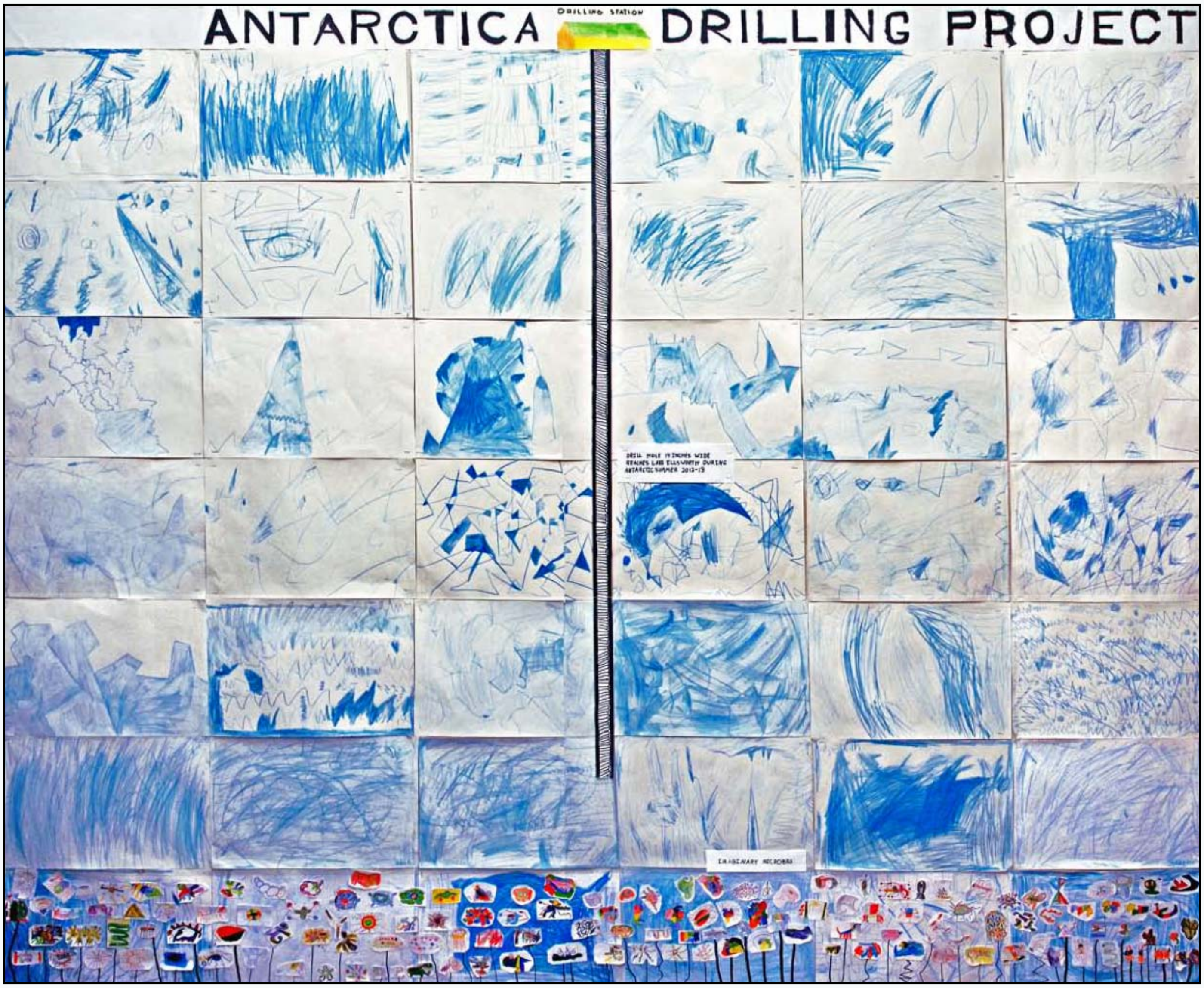
Proposed Exploration of Subglacial Lake Ellsworth Antarctica

Final Comprehensive Environmental Evaluation



Subglacial Lake Ellsworth Antarctica

May 2012

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 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 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 final 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.

The draft CEE was presented at the Committee for Environmental Protection (CEP) XXIV in Buenos Aires in June 2011. The full text of the comments received by the UK on the draft CEE are presented in Appendix 4, together with responses to the comments from the authors of the CEE.

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.

A field camp providing temporary accommodation and power for 11 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 split in the field, analysed in laboratories at the UK's Rothera Station, and then distributed to laboratories across the UK for detailed investigation.

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 3.4 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°58'4.44"S, 090°34'27.56"W in West Antarctica. It is positioned within the uppermost catchment of the Pine Island Glacier some 85 km west of the Ellsworth Mountains. The ice-sheet surface above the lake is at an 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 km^3 ±0.2 km^3. 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 CEE. This programme has been in a planning and design stage for eight 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" (the sudden release of high pressure gas from the lake) resulting from dissolved gas build up has been rigorously assessed, and the overall risk confirmed as very low, and with necessary precautions there is negligible risk to the safety of the field party.

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 final 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 biosecurity protocols) will be reported.

The microbial control methods have been tested during laboratory trials prior to deployment of equipment in the field. However, the full 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 will 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 biodiversity, 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.

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 environmental impacts can only be assessed after they have already occurred, a precautionary approach has been taken reflecting this risk.

We acknowledge, however, that CEEs are usually carried out for proposals with an environmental impact of more than minor or transitory. We followed the CEE approach as it 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 any potential impacts that the proposed programme is predicted to pose to the Antarctic environment, and justifies the activity proceeding.

Acknowledgements and further information

This final 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.

An edited version of this CEE was published in *Reviews of Geophysics* (Siegert et. al., 2012). We thank the three anonymous referees for helpful comments that were used to revise both the paper and this CEE.

The final CEE is made available on *www.antarctica.ac.uk/ellsworthcee* and *www.ellsworth.org.uk*

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Chapter 1: Introduction

It has long been hypothesised 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°58'4.44''S, 090°34'27.56''W** (Figure 1), has been shown to lie beneath 3.1 km of ice, is 12 km long, 3 km wide and up to 156 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.

A field camp, providing temporary accommodation and power for 11 scientists and support staff will be established on-site for an estimated eight weeks. The location of the field camp is shown in Figure 2.

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 split in the field and analysed in laboratories at the UK's Rothera Station, and then distributed to laboratories across the UK for detailed inspection and study.

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 (University of Bristol from 1st August 2012). 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 preparing the CEE and setting up the lake access experiment. The hot water drill equipment and probe will be designed, built and tested, and the field camp established directly above Lake Ellsworth.

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. 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 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 final CEE is made available to the public via both the BAS website (*www.antarctica.ac.uk/ellsworthcee*) and the programme website (*www.ellsworth.org.uk*). It is available in advance of the XXXV ATCM in 2012, and well before the exploration activity commencing. It is also distributed at ATCM XXXV.

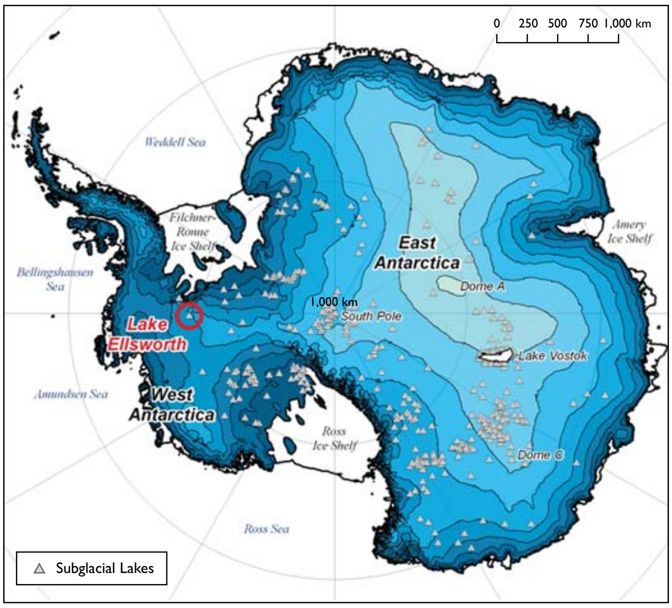

Figure 1. *The location of 386 Antarctic subglacial lakes (from Wright and Siegert, 2011). Lake Ellsworth is circled.*

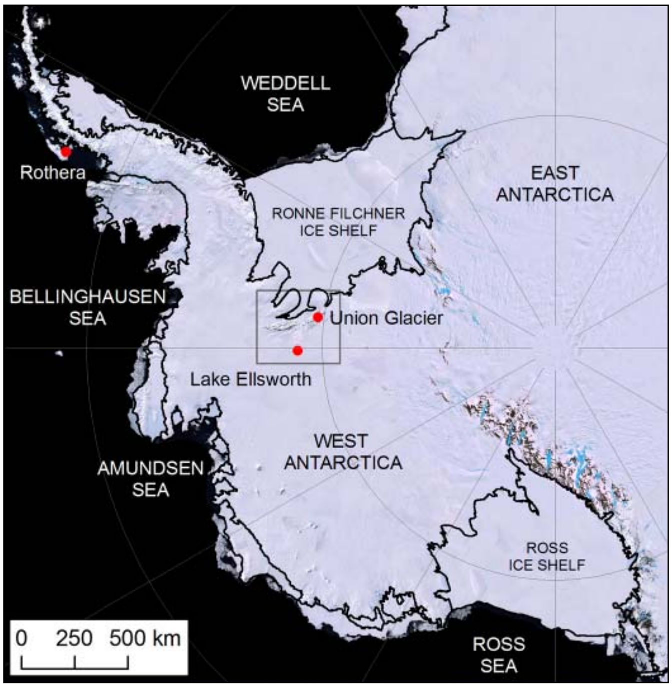

Figure 2a. *The location of the Lake Ellsworth drill site, Rothera Research Station and Union Glacier.*

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 were carried out to better characterise the lake (Woodward et al., 2010; Ross et al., 2011a) and identify the best place to access it. These results, described in Chapter 3, confirmed Lake Ellsworth's suitability for addressing the scientific aims. At the proposed access location (78°58'4.44"S, 090°34'27.56"W), the lake 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. The ice-sheet surface above the lake is at an elevation of 1895-1930 m. The centre of the lake is located only 30 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 3.4 km of ice.
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- 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.

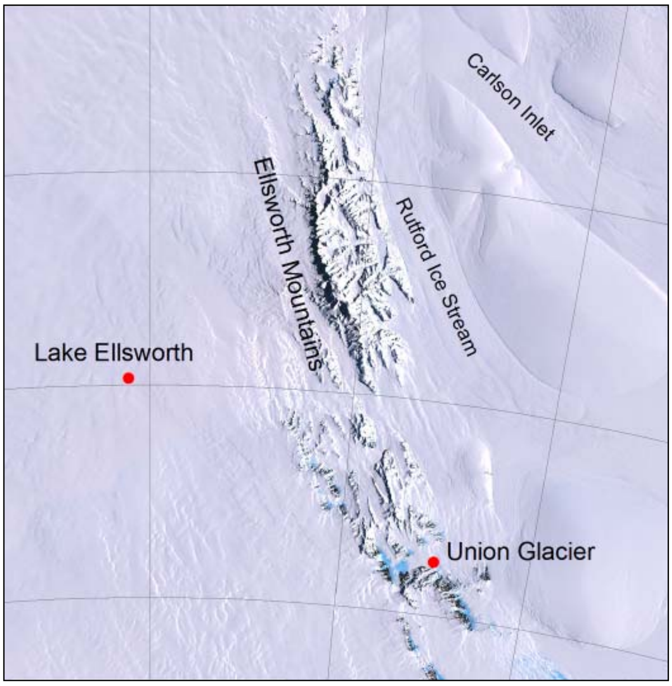

Figure 2b. *The location of the Lake Ellsworth drill site and Union Glacier in relation to the Ellsworth Mountains.*

Chapter 3: Baseline conditions of Lake Ellsworth

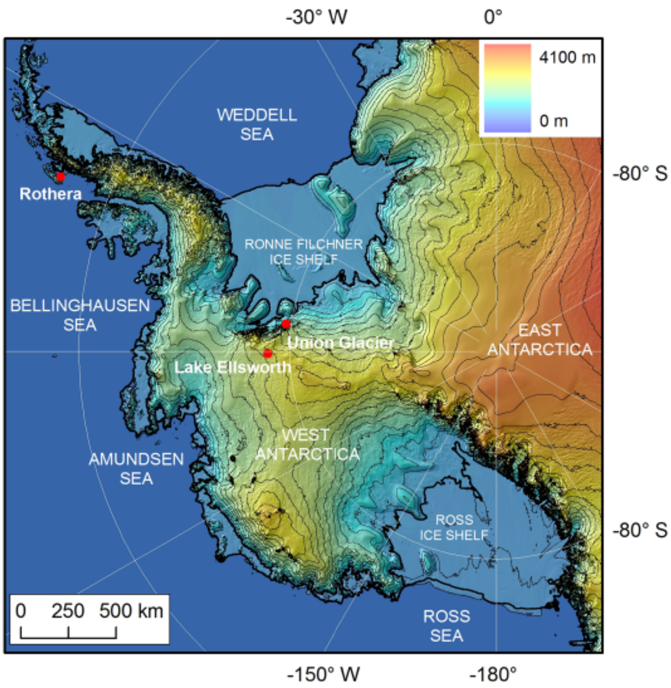

Figure 3. *Location of Lake Ellsworth in West Antarctica. The base map is the Antarctic 1 km Digital Elevation Model (DEM) from Combined ERS-1 Radar and ICESat Laser Satellite Altimetry (Bamber et al., 2009) with contours at 200 m intervals.*

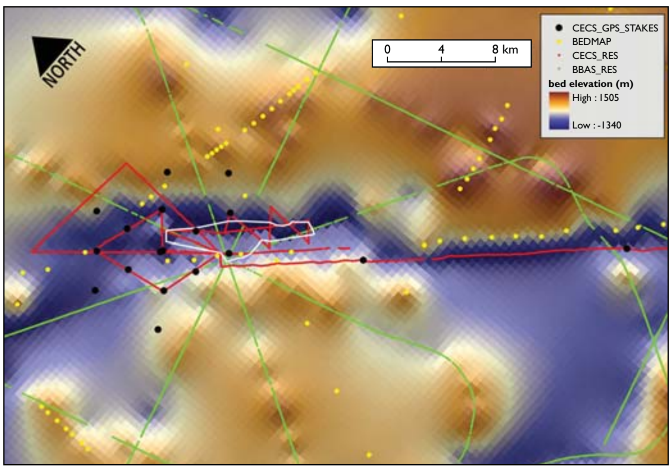

Figure 4. *Location of RES and GPS datasets pre-dating the Lake Ellsworth geophysical survey. Yellow dots = BEDMAP points (including original SPRI-NSF-TUD RES line and 1957 IGY traverse), red lines = CECS ground-based RES data, green lines = BAS airborne RES data. The gridded basal topography was constructed 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 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; Ross et al., 2011a).

Location

Lake Ellsworth, at 78°58'4.44''S, 090°34'27.56''W, is located within the uppermost catchment of the Pine Island Glacier some 85 km west of the Ellsworth Mountains at an ice-surface elevation of 1895-1930 m above sea level, as shown in Figure 3.

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 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.

Survey type	Year	Party/Team
Traverse	1957/58	Sentinel Range (Marie Byrd Land) traverse
Airborne radio echo sounding	1977/78	SPRI-TUD-NSF
Airborne geophysical survey Pine Island Glacier	2004/05	BAS
Radio echo sounding/GPS measurements	2005/06	Centro de Estudios Cientificos
Geophysical survey inc	2007/08	BAS, Univ. of Edinburgh, Northumbria Univ.
RES, temporary glaciopole network and GPS readings	2008/09	BAS, Univ. of Edinburgh, Northumbria Univ.
Survey flight	2010/11	BAS, Univ. of Edinburgh, Northumbria Univ.

Table 1. Summary of baseline surveys at Lake Ellsworth

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 (Drewry and Meldrum, 1978). Previous to that, it had been crossed by the 1957-58 Sentinel Range (Marie Byrd Land) traverse (Bentley and Ostenso, 1961). The lake was documented again in the mid-1980s 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 4).

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 4). 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. 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 (RES) surveys

A detailed grid of RES survey lines was acquired over Lake Ellsworth and its surrounding area using the ground-based 1.7 MHz pulsed DELORES radar system (Figures 5 & 6). The RES survey was designed to define: i) the outline of Lake

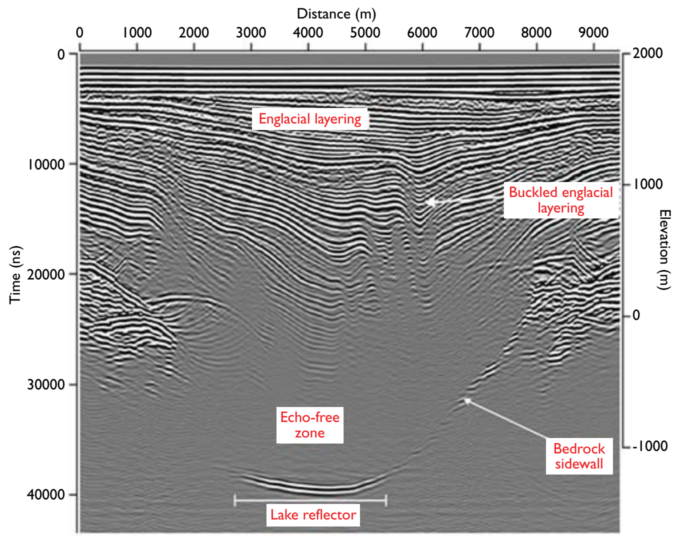

Figure 5. *DELORES radio echo sounding data across Lake Ellsworth (Line D7.5). A prominent lake-like reflector is observed between 2600 and 5400 m along the profile at depths of ~3100 to ~3220 m. Buckled englacial layers generated by ice flow over a zone of pronounced subglacial topography southeast of Lake Ellsworth (see Figure 6) are annotated. Ice flow is approximately into the page. See Figure 6 for location.*

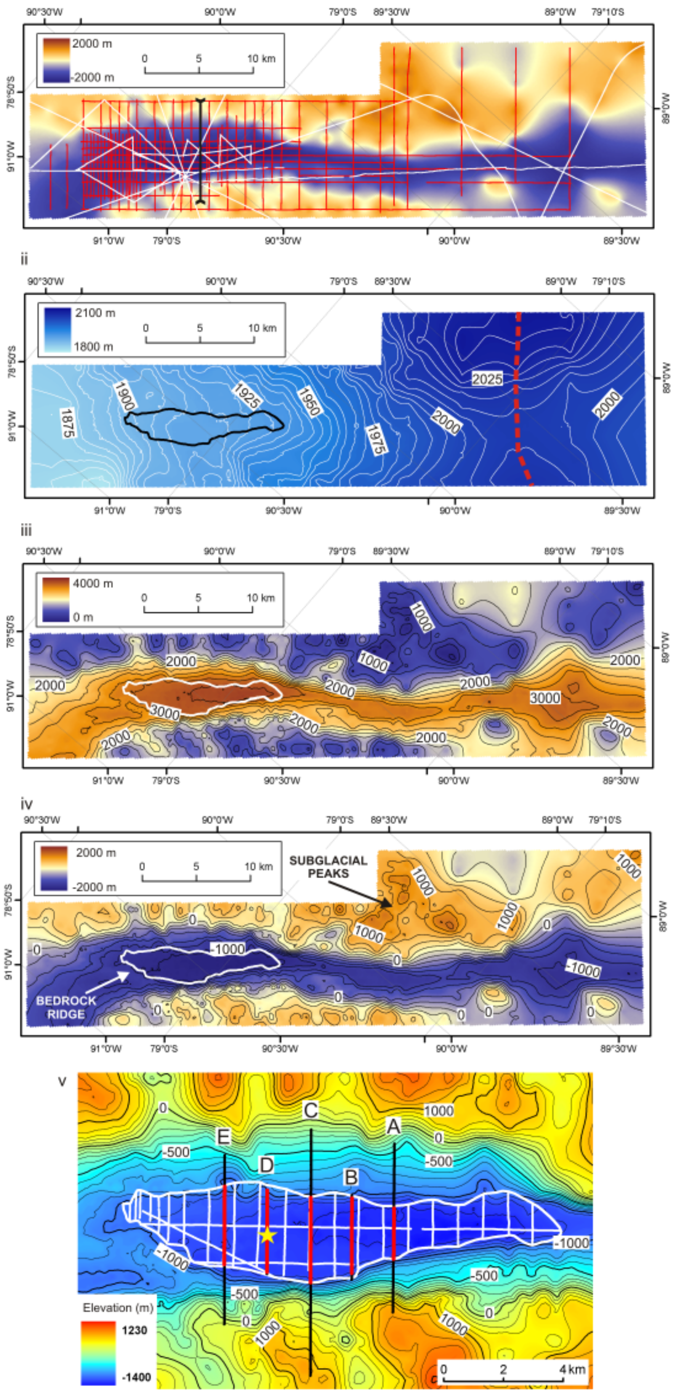

Figure 6. *Images produced from DELORES RES datasets: (i) map showing location of acquired RES data. Red lines represent DELORES data, white lines represent BAS and CECS 150 MHz data also used for the gridding of ice thickness and subglacial bed grids. Line D7-5 (Figure 5) is shown with a black line; (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.*

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 6). Roving GPS data, acquired along the RES profile lines during the surveys, were used to generate a matching DEM of the ice surface (Figure 6).

The DELORES RES data are characterised by strong, well-defined intra-ice reflections in all profiles (e.g. Figure 5). 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.

Ice sheet surface

The ice surface map (Figure 6) 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 6). 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 and 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 6), 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 above sea level (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 6). 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 a 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 5) 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. 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., 2011b).

