fundamental part of the environmental impact assessment process, allowing environmental issues to be considered at the project design stage, and assisting in the selection of the option with the least the environmental impact. This chapter summarises the alternative options considered by the Lake Ellsworth Consortium before the proposed methods described in Chapters 4, 5 & 6 were selected. Options relate to drilling method, microbial control, exploring alternative subglacial lakes, and not proceeding with the project.

The Lake Ellsworth programme has been in a development stage for around six years. During this time, the options available for lake access, direct measurement and sampling have been carefully considered. We are therefore extremely confident that there are no realistic alternatives to the scientific plan and goals discussed in this document.

Lake access technique

Hot water drilling was identified as the only means of obtaining rapid, clean access to Lake Ellsworth through 3 km of overlying ice, allowing the cleanliness criteria to be met, affording the maximum environmental protection without compromising the science aims.

Mechanical drilling with the use of antifreeze fluids is inconsistent with the science and environmental aims of the project for two reasons. First, mechanical removal of ice requires both a substantial logistic effort and considerable time (at least two full seasons to drill to the ice sheet base). The consequence would be to drastically increase the cost of the programme. Second, and most importantly, mechanical coring requires 'antifreeze', which is commonly kerosene. Clearly such a substance, as the drill enters the lake, would pose a major contamination risk. Moreover, even if clean lake access was achieved, lowering a probe through the antifreeze-filled borehole into the lake would likely invalidate the scientific experiment (and offer further contamination risks).

Access to the lake using a 'Themoprobe', a device that melts itself into the ice sheet unravelling a communications tether as it does do, is also not considered feasible for three reasons. First, in tests on glaciers thermoprobes have proven very unreliable. The issue is that they melt out and accumulate non-ice particles in front of the probe that cannot be melted downward, hence the probe direction is adversely affected. Second, the capacity to undertake science using a thermoprobe is restricted as a consequence of the large payload devoted to the unwinding tether. In effect, once sent down 3 km of ice, all that would be left is a hollow tube. Third, the journey for the thermoprobe will likely be one-way; i.e. no return journey and no samples returned to the surface.

This assessment, concerning the inappropriateness of ice cores and thermoprobes for subglacial lake access, is consistent with the US National Research Council (2007) report on the exploration of Antarctic subglacial aquatic environments. The US National Research Council (2007) report also concludes that holes developed through hot water drilling "could be considered clean because the water used to melt the holes comes from the melted ice itself".

Alternative lakes

Lake Ellsworth has been carefully considered as the most appropriate subglacial lake to meet the scientific aims of this project.

Siegert (2002) undertook an assessment of all the subglacial lakes within the existing Antarctic inventory (Siegert et al. 1996). Using six criteria (Does the lake provide the greatest likelihood for attaining the scientific goals? Can the lake be characterized in a meaningful way (e.g. size, postulated structure)? Is the lake representative of other lakes and settings? Is the geological/glaciological setting understood? Is the lake accessible (closest infrastructure)? Is the program feasible within cost and logistical constraint?) Siegert concluded that a small lake at the ice-sheet centre, with access to appropriate nearby logistics, and with ice cover <3.5 km would be ideal as a candidate for lake exploration. In 2004 Lake Ellsworth was the only known candidate in West Antarctica that met these criteria (and still is). Other lakes in West Antarctica are likely to either be logistically challenging to gain access to, are located away from the ice divide or, in the case of Siple Coast lakes, are far younger than Lake Ellsworth, and therefore unlikely to be a habitat in which life, and an ecosystem, has developed over long periods of time. Furthermore, only very old lakes at the centre of the ice sheet are likely to persistently accumulate sedimentary material necessary for the development of a record of glacial and climate history. For these reasons, Siegert et al. (2004) proposed Lake Ellsworth as the best candidate for exploration in West Antarctica. As a consequence, the geophysical exploration of Lake Ellsworth was undertaken in 2007/8 and 2008/9. The result is a full appreciation of the ice cover, ice flow, water depth, water flow and lake floor substrate of Lake Ellsworth. No other lake has such information regarding its physiography, which makes Lake Ellsworth unique in its appropriateness for direct measurement and sampling.

The scientific questions regarding West Antarctic ice sheet history cannot be answered, obviously, in East Antarctica, thus ruling out such lakes for this particular programme.

Microbial control

The most significant environmental impact results from the potential to affect the lake's natural microflora, and a great deal of consideration has gone into the selection of microbial control methods. Alternative methods considered, but ruled out in favour those described in Chapter 6, include:

Chemical washes: Chemical wash methods include: commercial preparations such as Virkon©, (Hernandez et al., 2000), neurotoxicant sodium dodecylbenzenesulfonate (Gasparini et al., 1995), Descosal© and Domestos© (Pap and Kisko, 2008), Ethylene oxide gas (EtO) (Agalloco, 2004; Mendes et al., 2007), enzymes, peptides and metabolites, (Benkerroum, 2008; Maqueda and Rodriguez., 2008; Zasloff and Magainins, 1987; Meng et al., 2010), chlorinated cleaners (Silva et al., 2008; Aarnisalo et al., 2007; Wirtanen et al., 2001), peracetic acid (Silva et al., 2008; Aarnisalo, et al., 2007; Wirtanen, et al., 2001; Pavlova and Kulikovsky, 1978; Sagripanti and Bonifacino, 1996; Holah et al., 1990), peroctanoic acid (Fatemi and Frank, 1999), tenside (Wirtanen et al., 2001), sodium hydroxide

(Antoniou and Frank, 2005) and alcohol based disinfectants (Aarnisalo et al., 2007; Wirtanen et al., 2001), glutaraldehyde (Sagripanti and Bonifacino, 1996; Manzoor et al., 1999), quaternary ammonium, (Silva et al., 2008; Holah et al., 1990; Dhaliwal et al., 1992) formaldehyde, (Sagripanti and Bonifacino, 1996), hydrogen peroxide liquid (Khadre and Yousef, 2001; Wardle and Renninger, 1975; Sagripanti and Bonifacino, 1996), cupric ascorbate (Sagripanti and Bonifacino, 1996) sodium hypochlorite (Sagripanti and Bonifacino, 1996), phenol (Sagripanti and Bonifacino, 1996) and ozone (Khadre and Yousef, 2001). Many of these cleaners lead to degradation of the materials being cleaned and hence will not be used in this programme (Barbut et al., 2009).

Plasma Treatment: This uses highly energized gases. Low temperature plasma treatment (LTPT) is suitable for heat-sensitive materials, such as electronic components. LTPT exposes any microorganisms present in the sample to an electrical discharge with biocidal effects, (Moisan et al., 2001). Low pressure plasma treatment (LPPT) is used for surgical instruments and usually includes a UV irradiation step for genetic material destruction, (Kylian and Rossi, 2009). Chlorine dioxide vapour (CDV) is suitable for heat-sensitive materials and thus could be used for electronic components. Large scale applications of this method are currently developed for the decontamination of whole buildings from *Bacillus antracis*, (Wood and Blair Martin, 2009). Whilst effective these methods are less suited to the Lake Ellsworth experiment either because of disposal, the infrastructure required, or flexibility.