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 6, 7 and 8). 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 7. The ice-base reflection can be clearly identified in all five of the processed seismic

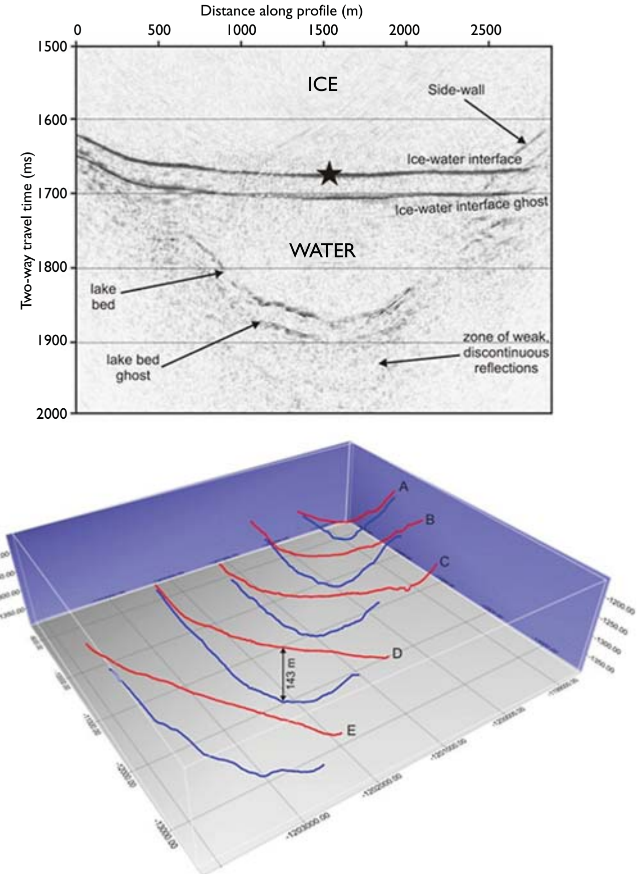

Figure 7. *Seismic reflection profile D (Figure 6). View is uplake with ice flow aligned roughly out of the page. Black star marks proposed point of lake access. Note that for visualisation purposes the uppermost 3000 m of the seismic profile has been removed; (ii) 3D visualisation of the lake surface 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).*

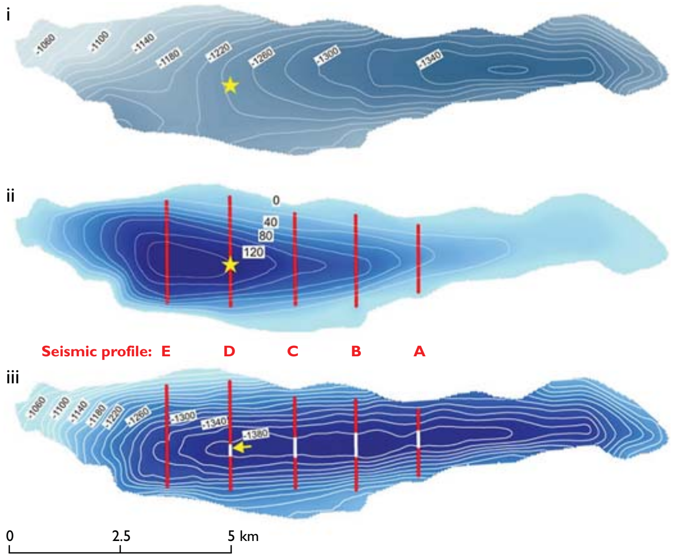

Figure 8. *Gridded seismic datasets: i) ice-water interface (integrated seismic and RES data); ii) water column thickness (seismic data only); iii) lake bed topography (ice-water interface minus water column thickness). Yellow stars and arrows indicate the proposed access location. Contours for all 3 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.*

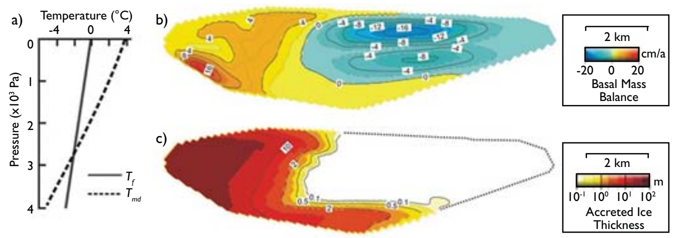

Figure 9. *Modelled ice-base and lake water characteristics: (a) Depression of freezing point (T_f) and temperature of maximum density (T_{md}) with overburden pressure; (b) Modelled basal mass balance; (c) Modelled accreted ice thickness (in metres). Ice flow is roughly from right to left.*

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 8).

The seismic data reveal Lake Ellsworth has a broad, generally U-shaped, lake-bed morphology (Figures 7 and 8). 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; Ross et al., 2011a).

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 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 9). 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 9). 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 7) 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 10). 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 10). 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 11), 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 2. 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 2. 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

	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 2. 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.

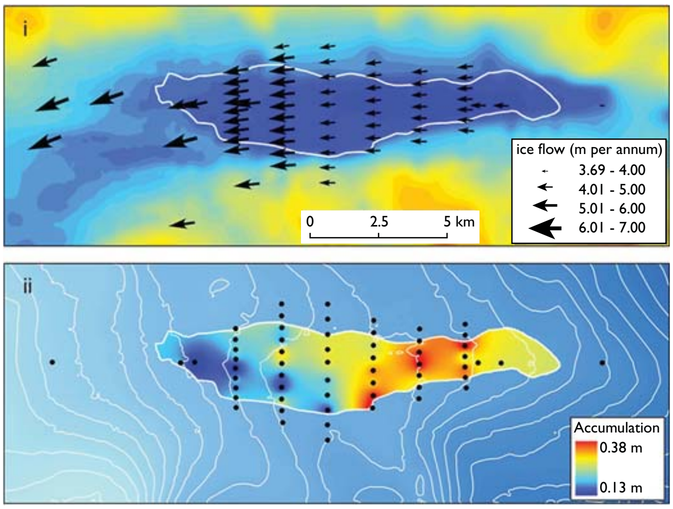

Figure 10. *(i) Direction and rate of present-day ice flow from GPS measurements of a network of surface markers. Size of arrows denotes rate of flow (larger arrows = faster flow); (ii) Surface accumulation (ma^{-1} ice equivalent) over Lake Ellsworth between 2008 and 2009. Black dots mark observation points. i and ii have a common scale with ice flow roughly from right to left.*

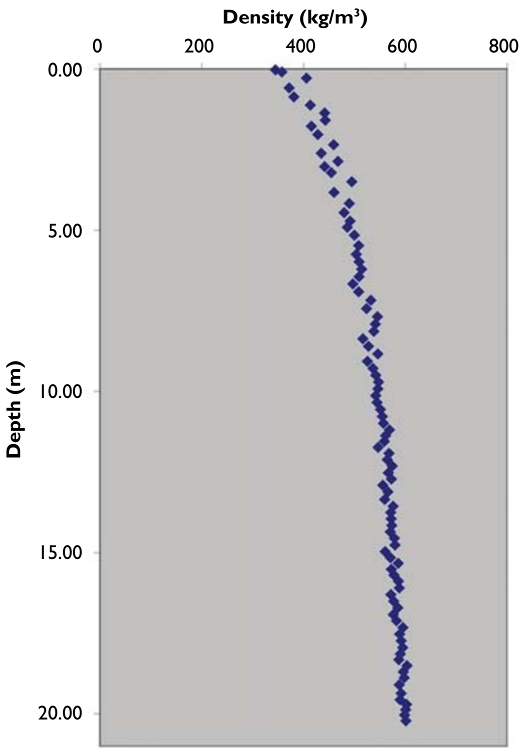

Figure 11. *Snow/firn density measurements from a 20 m deep borehole cored over the centre of Lake Ellsworth.*

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 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 10). 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 10). 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 (Barrett, Nicholls, Murray, Smith and Vaughan, 2009), 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. RES 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 78°58'4.44''S, 090°34'27.56''W, which is marked in figures 6, 7 and 8 because:

- The lake floor is deepest at this point (although the water column, at 143 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 RES 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 (±0.41) $\times 10^3$ and 1.68 (±0.31) $\times 10^3$ 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

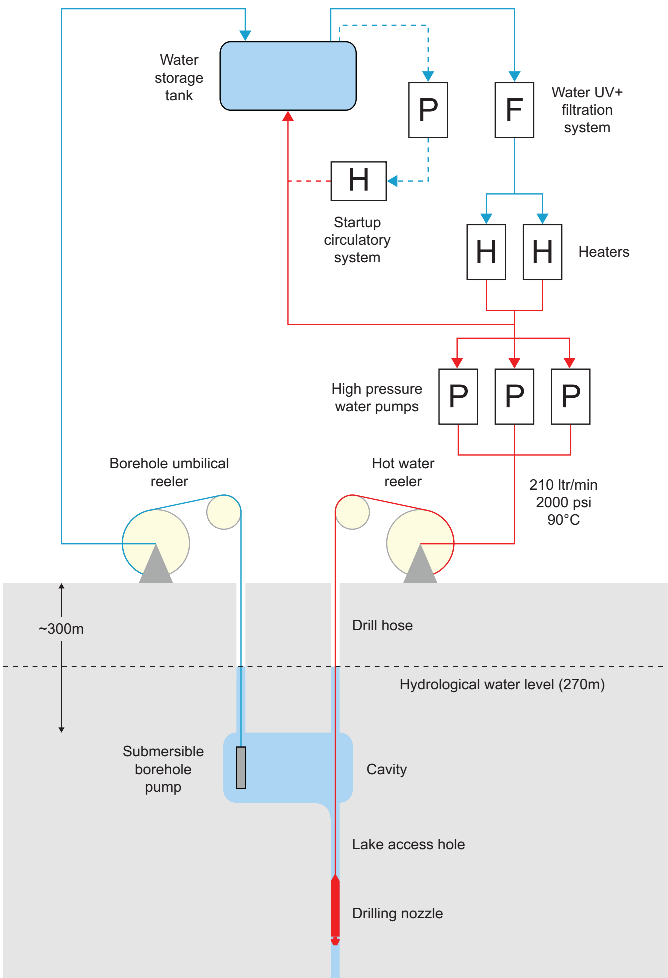

Figure 12. *Schematic diagram of the hot water drill system. H = heaters; P = pumps; F = filters.*

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 has been used to build the drilling system for Lake Ellsworth.

The drilling concept is simple, as shown in Figure 12. 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.

To initiate the hot water drilling process, some near surface snow will be used (~15-30 m^3). The remainder of the melt water will be supplied by ice from over 50 m below the ice surface.

A submersible borehole pump installed near the surface, but below the lake's hydrological level (284 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 min^{-1} and 0.5 m min^{-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.

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. Each stage will be provided with sampling ports so that water samples can be collected and analysed. All filters will be provided with dual redundancy in order to allow new filters to be brought online without interruption to the water flow. 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 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 and cleaned with 70% alcohol 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 speed 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. The drill fluid will be sampled an a 6 hourly basis as a minimum, subjected to DAPI staining and enumeration by epifluorescent microscopy. Any trend towards significant increases in cell numbers will lead to a cessation of activity pending an investigation of how contamination has occurred, (e.g. why the filters are not working) and an increase in the sampling/testing to an hourly basis. **The lake will not be penetrated if the microbial levels exceed background readings.**

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. It is anticipated that over the filter system operating period, one set of filters will easily maintain their filtration specification. However, if the particulate loading of the melt water is much higher than expected, the system is switched to a parallel set of new filters without any need to stop the drilling process. All filters will be available for post operational analysis. Filters will be preserved by freezing only.

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.

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 drill/borehole water from entering the lake.

We are able to control the temperature of the water at the drill head. We will maintain possible drill head temperature until approximately 50 m from the lake surface, at which point the temperature will be reduced to 40 °C.

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 (~24 hrs) 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.

To avoid mixing drill water and lake water, only lateral jets (and no forward jets) will be used during reaming. Furthermore, reaming (if required at all) will mostly be done in the middle depths of the lake where the highest freeze rate occurs, preventing mixing of drill and lake water.

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.

All individual component parts of the drill system were tested individually to ensure they met the factory acceptance criteria. These factory tests were observed by a BAS engineer.

Before shipping the entire hot water drill system was tested 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.

This testing involved connecting the entire drill system – the holding tanks, boiler, filtration system, high pressure pumps, main hose and nozzle assembly and running it for several hours.

The generators were commissioned and tested to ensure they met our acceptance criteria, then run for approximately 100 hours each under load.

At the end of the trial, the hoses were cleaned by blasting out all the water, and passing a pigging system through the hose to clean the hose interior.

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 (284 m below the ice surface at the proposed drill site).

The cavity linking the two holes will be created by pausing the drill nozzle for up to one hour at 300 m, allowing the hot water to make a bulbous cavity. This process is repeated in the other hole. A hot water feed to the submersible borehole pump can be used to maintain or enlarge the cavity if necessary. The cavity is expected to be 10-15 m^3.

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 13, 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/mechanical supports will be removed (3).

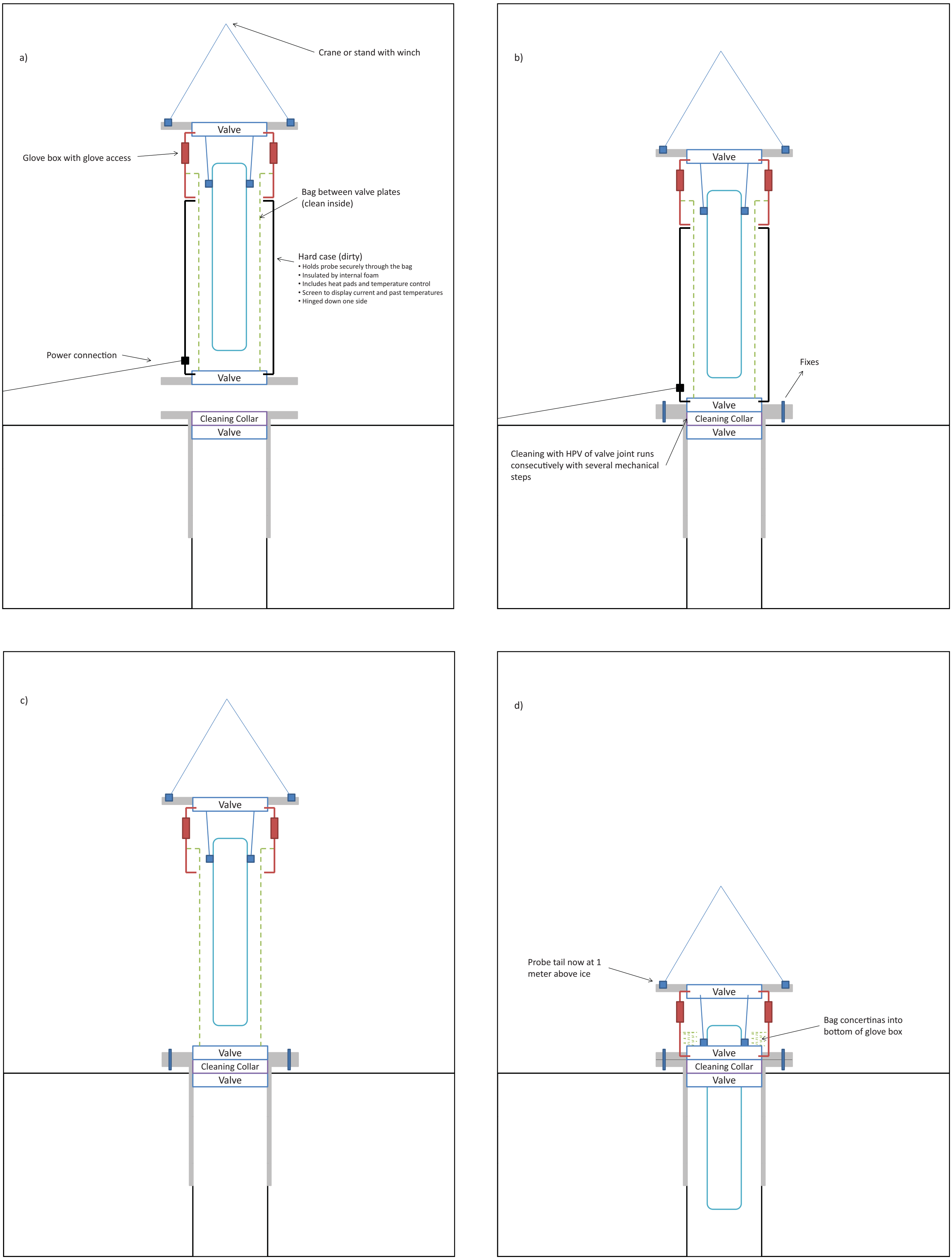

Figure 13. *Twelve stage sequence for deploying the scientific instruments.*

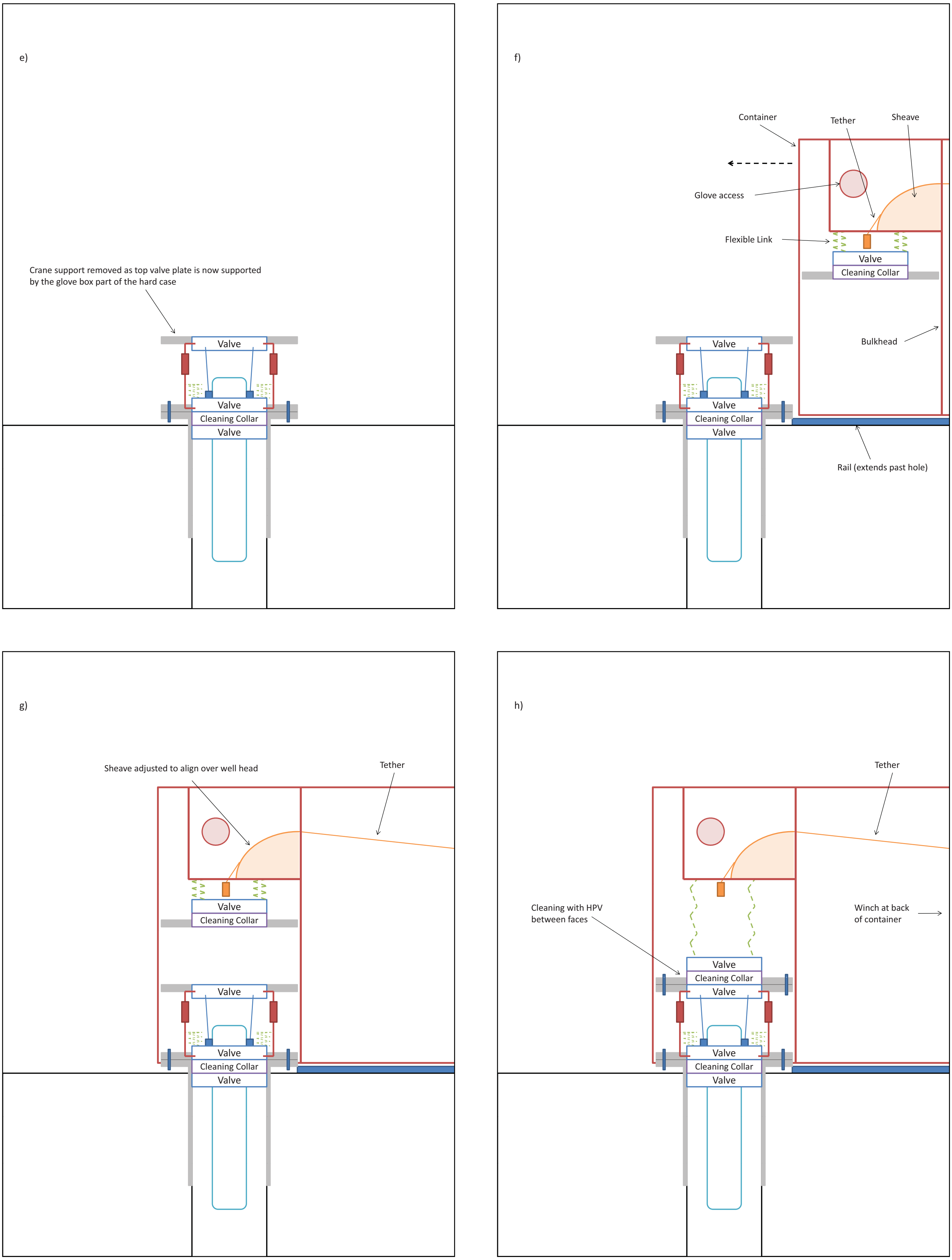

Figure 13. *Twelve stage sequence for deploying the scientific instruments.*

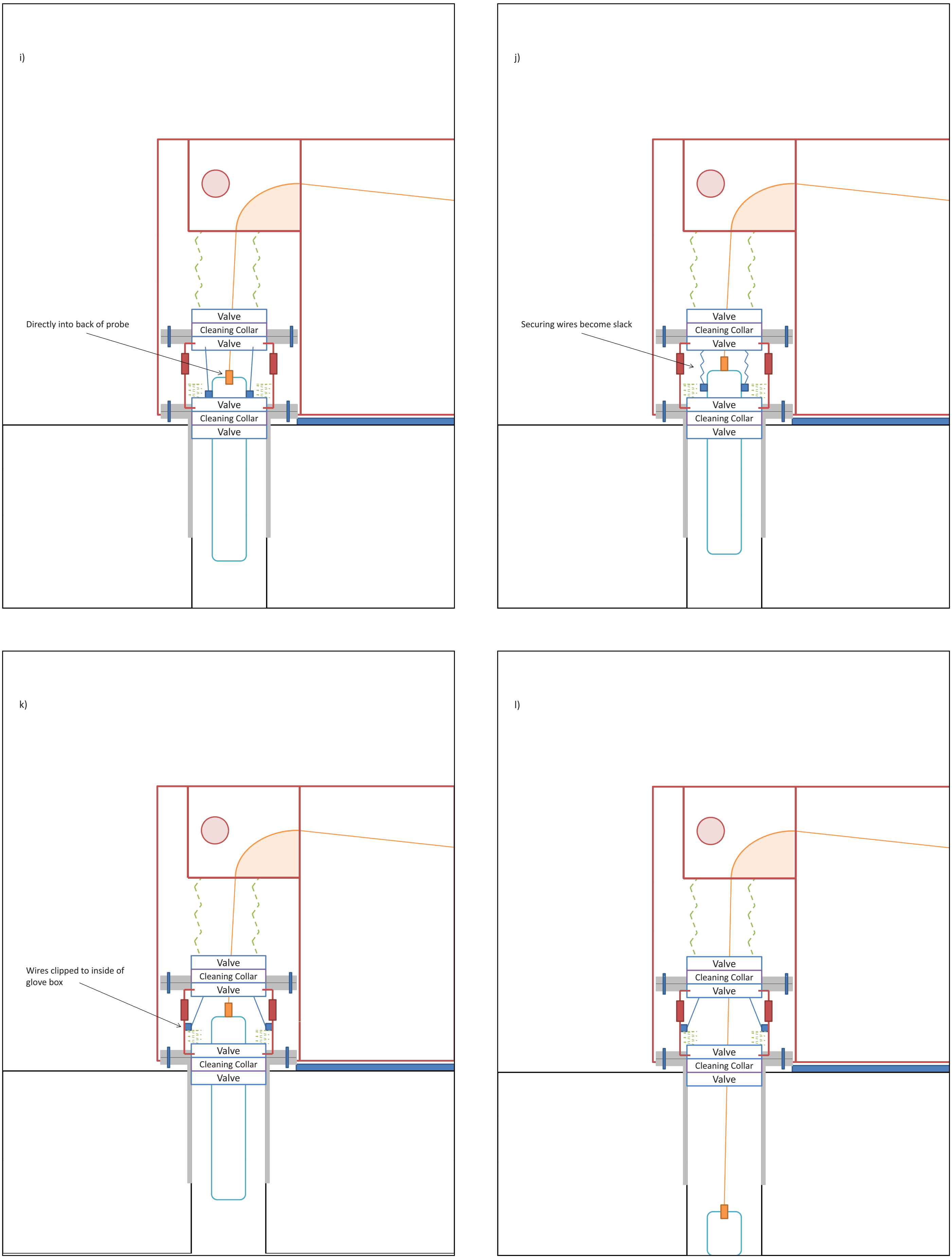

Figure 13. *Twelve stage sequence for deploying the scientific instruments.*

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 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 microbial control methods reduces the risk of contamination being introduced during deployments.

Probe description

Designs for the probe and its systems have been completed by the UK National Oceanographic Centre (NOC) in collaboration with the Lake Ellsworth Consortium over the last four years. Two probes (for contingency) have been produced.

The probes 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 14). 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 enables continued operation (e.g. sampling at predetermined intervals) and archiving of instrument data in case of communications failure.