Other techniques include anodic protection (Nakayama et al., 1998), and freeze-thaw cycling (Walker et al., 2006), special sample manipulation for sediments (Lanoil et al., 2009), permafrost (Vishnivetskaya et al., 2000), or ice cores (Bulat et al., 2009; Christner et al., 2005). Material is removed from the innermost portion of the solid sample, while the outer layers of the core protect the sample used in the measurement. Whilst these processes may be applicable to the treatment of samples they are not suitable for the engineered structures used in the Lake Ellsworth probe systems as they would either be ineffective, would create engineering challenges, or a better result could be obtained using alternative methods.

Not proceeding

Not proceeding with this project i.e. the "do nothing" option, would avoid realising the associated environmental impacts (as discussed in Chapter 6). It would however mean that the benefit to global science and policy would also not be achieved. Understanding the glacial history of the WAIS is critical to assessing the present-day risk of ice sheet collapse, and consequent sea-level rise. This information can only be sought through the retrieval of ice and climate records, held in sediment cores, from the exploration of subglacial lakes such as Lake Ellsworth. This information is urgently required to inform policy makers on their response to sea level change and climate change impacts. Identification of life within subglacial lakes would be a major scientific discovery. The Scientific Committee on Antarctic Research has been supporting scientific planning to achieve this discovery since 1999. Planning over the subsequent ten years has been necessarily slow yet purposeful. As a consequence of this planning, the scientific community is now ready to undertake the direct measurement and sampling of subglacial lake environments.

Chapter 8: Assessment and verification of impacts and monitoring

This chapter provides information on how the actual environmental impacts occurring as a result of the subglacial lake exploration project (compared to the predicted environmental impacts discussed in this report) will be assessed and reported. Information is also provided describing the monitoring on the effectiveness of microbial control. This assessment will require the monitoring of a range of parameters, as described below.

Monitoring

Table 7 sets out the general monitoring and reporting requirements to verify the environmental impacts. As discussed in preceding chapters, the greatest impact is considered to be the potential for affecting the microbial diversity of Lake Ellsworth and any subglacial aquatic environment that it may be connected to hydrologically.

The ability to monitor the effectiveness of the microbial control is therefore crucial in determining the success of the mitigation measures used, and importantly the actual impact this exploration has had. This assessment can only be completed once samples are returned to the UK laboratories, as extended facilities will not be available in the field and there is no known method of enumerating such low numbers of cells likely to be present on the drilling and exploratory equipment. Samples of drill water will be collected during the drilling activity for UK laboratory analysis to assess the cleanliness of the drill water and the effectiveness of the mitigation measures. Drill fluid samples can be collected hourly during the 24 hrs operation on site. The preservation of the sample will be two-fold. First, the fluid will be filtered onto a 0.22 micrometre GF/F filter which will be preserved in RNA later for further nucleic acid analyses. Second, the filtrate will be frozen and preserved as fluid for chemical analyses. The nucleic acid analysis will include qPCR, Nucleic Acid Sequence-Based Amplification (NASBA) and denaturing gradient gel electrophoresis (DGGE). The fluid sample will be chemically analysed for trace metals and enumerated by flow cytometry.

Environmental Audit

The Lake Ellsworth Consortium would welcome an independent environmental audit / inspection from a Treaty Party during the field work, subject to availability of logistical support.

Parameter	Data recorded	Reporting
Atmospheric emissions	Emissions of CO_2, NO_x, SO_x will be calculated on the basis of fuel consumed by aircraft, vehicles and generators.	Total emissions, wastes generated, environmental incidents (and how they were managed) for the entire field season (including mobilisation / demobilisation) to be calculated and reported to FCO by December 2013.
Wastes	Total volume of each waste stream generated and removed from Antarctica to be recorded.	
Fuel spills	Spills of AVTUR, petrol and any lube oil, their location, and how they were handled, to be recorded.	
Other environmental incidents	E.g. spills of other fluids such as grey water, windblown equipment or wastes, any breach of site waste, fuel handling and bio security protocols to be recorded.	

Table 7: Environmental monitoring and reporting to be undertaken – General parameters.

Chapter 9: Gaps in knowledge and uncertainties

Given the exploratory nature of this scientific research, there remain some unknowns, uncertainties and gaps in current knowledge. A significant amount of work is being carried out prior to commencement of field activities (November 2012) on the equipment design and trials, logistics planning, trials of the microbial control methods, and further interpretation of the existing data, which will add to our knowledge and reduce uncertainties.

The most substantial uncertainties and gaps in knowledge relate to the following:

- Whilst there is an unprecedented amount of baseline knowledge on the physical environment of Lake Ellsworth, the most sensitive receptor, the microbial bio-diversity is unknown, so the potential impacts of the project cannot be estimated with any certainty. Such information will only be made available through carrying out this project, and the realisation of associated impacts.
- While it is likely Lake Ellsworth is part of an open hydrological system, we do not yet know this and there is a low likelihood of the system being closed. If Lake Ellsworth is "closed" hydrologically water will not leave the lake, meaning that if contamination were to occur it would be confined within it. In a closed lake system, there is a risk of dissolved gas build-up over long periods that could lead under an extreme condition to surface blowout. In the more likely "open" system, contamination could become dispersed over a downstream area, but the risk of blowout is negligible. Further interpretation of existing data is planned to gain a better understanding of this, however the project plans for both "worse case scenarios" i.e. has fully assessed blow out risks, and has incorporated stringent microbial control procedures to minimise potential impacts in an open system where any contamination could affect downstream aquatic environments. Uncertainty remains over whether, and at what scale, subglacial aquatic environments are in continuity with Lake Ellsworth that could be affected by the project, should microbial control procedures be insufficient.
- The microbial control methods proposed for use are subject to further development and trial to confirm they will allow the programme standards to be met.
- Whilst the programme's primary scientific objectives are not dependant on deploying a thermistor string, such a deployment would provide an opportunity to obtain the first accurate depth-temperature record of the ice-lake-sediment column. No decision has yet been made on the use of a thermistor string, but if deployed it will meet the programme's rigorous microbial control criteria. However, unlike other equipment it will be left *in situ*.
- The arrangements for transporting equipment to the site are yet to be decided, therefore the associated atmospheric emissions will be re- calculated with greater accuracy in the final CEE. The figures quoted in this draft represent the worst case scenario emissions.

Chapter 10: Conclusions

The proposed exploration of Lake Ellsworth will make profound discoveries regarding life in extreme environments and the history of the West Antarctic Ice Sheet. The latter is critical in assessing the present day risk of ice sheet collapse and consequent sea level rise. The science is therefore of genuine interest to policy makers, the scientific community, public and media.

This programme has been in a planning and design stage for six years, throughout which environmental protection has been a central and dominant feature. Extensive information has been gathered on the baseline conditions to inform this CEE, and robust mitigation measures have been incorporated.

The proposed exploration programme involves a main field season of 8 weeks during which time 10 staff will be on site to establish a drill camp and run a hot water drill for 3 days through 3.1 km ice to penetrate the subglacial lake. A probe and corer will then be deployed to allow water and sediment sample collection.

A full assessment of potential environmental impacts is included in this draft CEE. The most significant impact predicted is the potential for contamination of the lake and subsequent impact on microbial function. The lake's microbial populations are currently unknown (and can only be determined through the exploration). This impact will be mitigated through the use of the hot water drill methodology (using melted ice water heated to 90 °C, filtered to 0.2 μm, and UV treated), and thorough microbial control contamination methods.

Having prepared a full CEE and adopted rigorous preventative and mitigation measures, the UK considers that the exploration of Lake Ellsworth will have a less than minor or transitory impact on the Antarctic environment. However, due to the uncertainties inherent in such exploratory science, there is a risk of greater impacts (more than minor or transitory). As the actual impacts can only be assessed after they have already occurred, a precautionary approach has been taken reflecting this risk.

This precautionary approach meets the recommendation of the NAS – EASAE report that "all projects aiming to penetrate into a lake should be required to undertake a Comprehensive Environmental Evaluation".

The UK concludes that the global scientific importance and value to be gained by the exploration of Lake Ellsworth outweighs the impact the proposal has on the environment and justifies the activity proceeding.

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Appendix 1: Access to Subglacial Lake Ellsworth: blowout likelihood, risk analysis and mitigation

The level of gas concentration within Antarctic subglacial lakes will vary according to local glaciological conditions and the time over which these conditions occur. Crucially, under a closed hydrological situation, where lake water is created by melting ice and is lost by accretion, dissolved gas concentrations can increase. If closed, and conditions persist for long periods, up to many millennia; the dissolved gas concentration may reach saturation, at which time gas clathrates will accumulate. This presents serious issues for lake access experiments since gas blowout at the surface, no matter how unlikely, is potentially serious and requires mitigation and planning. Here, we outline the various ways in which gas may enter a deep-ice borehole penetrating a subglacial lake and, with specific reference to Lake Ellsworth, we estimate the period of hydrological closure necessary for gas clathrates development. We show that gas blowout will not occur unless the lake contains at least ~30% by volume of clathrate material, which would take at least 100,000 years to develop. We ascertain the likelihood of this situation occurring to be very low. We designed potential (engineering) mitigation measures to avoid gas blowout but conclude them not necessary given the very low risk of gas blow out occurrence. However, the temperature of the drill fluid will be reduced prior to lake penetration to further reduce the risk of blowout, and site staff will, as a precautionary measure, be moved from a pre-defined exclusion zone.

1. Introduction

Exploration of Antarctic subglacial lakes has been in a phase of planning since the first evidence that they were both deep-water bodies (Kapitsa et al., 1996) and a potential extreme environment for microbial life (Ellis Evans and Wyn-Williams, 1996). Currently there are three programmes aiming to access subglacial lake environment, to sample and measure lake water and sediment (Lake Vostok in central East Antarctica; Lake Ellsworth in central West Antarctica and Lake Whillans in the Siple Coast of West Antarctica). Gaining access to these subglacial lakes via holes drilled through the over laying ice sheet requires a good understanding of the likely range of conditions that will be encountered during the drilling process and more specifically upon entry into the subglacial lake.

Subglacial lakes are an element of the hydrological system beneath the Antarctic Ice Sheet, and are impacted by cycles of melting and refreezing. Meteoric ice melting into subglacial lake brings with it trapped air, which originates from small bubbles trapped in the ice during the compaction of snow into ice near the surface of the ice sheet. Ice pressure increases with depth and the bubbles are progressively squeezed until at depths of around 1 km the pressure is high enough for the ice and air to combine to form a solid air-hydrate crystal structure known as a clathrate. The clathrate has a typical size of 100-200 µm (Lipenkov and Istomin, 2001). These clathrates dissolve into the lake water where melting occurs at the lake roof, but in areas of freezing, dissolved gases and clathrates are not incorporated into the accretion ice at the ice sheet base (Jouzel et al., 1999). Hence, gases may gradually accumulate in isolated lakes and eventually saturate the lake water. Then, at the temperature and pressure beneath an ice sheet at depths of more than 1500 m, clathrates from the melting ice do not dissolve into the lake water but remain solid and stable. For example, McKay et al. (2003) calculated that Lake Vostok could contain a high concentration of dissolved gases and clathrates under the assumption that the lake is a hydrologically isolated or closed system. These conditions may also occur in Lake Ellsworth.

The presence of large volumes of dissolved gases and clathrates potentially contained within a subglacial lake could pose a hazard to the drilling and sampling operations, in the form of a blowout, where a mixture of drilling water, lake water, and gases are accelerated up the borehole and ejected at the ice sheet surface. Regardless of the likelihood, even if very low or even negligible, the potential for a blowout needs assessment and mitigation, as the safety consequences are potentially serious. This issue has been recognised by the Scientific Committee on Antarctic Research, whose code of conduct for the exploration and research of subglacial aquatic environments (Alekhina et al 2010) states that *"Water pressures and partial pressures of gases in lakes should be estimated prior to drilling in order to avoid down-flow contamination or destabilisation of gas hydrates respectively. Preparatory steps should also be taken for potential blow-out situations."*

Here we discuss how gases and clathrates accumulate in subglacial lakes, the likely ways in which gas may enter a subglacial lake access hole, and ascertain the risks of such gas leading to significant and unexpected expulsion of borehole fluids at the top of the access hole, with specific reference to Lake Ellsworth. We analyse the likelihood of a worst case scenario of clathrate accumulation in the lake, and what the implications would be if lake water was allowed to enter the access borehole. A blowout emanating from a subglacial lake can conceivably be in three ways: water-pressure derived; dissolved gas derived; clathrates derived. We also discuss ways in which a blowout can be mitigated and each of these is dealt with in turn below.

2. Water-pressure derived blowout

Water has surged up the borehole and fountained over the surface during the drilling of access holes to the bed of certain valley glaciers (e.g. Trapridge, Yukon). For this to happen, the hydrological head of the basal waters must be above the level of the ice surface. In practice, this usually means that high water pressures are generated by contact with an upstream englacial or subglacial source well above the level of the ice at which penetration occurs via a series of confined englacial and/or subglacial channels. **These conditions cannot occur in the vicinity of Subglacial Lake Ellsworth, or indeed any subglacial lake at/near the ice divide.**

Radio-echo sounding (RES)measurements of basal topography around Lake Ellsworth shows that water generation is likely to come from elevations that are only 250 m higher than the edge of the lake (Woodward et al., 2010). The ice sheet is known to 'float' on the lake (i.e. the basal slope is ~-11x the surface slope) and is, hence, in hydrological equilibrium with the lake (Siegert et al., 2004; Vaughan et al., 2007).

As ice is lighter than water, the pressure at the base of a borehole completely filled with water will be far higher than the ice sheet basal pressure and, therefore, the basal water pressure. As a consequence of this fact a borehole water level, equivalent to the ice thickness multiplied by the fraction of the densities of ice over water, needs to be established prior to lake access, to allow the borehole and ice sheet/lake pressures to be approximately equal. If this is not done, borehole water is likely to flow into the lake. For the Lake Ellsworth drill site, approximately 270 m of water will need to be pumped out of the borehole and maintained at that level during the access experiment.