Power is supplied through the tether. Probe-to-surface communications (two way) is via an optical link and backup wire modem using commercial off the shelf (COTS) technology used in several deep sea remotely-operated vehicles.

There is a long track record of equipment deployment at depth. The tether is well engineered for the stresses that will be encountered. It is therefore extremely unlikely that the probe will be lost. There is no contingency plan to recover any equipment which becomes detached.

The probe includes three rosettes of eight bespoke 100 ml titanium water sample bottles (designed to withstand the large pressures generated when the water sample freezes at the surface following recovery of the probe). The use of titanium is a requirement for trace metal (e.g., Fe (II)) analysis. The sampling bottles can collect water at any time or depth (to be specified by the science programme or in response to *in situ* measurements, see Section 6.1). Each bottle can be flushed by several litres of water before capturing a sample (which will take 30 seconds). The bottle valves are actuated using magnetically-coupled electric motors enabling them to be opened and closed on demand. Samples are maintained at pressure, enabling quantitative analysis of dissolved gases. Each container with its two valves is detachable from a carousel frame for processing and storage. Each of the carousels has a robust gear pump fitted to a manifold to flush the sample bottles with sample.

In each rosette, seven of the bottles will be opened once immersed in the borehole. This significantly eases the problem of bottle opening at depth. The remaining bottle will contain sterilised water and will be heated to prevent freezing while in the borehole and lake. This bottle will act as a control sample. The sterile water has an ultra low nutrient and organic content and therefore there will be no inoculum or food source for microbial growth. Our tests on water stored for two months show that growth does not occur in this sealed and sterile environment. After capturing a sample, each bottle will be sealed from the environment, and opened after surface sterilisation in a closed, sterile microbiological cabinet.

The sampling method used maintains the *in situ* 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 will be minimised by purging/evacuation of valves and interconnecting pipes.

Independent of the water samplers, each sampling rosette contains two 0.2 μm filters, that will be used to extract filtrand from ~100 l of lake water (taking around 30 mins to do so). The filter membranes will be allowed to freeze at the surface and will be split/packed for immediate microscopy analysis at Rothera Research Station and, later, at UK laboratories for more detailed work.

Probe mounted corer

The tip of the probe is equipped with a narrow-diameter piston-corer. This can 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 on retrieval.

Instrumentation

The probe is equipped with >6000 m rated commercially available sensors to measure pressure, temperature, conductivity, oxygen concentration (electrode), redox potential and pH. Video cameras and sonar provide additional information on the lake environment. Redundant temperature, conductivity and oxygen (optode) sensors are also installed. The instrumentation is attached to the main body and at the front of the probe.

Table 3 summarises the performances of the instrumentation package (see following page).

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
Oxygen Optode	0-500 µM	<8 µM or 5% whichever is greater	<1 µM	25 s (63%)

Table 3. Probe instrumentation package performance.

Ranging sonars will be mounted on the forward face of the probe. A second sonar is mounted on the rear end of the probe, enabling ranging to the underside of the ice. Underwater video will be supplied with two video and light packages, one at each end of the probe, allowing imaging of both the lake bed and the borehole/underside of the ice. These will store data locally and transmit at high fidelity via the optical communications link.

Topside equipment

A winch system suitable for both the probe and the corer has been developed, and includes a winch, top sheave, power converters and slip rings, optical and electrical communications pickup, and interface to the cleaning system.

The tether is of synthetic composite construction and includes four copper conductors for power (2.5 mm^2), two copper conductors for backup communication channels, and six optical fibres. The tether is 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, diameter reduction for deployment down the borehole, and remote percussion to enable sediment penetration.

A percussion driven piston corer has been designed and manufactured by UWITEC (an established limnological engineering company based in Austria) and BAS (Figure 15). 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 are 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 (Figure 16). 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 stratigraphic and palaeomagnetic properties.

Sampling strategy

The rate of probe descent in the lake will be 1 m per 30 sec. Thus, water collection within one 100 ml bottle will sample ~1 m of the water column, unless the probe is halted during sampling. We will take samples in triplicate (activating three bottles each time) for bioassay, hydrochemistry and for organic geochemistry. This sampling approach 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 sampling strategy aims to minimise the missing of stratified layers by avoiding the use of propellers on the probe and other equipment, and by the slow rate of probe descent.

The corer barrel is highly polished and equipped with a double sediment catcher and piston rod lock which will minimise sediment release, although some is inevitable.

Usual practice in deep oceanographic and limnological sampling is to log the properties of the water column on descent, and to use this information to define sampling locations on ascent. In our case, it is prudent to collect samples on descent as there is a risk (albeit low) of being unable to sample on ascent (due to rupturing of the communication tether during retrieval of sediment). With this is mind, we will collect samples during initial descent at water depths of 10 m, 50 m, 90 m, 130 m and 140 m (i.e. 3 m from the lake floor). Measurements (P, T, EC, DO, Eh and pH) taken during descent will inform whether the remaining samples should be taken at specific locations of scientific interest (i.e., at sharp temperature/ chemical gradients) or at depths of 110 m, 70 m and 30 m (completing the water column sampling at a 20 m spacing). If necessary (e.g. if the chemical and physical stratigraphy of the water column is complex), all sample bottles can be flushed and refilled at any lake depth. In addition to the samples collected in the lake, control samples of the borehole water will be collected at regular (30 min) intervals during the drilling programme to determine background levels of biological and chemical parameters.

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 (i) manage the probe's sampling strategy, and (ii) 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 later to the international scientific community. First analysis, on the filtrand recovered by the probe's water pumps, will take place in laboratories at Rothera Research Station. The rest of the material recovered will be packaged into sterile containers and transferred to UK laboratories where detailed analysis can take place. Four independent laboratory analyses of lake-sample material will be undertaken, and these are summarised below.

The drill fluid will be sampled on a six-hourly basis as a minimum, subjected to DAPI straining and enumeration by epiflourescent microscopy.

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 18).

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 (see Table 4 on following page).

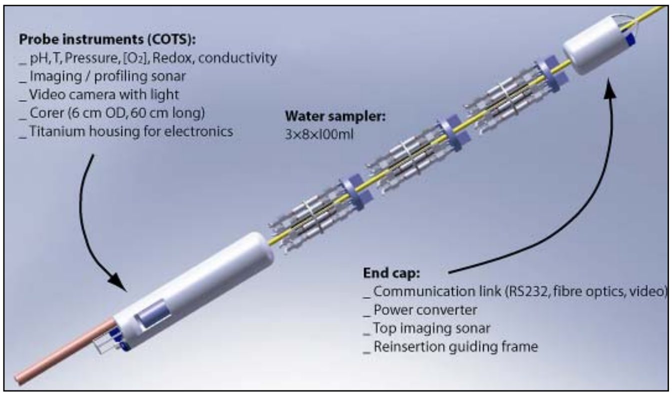

Figure 14. *Illustration of the probe concept and its instrument and sampling arrangement. The probe's dimensions are approx 4500 mm in length and 200 mm wide.*

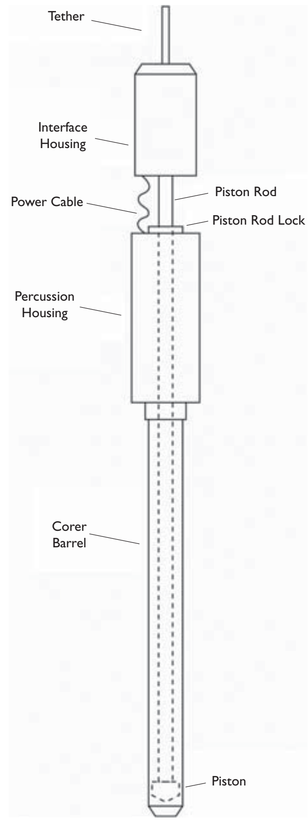

Figure 15. *The design and construction of the sediment coring system. The corer is approximately 5.8 m long.*

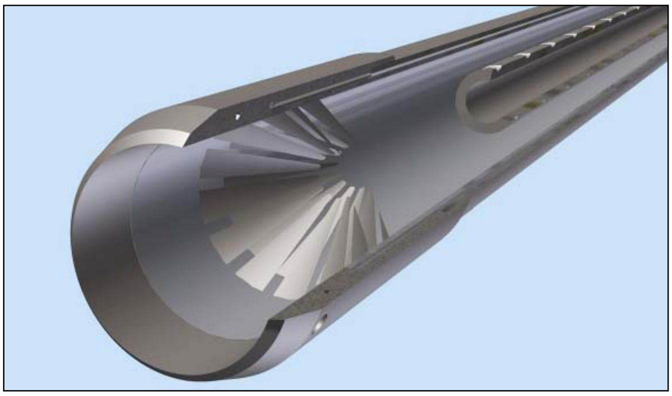

Figure 16. *The double core catcher.*

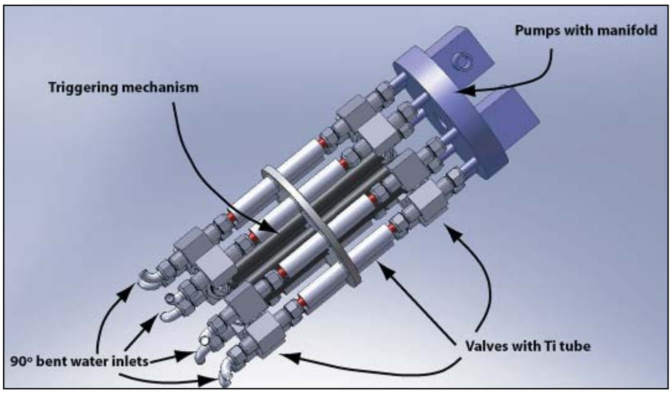

Figure 17. *3D representation of one carousel holding eight 50 ml sample containers. A full sampling unit will constitute of three carousels stacked together.*

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 4. Microbiological analysis of Lake Ellsworth water samples.

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.

The following three 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 genes involved in biogeochemical cycling to assay the water/ samples for the presence of genes involved in geochemical activity.
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.

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.

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.

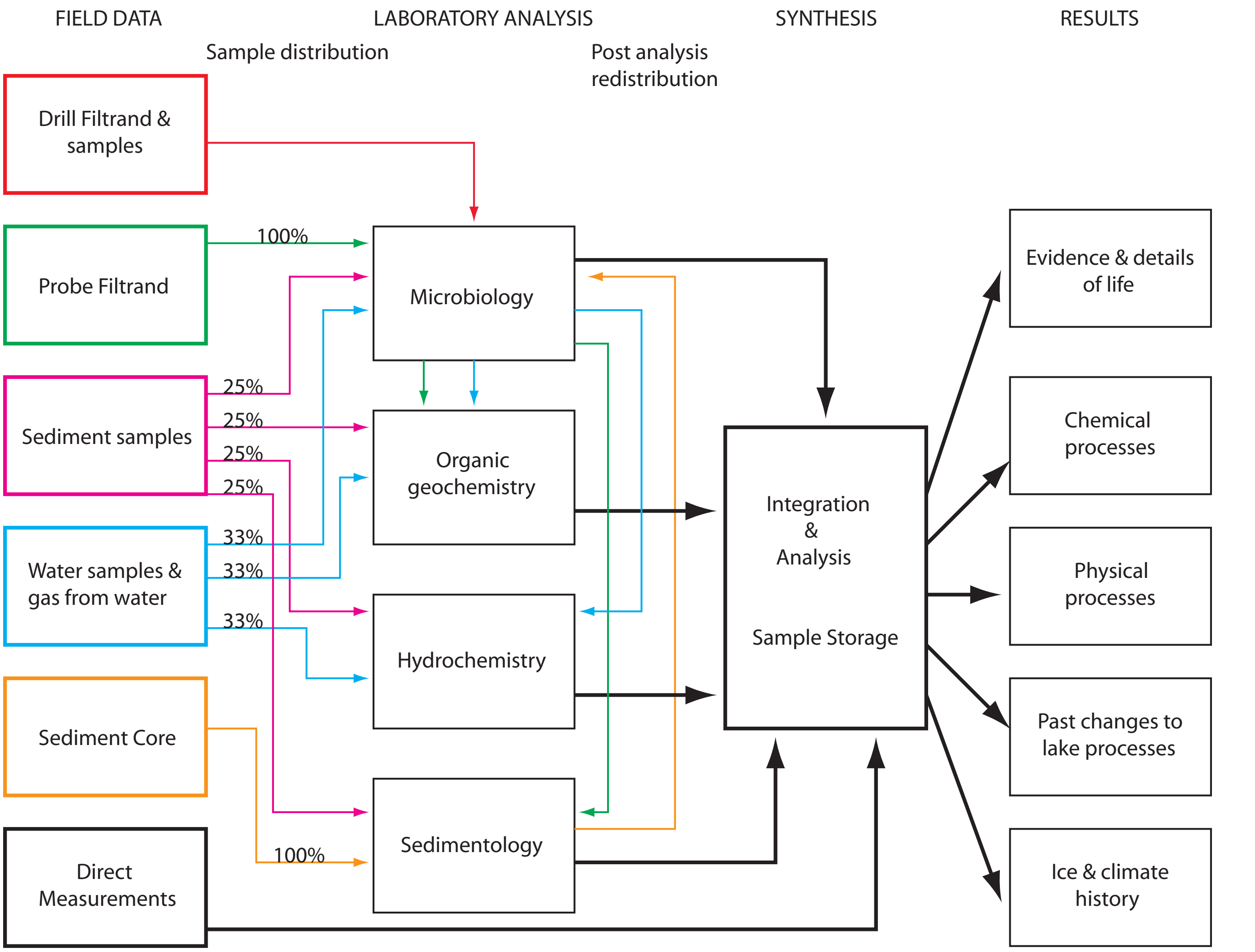

Figure 18. *Flow diagram of sample distribution and exchange, and analytical studies needed to meet the project aims.*

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 19 for layout).

The camp will be located approximately 100 m down-wind of the lake access point, which is at **78°58'4.44''S, 90°34'27.56''W**, and 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. The tractor train vehicles will also come and go from the site.

Power will be provided by four standard generator sets running on AVTUR fuel (Jet A-1). They will provide 240 v 50 Hz 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 of the equipment.

Personnel

The on-site team for the 2012/2013 drilling season will be composed of 11 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 4) – responsible for directing and handling the samples
- Camp Manager – responsible for running the domestic camp and waste management

In addition to the core team, it is likely that a media team (comprising a total of four people) will be on site for approximately two weeks during drilling.

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.

Power generation and fuel calculations

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

There will be 1 x 20 kVA generator (GEN1) to run the camp and 3 x 100 kVA generators (GEN2, 3, 4) which will have a combined output capable of running the drilling operation. There will also be two small, portable Honda generators for charging, welding, emergencies, etc.

Generators 2, 3 and 4 will load-share the main drilling operation. Any two generators can handle the load if one generator fails.

The main four generators will have to make an efficiency allowance for the altitude of the site and for the modification to run on aviation fuel (AVTUR) rather than diesel. Typical loss of efficiency is:

- 10% loss of efficiency for running on AVTUR
- 8% loss in efficiency for running at 2,000 m altitude

The plan is for an eight-week season = 56 days or approx. **1,300 hours**.

The main drilling operation will take approx. **100 hours**.

The preparation for the drilling operation will take approx. **72 hours**.

Each generator will require **30 hours** run in prior to going on load.

GEN1 will run the camp for the duration of the season but will be switched off at night.

- Run time – 896 hours (16 hours per day) @ 5 lph = 4,480 l (22 drums)

GEN2 will begin the drilling preparation.

- Run time – 202 hours (24 hours per day) @ 22 lph = 4,444 l (22 drums)

GEN3 will switch in after the first 24 hours and be combined with GEN2.

- Run time – 178 hours (24 hours per day) @ 22 lph = 3,916 l (19 drums)

GEN4 will switch in after a further 48 hours and be combined with GEN2 and GEN3 to begin drilling.

- Run time – 130 hours (24 hours per day) @ 22 lph = 2,860 l (14 drums)

HONDA generators will run on petrol and two drums has been allowed for this.

Boiler will run for 100 hours and will burn 19,500 l (95 drums).

Sno-Cat will be in use throughout the season and will use approx. 2,460 l (12 drums)

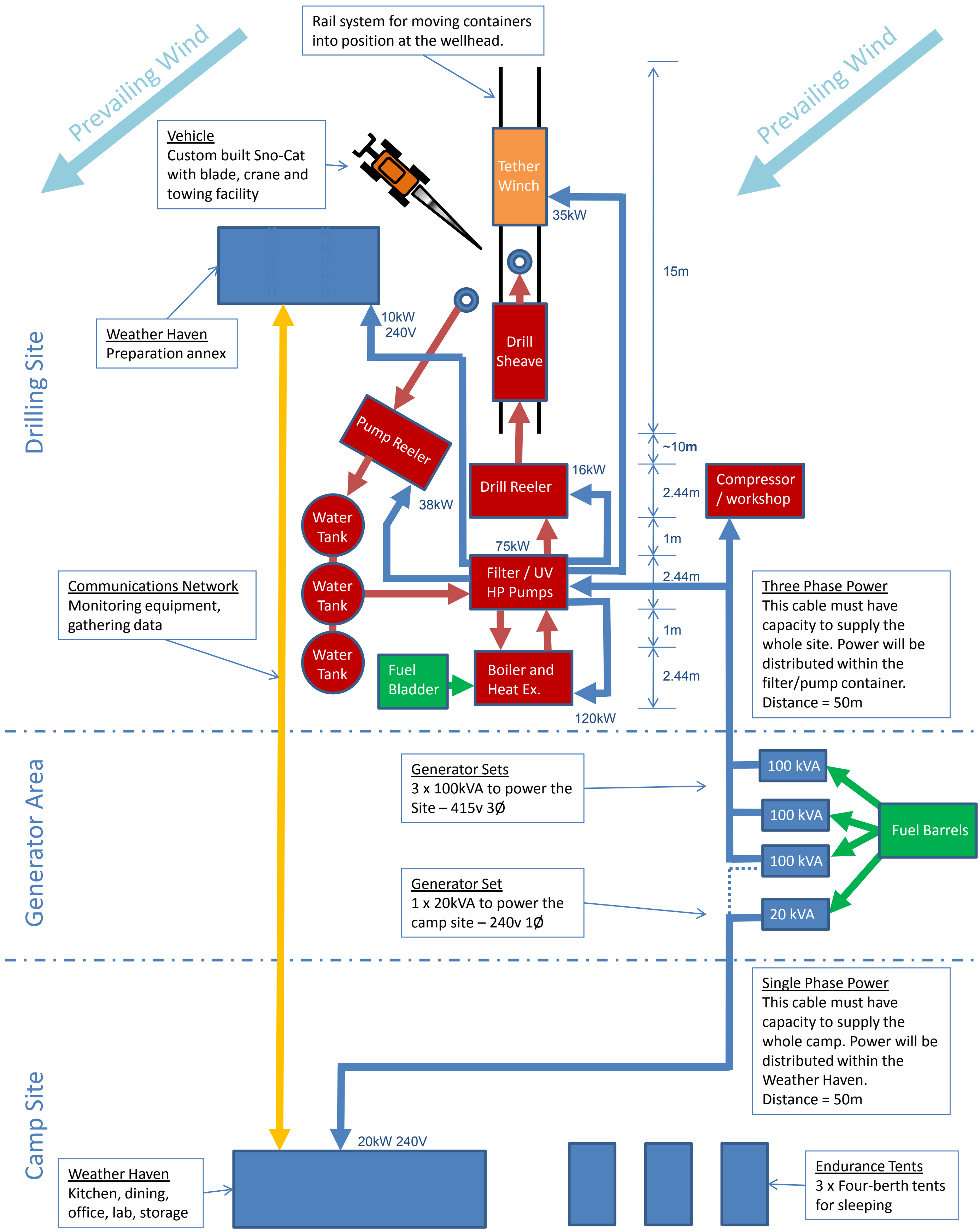

Figure 19. *Schematic layout of the camp.*

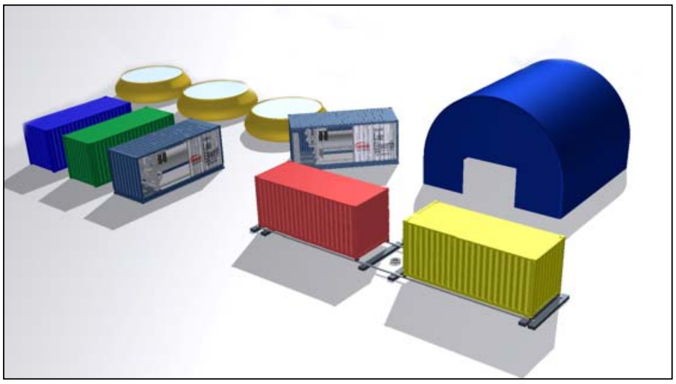

Figure 20. *3D Model of the drilling site as per the layout in Figure 19.*

Twin Otters will resupply the site and will need to be refuelled.

- Estimate six flights at five drums per flight = 6,150 l (30 drums)

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

TOTAL AVTUR = 51,250 l (250 drums)

TOTAL PETROL = 410 l (2 drums)

The fuel required on site for drilling, power generation and other logistics will amount to approximately **51,250 l** of **AVTUR** and **410 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). This fuel use is estimated to be 32,000 l and 485,000 l respectively.

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.

The ALE tractor train vehicles (Two No Prinoth BR 350 – shown in Fig 23) are also well maintained according to the manufacturer's specification.

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.

With the exception of grey water (which will be strained before being disposed of at the camp site), 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. Table 5 summarises waste types, estimated amounts and how they will be packaged.

Waste type	Estimated volume/ amount	Packaging
Solid human waste	100-150 kg	UN-approved plastic drums
Liquid human waste	350-700 l	Metal-framed IBC
Food waste and general packaging material	100-300 kg	Wooden NEFABs
Fuel drums	255	n/a
Batteries (AA)	5 kg	UN-approved battery box
Waste oil	15 l	Oil drum
Used spill kit/ absorbants/oily rags	15 kg	Overpack drum
Other wastes not listed will be disposed of in accordance with the BAS Waste Management Handbook.		

Table 5. Summary of waste arisings.

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 (predominantly a screen) of remote monitoring of the drilling equipment and generator plant. There will be no remote operation of the equipment, except at the point of lake penetration when staff will retreat for safety reasons, but still remain in view of the drilling system.

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 72 tonnes (approx) and the fuel supplies a further 55 tonnes (approx).

The majority of this equipment will be shipped commercially to Punta Arenas, Chile. From there, it will be moved to the ALE base camp by Ilyushin IL-76 heavy lift aircraft. Seven 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 and from the drill site.

The tractor route is as shown in Figure 22 and is estimated to be approximately 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 workable. This route was successfully used in the 2011/12 field season to depot equipment at the drill site.