If we under-pressure the borehole with respect to the lake, however, lake water will escape up the borehole to the level at which the pressure will equilibrate (following some small-scale oscillation). This is a normal feature of ice-sheet bed access (Bentley and Koci, 2007).

Conclusion: there is a zero risk of blowout upon access to Subglacial Lake Ellsworth due to lake water pressure alone.

This conclusion may not hold for subglacial lakes far away from the ice divide, however. A Digital Elevation Model (DEM) and quite simple hydrological calculation will assist planning for this access issue for lakes in such regions.

3. Gas-pressure derived blowout – open lake system

In an open hydrological situation, gases may enter a subglacial lake via melting of gas-containing ice, such as meteoric ice, and are removed from the lake by water transport to downstream environments. Recent satellite investigations of ice surface elevation changes shows that many subglacial lakes fill and discharge by significant (>1 km^3) volumes (Smith et al., 2008), sometimes resulting in transport of basal water over large (>100 km) distances (Wingham et al., 2006; Carter et al., 2009), suggesting much of the Antarctic ice sheet base can be thought of as an open hydrological system.

We calculate the likely maximum gas concentration of a hydrologically open Lake Ellsworth by assuming that the overlying meteoric ice at Ellsworth has the same gas content as the meteoric ice overlying Lake Vostok. The average composition of Vostok meteoric ice contains 0.09 cm^3/g of gas at STP (standard temperature and pressure, 25 °C and 1 atms respectively), equivalent to 0.09 l/kg or ~90 l/m^3 of ice (Lipenkov and Istomin, 2001). The bulk of this is nitrogen (~79%) and oxygen (~21%). We assume that Ellsworth meteoric ice contains this gas content and composition too, and it follows that Lake Ellsworth contains this amount of gas with a comparable composition.

It is important to realise that dissolved gases form bubbles and degas safely during normal hot water drilling of meteoric ice. This is because the atmospheric gas content of meteoric ice exceeds the solubility of these gases in the resultant ice melt, as the following illustration shows. We assume that the water used for drilling contains air saturated at the surface at a temperature close to 0° C, as is realistic for melt waters in the holding tank. This is a maximum value since gas solubility decreases with temperature. This gas content is ~0.04 cm^3/g x 80% (the approximate air pressure of the Ellsworth drilling site in relation to sea level) or ~0.03 cm^3/g. Melted meteoric ice will equilibrate to this value as it returns to the surface and is held in the holding tanks for ~2.5 hrs. The amount of degassing can be calculated as follows. Some 0.09-0.03 or 0.06 cm^3 of gas must diffuse out of the holding tank for each g of meteoric ice that is drilled.

To determine the drilling melt rate, we assume that the drill nozzle water flow rate is fixed at 180 kg/min, the temperature near the surface is 90° C, falling to 47° C at the base of the ice, while the ice temperature is -32 °C in the upper 2000 m of the ice column, increasing to the freezing point at the base. This gives a melting rate of

180 kg/min x 4.2 kJ/kg°C x 90°C / 333 kJ/kg + (2 kJ/kg°C x 32°C) = 171 kg/min near the surface and

180 kg/min x 4.2 kJ/kg°C x 47°C / 333 kJ/kg + (2 kJ/kg°C x 0°C) = 107 kg/min at the ice base.

Therefore during drilling of meteoric ice the typical gas venting rate is initially

171 kg/min x 0.06 l/kg = ~10 l/min of gas reducing to

107 kg/min x 0.06 l/kg = ~6.5 l/min of gas at the bottom of the hole.

Shallow drilling of boreholes on ice masses around the globe produces gas bubbles that rise harmlessly through the water column with no blow out problems. Deep drilling of meteoric ice has also encountered no gas or blow out problems [e.g. RABID and IceCube] to date since two further factors serve to hold the gas in solution until the deep drill fluid returns closer to the surface. First, the solubility of gases increases with depth. Crudely, the solubility of O_2 and N_2 increases to ~ 0.77 x 10^{-3} and 1.48 x 10^{-3} mole fractions respectively at ~28 MPa, the pressure in Lake Ellsworth (after Lipenkov and Istomin, 2001). One mole of water weighs 18 g and 1 mole of gas occupies 22.4 litres at STP. The air pressure at the Ellsworth drilling site is ~0.8 atms and the air temperature is ~-15 °C (or ~258 K). The gas volumes at the drilling site will be ~8% lower than at STP, since the effect of the temperature difference on gas volume, which serves to deflate the gas volume, is slightly greater than the decrease in pressure, which serves to inflate the gas volume

Oxygen solubility is calculated as follows:

0.77/1000 (moles of O_2 per mole of H_2O) x 22.4 (litres of O_2 at STP/mole of O_2) x 1000 (cm^3/litre) x 1/18 (mole of H_2O/ atomic weight of H_2O in g) = 0.96 cm^3/g

Similarly for nitrogen, solubility equals:

1.48/1000 (mole/mole) x 22.4 litres/mole x 1000 (cm^3/litre) x 1/18 (mole/g) =1.84 cm^3/g.

In total, this is 0.96 + 1.84 cm^3/g = ~2.8 cm^3/g.

So, Lake Ellsworth water can hold~2.8 cm^3/g of gas (at STP).

Meteoric ice melted at the surface can vent gas via diffusion through the water-atmosphere interface in the drilling water reservoir that the circulated drill fluid is returned into. Bubbles may form during shallow drilling, but they are insufficient to cause a blow out of dangerous proportions being so close to the surface. As drilling proceeds to greater depth, any gas or clathrate released from the meteoric ice is dissolved into solution because the gas solubility increases with depth (to a maximum of 2.8 cm^3/g compared with 0.09 cm^3/g in the melted meteoric ice).

The second factor is that the mixing ratio of circulating drilling fluid (undersaturated with gas at < 0.3 cm^3/g) and melted meteoric ice is high, so that gas saturation is never actually approached. The circulating drill fluid will be warmer than 0 °C and so holds less gas, but this general assertion is true given the water depths (up to 3000 m) that we are dealing with. Circulating drill fluid that reaches the surface will be slightly oversaturated, but will vent gas either via the formation of bubbles near the surface or diffusion as it makes free contact with the atmosphere in the holding tanks, before being reheated and recirculated.

Conclusion: There is no risk of blowout since the water is highly undersaturated (0.09 cm^3/g) compared to the gas solubility at 28 MPa (~2.8 cm^3/g).

Any lake water which entered the base of the drill hole, say to 20 m, would not make it back to the surface without mixing with existing drill fluid in the hole (during reaming, for example). Normal diffusional venting would remove this gas at the surface. This conclusion is likely to hold true for all hydrologically open subglacial aquatic environments, and is supported by at least two boreholes drilled to the ice sheet base (Bentley and Koci, 2007). In both EDML (East Antarctica) and NGRIP (Greenland), neither experienced 'blowouts'. In the case of NGRIP, a subglacial aquatic environment was hit. The water from this environment entered the bottom metres of the hole and froze, forming pink ice. It was later found that the pink coloration was due to iron oxidation, meaning that the original waters were lacking in oxygen at the bed (Christner et al 2008).

4. Gas-pressure derived blowout – closed lake system

In this case, gases enter the lake due to melting of gas-enriched ice, but none are taken out of the lake due to there being no transport of lake water downstream. Water balance is maintained by creation and transport of accretion ice, which contains no gas (McKay et al., 2003). Hence, gas build-up in the lake can occur.

Accretion ice has been identified in both ice core and RES records for Lake Vostok, and in RES records for Lake Concordia. Modelling (under a closed system), confirms that all lakes will have accretion ice formation in a closed system and, hence, gas build-up. No accretion ice has been identified in RES records over Lake Ellsworth, however.

The calculations below assume a permanently hydrologically closed system for Lake Ellsworth, the likelihood of which is discussed afterwards.

Woodward et al. (2010) show that, under a closed system, the average freezing/melt rates are 4 cm yr^{-1}, with a maximum value of 15 cm yr^{-1}. In the calculations below, we assume that meteoric ice melts into 50% of the ice roof at rates of both 15 and 4 cm/yr, and accretion ice freezes onto the other 50% of the roof at the same rates. We assume the meteoric ice melting into the lake has a gas content of 0.09 cm^3/g and that all gas remains in the lake. We estimate the lake volume to be 1.37 km^3, and the surface area to be 28.9 km^2. So, the residence time of water in the lake (equivalent to how long it takes for melting/freezing to produce/remove the entire volume of water in the lake) is:

1.37 km^3 x 109 m^3/km^3 / (28.9 km^2 x 0.5 x 106 m^2/km^2 x 0.15 m/yr) = ~630 years (melt rate = 15 cm/yr)

1.37 km^3 x 109 m^3/km^3 / (28.9 km^2 x 0.5 x 106 m^2/km^2 x 0.04 m/yr) = ~2,370 years (melt rate = 4 cm/yr)

The residence time of water in Lake Ellsworth is therefore ~ 630 - 2,370 years (melt rate = 15 - 4 cm/yr).

For each residence time, the concentration of gas in the lake increases by 0.09 cm^3/g. This continues until the lake water becomes saturated with gas at 2.8 cm^3/g. The time required for waters to reach gas saturation is therefore approximately:

630 years x 2.8 cm^3/g / 0.09 cm^3/g = 19,600 years (melt rate = 15cm/yr).

2370 years x 2.8 cm^3/g / 0.09 cm^3/g = 73,700 years (melt rate = 4 cm/yr).

Closed system waters in Lake Ellsworth therefore become gas saturated in ~19,600 - 73,700 years (melt rate = 15 - 4-cm/yr). This calculation is approximate because nitrogen and oxygen saturate at slightly different times, and assumes that normal box model rules apply, such as homogeneity in the box (or a completely mixed lake in our case).

Thereafter, melting meteoric ice into a closed Lake Ellsworth causes clathrates to form. This becomes a potentially big problem for access since, for example, if the lake has existed since Marine Isotope Stage 11 (400 ka), then the clathrate content in terms of gas at the surface could be as high as:-

(400,000 years x 0.09 cm^3/g / 630 years) – 2.8 cm^3/g = ~54 cm^3/g (melt rate = 15 cm/yr)

(400,000 years x 0.09 cm^3/g / 2370 years) – 2.8 cm^3/g = ~12 cm^3/g (melt rate = 4 cm/yr)

These are very large numbers, and would imply (in the worst case) that all of the lake water is bound up in clathrate gas cages. Any free clathrates would either float if CO_2 was in low (<10%) concentration (McKay et al., 2003), which is most likely, else it would sink (and would probably not then be a problem for lake access).

We can calculate how much of a problem this might be on lake access by assuming that this type of water enters the base of the borehole, which near to lake access will have an area of 0.1 m^2, to a height of 20 m. This means that 2 m^3 of lake water could enter the base of the borehole. If this was warmed by a few degrees C, due to mixing with drilling fluid for example, the clathrate may destabilise to produce a gas bubble. This would produce a potential water displacement at STP of

[2 m^3 x 54 cm^3/g x 10-6 m^3/cm^3 x 106 g/m^3 (of water)] / 0.1 m^2 = 1080 m

A possible worst case scenario is that up to 1080 m, or ~ 1/3, of the drill fluid in the borehole could be displaced if 20 m of heavily clathrate-laden water were to be allowed to rise up the borehole. The actual water displacement would be nearer 1080 m * 1 atms / 280 atms or ~ 3.9 m if the bubble remains at the bottom of the borehole. Displacement of only 3.9 m of water from the borehole would cause the bubble to expand and displace further water, so producing a potential blowout.

In this worst case scenario, what would be expected to be seen at the ice surface, as lake/clathrate water gets into the borehole?

1. The water level in the borehole cavity will increase in an exponential manner.
2. If nothing was done, a run-away situation could occur, leading to borehole water and gas (air) escaping from top of the borehole.

Potential engineering methods to mitigate blowout are scoped up in Annex 1, but their deployment is not considered necessary given the very low risk of blowout occurring.

5. Mitigation: geophysical observations – open or closed lake system?

It is clearly important to establish whether Subglacial Lake Ellsworth is an open or closed hydrological system when evaluating the potential risks associated with blowout. Two methods of analysis derived from radio-echo sounding (RES) data can be used to infer the hydrological system:

3. Analysis of the hydrological potential
4. Analysis of the radar energy (power) returned from the sub-ice interface.

A map of the hydrological potential (Figure 1), used to predict the direction in which water will flow at the base of the ice, shows that basal water flow in the Subglacial Lake Ellsworth catchment is strongly influenced by the bedrock topography. Basal meltwaters from the upper hydrological catchment can potentially flow along the base of the subglacial bedrock trough for a distance of ~20 km from the basal hydrological divide to the lake (Figure 2). This shows that basal meltwaters from the upstream catchment will flow, apparently unimpeded, into Subglacial Lake Ellsworth. Some limited ponding of water may occur upstream of the lake however; two of the RES survey lines across ice-flow in the upper hydrological catchment are characterised by sections with bright basal returns, suggestive of the presence of localised subglacial water (diameter of <1 km).

Downstream of the lake the situation is rather different. A large (~200 m high) ridge, which lies obliquely across the base of the trough, delimits the downstream boundary of the lake. The hydrological potential data clearly show that this landform impounds the bottom end of Lake Ellsworth and is a clear obstacle to outflow of water from the lake. This increases the risk of the lake having a 'closed' hydrological system.

To assess this probability, a map of the reflected electromagnetic energy returned from the boundary between the ice and underlying materials (Bed-Reflection Power – BRP) around Subglacial Lake Ellsworth has been produced (Figure 3). It is widely accepted that high amplitude returns from the base of ice sheets in RES data represent water bodies or water-saturated sediments. By mapping the spatial distribution of BRP, we utilise this established relationship to assess whether water is able to exit the lake by outflow between the ice and the bedrock ridge.