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 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

Figure 21. *shows an image of the proposed flexible bulk fuel container on a skid base.*

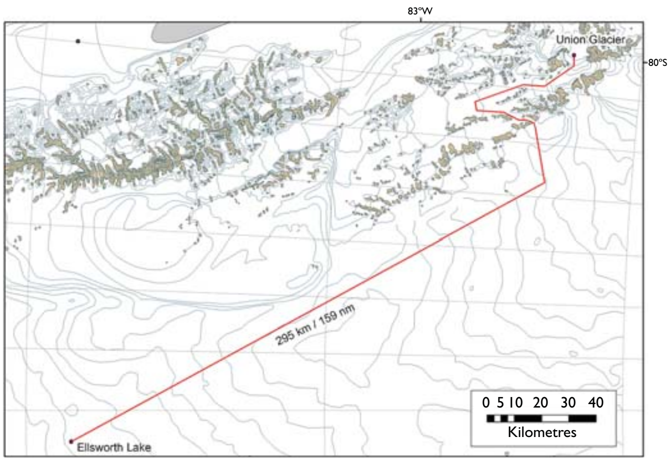

Figure 22. *The transport route for equipment and fuel from the ALE base camp at Union Glacier to the proposed drill site.*

Figure 23. *The tractor and sledge used to transport equipment and fuel to the drill site.*

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, including those related to SLE team members plus ALE activities associated with this programme. 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.

Reducing the temperature of the drill fluid to 40 °C and drawing down the drill fluid level in the hole minimises drill/borehole water from entering the lake.

We are confident that if any drill water were to enter the lake, the temperature of the water would not compromise our science aims or the lake's microbial function.

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) with the sub aquatic environment.
2. All engineered structures were 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 for all materials used in systems in contact with the borehole or lake (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 have been 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 (i.e., the stainless steel wellhead formed from a tube that occupies the top 3 m of the borehole and a flange that secures the wellhead at the ice surface and enables connection to other systems; the sheaves, winch and associated equipment used to load and lower equipment into the borehole; the hot-water drill hose and head for creation of the borehole; the probe used to take measurements and take samples, and its tether; and the sediment corer).

Microbial control at design stage

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

1. Materials selection of probe and sampling 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. Hence a list of qualified materials has been generated. This includes polyurethane, PTFE, PEEK, anodised aluminium, and titanium which is particularly robust. Titanium is therefore used extensively on the probe. This simplifies microbial control and also enables trace iron analysis (see Table 6) and reduces the thickness of load bearing structures giving more room for ancillary equipment. Using HPV we have demonstrated a reduction of log-6 for spore forming bacteria *Geobacillus stearothermophilus*, and log-6 for *Pseudomonas fluorescens*, for the titanium surfaces.
2. Minimisation of recesses. Recesses and intricate surface topography has been shown to promote microbial growth (Ploux et al., 2009). Autoclaving (sterilisation using high pressure superheated steam) 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 have and will ensure that these recesses are flushed with a chemical wash and then hydrogen peroxide vapour (HPV) as described below. All fluidic systems (e.g. the valve and pump system for the water sampler) are designed to enable flushing to enable cleaning with hydrogen peroxide vapour (HPV) and/or chemical wash (in our case, 70% ethanol).
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 which protect them against unavoidable handling. For example the probe is placed inside a transit case which is air tight. This is sterilised internally prior to placing the sterile probe inside it. This operation is completed in a bespoke microbiological isolation cabinet which is itself sterilised internally.

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 are chemical cleaning, UV and HPV (see below). Which is used in each operation depends on the function, material and design of the component. Assessment and verification has been undertaken at a process level in all cases and at a component level where required. Components are assembled 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. Subsequent to final terminal cleaning equipment will be placed in a protective environment (e.g. heat sealed bagging or transit case). A visual check will be made to confirm that no protective environment has been breached during transport of the equipment.

The **sheaves**, **probe tether** and **sediment corer mechanical systems** will all be sterilised using a combination of chemical wash, HPV and UV (see below) post construction

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

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. They are also simple in design and do not have enclosed recesses.

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 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** has been cleaned internally by flushing with hot (95 °C) filtered (0.2 μm) and UV sterilised water, and then dried using multiple "pig" passes and compressed air. The effectiveness of this cleaning has been verified via sample analysis (no culturable micro-organisms found, no detectable chemical contamination). The internal surface of the hose was then capped prior to transport to site in Antarctica. Prior to deployment the inside of the hose will be flushed again with 90 °C filtered (0.2 μm) and UV sterilised water. The outside of the hose will be mechanically cleaned with 70% ethanol (by passing through a flushed stuffing gland). Both the internal and external surfaces of the hose will be flushed during the drilling operation with filtered and UV treated water.

The cell count within the overlying snow at Lake Ellsworth is 3.32×10^5 cells ml^{-1}. We expect the glacial ice to have a value no greater than this (probably lower), and the same holds for the lake also. Assuming we made no attempt to clean the borehole fluid, this would also be the upper value for the cell count within the borehole water. However, since we are UV radiating and filtering to >0.2 μm, we anticipate the borehole fluid to be far cleaner than the glacial ice it uses. In fact we estimate removal of all, if not the vast majority, of the bacterial cells by the cleaning process. We are therefore confident that the borehole fluid will contain fewer cells than the overlying ice sheet that melts into the lake.

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. After cleaning, the tether (used for both the probe and the corer) is stored inside a sterile and air tight tent together with the winch and the main sheave. This whole assembly is placed inside a shipping container, which also contains the control systems for the probe and corer. An HPV steriliser and backup UV system are also included in this container and can be used to sterilize the system again should there be any breach of the seal, and is also used during the deployment procedure (see below). 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. Operation of the probe and corer without contact with the environment outside of the borehole is achieved by the use of air tight transit cases. These transit cases consist of a flexible bellows covering the majority of the length of the probe or corer. Joined to one end of the bellows is a larger flexible bag containing integral gloves, ports for connecting the HPV unit and a metal support frame which together form what is known as the transit case glove box. The metal frame at the junction between the bellows and glove box contains a secure attachment point on which the probe or corer is held. The other end of the glove box (the exterior face) is sealed with a flap valve which opens outwards and is secured on a flange plate. The other end of the bellows has a similar valve mounted on a similar flange plate with a metal structure that protects the bellows when it is compressed in the deployment procedure (see below). This framework also supports the transit case glove box at the correct height once the bellows has been compressed (again see below).

The deployment procedure does not include assessment to provide data for control or verification of the processes once these are underway other than a visual check, 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. The drilling and deployment procedure is as follows: a mechanical drill will be used to create the top few meters of the borehole. The **wellhead** will be placed into this predrilled shallow borehole and allowed to freeze into the surrounding snow/ice.

The drill hose will be mounted onto a winch and passed over its sheave and uncapped prior to commencing drilling. Drilling operations will then begin via hot water drilling using filtered (0.2 μm) and UV sterilised water. The resultant borehole and the water within it will therefore have a lower microbial content than the surrounding ice, and will have a very similar chemical makeup. However, the top air filled part of the borehole is exposed to the atmosphere and will not be sterile at the end of the drilling operation. At the end of drilling operations the hydrostatic level (i.e. the level of water in the borehole following breakthrough into the lake) is predicted to be approximately 284 m below the ice surface.

At the end of drilling operations the well head will be capped with a glove box (the well head glove box) which is similar to that used in the transit case. This is transported to site sealed and sterile, and has a removable sealed lid on its top face, and a flap valve on its lower face. Prior to removing the lid the glove box will be heated and sterilised with HPV (UV and alcohol wipes available as a backup). To sterilize the air filled section of the borehole and the wellhead we will lower through the well head and borehole a >30W, 254 nm UV source travelling at <1 m/s providing > 10^4 reduction in the microbial population (requires >16 mJ/cm^2 as per ANSI/NSF Standard 55-1991). This provides a sterile top section to the borehole.

The UV source is loaded into the wellhead without breaching the air tight seal or coming into contact with contaminated surfaces. To do this it is also transported to site in an sterile and air tight transit case as previously described. Both the probe and the UV corer are deployed using the same procedure a description of which follows:

1. The lid is removed from the well head glove box, and a crane used to position the appropriate transit case (e.g. containing the UV source) so that the lower end of the transit case can be joined to the top of this glove box. At this stage all valves are closed.
2. The inside of the well head glove box is then sterilised (HPV, with UV / alcohol wipes as a backup) which cleans the exterior of the lower valve on the transit case.
3. The lower valve on the transit case is opened and the UV source (or probe) lowered into the open wellhead collapsing the bellows until the transit case glove box rests on the metal frame for this purpose. This bears the weight of the transit case and its contents.
4. The crane is removed, and the container containing the tether and winch etc. moved into position such that the sheave is directly above the wellhead. This is achieved by having the container on rails.
5. The container and hence the sheave is connected to the top of the transit case using a short flexible link (tube) with one end connected to the sheave box, and the other connected to another glove box (the deployment container glove box). This glove box is connected to the top of the transit case, and sterilized (as above) which also sterilizes the exterior of the top flap valve in the transit case.
6. The top flap valve in the transit case, and the valve in the deployment container glove box are both opened.
7. The sterile tether is pulled over the sheave and connected to the top of the UV source (or probe) using the gloves in the glove boxes. The gloves are also used to release the clamps at the attachment point that otherwise prevent the UV source (or probe) moving upwards. The clamps preventing lowering remain in place.
8. The weight of the UV source (or probe) is taken up by the winch, and the clamps preventing lowering removed.
9. The UV source or probe is deployed.
10. Recovery is the reverse process but does not required the sterilisation steps.

The procedure for microbial control during deployment of the probe is identical to that for the UV source. The corer deployment is also identical apart from the retrieval where the size of the corer once filled with sediment sample necessitates a breach of the air tight seal. Therefore if a second probe or corer were to be deployed, the air tight seal would need to be re-established and the UV source used to re-sterilise the borehole before further deployments. The resultant delay may also make it prudent to ream the hole with the hot water drill prior to attempting this procedure.

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 be the preferred option at the field site to reduce exogenous micro organism populations. To protect against failure of the HPV system a UV light source and 70% alcohol wipes will be available as a back up. HPV 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 (~20 minutes 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 as a backup to HPV treatment and for the air filled section of the borehole (see above). 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).

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) primarily as a backup to the HPV system but also for laboratory sterilisation and preparation of small items.

Verification and assessment

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

We have used positive control contamination by adherent bacteria *Pseudomonas fluorescens* to contaminate engineered surfaces and components in experiments to evaluate the efficacy of our population reduction and assessment methods. This species is commonly used as model system and is representative of likely contamination of engineered structures. 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.

Analytical methods

Our primary tool for visualisation of cells is 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).

We also use 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). We also combine qPCR with fluorescent staining for positive contaminant live/dead discrimination (Rawsthorne and Dock et al., 2009)

Adenosine Triphosphate (ATP) has also been used as a marker of cell presence on probe components and is 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 have been used in the preparation of engineered systems. In the field, the drill fluid will be sampled on a six-hourly basis as a minimum, subjected to DAPI straining and enumeration by epifluorescent microscopy.

Results of efficacy assessment

Each of the population reduction methods and analytical methods has been optimised and adapted for each of the materials and systems used in the Lake Ellsworth experiment. The primary materials used in the engineered systems, together with their usage and appropriate microbial reduction methods for each is shown in Table 6. We have demonstrated a log 6 microbial population reduction for all materials using these methods.

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 6. 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.

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.

We estimate 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 (including emissions from using Avtur for site activities including the drilling, the BAS Twin Otters, the ALE Ilyushin flights and tractor train, and using petrol for all site activities) are calculated in accordance with the methodology set out in 2010 Guidelines to Defra/DECC's GHG Conversion Factors for Company Reporting (see *www.defra.gov.uk/environment/business/reporting/conversion-factors.htm*). The emissions associated with shipping the equipment from the UK to Punta Arenas are based on an estimate provided by the commercial shipping company, and the emissions associated with flying the staff from the UK to Rothera are estimated using BAS's own carbon database which uses the Defra/DECC conversion factors. These emissions are summarised in Table 7. An approximate total of 1860 tonnes of carbon dioxide equivalent (CO_2e) will be emitted throughout the duration of this programmes Antarctic field work.

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 long-term 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 base camp.

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 the exception of grey water, 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. Grey water will be sieved to remove any wastes and poured into a trench to minimise visual impact.

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 7: Summary of predicted atmospheric emissions associated with the SLE Programme.

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*	-			-	-	-	-	-	-	-	-	-	-	-	14285
AVTUR	flights from UK to Rothera**	-	-		-	-	-	-	-	-	-	-	-	-	-	36443
AVTUR	site activities including drilling	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	485800	litres	x	2.5218	0.0012	0.0248	2.5478	0.4687	3.0165	1225090	581	12048	1237721	227694	1465416
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 including drilling	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	-	-	-		-	-	-	-	-	-	-	-	-	-		1859357

* *Figure estimated for shipping emissions associated with transporting the equipment from the UK to Punta Arenas is based on an estimate provided by the commercial shipping company.*

** *Figure estimated using BAS's own carbon database.*

Note: CO_2e (carbon dioxide equivalent) is the universal measurement that allows the global warming potential of different greenhouse gases to be compared.

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 biosecurity 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'). Detailed biosecurity procedures for the containerised equipment are given in Appendix 3. The COMNAP/SCAR non-native species checklist regarding boot washing, cleaning, personal equipment and food will be followed as is standard BAS practice. 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 drill 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. It is not possible to ream the borehole to release equipment if it is the probe or corer that has become stuck.

Were any equipment to be lost in the lake it could not be recovered easily and there is no contingency plan to recover lost equipment. 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 11 core staff and the media team. 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.

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.

[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.*

Identification or prediction of impacts, including preventative or mitigating measures *continued*

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. They operate to their own environmental policy which is consistent to that required by the Lake Ellsworth programme team.

All activities (including those performed by ALE), associated with the Lake Ellsworth programme will be subject to full authorisation under the UK Antarctic Act 1994, and the necessary permit sought from the UK authority.

For clarity, we have agreed that ALE's role in this programme will not be covered by ALE's multi-year IEE agreed with the US authority.

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 8 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.

Table 8: 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 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.
	Tractor train route	Affect on wilderness and aesthetics	Certain	Local	Short	Very low	The 295 km tractor route will not be flagged on the ground but the traverse route may remain visible for one or two seasons.

Table 8: 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.
	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.
	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. Wastes (including human waste) will be collected and packaged, then transported back to the ALE Basecamp and ultimately out of Antarctica where they will be reused or recycled wherever practicable. Grey water will be sieved and disposed of on site.
	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 core team of 11 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. The COMNAP/SCAR non-native species checklist will be followed.

Table 8: 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. 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 • There is no contongency to recover any equipment that detatches during deployment

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 since 2004. 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. Should such a substance enter the lake, it would clearly 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 aims of the project (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.

Over 350 subglacial lakes are now known. Each of them may be of interest scientifically from the point of view of life in extreme environments and sedimentary records.

The question of which lakes would make the most suitable candidates for exploration was considered by the SCAR SALE group (Kennicutt et al., 2001; Siegert, 2002; Priscu et al., 2003).

A SCAR report on subglacial lake exploration put forward six questions that must be answered to guide the selection of an appropriate subglacial lake to explore. They are as follows:

1. Does the lake provide the greatest likelihood for attaining the scientific goals?
2. Can the lake be characterised in a meaningful way (e.g. size, postulated structure)?
3. Is the lake representative of other lakes and settings?
4. Is the geological/glaciological setting understood?
5. Is the lake accessible (closest infrastructure)?
6. Is the programme feasible within cost and logistical constraint?

The first five questions can be addressed by examining what we know of the physiographies of subglacial lakes (Dowdeswell and Siegert, 2002; Wright and Siegert, in press). All subglacial lakes have the potential to attain the SCAR scientific goals (life in extreme environments and glacial history records), as they all have ice above, water within and, in all probability, sediment beneath. In trying to assess which lake has the greatest chance of meeting the goals, it must first be examined with questions #1-5 in mind. Table 9 summarises Siegert's (2002) analysis of subglacial lakes within nine regions and categories.

Lake Ellsworth was not considered explicitly within such an analysis until 2004, when it was re-identified and, based on these criteria, considered to be an ideal candidate for exploration (Siegert et al., 2004) compared with other known lakes.

Subsequently, a two-year geophysical programme quantified Lake Ellsworth's glacial (and to some degree geological) setting, and confirmed its appropriateness for exploration (Woodward et al., 2010).

Since 2006, it has been recognised that some subglacial lakes lay closer to, or within, enhanced ice flow. These lakes were not considered in the initial analysis by Siegert (2002). Satellite information on surface height changes above these lakes suggests they experience substantial input/output of water, and may at times be completely drained. This has rather negative implications for the longevity of an ecosystem in such lakes and in the preservation of sedimentary records. Moreover, since the lakes are at the downstream end of quite a complex hydrological system, it would be far more difficult to acquire detailed knowledge of the glaciological regime than for lakes close to the ice divide. Hence, we believe although subglacial lakes in such systems are of interest, they do not address the SCAR criteria as well as some other lakes.

Table 9: Summary of Siegert's analysis of subglacial lakes (2002)

	Dome C	**Ridge B**	**Titan Dome**	**Whitmore Mts.**	**Hercules Dome**	**Lake Vostok**	**Astrolabe**	**Byrd Glacier**	**West Antarctica**
Lake Class	**Type I**	**Type I**	**Type I**	**Type II**	**Type I**	**Type I – unique size**	**Type III**	**Type III**	**Type I**
Q1. Likelihood of attaining scientific goals? **(n.b. no attempt is made to select a 'best' lake)**	Goal I: YES Goal II: Probably	Goal I: YES Goal II: Probably	Goal I: YES Goal II: Probably	Goal I: YES Goal II: Probably	Goal I: YES Goal II: Probably	Goal I: YES Goal II: YES	Goal I: YES Goal II: Probably	Goal I: YES Goal II: Probably	Goal I: YES Goal II: Probably
Q2. Can the lake be characterised?	Yes: Lake is < 10 km wide and topography is flat	Possibly: Lake is <10 km wide, but topography is quite steep	Possibly: Lake is <10 km wide, but topography is quite steep, though not as steep as in Ridge B	No: Although lake is small, topography is very steep	Possibly: Lake is <10 km wide, but topography is quite steep	Yes: in terms of macro character No: in terms of small scale detail, as the lake is too large, topography too steep	Possibly: Although lake is ~30 km wide, its hydrological system is better known than any other lake	Yes: Lake is < 10 km wide and topography is flat	Yes: Lake is < 3 km wide and topography is flat
Q3. Is the lake representative?	Yes: of numerous lakes at Dome C and the ice sheet centre	Yes: of 5 or so lakes found at Ridge B and the ice sheet centre	Yes: of numerous lakes at the ice sheet centre	Yes: but only for Type II lakes	No: the ice dome here is not similar to Dome C or Ridge B	No: Lake Vostok's size makes it unique. Yes: Processes operating in Lake Vostok may be applicable to other lakes.	No: This lake is positioned at the mouth of a large valley with fast ice flowing through it.	Yes: of Type III lakes	Yes: in terms of physiography No: in terms of tectonic and glaciological history
Q4. Is the geological setting understood?	No: although basal sediments are thought to exist here (Siegert, 2000)	No	No	No	No	No: but probably better known than any other lake & sediments are known to exist on the floor	No: but the topographic and glacial setting is known well.	No	No
Q5. Is the lake accessible?	Yes: located close to the EPICA Dome C ice core site	No: located 100 km east of Vostok Station, at the centre of EAIS	Yes: located near South Pole, on flight path between SP and McMurdo	No: located >200 km from any station	No: located >200 km from any station	Yes: southern end of the lake located beneath Vostok Station. No: Northern end of the lake located >200 km from Vostok Station	Yes: located near Dumont d'Urville, at the ice sheet margin	No Yes: located near McMurdo Station, at the ice sheet margin	Yes: located near to the Byrd Ice Core

We conclude that other locations for exploration has been well considered, and the Lake Ellsworth stands out among known subglacial lakes as an ideal candidate.

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 10 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. Samples of drill water will be collected for UK laboratory analysis on an hourly basis. 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.

In the field, samples of the drill fluid will be collected during drilling on a six-hourly basis as a minimum, subjected to DAPI straining and enumeration by epiflourescent microscopy. Any trend towards significant increases in cell numbers will lead to a cessation of activity pending investigation of how contamination has occurred and an increase in the testing to an hourly basis.

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 10: 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.

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 since 2004, 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 11 core 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 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 environmental impacts can only be assessed after they have already occurred, a precautionary approach has been taken reflecting this risk.

We acknowledge, however, that CEEs are usually carried out for proposals with an environmental impact of more than minor or transitory. We followed the CEE approach as it 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 any potential impacts that the proposed programme is predicted to pose to the Antarctic 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:

1. Analysis of the hydrological potential
2. 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

On 5th February 2012, Russian scientists successfully penetrated the surface of Lake Vostok using ice coring from Vostok Station. As expected, the lake fluid rose up the borehole and then froze. While borehole fluid overtopped the hole, no reports of gas emissions were made. As Lake Vostok is known to have accretion ice above it, and is therefore, at least in part, a closed system, the lack of serious gas emission from the lake access is very helpful to affirm the low risk of blowout on access to Lake Ellsworth. 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. Quantitative assessment of risk

In order to quantify risk we need to clearly define it. Risk is a combined assessment of the probability and consequences of an incident. So, there are three components to be considered in estimating the risk - the probability, the event to which the probability attaches to (in this case, gas blowout) and the severity of the consequences (in the worst case, death).

A formal judgement elicitation exercise was conducted [*M. Brito et al.*, manuscript submitted] to link expert judgements concerning the probability of blowout for six different scenarios and the probability of death due to blowout [after *O'Hagan et al.*, 2010]. The experts' judgements were mathematially aggregated in order to produce an assessment that would represent the group's view.

Based on this quantitative risk assessment exercise, the estimated probability of blowout upon accessing the surface of Lake Ellsworth is lower than 1.23×10^{-3}, with 95% confidence. This value reflects the probability of blowout not the actual risk of death due to blowout. Risk to life is an area covered in length in the Health and Safety Exectuive (HSE), UK, documents (HSE 1992, HSE 2001). The Health and Safety Executive, UK, sets a tolerable risk (TR) for employee death per annum to 10^{-4}. If blowout meant certain death, then the risk of blowout would have been unacceptable. However, if a blowout takes place, the scientists will have enough time to put in place a structured evaluation plan, leaving the drill site to a safe haven ay least 100 m away. Thus, in this case, blowout does not mean certain death. The quantitative assessment of the probability of death due to blowout given that a structured evalucuation is put into place, led us to an estimated risk lower than 8.96 x 10^{-5}, with 95% confidence. This is lower than the tolerable risk specified by the Health and Safety Executive. As a result, potential engineering methods to mitigate blowout are not considered necessary.

10. 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 40 °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.

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Annex 1: Engineering blowout prevention strategies

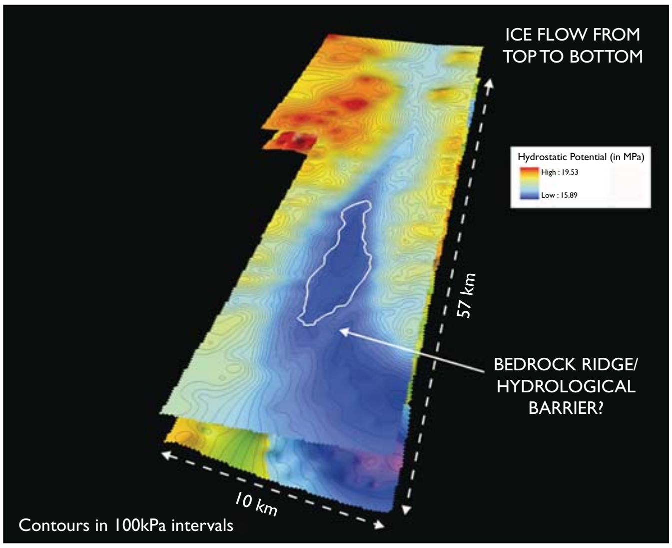

Figure 1. *3D representation of the hydrological potential of the Lake Ellsworth catchment. Basal water will flow from areas of high (red) to low (blue) pressure, perpendicular to the contours. Lake Ellsworth is clearly a hydrological sink for the entire upstream basal hydrological catchment.*

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 tonnes 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

Borehole diameter (m): 0.4;

Borehole area (m^2); 0.12566371

Force (N); 3603040

Mass snow required (kg); 367282

Snow depth (m); 7

Snow density (kg/m^3); 600

Required radius (m); 5.27594722

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Woodward J, Smith A.M., Ross N., Thoma M., Corr H.F.J., King E.C., King M.A., Grosfeld K., Tranter M., Siegert M.J. 2010. *Location for direct access to subglacial Lake Ellsworth: An assessment of geophysical data and modelling.* Geophysical Research Letters, 37, doi: 10.1029/2010gl042884.

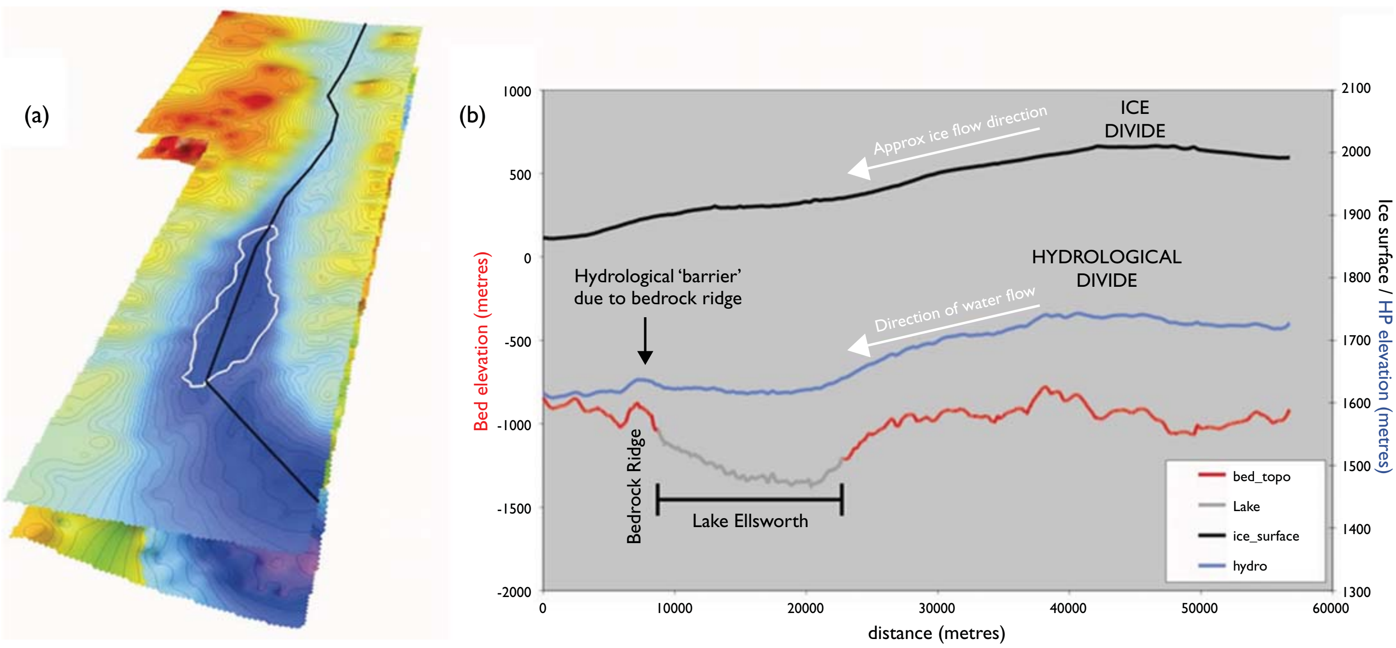

Figure 2. *Profile of the hydrological system within the Lake Ellsworth trough:*
(a) Location of profile (roughly along the axis of the catchment hydrological low);
(b) Hydrological profile (blue line) is shown alongside profiles of the ice surface elevation (black line) and bedrock topography (red line).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

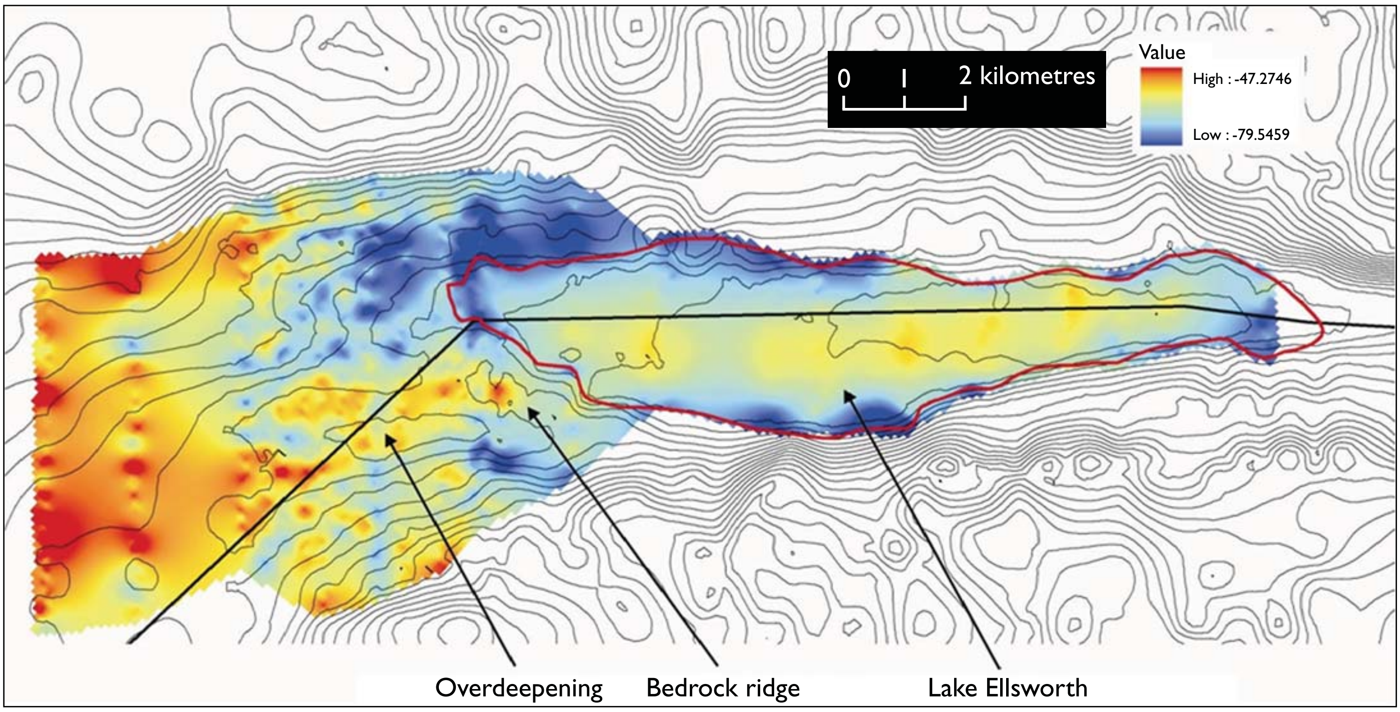

Figure 3. *Map of bed-reflection power (BRP) over and downstream of, Lake Ellsworth. The scale is arbitrary, but red represents higher values of BRP, blue colours represent lower values of BRP. Black lines are elevation contours at 100 m intervals. The thick black line defines the position of the profile 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.*

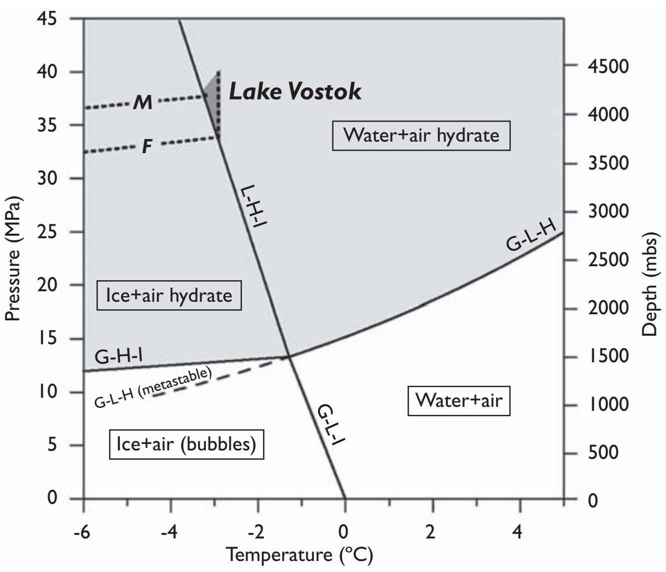

Figure 4. *The phase diagram of air clathrate hydrate from Lipenkov and Istomin, 2001. Shaded region shows field of air hydrate stability. Small darkened triangle within this field covers the range of in-situ conditions in Lake Vostok with* ***M*** *and* ***F*** *located in the zones of subglacial melting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

Appendix 2: Subglacial Lake Ellsworth Programme – Advisory Committee

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Appendix 3: Sea container biosecurity procedure

Internal Container Inspections

Prior to loading all containers need to be inspected for organic contamination, such as, but not limited to, soil, seeds and insects. A torch should be used during this visual inspection to enhance visibility. Remember to open both container doors to check around the door seals and to look up at the roof of the container. If any contamination is observed it will need to be removed or washed down dependent on what is required to remove the contamination.

When loading the container care needs to be taken to ensure that contamination is not introduced to the container. For example mud on shoes or wheels of forklifts. If any of this is seen it needs to be cleaned up immediately. Care needs to be taken during loading to ensure that hitchhiking organisms, such as insects, rodents and windblown seeds do not gain access to the container. The chances of this can be restricted by closing the container doors during breaks taken in the loading process.

When loading cargo it must be checked to make certain that no contamination is being introduced to the container. This can take the form of soil, plant material, seeds or insects etc on pallets or on the cargo itself. If any is noted it must be remedied prior to loading.

After loading the cargo a residual spray can be applied around the door seal area. This will hopefully prevent any hitchhiking insects from entering. Before closing the doors spray can be applied into the container to lessen the chance of any hitchhiker insects surviving (Annex C). An alternative to both these processes could be to use a spray similar to that used in disinfection of aircraft holds, with a residual and knockdown component. This is set in the container and continues to go off once the container doors are closed.

External Container Inspections

If the containers are loaded directly onto the aircraft and not taken off prior to reaching final destination then a system should be put in place to insure the undersides are free of visual contamination prior to loading. This would normally entail using a stand to inspect the underside. Alternatively a temporary stand can be made using 2 containers on either side to support the weight of the container whilst the underside is inspected. This is for health and safety reason but the alternatives could be to do it whilst raised by a forklift. If they are found to be contaminated with soil or plant material then a water blaster can be used to clean this off. No chemicals are required as the water will effectively remove soil and plant debris if the PSI is sufficient. If however live contaminants are observed they can either be physically removed, for example cases of one off spiders. If however they are contaminated with a large number of insects for e.g. ants then fumigation of the entire container with methyl bromide may be the only option. The rates will be dependent on the type of cargo present.

Every sea container being carried to Antarctica must have an accompanying biosecurity declaration (Annex A). This attests to the cleanliness of the sea container and whether or not it is carrying wood packaging, which can harbour wood-boring insects or fungi. All wood packaging material must be either ISPM 15 stamped or treated according to Annex B. A certificate to verify this treatment may be asked for. The container must be inspected internally and externally to ensure it is clean (free of dirt, grass, insects, seed, etc). No restricted packaging material can be used in the containers (Annex A). The declaration should then be completed and signed by a manager of the packing or exporting facility.

If containers are landed, for e.g. in Chile, prior to final shipment then it would pay to ensure the area where they are stored is preferably a sealed hardstand area or at least a gravel yard. If this is not possible then placing wood under them to ensure they are not in direct contact with the ground is recommended. This should prevent contamination firstly from soil and plant material and would also reduce the likelihood of insects gaining access to the underside of the container. Whilst these containers are being held in these areas it is a good idea to ring spray around them with residual spray to keep out hitchhiker type insects. This is obviously not effective on open ground and could be used on the wooden stands that the containers are resting on in this case. If the area that they are being held in has large populations of ants then it may be necessary to bait the areas around the containers for ants.

The external check container process can be done prior to loading cargo into the container at source as long as it can be certain that it is not going to be contaminated at any stage during its transit to the final destination. This will also help to reduce any contamination being introduced to the aircraft. Alternatively it can be done at a stopover point if they are being offloaded. This should be done just prior to being put back onto the aircraft. This has the benefit of ensuring that the containers have not been re-contaminated whilst waiting at the stop over. If you do it at source you then may have to repeat the process if they are taken off and stored for a period of time at the transit point in a manner that may result in contamination being introduced.

Annex A: Sea container biosecurity declaration

Please produce this declaration on Packer or Exporter letterhead

SEA CONTAINER BIOSECURITY DECLARATION

Vessel Name:

Voyage Number:

Container Number or Numbers:

Cleanliness, Restricted Packaging and Wood Packaging Declaration

1. **Cleanliness**
   At the time of packing, the container/s were inspected internally and externally, and are clean and free from contamination with live organisms, material of plant or animal origin, soil and water
   Yes ☐ No ☐

2. **Restricted Packaging Materials**
   Has any soil, peat, moss, used sacking material, used tyres, hay, straw, chaff or any packing material contaminated with the above been used within the container/s listed above?
   Yes ☐ No ☐

3. **Wood Packaging**
   Has any wood packaging been used within the container/s such as cases, crates, pallets or wood used to separate, brace, protect or secure cargo in transit?
   Yes ☐ No ☐

   3a. If yes to question 3, has the wood been ISPM 15 treated and marked or is the packaging made from material exempt from these requirements (such as Plywood or Medium Density Fibreboard)?

   Yes ☐ No ☐

   Certification is not required for ISPM 15 treated and marked wood packaging.

   3b. If no to 3a, has the wood been otherwise treated and certified as per the Import Health Standard?

   Yes ☐ No ☐

   How was the wood treated?

Please attach the original treatment certificate

I CERTIFY THAT THE ABOVE IS TRUE AND CORRECT

Signed:

Name:

Position in Company:

Date:

FAILURE TO SUPPLY THIS INFORMATION, OR SUPPLYING ERRONEOUS INFORMATION, MAY RESULT IN DELAYS AND INCREASED COSTS

3. SPECIFIC REQUIREMENTS FOR WOOD PACKAGING MATERIAL

3.1 SPECIFIC REQUIREMENTS

3.1.1 Wood packaging material must be:

a. Free of insects
b. Free of extraneous material (e.g. leaves, soil)
c. Bark-free, in accordance with section 4.3.2
d. Treated, in accordance with section 3.2
e. Certified, in accordance with section 3.3

3.2 TREATMENT REQUIREMENTS

3.2.1 Wood packaging must be treated according to the schedules set out in ISPM 15 (**Appendix B1**) OR according to the treatments in **Appendix B3**.

3.3 CERTIFICATION REQUIREMENTS

3.3.1 Wood packaging treated to the ISPM 15 standard (see **Appendix B1**) must be marked according to **Appendix B2** or have a treatment certificate.

APPROVED METHODS OF TREATMENT ACCORDING TO ISPM 15
1. Heat Treatment
Wood packaging material must be heated in accordance with a specific time-temperature schedule that achieves a minimum temperature of 56°C for a minimum duration of 30 continuous minutes throughout the entire profile of the wood (including at its core). Kiln-drying, chemical pressure impregnation, or other treatments may be used as a means of achieving heat treatment provided that the above temperature and time requirements are met.
Note: For heat treatment, the removal of bark can be carried out before or after treatment.

OR

2. Fumigation
Wood may be fumigated with methyl bromide at normal atmospheric pressure at the following rates:

Table 1 Minimum CT over 24 hours for wood packaging material fumigated with methyl bromide.

Temperature	*CT[1] (g-h/ m^3) over 24 h*	*Minimum final concentration (g/ m^3) after 24 h*
21^o C or above	650	24
16^o C or above	800	28
10^o C or above	900	32

[1]The CT product utilised for methyl bromide treatment in this standard is the sum of the product of the concentration (g/m3) and time (h) over the duration of the treatment.

One example of a schedule that may be used for achieving the specified requirements is shown in Table 2.

Table 2 Example of a treatment schedule that achieves the minimum required CT for wood packaging material treated with methyl bromide (initial doses may need to be higher in conditions of high sorption or leakage)

Temperature	***Dosage g/m^3***	***Minimum concentration (g/m^3) at:***		
		2 hrs.	***4 hrs.***	***24 hrs.***
21^o C or above	48	36	31	24
16^o C or above	56	42	36	28
10^o C or above	64	48	42	32

Please note that methyl bromide is an ozone-depleting substance and its use is not encouraged when alternatives are available. Although its use as a quarantine treatment presently exempts it from consumption controls under the Montreal Protocol, it is not known how long this exemption will remain in effect.

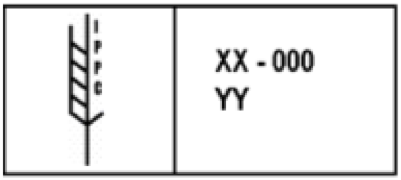
Annex B2: Systems acceptable for the marking of wood packaging materials treated according to ISPM 15

SYSTEMS ACCEPTABLE FOR THE MARKING OF WOOD PACKAGING MATERIALS TREATED ACCORDING TO ISPM 15

Wood packaging material that has been treated by one of the methods specified in **Appendix 1** and in a manner that is officially endorsed by the NPPO of the country from which the wood packaging material originates, may be permitted entry into New Zealand provided the wood packaging material is marked as follows:

1. The mark must include:

- The IPPC symbol for treated wood packaging materials (as per Annex II of the *"International Standard for Phytosanitary Measures #15: Guidelines for Regulating Wood Packaging Material in International Trade"*). An example is reproduced below.



Where XX represents the International Standards Organisation two letter country code for the country in which the wood packaging is produced and 000 represents the official certification number issued to the facility producing the compliant wood packaging by the National Plant Protection Organisation and YY represents the treatment carried out (e.g. HT for heat treated wood or MB for methyl bromide treated wood).

2. No other information shall be contained within the border of the mark. If additional marks (e.g. trademarks of the producer, logo of the authorising body) are considered useful to protect the use of the mark, such information shall be provided adjacent to but outside of the border of the mark.

3. Markings should be:

- legible
- durable and not transferable (tags are not allowed)
- placed in a visible location on at least two opposite sides of the article being certified
- not hand drawn

4. The colors: red or orange should be avoided.

Annex B3: Other approved treatments

OTHER APPROVED TREATMENTS

1) Fumigation with phosphine at 200ppm minimum atmospheric concentration for the temperature and time rates specified in the following table:

Temperature (^oC)	*Duration*
10-15	15 Days
16-20	12 Days
21-25	9 Days
26-35	5 Days

2) Chemical preservation to full sapwood penetration as specified in the following table:

Chemical	*Minimum Retention*
Boron compounds *(insecticidal and limited fungicidal protection)*	0.1% Boric Acid equivalent minimum loading in the sapwood core for Soft Wood 0.2% mass/mass sapwood core for Hardwood
Copper + didecyldimethyl ammonium chloride (DDAC) *(insecticidal & fungicidal protection)*	0.35% mass/mass **OR** 2.8 kg/m^3 in softwood timbers, 5.60 kg/m^3 in hardwood timbers.
Copper azole *(insecticidal & fungicidal protection)*	0.23% mass/mass **OR** 1.35 kg/m^3 in softwood timbers, 2.7 kg/m^3 in hardwood timbers.
Copper Chrome Arsenic (CCA) *(insecticidal & fungicidal protection)*	0.32% mass/mass **OR** 3kg/m^3 minimum preservative retention
Propiconaole and Tebuconazole *(insecticidal & fungicidal protection)*	Minimum retention of 0.3% Propinazole + 0.03% Tebuconazole m/m.

Annex C: Suitable aerosol sprays for sea container

Suitable Aerosol Sprays for Sea Container
These are examples of dual action aerosol sprays that meet the requirements for sea containers.

Prior to sealing the containers use the spray application to kill any unwanted hitchiker insects that may have entered the container unnoticed. Examples of aerosol sprays with combinations of knockdown and residual components are shown in Table 3 below.

Table 3 Examples of aerosol sprays

Product Name	*Media Desc*	*Pclass Desc*
Raid Multipurpose Fastkill Plus 30 Day Kill www.johnsondiversey.com	Aerosol	Insecticide
Raid Multipurpose Odourless Fly and Insect Killer www.johnsondiversey.com	Aerosol	Insecticide
Mortien Multipurpose Insect Killer www.mortein.com.au	Aerosol	Insecticide
Black Flag Lemon - Low Irritant Fly & Insect Killer http://www.blackflag.com/	Aerosol	Insecticide
Pams Swipe Odourless 500ml.	Aerosol	Insecticide

Application: as a general guide apply spray for approximately 12 seconds for a twenty foot container (this is based on 1% active ingredient)

Disinfection Aerosols suitable for aircraft interior
Preparations of chemicals currently used in aircraft disinfection are based on two active ingredients, permethrin and *d*-phenothrin, currently recommended by WHO. The difference between permethrin and *d*-phenothrin is principally one of residual effect; permethrin is a residual pyrethroid and *d*-phenothrin a non-residual pyrethroid.

d-phenothrin works by treating the airspace within the cabin, and quickly kills small soft bodied insects which may be present. Permethrin (although slower acting) not only treats this same space, but also provides a fine residual coating to many of the internal surfaces. When insects come in contact with these treated surfaces they will be knocked down to the floor where they will receive a lethal dose.

Aerosol products used for entry must be fit for purpose and contain the following active ingredients for each treatment type:

Treatment	**Active Ingredients**
Pre-embarkation	2% permethrin
Holds	2% *d*-phenothrin and 2% permethrin
Touch Ups	2% permethrin

Appendix 4: Comments received by all Treaty parties

In accordance with Annex I of the Protocol on Environmental Protection, the UK notified Parties (through ATS Circular 8/2011) of the availability of the draft CEE for the "Proposed Exploration of Subglacial Lake Ellsworth, Antarctica" that had been prepared by the Lake Ellsworth Consortium and was available for download from *www.antarctica.ac.uk/ellsworthcee*

An Intersessional Contact Group (ICG) was established, convened by Norway, to review the draft CEE. ICG correspondence was available to CEP members and Observers via the CEP discussion Forum, which also provided the Non-Technical Summary translated into the official Treaty languages.

The draft CEE was presented at the CEP XIV Buenos Aires in June 2011.