A zone of BRP elevated relative to surrounding values extends from the bedrock ridge downstream (Figure 3). The onset of the enhanced BRP zone corresponds with a low in the topography and hydrological potential in the elongated ridge. The simplest explanation for the elevated BRP values mapped downstream of Lake Ellsworth is that they represent a narrow zone of basal water. We suggest that this is caused by outflow from Lake Ellsworth and that, consequently, the lake is characterised as an open hydrological system.

It should be noted that our analysis of BRP must be considered *very preliminary*, as the calculated BRP has not been corrected for attenuation of radar energy in the ice column caused by englacial temperatures and chemistry. Instead, the values presented are simply the 'raw' measurements of power returned from the bed of the ice. Modifications are also needed to the 'time window' used to calculate the retuned power. Despite the preliminary nature of the BRP analysis, we do have some confidence in our current interpretations. This is for two primary reasons: (i) the spatial pattern of the zone of elevated BRP (relative to the surrounding ice sheet bed) appears to be independent of topography (the top of the elongate ridge is associated with relatively low values of BRP, whilst an overdeepening just downstream of the ridge is associated with elevated values (Figure 3) – the opposite of what you would expect if the pattern were due to ice thickness), suggesting that the elevated BRP is likely due to factors other than variations in ice thickness; and (ii) the clear correspondence between the spatial pattern of high BRP and the topographic and hydrological low in the bedrock ridge is expected from water outflowing from a subglacial lake outlet when the lake is impounded by a large bedrock ridge. Improvements to this analysis (currently underway) will account for attenuation in the ice column and will hopefully refine levels of confidence in these data and our interpretations.

6. Mitigation: The inclined roof of subglacial lakes mitigates clathrates entering a borehole

The ice-water interface of subglacial lakes have notable slopes (~-11x the ice surface slope), which in the worst case scenario will offer a defence against clathrates entering the borehole provided the access hole is well placed.

Clathrates heavier than lake water will not rise up the borehole. Even if they become unstable and degas, the gas will rise up the lake water column and, once at the ice water interface will continue to travel upslope to the upstream end of the lake. The borehole presents a place where gas can escape, but the hole is minute compared with the wider lake surface and, even if some gas is transmitted to the borehole, it will have opportunity to re-dissolve in borehole water.

Clathrates lighter than water will not necessarily rise up the borehole. As the lake has a tilting ice surface, any clathrates currently lighter than lake water will be located at one end of the lake. It will only be possible for such material to enter the borehole if the upper levels of the lake (for Subglacial Lake Ellsworth this volume is 0.4 km^3) are completely saturated with clathrates. For Subglacial Lake Ellsworth, this is likely to take at least 114,000 years assuming the maximum rate of ice melting of 15 cm yr^{-1}.

One might imagine that clathrates at the same buoyancy of lake water may travel up the borehole if the borehole is underpressured with respect to the lake pressure. According to Mackay et al. (2003), however, this eventuality cannot happen, as clathrates are either lighter or heavier depending on the level of CO_2 concentration.

7. Mitigation: Likelihood of permanence of a closed system in the West Antarctic Ice Sheet

Over glacial cycles, the ice sheet surface is known to rise (glacial) and lower (interglacial). For West Antarctica, the glacial rise above modern levels is estimated to be as much as 3-400 m in the Lake Ellsworth region (Bentley et al., 2010). At the centre of large ice sheets, the depth-temperature record will be affected by such cycles of decreases in surface temperature and rates of ice accumulation. Modelling (Huybrechts 1993) shows that these factors tend to cancel each other out, leaving the depth-temperature profile unchanged. Consequently, if the ice surface increases, so too will the ice thickness and, hence, the region over which melting takes place will also increase (Huybrehcts 1993). For Lake Ellsworth, even if the lake is closed today, broadening the basal melt zone would likely allow water to flow downstream. ***The implication is that Lake Ellsworth is unlikely to have remained as a closed system during glacial cycles even if it is at present.***

Ice sheet relaxation to modern levels occurred around 10,000 years ago, hence the maximum time available to be a closed system is likely to be <10,000 years.

In this glaciological scenario, the lake is likely to be hydrologically open during >90% of the last glacial cycle, meaning clathrate build-up will not occur (as this takes at least 19,600 years) or, if it does, accumulate to a serious level (as it would take >100,000 years to be a problem).

8. Lake Vostok timetable

Lake Ellsworth is likely to be accessed at least one season after the Russian experiment at Subglacial Lake Vostok. Clearly there will be lessons to be learned from access to Subglacial Lake Vostok that may require our assessment of blowout risk to be re-evaluated. We welcome discussions with Russian colleagues on their experience with gaining access to an Antarctic subglacial lake.

9. Summary of the risks

Risk of water-pressure-driven outpouring at ice surface: NEGLIGIBLE

Risk of gas blowout due to hot water drilling: NEGLIGIBLE

Risk of blowout from gasses in lake water, under an open hydrological system: NEGLIGIBLE

Risk of blowout from lake clathrate gases in an open system: NEGLIGIBLE

Risk of blowout from lake clathrate gases in closed system (assuming melt/freeze rates of 15 cm yr^{-1}):

a. closed lake system for 400,000 years: HIGH

b. closed lake system for 100,000 years: LOW

c. closed lake system for 8000 years: NEGLIGIBLE

The likelihood will be reduced if we assume melt/freeze rates of 4 cm yr^{-1} (modelled average rather than modelled maximum values) as follows:

d. closed lake system for 400,000 years: LOW

e. closed lake system for 100,000 years: VERY LOW

f. closed lake system for 8000 years: NEGLIGIBLE

Likelihood of closed lake system

a. last 400,000 years: VERY LOW

b. last 100,000 years: VERY LOW

c. last 8000 years: MODERATE

This likelihood may be reduced once we evaluate the PRC evidence of basal melting around the lake (we take a worst case at present).

We summarise the overall risk of gas blowout upon entry to Lake Ellsworth is VERY LOW.

9. Safety

The safety of field workers is paramount.

Whilst engineered mitigation measures have been designed (Annex 1), they are not deemed necessary for use given the very low risk of gas blow out occurring.

The temperature of the drill fluid will be reduced (to approximately 25-30 °C) just before lake penetration to further reduce the potential for blowout.

Safe site procedures will be in place and will ensure that personnel are clear of a pre-defined exclusion zone before the lake is penetrated.