Comments on the draft CEE were received from the following respondents:

- Australia
- Norway
- United States
- France
- Russia
- Germany
- Netherlands
- ASOC
- New Zealand

These comments were compiled by Norway and presented in WP014 to CEP XIV.

The comments are printed in full below and responses have been inserted below each specific comment.

The CEP advice to the ATCM XXXIV on the Draft CEE is also included at the end of this section.

AUSTRALIA

Thank you for the opportunity to comment on the draft comprehensive environmental evaluation (CEE) for the "Proposed Exploration of Subglacial Lake Ellsworth Antarctica".

As the lead agency for Australia's Antarctic program, the Australian Antarctic Division (AAD) of the Department of Sustainability, Environment, Water, Population and Communities coordinated a review of the draft CEE within Australia. The document was made available to the public, to relevant government agencies, and to operational, scientific and environmental experts within the AAD.

In short, Australia congratulates the British Antarctic Survey / Lake Ellsworth Consortium and the United Kingdom for preparing a very high quality and rigorous environmental assessment. It is clear that detailed consideration has been given to managing the environmental aspects of the proposed activity, with a view to ensuring successful scientific and environmental outcomes. We note with particular interest:

- The substantial effort applied to developing a suite of measures to minimise the risk of microbial contamination of Lake Ellsworth and possible connected subglacial water bodies;
- The well considered approach to managing environmental aspects of the logistics and field support, including waste and fuel management, and measures to prevent the introduction and between locations transfer of species;
- The stated intention to include further information in the final CEE (e.g. anticipated atmospheric emissions associated with transport, detailed plans for the deployment of the thermistor string, final selection of population control methods); and
- The indication that the Lake Ellsworth Consortium would welcome an independent environmental audit or inspection of the activity.

We also note the indication in the draft CEE that the penetration of subglacial Lake Ellsworth is to be undertaken in a manner consistent with existing guidelines and principles presented in reports by the National Research Council and the Scientific Committee on Antarctic Research. The Australian Antarctic Division does not have experience in the exploration of subglacial lakes, and was not directly involved in the preparation of these reports. We trust that other Parties and organisations with greater experience in this field will provide useful feedback on the plans outlined in the draft CEE. *We would also encourage the United Kingdom to seek to ensure that experience gained at Lake Ellsworth is fed back into the future review and continual improvement of the guidelines and principles.*

UK response: One of the project aims (stated on Pg 4) is to inform future management and exploration of subglacial lakes in Antarctica. We do seek to ensure that experience gained at Lake Ellsworth is fed back into the future review and continual improvement of the guidelines and principles.

The following comments are structured around the terms of reference for the intersessional open-ended contact group of the Committee for Environmental Protection:

1. The extent to which the CEE conforms to the requirements of Article 3 of Annex I of the Environmental Protocol

In Australia's view, the draft CEE conforms well to the requirements of Article 3 of Annex I of the Environmental Protocol. The following comments relate to specific matters for the United Kingdom's consideration when preparing the final CEE:

- Chapter 5, page 28, 'Water and waste': the intention to remove all wastes is to be commended. Further information on the amounts of waste that are expected to be generated and the 'appropriate' waste storage containers would be useful.

UK response: Additional detail on the types and volumes of wastes likely to be generated, and how they will be packaged prior to removal from Antarctica, are provided in the final CEE.

Unfortunately due to logistical constraints we are no longer able to remove grey water from the camp site. This is a change to that stated in the draft CEE.

- Chapter 6, page 37, 'Impact to native flora and fauna (on the ice surface)': the stated intention to clean all equipment and wash clothing before departure to Antarctic is supported. Further useful measures would include vacuuming of pockets, bags etc and relevant treatments for footwear.

UK response: Further detail on biosecurity practices, including reference to the COMNAP/SCAR non-native species checklists have been added to the final CEE.

- Chapter 6, Table 6, page 40: for 'Operating the science camp' reference could also be made to the possibility of fuel spills, and the intended mitigation/prevention measures (including the use of proven fuel bladders, drip trays etc).

UK response: Reference to the possibility of spills, how they will be avoided, or dealt with should they arise, has been added to this table. Further detail on the spill prevention and response included in the final CEE.

2. Whether the conclusions of the draft CEE are adequately supported by the information contained within the document

Australia supports the proponent's decision to conduct a CEE level assessment for this activity. The information presented in the document supports the conclusion that, with the application of rigorous measures to minimise the predicted environmental impact, the significance of the anticipated scientific outcomes justifies the activity proceeding.

3. The clarity, format and presentation of the draft CEE

The draft CEE is well presented, and provides a clear and thorough description of the proposed activity, predicted impacts and planned mitigation measures.

Australia wishes the United Kingdom well with this significant undertaking, and we look forward to learning the outcomes of the Lake Ellsworth project in due course.

NORWAY

Norway has limited experience in the exploration of subglacial lakes, and we have therefore not dived into the technical details of the proposed project. We note that other Parties have submitted considerable input in this regard, and trust that these will be useful in the further development of the CEE. Our comments below are therefore of a very generic nature against the ToR of the ICG, reflecting our overall impression that the Draft CEE is comprehensive, well-written and provides a good basis for considering the overall impact of the project.

The extent to which the CEE conforms to the requirements of Article 3 of Annex I of the Environmental Protocol

It is our assessment that the present draft CEE conforms to the requirements of Article 3 of Annex I of the Environmental Protocol.

TOR 2) Whether the conclusions of the draft CEE are adequately supported by the information contained within the document

The draft CEE concludes that the level of the environmental impact of the construction of Proposed Exploration of Subglacial Lake Ellsworth is expected to be less than minor or transitory. We note that CEEs normally are developed for activities that are expected to have more than minor or transitory impacts, but we fully concur that a CEE process could reach a different conclusion as is the case here. Considering the evaluation provided in impact matrix presented in Table 6 we feel the conclusion reached can be supported. We note, however, that it might be useful to reflect on this in the concluding section, due to the expectation that a CEE is for activities with "more than" impacts.

UK response: We note your point and have added a comment in the non-technical summary and conclusion to reflect this point.

TOR 3) The clarity, format and presentation of the draft CEE

In general the Norwegian reviewers feel that the document is well written and organized. We acknowledge the efforts made by United Kingdom in preparing and communicating the document.

UNITED STATES

In general US reviewers felt that the document was well written and well organized. However, there were several elements that we feel need further clarification.

Compliance with requirements of the Protocol

1. Phase I indicates that activities related to the Lake Ellsworth project have been ongoing since 2009. It may be beneficial to add a "Pre-drilling Characterization" section that would identify and briefly describe activities which supplied data for this CEE but were covered by environmental documents other than this CEE. These pre-drilling studies with the CEE activities could then clarify the analysis basis for direct/ indirect and cumulative impacts (see page 6).

UK response: A table summarizing the pre-drilling characterization works, done under separate Environmental Impact Assessments, has been added to Chapter 3.

2. There is limited discussion of alternate sites. The proponents should consider including a short paragraph describing why shallower, less important lakes were not selected. This may be accomplished by strengthening the justification presented in Chapter 2 (see pages 41-43)

UK response: A more comprehensive discussion on lake selection has been included in Chapter 7.

3. The CEE concludes that the proposed activity will have less than minor or transitory impact. However, the assumption to prepare a CEE implies the impact may be more than minor or transitory. (i.e., Annex I to the Protocol indicates that if an IEE indicates or it is otherwise determined that a proposed activity is likely to have more than minor or transitory impact, a CEE shall be prepared) Given this apparent inconsistency, the conclusion should explain why a "less than minor or transitory impact" is brought forth even though the CEE process often suggests a more than minor or transitory impact is applicable

UK response: A comment on this point has been added to the non-technical summary and conclusions. Although CEEs are required for *projects with more than minor or transitory impacts, we compiled a CEE for this project to meet a recommendation of the NAS-EASAE report.*

Technical Comments

1. The proponents indicate that they will melt pre- 1800 yr old ice for the drilling fluid (page 16). How will this process be started? Will any surface snow be used?

UK response: Text has been added to state that some near surface snow will be used to initiate the hot water drilling process (approximately 15-30 m3), with the bulk of the melt water coming from ice over 50 m below the snow surface.

2. The proponents indicated that they will sample the drill fluid to assess the quality of microbial control and to provide a comparator for lake samples. What will be the sampling frequency (page 17)?

UK response: The borehole fluid will be sampled an a minimum on a six hourly basis and subjected to DAPI counts. This is stated on in the final CEE.

a. The proponents indicated that filters will be changed at set differential pressures. What will be the frequency of filter replacement (see page 17)?

UK response: It is anticipated that over the filter system operating period, one set of filters will easy maintain their filtration specification. However, if the particulate loading of the melt water is much higher than expected, the system is switched to a parallel set of new filters without any need to stop the drilling process. This is now stated in the final CEE.

3. The document discusses saving filters for later evaluation. How would these filters be preserved?

UK response: The filters will be preserved by freezing. The final CEE includes this information.

4. How will the mixing of drill water with lake water be limited if the hole is reamed to extend lake access time (page 17)

UK response: If the hole is reamed, there will be no forward jetting of water and only lateral jets will be used, minimizing any mixing with the lake water. This is now stated in the final CEE.

5. Please list what testing will be done on the hot water drill system prior to shipping. Providing a list of what is expected to be tested and expected not be tested will be more useful to reviewers than stating that testing will be conducted "as far as practicable" (page 17).

UK response: Text describing the testing regime has been included in the final CEE. In summary, all equipment was factory tested to ensure it met our acceptance criteria. All the equipment was then assembled at a test site in the UK to allow testing and running of the whole system.

6. Please provide details describing how the cavity below the hydrological water level (270 m) will be formed and what its dimensions will be (page 17).

UK response: The cavity linking the two holes will be created by pausing the drill nozzle for up to one hour at 300 m, allowing the hot water to make a bulbous cavity. This process is repeated in the other hole. A hot water feed to the submersible borehole pump (now shown in Figure 12) can be used to maintain or enlarge the cavity if necessary. The cavity volume is expected to be 10-15 m3. Information on this is given in the final CEE.

7. Flow rate for an "admixture of filtered drill water and melt water" is stated as 1.8 m per minute (m/min). Should it be litres (l) per minute instead (page 17)?

UK response: This has been changed to "flows up the hole at a speed of 1.8 m per minute".

8. The term "tapping of points" is confusing - perhaps "sampling ports" would be a better term (page 17).

UK response: The term sampling ports has been included in the relevant text.

9. What is the potential that the probing connections will fail, or be connected improperly, and the probe will be lost (page 21).

UK response: in the view of the UK it is extremely unlikely that the probe will be lost. There is a long track record of equipment deployment at depth and the tether is well engineered for the stresses it will encounter. This information is now included in the final CEE.

10. Is there a contingency to recover any components of the hot water drill, probe, corer or ancillary equipment that detaches from its deployment hose or cable (page 21)?

UK response: There is no contingency to recover detached equipment. This is now made explicit in the final CEE.

11. What material will the thermistor string be made of? Specifically will it be resistant to corrosion or made of any hazardous materials (page 22)?

UK response: A thermistor string will not be deployed

12. What will be done to minimize mixing of stratified layers (dilute, mixed, and concentrated) in the lake? Similarly, what will be done to prevent sediment in or on the outside of the corer from being released in the water column upon retrievable of the sampling device (page 24)

UK response: The mixing of stratified layers in the lake will be avoided by the slow rate of descent of the probe and by probe design (e.g. the lack of propellers). The corer barrel is highly polished and equipped with a double sediment catcher and a piston rod lock, which will minimize sediment release, although some is inevitable. Text describing this has been added to the final CEE.

13. If the communications link between the drill site and the domestic camp that allows remote monitoring and operation of the equipment is mentioned as part of the site safety plan, it would be helpful to know more about the remote operation procedures (page 26, 28, 29)

UK response: No remote monitoring or operation of equipment is planned (except at the point of lake penetration when the drill will be operated remotely for safety reasons). The communications between the domestic camp and drill site will predominantly comprise a screen in the domestic camp so that off-duty staff can observe what is happening at the drill site. This information is incorporated in the final CEE.

14. The power generation and fuel calculations are a bit confusing. Some numbers seem rounded (e.g., 8 week season = 56 days at 24 hours/day = 1344, not 1300) others seem arbitrary (Generator 1 = 650 hours). Presenting the information in a table with appropriate footnotes would be helpful (page 27)

UK response: This has been simplified in the final CEE.

15. The statement is made that "The only vehicle used on site will be a Tucker Sno-Cat...", but then there are discussions about the ALE tractor train in a subsequent section. It might be helpful to point out that transient tractor train vehicles will come and go from the site (page 28).

UK response: A statement to this effect has been added to the CEE for clarification.

16. It seems that the activities of the support contractor, ALE, are not being assessed in this CEE. That seems to be an omission.

UK response: ALE activities associated with this project are assessed in the CEE in terms of emissions associated with flights and the tractor train, waste handling, non-native species etc. This is made more explicit in the final CEE.

17. The types of wastes generated are listed, but no estimates of the amount of wastes generated is provided (page 28).

UK response: Additional detail on the types and volumes of wastes likely to be generated, and how they will be packaged prior to removal from Antarctica are provided in the final CEE.

18. No details are provided describing the borehole liner and gate valves to provide an air-lock. Please explain what these devices are intended to do, how they will be deployed, recovered, and decontaminated (page 31)

UK response: There will be no borehole liner, just the 3m stainless steel casing which is essential for producing an air lock. They will be cleaned by UV, then removed at the end of the drilling period by being melted out of the snow with the hot water drill. The text and figures in the final CEE have been amended to explain this further.

19. The proponents mention that the hose will be jet washed during drilling. Is this a separate step, or a normal part of the drilling? If this is a separate step, what efforts will made to capture the wash water (page 32)?

UK response: The text in the final CEE has been amended to describe the cleaning of the hose outer. This involves passing the hose through a chamber filled with ethanol soaked wadding to wipe and sterilize the hose exterior. This differs from the method presented in the draft CEE as the water jetting presented too complex a solution.

a. What criteria will be used to decide if an object needs Hydrogen Peroxide Vapour treatment in the field (page 33)?

UK response: There will be little on site decision making in the field regarding the use of HPV. The team will follow pre-agreed procedures to achieve the level of cleanliness required. However, all the equipment will be inspected visually and if the integrity of the sterile bag containing the equipment is compromised then the item will be subjected to HPV. The sterile bagging is made of strong and robust polyurethane which is rated for use down to -30°C, and please note that the equipment has already been delivered to the drill site without any damage occurring in transit.. The HPV treatment will take place in a sealed flow container – it is important to note that there will be no hydrogen peroxide in contact with the wider environment.

20. What methods for verification and assessment will be used to ensure that equipment which were pre-cleaned, treated, and sealed prior to transport to the drill site are not contaminated during handling and shipping (page 33)?

UK response: As discussed above, a visual check will be made to assess the integrity of the sterile bag. There will be no testing for the reasons cited on page 34 of the final CEE.

a. Are there any data that indicate that sterile water samples, which will be loaded into to water sampler before shipping, will stay sterile for a year?

UK response: The bottle will be sterile and filled with sterile water with ultra low nutrient and organic content. There will therefore be no inoculum or food source. Our tests on water stored for two months show that growth does not occur in this sealed and sterile environment. This is made clear in the final CEE.

21. Define the term "CO2e" the first time it is used. The term is also used frequently in Table 5; consider adding a footnote to page to explain the meaning (pages 35-36)?

UK response: Carbon dioxide equivalent (CO2e) is a universal unit of measurement that allows the global warming potential of different GHGs to be compared. This meaning has been included in the text and added as a footnote as suggested.

22. The CEE indicates the borehole may be re-reamed to melt potential sticking points. Can (and will) the same approach be used if the probe, corer, or other device becomes stuck in the borehole (page 37)?

UK response: It is not possible to ream the hole if a device becomes stuck in the hole as the drill hose will become entangled and also stuck. This is stated in the final CEE.

23. On page 55 the term "~400 T thrust force" is used. What unit is represented by "T" (page 55)?

UK response: It is 400 Tonnes thrust force. This is made clear in the final CEE.

24. Are there any devices which contain components that could potentially decompose and contaminant the water body if not recovered?

UK response: No.

25. The biggest potential for disturbance of the lake is the initial break through at the ice water interface. Ensuring that the hole is finished and wide enough will require the hot water drill to blast away at the top of the otherwise pristine water column. It might be better to switch to a passive thermal probe for this final stage.

UK response: There are no plans to use a passive thermal probe to gain access to the lake as in the view of the UK this would increase the risk of contamination. The modification of the drill nozzle design, with a higher proportion of lateral jetting will significantly reduce the disturbance to the lakes upper water column.

With such a small on-ice team, will there be sufficient people and expertise to perform effective mitigation in the case of a blowout or big spill?

UK response: The number of scientists on site has been increased. We are confident that our efficient team can undertake mitigation measures that may be required.

26. The deployment of a thermistor string is viewed as being an important contribution to future science; so hopefully, this can be achieved, perhaps using a temperature sensor on a fibre-optic cable, if the power requirements permit.

UK response: There will be no deployment of the thermistor string. This is now reflected in the final CEE.

General Comments

1. It is essential to have the on-site monitoring and to have a response plan should there be surprises in real-world conditions not conforming to the laboratory certifications. There is mention of on-site microscopy, but no discussion of how the on-site measurements will (or won't) be used in decision making on site. Thresholds and responses should be defined a priority.

UK response: The drill fluid will be sampled an a 6 hourly basis as a minimum, subjected to DAPI staining and enumeration by epifluorescent microscopy. Any trend towards significant increases in cell numbers will lead to a cessation of activity pending an investigation of how contamination has occurred, (e.g. why the filters are not working) and an increase in the sampling/testing to an hourly basis. The lake will not be penetrated if the microbial levels exceed background readings. This is made more explicit in the final CEE.

2. Consider providing the definition for "blowout" in the summary.

UK response: A definition has been provided in the summary section of the final CEE.

3. The four day window for drilling and sampling seems too short. Consider doubling the window for these activities to allow for the types of complications that invariably occur at deep field sites.

UK response: We are not restricted to a four day time span – that is merely the time we estimate to be required, however we are confident that the time suggested is sufficient. We aim to work efficiently allowing time on site (and environmental impact) to be minimized.

4. On page 31, first paragraph, right side, the term HPV is first introduced but is not defined until page 32 (lower right corner) under "Population Reduction Methods". This acronym is used frequently on pages 31-33, so it would be helpful to say "hydrogen peroxide vapour" earlier in the section.

UK response: Section amended in the final CEE as suggested.

5. Please provide more details on the HPV method, particularly non-medical field applications.

UK response: In the field HPV is used in two ways. 1) It will be used to sterilise equipment that has been accidently compromised (e.g. by a breach of containment). Here the breach will be mended and the item and container heated to above -5 °C. The unit will then be pressurised and checked for leaks, thereafter it will be dosed with HPV as per the operational instructions for the HPV unit which includes a ventilation step that removes all traces of HPV. 2) It is used to sterilise airlocks formed by glove boxes and valves during the deployment procedure. Here the interface is sealed, heated to above -5 °C, HPV applied, and then the area ventilated. These procedures have been practiced in a cold room in the UK. Further details on its specification and deployment are given in the final CEE. This equipment has a proven track record in medical applications, which is sufficiently rigorous for our purposes, however there are no studies we can rely on for non-medical field applications.

FRANCE

We have first to acknowledge the efforts developed by our UK colleagues for the preparation and communication of the draft on Comprehensive Environmental Evaluation for the proposed investigation of Ellsworth Subglacial Lake in West Antarctica. This draft is received in timely way in accordance with the Annex I of the protocol on Environmental Protection to the Antarctic treaty (1998).

The project aims to collect samples of lake water, of bottom sediments, and to perform a series of in-situ measurements to characterize the water properties and the environment of a small subglacial Lake located in West Antarctica, with a more specific focus on the search of the microbial life. Exploration of the Subglacial Lakes is of interest for the scientific community (life in an extreme environment and as possible analogue for the search of extra-terrestrial life, the history of Antarctica as likely preserved in lake sediments) and has been promoted by the SCAR since mid-90's by a series of meetings and international conferences. So, from a general point of view, the scientific interests are well established; they are multidisciplinary and involve a wide scientific community. The project is therefore of interest for the fundamental research and is also subject to attract curiosity of the public as a first direct exploration of a hidden, isolated world under harsh environment where life is may be present. It is worthy to publicize the whole story through educational programs.

The target is the sub glacial lake Ellsworth which is located at a reasonable distance to for an acceptable logistic payload. The lake is ~ 36 km² in area and ~1.5 km³ in volume. It lies under ~ 3km thick ice. It is one water mass amongst ~350 or more subglacial lakes detected from recent inventory, and it is of small size by comparison to the ~12,000 km² largest Vostok subglacial lake. In spite of its size, it is speculated that Lake Ellsworth water may be renewed and as ice melts and water refreezes, the lake may accumulates air if the system is closed. The risk for blow out as the drill penetrated into the lake is envisaged in the report and is estimated to be low.

To perform the project, the drill equipment will allow making a ~3000 m hole (30 cm diameter) in ice by using a hot water system. The use of hot water is preferred to bore hole organic compound filler (e.g. kerosene) because the chemical impact is significantly minored. The water from the glacier is heated to 90 °C and send through a hose to depth to melt efficiently the ice. The resulting melt water fills the hole prevents its closure, and is keep warm by recycling. The recycled water is pumped from a reservoir (cavity made in the ice) ~300 m below surface, then filtered and UV treated, then heated and passed through the high pressure pump system and delivered to the hole bottom by the 3 km hose.

Once the hole completed a probe will be lowered into the lake for in-situ water sampling, geochemical studies, and video observations. Then a piston corer will be used to collect sediment at the bottom of the lake. Finally a string for temperature and physical properties monitoring will be deployed and likely left behind.

TERMS OF REFERENCE

TOR 1) The extent to which the CEE conforms to the requirements of Article 3 of Annex I of the Environmental Protocol

In order to answer to this question, we have checked the content of the CEE in the light of the table produced in the "Guidelines for Environmental Impact Assessment in Antarctica", Resolution 4 (2005).

	CEE from the guidelines	**Status in the present CEE**
Description of the purpose and need of the activity	√	**Chapters 1 - 2**
Description of the proposed activity and possible alternatives and the consequences of those alternatives	√	**Chapter 2**
Alternative of not proceeding with the activity	√	**Chapter 7**
Description of the initial environmental reference state and prediction of the environmental state in absence of the activity	√	**Chapter 3**
Description of methods and data used to forecast the impacts	√	**Chapter 6**
Estimation of nature, extent, duration and intensity of direct impacts	√	**Chapter 6**
Consideration of cumulative impacts	√	**Page 37**
Consideration of possible indirect impacts	√	**Not developed**
Monitoring programs	√	**Chapter 8**
Mitigation and remediation measures	√	**Included in Chapter 6**
Identification of unavoidable impacts	√	**Chapter 6**
Effects of the activity on scientific research and other uses or values	√	**Cf Chapter 2**
Identification of gaps in the knowledge	√	**Chapter 89**
Preparers and advisors	√	**Page 46**
References	X	**Pages 47-49**
Non-technical summary	√	**Pages 4-5**
Index	X	**No**
Glossary	X	**No**
Cover sheet	X	**Yes** but details on authors and corresponding authors appears only in the Non-technical summary

√ required by Annex I; X often useful

This synthetic table indicates that the draft CEE takes into account all items required by Annex I, except perhaps some considerations on the possible indirect effects of the activity.