Annex 1: Engineering Blowout Prevention Strategies

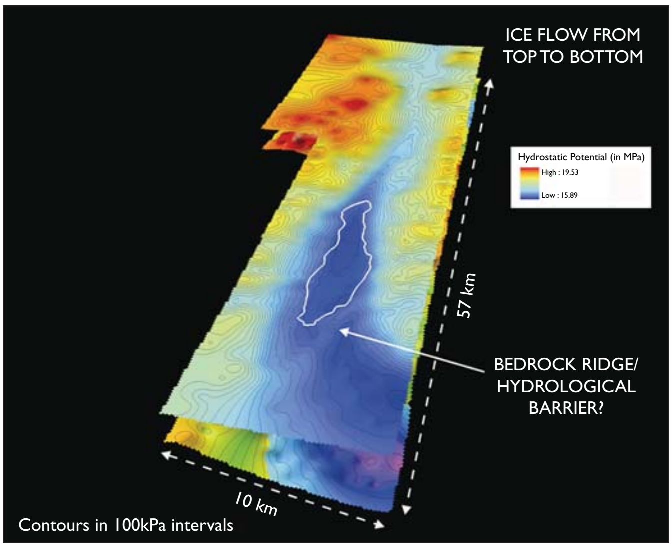

Figure 1. *3D representation of the hydrological potential of the Lake Ellsworth catchment. Basal water will flow from areas of high (red) to low (blue) pressure, perpendicular to the contours. Lake Ellsworth is clearly a hydrological sink for the entire upstream basal hydrological catchment.*

1. Minimise the temperature of the hot water drill at and near lake access

Advantages: a simple technique that is easy to maintain and manage. The science experiment could continue even if the lake contains clathrates.

Disadvantages: Clathrate enriched lake water may degas due to loss of some pressure; hence reducing the temperature alone may not be sufficient.

Given that clathrate rich water might degas if the temperature increases due to mixing with warm water, one mitigation strategy would be to cold-drill (<5 °C) below the clathrate disassociation temperature (Figure 4) over the last 10-20 m of the ice sheet, although drilling speeds would be reduced to around 6 m hr^{-1}. This is feasible, given the temperature of the ice sheet here is close to the pressure melting point of -2.184 °C.

2. Continuous over pressurising of the borehole

Advantages: a simple technique that is easy to maintain and manage. The science experiment could continue under the worst-case scenario.

Disadvantages: Borehole water (melted ice) will be forced into the lake.

Method: By slightly over pressurising the borehole with respect to the ice sheet base (and therefore lake water pressure), newly melted glacier ice would be forced into the lake, preventing lake water, and therefore any clathrates, to enter the borehole. This is easily done by maintaining the borehole water level above the lake hydrological level, which is at 270 m below surface level.

Previous work by Engelhardt and Kamb (1997) observed that when drilling through the 1200 m thick Siple Coast ice streams the water level in the boreholes fell almost exponentially upon breakthrough to the basal hydrological system, from an over pressured borehole down to the hydrological head, which was always deeper than the flotation level. Almost all the 70 m water level change occurred within 2-4 minutes. At breakthrough into the sea on Ronne Ice Shelf, the water level changed more rapidly, overshooting the floatation level slightly before recovering to the floatation level. The overshoot oscillation was over an order of magnitude smaller than the initial water level change of up to 10 m.

3. Managed over pressuring of the borehole

Advantages: a simple technique that can be managed with existing skills and resources.

Disadvantages: Some borehole water (melted ice) will be forced into the lake. The science experiment would not continue under the worst-case scenario until stability of the borehole is ensured and provided we are happy to let further borehole water into the lake (as in 2).

Method: A similar technique to 2 (which is also does not require much additional engineering) is to have early detection of the rise (e.g. using the pressure sensor at the return pump) to detect some expansion has occurred and dump water into the hole to increase borehole pressure and flush clathrates etc deeper / back into the lake.

As we would prefer not to put borehole water into the lake (unless health and safety requires it), we will monitor the borehole to detect any early pressure rise. The risk is that a blowout is not caught early enough. We would already have a large surface reservoir of water available that could be dumped down the hole once a rise in the borehole water level was detected.

4. Physical blow-out preventer

Advantages: a minimum level of borehole material will enter the lake.

Disadvantages: this method would halt the science experiment. At some point, the pressure on the physical seal will likely be significant (up to ~300 bar). If the seal were to fail it would likely fail suddenly with serious local short-term surface environment implications. Hence, evacuation of the drill site would be needed even if a physical preventer were deployed, until borehole pressures relaxed.

Method: The pressure is calculated assuming a 3170 m ice depth and density 922 kg/m^3. This results in a ~400 T thrust force at the surface for each hole. This could be counteracted by loading snow onto an inverted top hat or plate (this could be in sections for manufacture and shipping). This needs to be ~5.2 m in radius and buried 7 m deep (per hole). This is a challenge but not impossible. This could be reduced if the density of the snow / ice loaded onto the plate could be increased (e.g. with partial melting or with use of hot water soaking). There are a number of designs for blow out preventing at well heads available (in ceased patents) that we could use or adapt for Ellsworth. Two features would be useful: 1) the ability to shut off the well head and seal against the blow out pressure; and 2) the ability to inject water beneath the seal to affect a top kill. Both can be found in the patents. The particular problems for Ellsworth are: 1) dealing with the drill hose which is not rated to the max blow out pressure. It would either have to be cut below the seal, or crushed / capped by the blow-out preventer; and 2) dealing with the porosity in the fern ice. The hole would either need to be lined, or pre-soaked with water to ensure that it was not porous. If left porous blow-out prevention via top kill is still possible, but would require the injection of more water.

The pressure sensor placed at the return pump would give warning of impending blow-out. The use of the seal and injecting water would halt the runaway and should result in only modest pressures being present at the preventer / surface. It would be possible to back off on the size of the plate if we were confident that this technique would work. Indeed, this is how it is done in the oil industry.

Max pressure (Pa): 28672079.4

Borehole diameter (m): 0.4;

Borehole area (m^2); 0.12566371

Force (N); 3603039.76

Mass snow required (kg); 367282.34

Snow depth (m); 7

Snow density (kg/m^3); 600

Required radius (m); 5.27594722

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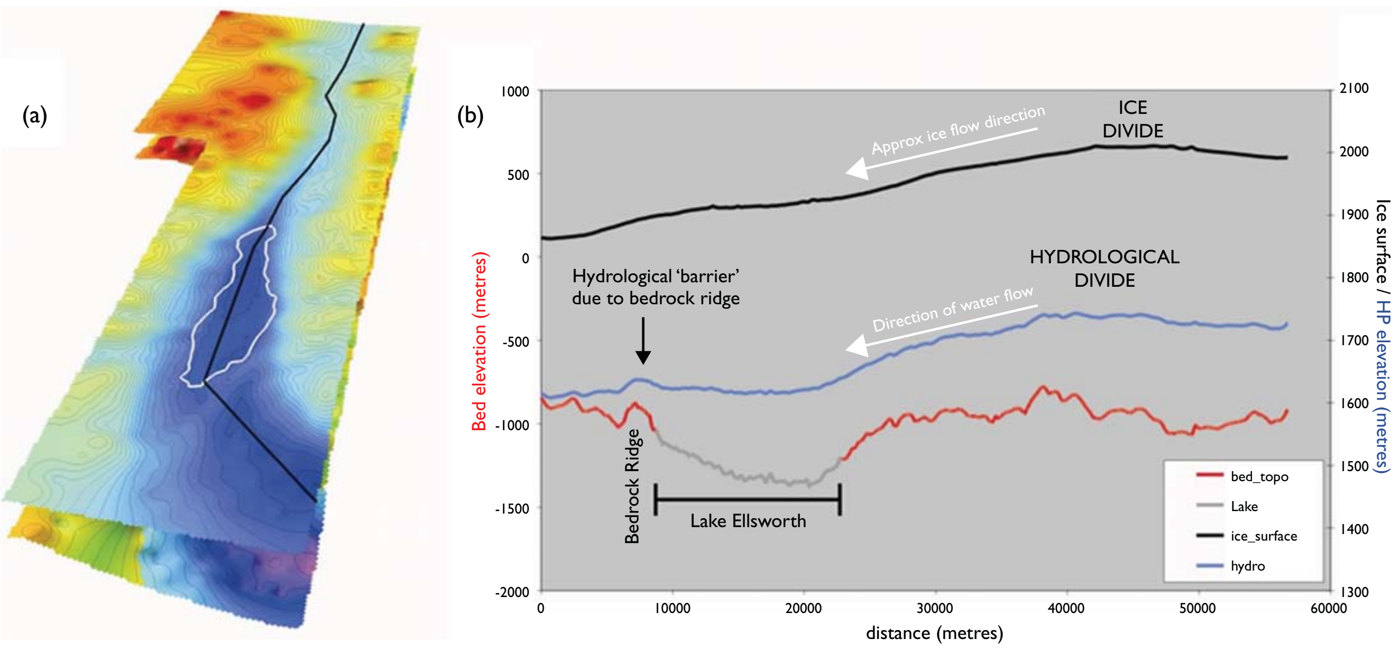