Our conclusion is that the present draft CEE conforms to the requirements of Article 3 of Annex I of the Environmental Protocol.

However, we have pointed few issues which are considered as possible weaknesses in the current document and which could be improved in the final CEE:

1. International collaboration

We note that the Lake Ellsworth Consortium is composed of several UK Universities and Institutes but apparently without collaborations from other countries whereas both the SCAR Code of conduct for the exploration and research of subglacial aquatic environments (guiding principle #3.3) and the NAS guidelines on environmental stewardship when exploring subglacial lakes (Recommendation 5) encourage multinational participation in SAE exploration.

UK response: Our Advisory Committee is multinational (for further information please see Appendix 2 of the CEE).

2. Ice geochemistry and biological content

At the step of preparation of the project, and as presented in the draft, only a small attention was given to the ice geochemistry and its biological content in spite of collection of the snow samples from a season. Typically, the ion chemistry which is presented (p 14) is very strange and the presence of HCO3- in Antarctica ice is very questionable and likely wrong. Referring the Byrd ice core as done in the report, the ice is acidic and the electric conductivity measurement is possible even in the "dusty" ice from the last glacial maximum. This is not the case for Greenland ice where carbonates are present in excess in the glacial ice.

For the biological content, concentration of ~103/ml is likely for coastal region or for dirty snow, but such a value is likely not representative of clean snow of for inland Antarctic ice. We can expect that contamination occurred during the sampling or cell measurement of the snow surface as reported page 16. Caution should be exercised for biological investigations and because the unexpected low content of Antarctic snow, we recommend the combination of biological analysis to be conducted according to protocol and along with the chemical analysis.

We therefore recommend that the ion chemistry and the biological investigation of the samples to be conducted/advised according to the standards from the ice chemists who have a great experience in this field (e.g. BAS researchers who participated to EPICA project as an example).

UK response: The project involves scientists with great experience of glacier geochemistry and micro biology, and the laboratory experiments and cleanliness protocols established here are appropriate.

3. Corrosive properties of the water and contamination contribution of the heating system, the high pressure and from the hose

The recycled water is from glacier melt and will be filtered and UV treated and supposed to be very clean at this stage. Indeed, the very low ionic content makes the water very aggressive with respect to any metal or organic based tubing. Therefore, question is open about the behaviour of the hose when heated at 90C under high pressure and under high debit. Here we can regret that no reference is given in the present document from the experience gained by the "Ice Cube" project which was deployed during the last 10 years, at the South Pole station. The Ice cube project (*http://icecube.wisc.edu/*) used a similar hot water drill (may be more powerful) developed for lowering down to 2 km depth into ice, long grape of instrument (neutrino telescope). Report on the operations, how they impact the snow and the borehole cleanness, would have been relevant in respect to this draft CEE.

We understand that the hose is made from carbon fibres and likely with organic material, the produced dust may disturb carbon and organic content of the water filling the hole and in some way the water from the lake. One would expect a lot of dissolved organic carbon from the tubing will be present in the hole. Natural concentrations of Dissolved Organic Carbon in Antarctic ice do not exceed a few ppb (10-9g/g) (Prunkert et al, Environ. Sci. Technol. 2011, 45, 673–678).

Our recommendation for the Ellsworth project would be that at time of the probe is lowered in the hole for sampling the lake water, a sampling of the water from the hole a few meters above the lake will serve as a field truth for its potential impact on the lake geochemistry.

UK response: We are aware of the potentially aggressive nature of very clean water and how this will interact with various components of the drill system. The material specifications and selections have attempted to account for this situation to minimize corrosion and leaching processes. The drill hose specification also accounts for these processes and is designed to operate at high temperature, pressure and load simultaneously. As the materials used in the Ice Cube drill hose are different, no reference was made to the project, while other impacts are relatively generic.

We can't sample the ice just above the lake. This sounds like a good idea, but it would add complexity to the programme at the very moment when simplicity is needed, and would actually form additional risk of contamination. Our cleanliness protocols are designed to allow us to drill into the lake cleanly, rather than the 'measuring as we go' approach that some have advocated. When one works out the details of the methodology, we consider the latter approach is unfeasible as a means of cleanly accessing a subglacial lake, as it requires: exposing the drill to the air to recover the ice, additional time to analyse the material, and extended drill time to keep the hole open. Considering our procedures, we believe the additional time and risk needed to recover ice using hot water drilling is contrary to achieving clean and efficient lake access

4. Prevention of freezing water in the hose

Could you confirm that no antifreeze liquid (glycol or other) will be used to prevent water in the hose to freeze, especially at the beginning of the operation and at the end? This point is very important because if such an antifreeze liquid is used, this rise issues 1) for the storage of the antifreeze when the hole will be used for water 2) for the cleanness of the hose and the contribution of the antifreeze to the dissolved organic carbon in the hole. Such problems will not happen if only hot water is used.

UK response: UK can confirm that no antifreeze liquid (glycol or other) will be used to prevent water in the hose freezing. This is now made explicit in the final CEE.

5. Instrument recovery

Is there any risk of loss of equipment in the lake? For example, are we sure that the corer will easily re-enter into the bore hole at the contact of water and ice. Can drift in water (if any) carry away the equipment which will have difficulty, if not in a vertical position, to re-enter into the hole?

If such an accident happens, we assume that the risk for the lake environment is very low, but this hypothesis, if realistic, should be considered.

UK response: The risk of equipment loss has been reduced as far as is practicable. The equipment is unlikely to drift as there are insignificant currents based on the assessment of the flow regime. The equipment is made from non-toxic components so it poses a negligible risk in the unlikely event of being lost. This is made more explicit in the final CEE.

6. Logistics, transport of cargo and personnel (Chapter 5)

Main part of the logistics will be provided by "Antarctic Logistics & Expeditions" (ALE). ALE will act as contractor and will provide aircraft support, provision of drummed fuel, transportation of equipment and fuel, removal of equipment, materials and waste, carriage of personnel. Between 10 and 12 tractor traverses (2 tractors, sledges, 18 tonnes per traverse) will be necessary using a 295 km long route. The majority of equipment will be moved from Punta Arenas to the ALE base camp (Union Glacier) by Ilyushin IL-76 heavy lift aircraft (5 rotations over 2 Antarctic seasons). About 250 AVTUR drums will be delivered on site.

It is not clear if these specific activities will be covered by the multi-year IEE approved by the US Environmental Protection Agency (as mentioned page 38) or if authorization will be provided by the UK as part of the permitting process. This point must be clarified.

This approach is acceptable but we think that a draft CEE incorporating all the aspects related to the drilling activity at Lake Ellsworth, including the whole logistics, would be better and clearer in terms of impact analysis.

Concerning the transport of personnel by BAS Twin Otter, very few information is given. Taking into account the number of drums for refuelling page 27 (6 flights, 5 drums each) and the flight range of a Twin Otter, it implies that refuelling is necessary during its flight to Rothera. No information on the refuelling site (Sky-Blu?) is given, and no information on the consequences on this site (fuel depot etc.).

From our point of view, the Chapter 5 about camp and logistics could be improved in the context of this draft CEE.

UK response: Clarity on the permitting arrangements was given in IP 13 presented at CEP XIV and has been included in the Final CEE. The environmental impact of ALE's activities associated with this project are assessed in the CEE. This is made more explicit in the final CEE.

Refuelling activities will be carried out at Sky-Blu and are already covered by BAS' operating permit, EIA and Environmental Reporting requirements. There will be no additional flights and refuelling activities at Sky-Blu as a result of the SLE programme (as the Twin Otters would be used on other projects if it weren't for this one).

The camp logistics are as shown in the updated Figure 19.

Other minor remarks or suggestions:

- Page 7 it is said that it is expected to recover a 1-3 m sediment core from the floor of Lake Ellsworth. We are surprised that such precise information about the sediment thickness can be obtained from the surface, especially because the free water reflection usually influences the results. Could you confirm that the method used can provide such accuracy?

UK response: The seismic information included in Chapter 3 of the CEE provided this information. The acoustic impedance of the returned seismic waves matches that from soft fine grained muds. When one considers the wavelength of the seismic wave in lake and the sediments, this impedance is gained from the area 1-3 m beneath the lake floor, hence our judgement of the likelihood of soft sediments to this thickness.

- Page 16, right column - correct the drill speed: 1.0 m.mn-1 and 0.5 m.mns-1 instead 1.0 m s-1 and 0.5 ms-1 (is it correct?)

UK response: The drill speed is 1 m/min and not the 1 m/second erroneously quoted in the draft CEE. This has been corrected in the final version.

- Page 22: the size of the sediment coring system is not very clear. A scale would be useful on Figure 14.

UK response: An updated figure showing the sediment corer is now included in the final CEE. (The sediment corer is approximately 5.8 m long)

- Page 26: number of people at site - 10 people is a very small team and we wonder if there are enough technicians to guarantee the success of the drilling. For example, only one technician responsible for power generation, vehicles and fuel management seems very few.

UK response: The number of scientists on site has been increased. We are confident that our efficient team can undertake mitigation measures that may be required.

- Table 5 page 36: this table is not clear. There are 2 parts. Do they cover field camp and drilling operations, respectively? Headings are needed to clarify the table.

UK response: This table has been revised for the final CEE. Fuel use for the field camp, drilling operations and logistics associated with the project have been included.

- Page 37: "the thermistor, if deployed, would be left in situ permanently". In such a case, temperature measurements will be planned only 1 time or is it expected to make several measurements during several years, implying new visits on site?

UK response: The thermistor will not be deployed.

- Page 39 and followings: the impact matrix is very good.
- Annex 1 Physical blow-out preventer. As far as the hole is not cased by a tubing, hole pressure does not apply to the valve. In case of blow out, the water column and gases from the hole will be flushed back through the porous snow. The blow out preventer has likely no utility.

UK response: We agree that a blow out preventer has no likely utility so do not propose to use one. However all potential options were considered and ruled out where their use was not justified.

- P 56, left column, middle: are all numbers significant?
- *UK response: The decimal points have been removed in the final CEE.*

- We recommend adding a very simple map showing the location of the main sites cited in the text: Lake Ellsworth, Union Glacier, Patriot Hills, Rothera.

UK response: A figure has been included to show the locations of the drill site, Union Glacier and Rothera.

TOR 2) Whether the conclusions of the draft CEE are adequately supported by the information contained within the document

The conclusions of the draft CEE are extremely honest. The impact will likely be less than minor or transitory. But the authors admit that this impact can be more important if something wrong happened during the drilling operation.

In addition, we consider that the scientific interest justifies the activity.

TOR 3) The clarity, format and presentation of the draft CEE

The draft CEE is very clear, well written with many details. Its structure is logical and the document is easily read. The chart of impacts appears well evaluated.

RUSSIA

Study of the subglacial lakes of Antarctica is obviously one of the most interesting and important issues of modern Antarctic science. In this regard I have considered with great attention the draft CEE for the "Proposed Exploration of Subglacial Lake Ellsworth, Antarctica", prepared by specialists from the United Kingdom" (Note No. 011/11).

Without false modesty I can say that at present I am most experienced among the international Antarctic community in preparing draft CEEs and different answers to the comments related to the problem of penetrating subglacial Lake Vostok. I want to remind you that the first document on this theme was prepared and submitted by Russia at ATCM XXIV in St. Petersburg in July 2001. After that we were annually submitting different work and information papers on this problem at the next ATCMs. The last of them was submitted at ATCM XXXIII in 2010 in Uruguay (WP 059 "Answers to comments on CEE for "Water sampling of Subglacial Lake Vostok"). In this document we have discussed as an alternative technology for penetrating the subglacial Lake Vostok the US technology FASTDRILL, which uses hot water with a temperature of about 90 °C for drilling. Exactly this technology will be used by our British colleagues for penetrating and subsequent study of the subglacial Lake Ellsworth.

UK response: The drill is not the same technology as FASTDRILL. It is a completely new design, more akin to the IceCube drill at South Pole, but with ever-greater additional attention to cleanliness.

In the aforementioned Russian WP in 2010, we were speaking about an extremely dangerous influence of hot water on living organisms that can inhabit the water layer of the subglacial lake, the more so as the real water temperature in situ in the surface layer of this lake is unknown. The microorganisms in this layer will be simply boiled in hot water coming from the borehole. As is known from the physics postulate, the heat flux propagates in the direction of the temperature gradient, i.e., from large values to smaller ones. So the heat flux from the borehole will be by all means directed towards the lake water body, the water temperature of which should be less than +90 °C. We have made calculations using a hydrothermal dynamic model of the ultimate values of thermal convection spreading from the borehole to the lake. Our calculations showed the heat flux to have a "pear-shaped" form with thickening downwards and it will reach the bottom of Lake Ellsworth, which is located at a depth of 200 m from the bottom ice sheet surface. To have a possibility of lowering equipment for investigating the water and bottom characteristics of the lake a temperature of about +40 °C should be maintained in the borehole. This will of course reduce the influence of temperature convection, but at the moment of hot water penetration to the lake, it will have exactly such values. In any case the heat flux from the borehole will be directed to the lake water strata and will significantly disturb the hydrophysical and microbiological characteristics of the lake, existing under the conditions in situ. In this regard, determination of the required adaptation time of the submerging device to the real aquatic environment conditions is not clear as it will be too heated at passing through hot water in the borehole.

These facts create serious preconditions for doubting the accuracy of any hydrophysical, hydrochemical and microbiological measurements of the lake water strata. Obviously the heat convection will not have any significant influence on bottom sediments of the lake, which could be sampled with sufficient correctness.

UK response: The comments on water temperature are over-exaggerated. The drill temperature on entering the lake can be as low as we like, and indeed we have discussed that. The drill water cannot be 90 °C at the lake, because it loses heat as it goes down the borehole, a maximum temperature of 45 °C on lake penetration is realistic.

We are able to reduce the temperature of water at the drill head in a controlled manner. We will maintain the maximum possible drill head temperature until approximately 50m from the lake surface, at which point the temperature will be reduced to 40°C. We are confident that this temperature will not compromise our science or the lake environment.

Water mixing on lake entry. This is an issue, and is one that's unavoidable with hot water drilling. It will affect the surface layer of the lake, but is unlikely to have an affect before a few metres at most.

The comments made here are a very useful reminder about the potentially complex behaviour of fresh water lakes at great depth beneath ice sheets. Until recently the equation of state for fresh water indicated that any warming of the lake water from a hot water drilling process would result in buoyant water that would remain in the hole or at the ice/water interface, minimising any disturbance to the lake water column. However, with the international adoption of a new equation of state (TEOS-10) in 2010, the waters of Subglacial Lake Ellsworth lie very close to the cusp between warming causing positive buoyancy (rising water), as was anticipated previously, and warming causing negative buoyancy (sinking), as happens in surface ice covered freshwater lakes. With an estimated water depth of 2885 m to the lake surface at the *proposed drill site, it remains likely that warming will cause positive buoyancy. If this were not the case then a body of sinking water would be created, locally disturbing the lake water column. However, any lake circulation would advect this disturbance away from the site. Further calculations are needed in the light of TEOS-10 to confirm the site specific conditions and if any mitigation procedures are required.*

In this connection I would like to receive the answers to these comments before the final text of CEE for the "Proposed Exploration of Subglacial Lake Ellsworth, Antarctica" is prepared. Besides, the UK draft CEE does not include a description of any alternative technologies for penetration to the lake, which are stipulated in the Madrid protocol.

UK response: Chapter 7 of the CEE (alternatives) considers the use of a thermoprobe and alternative drilling methods to those proposed. These alternatives were ruled out as they do not meet the cleanliness standards required by this projects environmental criteria and science aims.

GERMANY

Summary

Germany would like to thank the United Kingdom for the opportunity to comment on the CEE for the "Proposed Exploration of Subglacial Lake Ellsworth Antarctica" The Draft CEE conforms very well with the requirements of Article 3 of Annex I of the Protocol on Environmental Protection to the Antarctic Treaty and the Guidelines for Environmental Impact Assessment in Antarctica (Annex 7 to Resolution 4, XXVIII ATCM, 2005). The project promises high scientific benefit despite certain environmental risks well elaborated in the Draft CEE. Germany welcomes the purpose of using innovative drilling techniques with low impact approaches to minimise the impacts on the Antarctic environment. In terms of contents, the Draft CEE still needs some further clarification (see comments below).

Preliminary Remarks

The Federal Environment Agency has submitted the Draft CEE for public examination in accordance with article 16 paragraphs 1 and 2 of the German Act Implementing the Protocol of Environmental Protection to the Antarctic Treaty of 4 October 1991 (AIEP). The document was also passed on to the Alfred Wegener Institute for Polar and Marine Research and to those German authorities whose areas of responsibility are concerned. Pursuant to article 6 AIEP, nearly all involved institutions have commented on the Draft CEE.

Comments

1. The extent to which the CEE conforms to the requirements of Article 3 of Annex I of the Environmental Protocol

The structure of the Draft CEE is formally in accordance with Annex I to the Protocol of Environmental Protection to the Antarctic Treaty and the Guidelines for Environmental Impact Assessment in Antarctica (Annex 7 to Resolution 4, XXVIII ATCM, 2005). However, there are some (technical) aspects that require further clarification (see below).

Fuel calculations

The fuel calculations in chapter 5 (p. 27) are comprehensible and obviously correct. However, due to safety aspects the contingency of 15 % is tightly allocated and possibly not sufficient for such a project.

UK response: Since production of the draft CEE the equipment has been rigorously tested and it has proved to exceed our expectations with regard to fuel efficiency. We are therefore confident that the level of contingency allocated is sufficient.

Camp and logistics

Further information on the expected extent of the planned camp and its components (containers, tents etc.) would be useful (p. 26).

UK response: The camp layout and component parts are shown on the revised Figure 19 in the final CEE.

It must be clear which activities are covered by the Draft CEE and which are not. What about the activities of the support contractor ALE closely related to this project (p. 38), has a permit be granted by the US (see p. 38)?

UK response: Clarity on the permitting arrangements was given in IP 13 presented at CEP XIV and has been included in the Final CEE. The environmental impact of ALE's activities associated with this project are assessed in the CEE. This is made more explicit in the final CEE.

Waste Management

Information on the waste generated throughout the project is given on page 28.

Additional information on the expected amount or volume and type of waste would be helpful. Regarding storage facilities, what does "appropriate containers" exactly mean?

UK response: Further information on the types of wastes likely to be generated and the waste packaging materials have been included in the final CEE.

2. Whether the conclusions of the draft CEE are adequately supported by the information contained within the document

The Draft CEE concludes that the proposed activity will have a less than a minor or transitory impact on the Antarctic environment. However, there are a number of uncertainties and risks which gave reason to assume that the activity could have "more than a minor or transitory impact" entailing the compilation of a CEE. The conclusion should have an explanation for the strongly differing vote.

UK response: An explanation is provided in the non-technical summary and conclusions of the final CEE.

3. The clarity, format and presentation of the draft CEE

The CEE is well written and presented. The document is very clear and comprehensive and contains very detailed and useful information with high quality graphs and figures.

NETHERLANDS

One of the two point for justification of the project as formulated on page 4

"This is critical to assessing the present-day risk of ice sheet collapse and consequent sea-level rise" is questionable. If we assume the project is successful in retrieving a sediment core and analysis are successful it remains questionable whether those findings can be applied to the present day conditions where the forcing of the climate system and the state of the system is very different preventing an over interpretation of the results.

UK Response: At one level there is a danger of speculating about the usefulness (or not) of material yet to be recovered. There is very little we can do about people's opinions on this, given the lack of actual material. If the lake sediments reveal past change, however, then, and in contrast to the views of the Netherlands, we believe it would have profound implications for our comprehension of modern risk of change for three reasons. First, it would show unequivocally that the whole ice sheet is capable of collapse, and has done so in the past. This in itself would be significant. Second, although many climate parameters are unique in today's (anthropocene) world, the drivers in West Antarctica are likely to be oceanic, which have a longer historical legacy than other, CO2-led, drivers. Third, and regardless of the causes of change, if we know the timing of ice sheet decay and, by inference the environmental boundary conditions that led to it, we can ascertain how close we are to those conditions now (albeit possibly for differing reasons).

We argue, therefore, that we should not underestimate the potential importance of sedimentary sequences from Lake Ellsworth.

Add 4. It is worth mentioning that by the time the project is in operation there is probably no need anymore for a communication cable in the ice for the thermistor measurements. Ongoing technological development points to wireless communication with measuring devices within the ice. It might be useful to add a statement along the line in the proposal.

UK response: We are not planning to deploy a thermistor string in the Lake Ellsworth programme.

On the latter point, we are grateful to the Netherlands for drawing us to the attention of remote devices. While these are in a developmental stage, being applied in shallow glaciers and outlets of Greenland, it may well be that in years ahead they have a considerable part to play in developing our knowledge of subglacial Antarctica. That is someway off, however. Consequently, at present, if a thermistor string were to be used traditional technology would seem the most sensible option.

In general I think that the scientifical expectation as formulated in the proposal are rather optimistic and maybe somewhat speculative. Whether the water is really old remains to be seen

UK response: It is this unknown that will be investigated.

A very extensive pre-site survey has taken place enhancing the logistical success, including radar, shallow cores and modelling attempts of the physical properties. Drilling technique smart idea to use old water. Clearly the consortium is extremely well prepared to undertake the very challenging technological tasks posed. They are well aware of the risks and I therefore concur with the final conclusion:

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

ASOC

1. Introduction

ASOC would like to congratulate the UK and the Lake Ellsworth Consortium for a thorough and in-depth CEE on the Proposed Exploration of Subglacial Lake Ellsworth. The document demonstrates clearly the fruits of years of development and the strength of consortium collaboration. The use of the hot-water drilling technique greatly reduces the risk of contamination, the target goal of no measurable microbial populations on engineered structures in contact with the lake is commendable and the analysis of blow-out risk is very thorough.

From a long-term and large-scale perspective, ASOC is concerned that the first penetration into the Antarctic subglacial lake system would open the gates to the "shifting baselines syndrome", where the next generation accepts their current environmental conditions as "normal" as past conditions are forgotten and the baseline of what is normal and acceptable is shifted down generation after generation. Because a precedent will have been set after the first penetration into the Antarctic subglacial system, it will become easier to justify future projects that enter into the subglacial lake system. The first penetration into the Antarctic subglacial lake system could potentially lead us down the spiral of shifting baselines, with a lowered quality of the environment becoming more acceptable as "normal". One can imagine a day when the subglacial lake system is considered to be no longer pristine. Therefore, we are currently at an important point in science history as the first few subglacial lakes are about to be penetrated for the first time.

ASOC appreciates greatly this thorough and in-depth CEE and acknowledges that the Lake Ellsworth Consortium has put in a lot of effort into minimizing environmental impacts possible using today's technology. Because this is a high-quality CEE and the project is an important first in history, ASOC would like to probe deeper and ask some more questions about the project, in order to take this opportunity to help establish a strong environmental precedence for exploration of Antarctic subglacial lakes (if it is deemed worthy to continue pursuing) and to push the bar for environmental standards in the Antarctic as high as possible.