Figure 2. *Profile of the hydrological system within the Lake Ellsworth trough:*
(a) Location of profile (roughly along the axis of the catchment hydrological low);
(b) Hydrological profile (blue line) is shown alongside profiles of the ice surface elevation (black line) and bedrock topography (red line). The part of the bedrock topography coloured grey defines the extent of Lake Ellsworth.

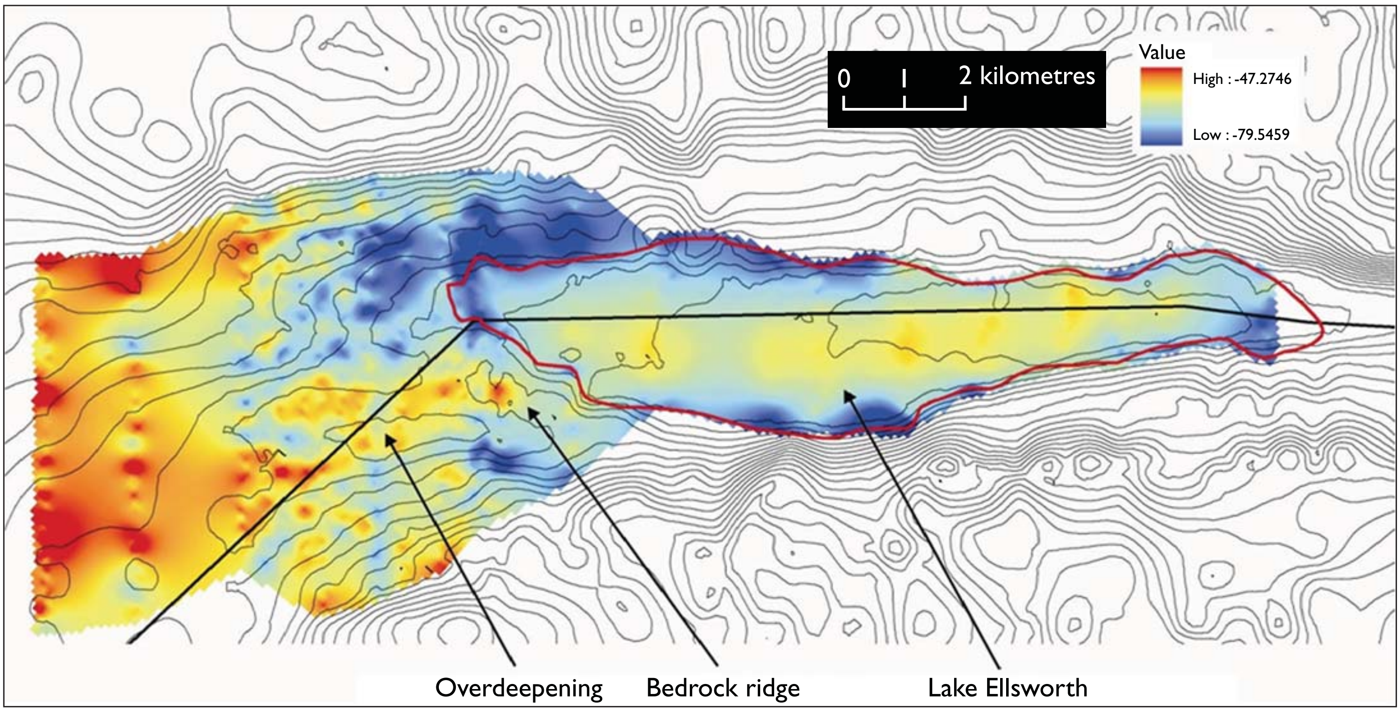

Figure 3. *Map of bed-reflection power (BRP) over and downstream of, Lake Ellsworth. The scale is arbitrary, but red represents higher values of BRP, blue colours represent lower values of BRP. Black lines are elevation contours at 100 m intervals. The thick black line defines the position of the profile data from Figure 2. Key features are also labelled. The zone of higher BRP to the left of the image likely reflects a combination of a thinner ice column and possibly the presence of more widespread basal water.*

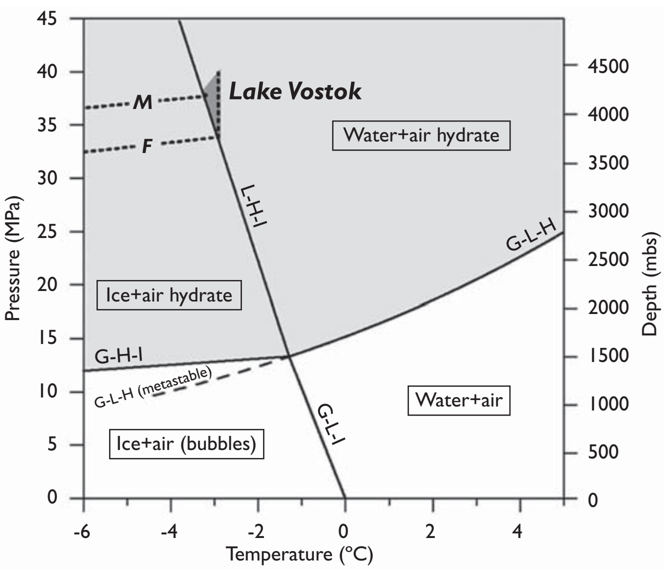

Figure 4. *The phase diagram of air clathrate hydrate from Lipenkov and Istomin, 2001. Shaded region shows field of air hydrate stability. Small darkened triangle within this field covers the range of in-situ conditions in Lake Vostok with* ***M*** *and* ***F*** *located in the zones of subglacial melting and freezing. Conditions within Subglacial Lake Ellsworth lie between depths of 2600 m and 3000 m.*

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