2. Terms of reference

TOR 1 -The extent to which the CEE conforms to the requirements of Article 3 of Annex I of the Environmental Protocol

The draft CEE conforms to the requirements of Article 3 of Annex I of the Environmental Protocol.

TOR 2 – Whether the conclusions of the draft CEE are adequately supported by the information contained within the document

The draft CEE concludes that the proposed activity is expected to have "less than a minor or transitory" impact. This raises some questions as to the level of EIA required and as to the assessment itself.

1 This phenomenon-is often documented in fisheries and conservation science (e.g., Papworth et al., 2009; Pauly, 1995).

Generally CEEs are either produced in anticipation that the proposed activity will have "more than a minor or transitory impact" or, in a different school of thought, if the activity has demonstrably a "more than a minor or transitory impact". The approach used here takes a different approach, in that a CEE has been produced despite the consideration 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." (CEE, p. 45).

In our view, given the scale of the activity it might possibly be best assessed as having, at a minimum, "no more than a minor or transitory impact". However, after entering a subglacial lake for the first time that lake is no longer absolutely pristine. Therefore, the impact of penetration is, in a way, permanent, even though the environmental impacts strictu senso may be judged to be "less than minor or transitory" or "no more than minor or transitory" in the terminology of the Protocol.

UK response: We agree that a lake can only be accessed for the first time once, however lake penetration is required to fulfil the science needs, and given the mitigation measures designed, the impact associated with it are believed to be less than minor or transitory. We have however been very open that the impacts might exceed this and this point is clearly made in the CEE.

Furthermore, we question that the producing a CEE is in itself a measure that reflects the application of a precautionary approach. It rather means primarily a greater of information to be provided than for an IEE and a greater level of international scrutiny on the activity, all of which is of course welcome.

UK response: We agree that merely providing more information (than is typically required for an IEE) alone affords no additional benefit to the environment. However in this case the additional scrutiny on behalf of the SLE Consortium involved in the CEE production did generate additional mitigation methods that contributed to increased environmental protection.

Overall, there are a number of conceptual matters for discussion here, but in practical terms we are pleased that 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" has been followed in this case and that the planning process aims for rigorous preventative and mitigation measures in considerable detail.

We have some additional questions, below.

TOR 3 – The clarity, format and presentation of the draft CEE

The document is well written and presented to a very high standard. The approach used to assess impacts is very clear.

3. Fundamental questions

The CEE enters into a large amount of detail on the techniques used to reduce microbial population on equipment that will be in contact with the lake environment. What appears to be missing is a discussion of how to minimize the disturbance of the water column as a result of the presence of the scientific equipment, how to minimize the chance of cross-contamination or mixing across existing environments within the lake which are brought into contact because of the scientific equipment, e.g., between the ice and the water environments, between the water and the sediments, or between the different strata within the water column.

Specifically, we reference to some issues raised in Exploration of Antarctic Subglacial Aquatic Environments, Environmental and Scientific Stewardship (National Research Council, 2007) (referred after as NAS – EASAE) and Code of Conduct for the exploration and research of subglacial aquatic environments (SCAR 2010):

1. The EASAE raised the concern that

"Research activities targeting one component of the environment may potentially contaminate or alter another component. For example, sampling may disturb the internal stratification of the lake and change its physical and chemical structure. Sediment sampling may transfer biota from sediments and near-bottom waters to overlying water and ice, which may compromise subsequent measurements of the upper waters and ice. Sediments are likely to contain orders-of-magnitude higher concentrations of microbes, nutrients, and metals than are present in the water column. These benthic microbial communities also are likely to be different from those in the water column." (P. 120).

This is particularly relevant in the Lake Ellsworth project since sediment sampling is one of its central goals. The EASAE further identifies that:

"… the water environment of the lakes facilitates cell transfer from any object that may find its way into liquid water. If the lake has unique biological ecosystems, transfer may also occur as a robotic sampling device moves from ecosystem to ecosystem. In general, cleanliness requirements will have to be addressed in terms of (1) cleaning hardware (and quantification of bacterial levels and diversity) prior to penetration, (2) maintaining hardware cleanliness levels as much as possible during penetration, and (3) designing research techniques that minimize the possibility of cell transfer between different levels in the ice and the lake bed itself." (P. 100).

In particular, how is (3) addressed in the Lake Ellsworth project?

UK response: The mixing of stratified layers in the lake will be avoided by the slow rate of descent of the probe and by probe design (e.g. the lack of propellers). The corer barrel is highly polished and equipped with a double sediment catcher (shown pictorially in the final CEE) and piston rod lock which will minimize sediment *release, although some is inevitable. Text describing this has been added to the final CEE.*

The microbial control described in Chapter 6 describe the mitigation methods that will be deployed to prevent microbial contamination entering the subglacial environment. Preventing the microbial transfer between water/sediment is difficult to answer. We have designed a clean experiment to measure and collect samples in a controlled manner. Such an experiment minimises the likely exchange of microbes between environments. However, one cannot guarantee it can be prevented.

The EASAE further recommends that:

"It is not necessary to sample the environment in its entirety during the initial stages of exploration, because the physical, chemical, and biological properties of the water column need to be understood before realistic standards for contamination can be set and required advancements in engineering for more advanced exploration can be determined. Key data to be acquired in the first step of this progressive approach would ideally be geared toward helping understand partition coefficients, mixing regimes, habitats that have the potential for microbiological activity, and the fate of contaminants. The simplest approach would involve a CTD cast with other sensors, followed by a vertical profile and sample return of water and surface sediment." (p. 122).

ASOC appreciates that if the sediment sampling needs to wait until the basic environment of the water column is analysed and understood, it may incur large financial and environmental costs which might not be desirable. On the other hand, the issues raised by the EASAE have not been addressed in the CEE and ASOC would like the Lake Ellsworth Consortium to explain how they plan to minimize the possibilities of disturbances to the stratification in the water column and especially the contamination of the water column through sediment sampling. Can the consortium also give full consideration to the alternative option of delaying sediment sampling until the characteristics of the lake environment have been assessed and subsequently, acceptable levels of contamination can be defined (see point 2 below)?

UK response: The financial and environmental costs incurred by a phased approach to the sampling as, are ASOC suggests, undesirable.

As discussed above (and in the final CEE) the mixing of stratified layers in the lake will be avoided by the slow rate of descent of the probe and by probe design (e.g. the lack of propellers). The corer barrel is highly polished and equipped with a double sediment catcher and piston rod lock which will minimize sediment release, although some is inevitable.

Delaying sediment sampling until we have characterised the lake is not justified as it would involve additional risk of contamination, additional fuel use (in reaming / re drilling the borehole) or even an extra field season as there is only limited time to interpret data from the probe whilst the borehole is still open.

Acquiring a sediment sample from Lake Ellsworth, once the probe is retracted, is scientifically justified. Provided we retain cleanliness, as our project describes, the need to obtain information about WAIS history from such material demands that we undertake the work.

2. The EASAE refers to Rock and Bratina (2004) which is a report on a workshop that explored the technology for the exploration and sampling of Lake Vostok. Rock and Bratina (2004) identified a number of outstanding issues that needed to be tackled for the Lake Vostok project. One of them is: *"Quantifiable specifications that define acceptable levels of contamination do not currently exist and must be generated before detailed engineering efforts can proceed"* (P. 88 of EASAE).

In the case of the Lake Ellsworth project, what are the acceptable levels of contamination of the lake environment that have been defined? The CEE describes detailed methodology in the cleaning of the equipment in the design and deployment stages. P. 17 describes that the drill fluid will be analysed for microbial control. Are there no procedures in place to monitor the potential contamination of the lake environment during the project? Are there contingency plans in the case that the lake environment is thought to be contaminated during the course of the project?

UK response: The drill fluid will be sampled an a 6 hourly basis as a minimum, subjected to DAPI staining and enumeration by epi-fluorescent microscopy. Any trend towards significant increases in cell numbers will lead to a cessation of activity pending an investigation of how contamination has occurred, (e.g. why the filters are not working) and an increase in the sampling/testing to an hourly basis. The lake will not be penetrated if the microbial levels exceed background readings. This is made more explicit in the final CEE.

3) According to SCAR (2010), *"4.5 The total amount of any contaminant added to these aquatic environments should not be expected to change the measurable chemical properties of the environment."*

Echoing ASOC's point 2 above, what are the Consortium's plans to monitor the amount of contaminant added into the lake environment?

UK response: Very little if any drill fluid will enter the lake. We estimate that the microbial count associated with such drill fluid would be around 1/1000 x lower than the detection limit of our most sensitive assay. The drill fluid will be retained for laboratory analysis, to provide a control to compare the lake material with. The lake fluid may be identical to the borehole fluid (both are made of melted ice after all), so their comparison is important to understand. The drill fluid samples will be shipped back to the UK with lake samples for microbial, hydrochemical and organic geochemical analyses.

4) According to SCAR (2010), *"5.2 Protocols should be designed to minimize disrupting the chemical and physical structure and properties of subglacial aquatic environments during the exploration and sampling of water and sediments."*

Echoing ASOC's point 1 above, what are the Consortium's plans to minimize the disruption of the chemical and physical structure of the lake environment?

UK response: disruption will be minimised through the equipment design and how it will be deployed (slow rate of descent of the probe and by probe design e.g. the lack of propellers, and the corer barrel being highly polished and equipped with a double sediment catcher and piston rod lock to minimize sediment release) *as discussed previously. Disruption of chemical properties will be unlikely as no drill fluids other than melted ice will be used in the exploration programme. The filtration will have no effect on ice chemistry, drill fluid chemistry or the lake.*

4. Specific comments

1. According to SCAR's Code of Conduct for the Exploration and Research of Subglacial Aquatic Environments, *"[3.7] … Subglacial lakes used as research sites should therefore be demarcated ASPAs to protect their long term scientific value, to regulate activities at these sites, and to formalize the requirements for full documentation and information exchange."*

Are there any plans to do so for Lake Ellsworth?

UK response: One aim of the Ellsworth project is to inform the future management and exploration of subglacial lakes. The ASPA designation will be considered on review of the science information gained on the lake and the performance of the equipment and drilling methods.

2. ASOC is happy to see that a good effort has been put into assessing impacts on wilderness and aesthetics (P. 37), which is certainly not an easy task. The impact of the thermistor left in situ is particularly thoughtful (a minor though not transitory impact). We suggest adding that the traverse route of 300 km also has transitory impacts on wilderness and aesthetic values. Presumably, like other existing traverse routes, the route will be marked by wands on the ground and tracks (and possible minor spills) will be visible at least for a season or two.

UK response: The thermistor string will not be used. The traverse route will not be flagged on the ground but other impacts associated with it has been added for inclusion in the final CEE.

3. It is mentioned in the cumulative impacts section (P. 37) that there has been previous field work on the site and there is likely to be field work in the future. It also mentions that future fieldwork will be subjected to future EIAs. However, there seems to be a lack of the assessment of the cumulative impacts of the past, present and future activities. What are the total cumulative impacts (including association with the ALE camp) of the previous field work + the present proposed field work + the future possible field work? This work has not been done for the previous field work since they have been subject only to preliminary environmental assessments. While the previous field work was assessed to have minor and transitory impacts they can still have effects that can cumulate with the effects of the present and the future possible field work. And certainly, the present proposed field work, since a CEE is being undertaken could have even longer and farther-reaching effects that can cumulate with future field work.

4. Cumulative impacts: We note that this project will partly be carried out with the logistic support of a tourist facility near the Union Glacier. Both this facility and the proposed project will contribute to the overall cumulative impact in this area. For the purposes of commenting on this draft CEE we will not discuss this matter in any detail, but we are surprised to find out that there is a new land-based tourist facility in this part of Antarctica. According to the draft CEE (p. 38) a multi-year IEE for this facility has been approved by the US Environmental Protection Agency. We reserve further comments on this matter until we have more details about this operation and have had a chance to examine the IEE. Plainly a land-based facility operating for multiple years (which according to the ATS EIA database is through 2014-2015) that will enable the penetration of a relatively little visited part of Antarctica is bound to have a "more than minor or transitory" impact. We fear that in this case the ability to physically remove the tourist land based facility when its life cycle is over has been taken as evidence of it being a non-permanent facility, when in fact it will operate for several consecutive years or perhaps, as the Patriot Hills camp, several decades.

UK response: Impacts from ALE's activities associated with this project are considered within this CEE, however activities at Union Glacier in support of other National Operators and the tourism industry are not with the remit or control of the SLE consortium therefore we have not considered their impacts in this report. Likewise it is not practical to consider the impact of any further fieldwork at Lake Ellsworth when the UK has no plans for further investigation (although further science work might be considered in the future dependant of the outcome of this project – but this is several years away and has been neither scoped up nor funded). Furthermore we have no insight into the plans of any other national programme who may want to undertake science work in this area. We do agree with ASOC that cumulative impacts should be considered within the EIA process, and that impacts of all visitation/ science in this area in the past and future will be greater than the impacts set out in this CEE, so this is a very useful discussion point. EIA is an important tool in environmental protection and one which could be developed further but this is perhaps best discussed in the remit of the CEP 5 year plan.

5. The drilling project is an energy intensive project. What are the plans to make use of renewable energy sources and energy efficiency applications in order to reduce atmospheric emissions? BAS has been and continues to be one of the leaders in this field.

UK response: We have no plans to install any renewable/ alternative energy sources for this project as the continuity of the power is too crucial in the operation. BAS routinely considers renewables on our Bases, field sites, and UK office, but only implements renewable systems where feasible, and environmentally and cost effective. Renewables are not appropriate or practical for our requirements on the SLE project.

NEW ZEALAND

The Document is extensive and well presented. I have no comments that should be considered serious and would prevent the operation going ahead. I have scanned the complete document; have no general comments to make. However I do have comments and questions on the sections relating to the drilling methodology and the operation of instruments in the bore hole and lake.

Chapter 4: Description of the technologies

1. General system

Separation of the heating loop from the drill water loop plus filtration and UV sterilisation should minimise downhole contaminants. The planned hose and instrumentation decontamination process should also be effective. However the following points could be clarified:

- Is the heating system loop separate at start-up while the cavity is being melted out or does drilling water go through the heater with filtration relied on to prevent contamination of drill water from the heater metal tubing etc?

UK response: The heating loop system is separate from the start. No drilling water will go through the boiler. This is clarified in the final version of the CEE.

- Is the flush water used to clean the hose exterior and instruments filtered and returned to the drill water circuit or disposed of separately?

UK response: The system to clean the hose exterior has changed since presenting the draft CEE. The revised plan set out in the final CEE is for the external surfaces of the hose to be cleaned using ethanol soaked wadding. No water will be used for this process.

- Can the filtration system capture contaminants such as hydrocarbons/glycols that may come from the hose, water storage bladders or greases etc that may have been used on pipe work fittings? The cleaning of equipment prior to transport to Antarctica is well documented but I am wondering about accidental contamination of large items such as the hose reel , during transport, customs inspections etc that are not under the direct control of the project.

UK response: There is no realistic source of e.g. hydrocarbon contamination in the hose/pipework fittings. Our procedures will ensure cleanliness of the hoses and other equipment. They have been run at temperature for over 10 hours during field trials before being cleaned by a standard pigging system prior to shipment. The equipment has already been transported near to the drill site without being compromised during transit.

2. Hot Water Drill Breakthrough into the Lake Water

The operational aim appears to be to minimise contamination of lake waters by controlling the head of water in the cavity. The pump and sensor system appears to be sophisticated and to enable a high level of control. The following could be clarified with comment on the operational procedure.

- Is there a remote sensing measurement planned to confirm the depth to the ice-water interface prior to the last part of the hole is being drilled to allow better control of the breakthrough process?

UK response: There are no plans to deploy a remote sensor as it would add complexity and risk to the drilling procedure. The hole will be very straight, and so we will have a good measurement of the hole length from the read-out of the hose being sent down. We will certainly know when we are within 1-2% of the base (30-60 m), which is when our lake entry drill temperature will be engaged.

- I note the ice thickness is 3 – 3.25 km page 9 and ranges ~3100 m - ~3220 m in fig 4 p 10. Is there a more accurate measurement at the specific drill site? What is the expected depth to bubble closure?

UK response: the expected depth is 3155 m (to the nearest 10 m), this is made more explicit in the final CEE.

- Is the intention to have the hole positive, neutral or negatively balanced at breakthrough? I note that a mitigation strategy to minimise blowout potential from dissolved lake gasses or floating hydrates would be to have a “slight” positive head and prevent lake water entering the bore hole.

UK response: The intention is for the hole to be neutrally balanced at breakthrough. Head of water would need to be: 284 m (assuming 910 kg m^{-3} for ice and 1000 kg m^{-3} for water). This information has been included in the final CEE.

- If this is the case; Is slow drilling, with lower flow in addition to a reduction in the heat of the drill water the primary option to minimise water incursion into the lake?

UK response: Slow drilling and cool drilling at breakthrough, to minimise impact of warm water and jets of water. This is now reflected in the final CEE.

- If a negative head is maintained to minimise water inflow into the hole at breakthrough what plan is there to dump the excess water from the well and prevent it returning through the firn into the hole?

UK response: There will be no excess water that would need to be dumped anywhere during the drilling operations – it will be taken up by dead volume in the system.

- Will a single hot water nozzle design be used to drill the entire hole, and also effectively open out the base of the hole without jetting a large volume of water into the lake? Or will two different nozzles be used requiring a trip out of the hose to change the nozzles and complete the borehole.

UK response: A single nozzle only will be used as its impractical to change nozzles for the last stage of drilling.

- Page 21. Table 2. (SV) annotation after three sensors what does this mean?

UK response: This refers to sound velocity, however this sensor has been removed from the probe instrumentation so it is no longer referenced in the CEE.

- Page 35. New generators and vehicles. What emissions level/ certification does this new equipment have?

UK response: Generators and vehicles were selected on the basis of their fuel economy but not any specific emission standard (as none apply to Antarctica). Full test certification is held by BAS engineers.

The following pages are from the ATCM XXXIV Final CEP Report (pp.w 100-102).

ATCM XXXIV Final Report

Item 6: Environmental Impact Assessment (EIA)

6a) Draft Comprehensive Environmental Evaluation

(40) The United Kingdom presented WP 16 *Draft Comprehensive Environmental Evaluation (CEE) for the Proposed Exploration of Subglacial Lake Ellsworth, Antarctica* on behalf of the Lake Ellsworth Consortium. The United Kingdom expressed its gratitude to Norway for convening the ICG, and to all ICG participants for their constructive comments on the draft CEE, noting that a preliminary response to their comments is set out in IP 13 *The Draft Comprehensive Environmental Evaluation (CEE) for the Proposed Exploration of Subglacial Lake Ellsworth, Antarctica.*

(41) Norway presented WP 14 *Report of the Intersessional Open-ended Contact Group to Consider the Draft CEE for the "Proposed Exploration of Subglacial Lake Ellsworth, Antarctica".*

(42) Norway remarked that, having reviewed the United Kindom's draft CEE for the "Proposed Exploration of Subglacial Lake Ellsworth, Antarctica" in accordance with the *Procedures for intersessional CEP consideration of draft CEEs*, the ICG advised the CEP that:

1. The draft CEE and the process followed by the United Kingdom generally conformed to the requirements of Article 3 of Annex I to the Protocol on Environmental Protection to the Antarctic Treaty.
2. There was general agreement with the proponent's conclusion that it will entail less than minor or transitory impact taking into account the rigorous preventative and mitigation measures proposed and adopted by the proponent. These have substantially mitigated the risks which justified preparing the CEE. There was, furthermore, general agreement that the proposed activity is justified on the basis of its global scientific importance and value to be gained by the exploration of Lake Ellsworth.
3. The draft CEE is clear and well-structured.
4. When preparing the required final CEE, the proponent should closely consider and address, as appropriate, the comments raised by participants in Appendix A of WP 14.
5. The final CEE could furthermore be improved by taking into consideration participants' editorial suggestions (identified in Appendix B of WP14).

(43) Several Members underscored the importance of the CEE, and thanked Norway for leading the ICG. France noted that during this intersessional work, a number of participants had commented that the CEE lacked details on logistics aspects of the proposal.

(44) Germany thanked the United Kingdom for IP 13. Germany wanted to highlight the purpose of utilising low impact drilling techniques that limit environmental impacts, and looks forward to the final CEE.

(45) The Netherlands raised a point of clarification with respect to the next step after consultation on the draft CEE. The Netherlands asked whether the United Kingdom was required to take into consideration the issues raised by the ICG and the Committee, before presenting the final CEE to the ATCM for approval.

(46) The Chair clarified that Annex I to the Protocol requires the proponent to address comments on a draft CEE received from other Parties. Accordingly, the CEP will offer technical advice to the ATCM on the adequacy of this CEE, as per the requirements under the Environment Protocol.

(47) The Russian Federation agreed with the Chair's comments, and suggested that the United Kingdom should take on board the advice of the CEP on the draft CEE in accordance with established national procedures. Russia asserted that the United Kingdom needs to mitigate all potential problems, and provide explanations for why it has chosen the methodology it will employ.

(48) ASOC mentioned reference to its comments during the ICG on this draft CEE, and added that the impact to the environment and adequate compliance with the Environment Protocol might be better addressed if the United Kingdom was to consider conducting an independent audit project of the drilling project such as that which New Zealand undertook for the ANDrill CEE. It suggested that after entry a pristine subglacial lake could be considered to have been permanently altered and was no longer pristine.

(49) The United Kingdom expressed gratitude for the comments from many Members, and indicated that it would make every effort to respond to these comments when preparing the final CEE next year. The United Kingdom also thanked Norway as chair of the ICG.

CEP advice to the ATCM

(50) The Committee discussed in detail the draft Comprehensive Environmental Evaluation (CEE) prepared by the United Kingdom for the "Proposed Exploration of Subglacial Lake Ellsworth, Antarctica" (WP 16 and IP 13). It also discussed the report by Norway of the ICG established to consider the draft CEE in accordance with the Procedures for intersessional CEP consideration of Draft CEEs (WP 14), and additional information provided by the United Kingdom in response to issues raised in the ICG (IP 13). Those discussions are summarised in paragraphs 40-50 above.

(51) Having fully considered the draft CEE, the Committee advised ATCM XXXIV that:

- The draft CEE and the process followed by United Kingdom generally conform to the requirements of Article 3 of Annex I to the Protocol on Environmental Protection to the Antarctic Treaty.
- The information contained in the draft CEE supports its conclusions that the proposed activity will have no more than a minor or transitory impact on the

Antarctic environment, taking into account the rigorous preventative and mitigation measures prepared and adopted by the proponent. Furthermore, the proposed activity is justified on the basis of the global scientific importance and value to be gained by the exploration of Lake Ellsworth.

When preparing the required final CEE, the proponent should consider, and address as appropriate, all comments raised by Members. In particular, the ATCM's attention is drawn to the suggestions that the final CEE should provide further detail regarding: assessment of the activities of the support contractor, further documentation/consideration as to the issue of potential mixing at break-through, further discussion as to how to minimise the disturbance of the water column as a result of the presence of the scientific equipment, assessment of risk of equipment loss in the lake, consideration of the size of the on-ice team in light of project safety and considerations relating to international collaboration.

- The draft CEE is clear and well-structured, well written and with high quality graphs and figures.

Subglacial
Lake
Ellsworth
Antarctica