Title: Probing the Limits of Technology: Exploration of Subglacial Aquatic Environments

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Opening Remarks

Distinguished guests and colleagues, on behalf of my co-author Jemma Wadham, it is my great pleasure to deliver the 36th ATCM Scientific Committee on Antarctic Research Science Lecture. I also thank the President of SCAR for the kind and generous introduction.

The yearly ATCM Science Lecture is an opportunity for SCAR to report on the latest and most exciting science being conducted in Antarctica and the Southern Ocean. In the past lecture topics have included climate change, terrestrial biodiversity, space weather, marine ecology, bioprospecting, human impacts, and non-native species.

The SCAR Science Lecture in 2004; in Capetown, Southern Africa; presented the state-of-the knowledge of Subglacial Lakes and today I provide an update on advances in understanding subglacial aquatic environments over the last 9 nine years. In 2004, entry into these environments was but a distant dream of a few dedicated scientists and today that dream is a reality!

THE FIRST SLIDE PLEASE

Slide 1: Title Slide

The title of today's presentation is: "Probing the Limits of Technology: Exploration of Subglacial Aquatic Environments'

One of the most dramatic developments in Antarctic science over the last two decades has been a concerted effort to better understand the untouched realms beneath Antarctica's ice sheets, now collectively referred to as Subglacial Aquatic Environments. In a reversal of a long held belief that most ice sheets were frozen to the basement rock, we now know that liquid water accumulates and flows over large areas of Antarctica at the base of the ice.

Subglacial Aquatic Environments are those localities where pressures and temperatures allow liquid water to occur. While it might seem counter-intuitive – these conditions exist at the base of massive ice sheets making liquid water a common feature across Antarctica. The widespread occurrence of subglacial aquatic environments in Antarctica has sparked considerable scientific interest and generated great public curiosity for nearly 20 years.

Speculation regarding these environments is often about what might be living in these unique settings isolated for many thousands if not millions of years from the warmth of the Sun.

After more than 15 years of international planning we stand at the threshold of a new era of subglacial exploration. The requirements for conducting experiments and collecting data and samples in these environments can stretch logistical capabilities to their limits and challenge even our most advanced technologies and that is the focus of today's lecture.

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Slide 2: Lecture Outline

Today's lecture reviews the history of subglacial exploration and sets out the scientific justifications for the financial and human investments required to conduct this research.

Next, I will review environmental stewardship issues related to subglacial exploration programs and the role that Antarctic Treaty Parties, the Committee on Environmental Protection, and the Scientific Committee on Antarctic Research have played in addressing various environmental protection issues over the years and how scientists have incorporated these concepts into program designs.

This is followed by an update of major, on-going subglacial exploration programs including programs by the Russian Federation at Subglacial Lake Vostok, the United States program along the Whillans Ice Stream, and the United Kingdom's program to enter and sample Subglacial Lake Ellsworth.

I will highlight the critical role of National Antarctic Programs logistics and support that enables these ambitious and difficult studies and field programs.

I will next summarize existing enabling technologies and new technologies that will be essential to fully explore, observe and characterize subglacial aquatic environments on a continent-wide scale in the coming years.

Finally, I will close with a few remarks about the current status of subglacial aquatic environment exploration and what the future may hold.

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Slide 3: 1. Introduction

These are exciting times as many years of intense planning and deliberations are translated into field campaigns to explore one of Antarctica's last frontiers. These exploration programs are interdisciplinary in scope and international in participation. They require substantial and sustained investments in science, equipment, infrastructure, and human resources.

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Slide 4 – The Story Begins at Vostok Station

But before we talk about the future, let's review the past. The story of subglacial aquatic environment exploration begins at the Russian Federation's Vostok Station. Few could have imagined more than 60 years ago when Vostok Station was established that beneath one of the world's most remote scientific stations waited a massive lake of liquid water that invokes wonder and amazement. Vostok Station, previously most well-known for its 400,000 year ice core record of past climate change, is now famous for what is beneath the ice – Subglacial Lake Vostok.

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Slide 5 – The Discovery of Lake Vostok

The first inklings that something unusual was taking place beneath the East Antarctic Ice Sheet came from aero-geophysical data collected by a Dutch, British and American team in the 1970s. In their field notes there were references to what looked like a "lake" even at the ice sheet surface as the area surrounding Vostok Station was unusually flat and level.

Further speculation arose during the processing of the seismic records from this expedition when an unusually flat segment of a seismic line was observed more than 4 km below the ice surface. It was noted that this unusual feature might indicate the presence of liquid water. For more than two decades little attention was paid to this data or the intriguing conjectures about liquid water.

One of the first international presentations on Subglacial Lake Vostok was made by the Russian Federation at the SCAR Delegates meeting in Rome in 1994. A few years later, as Dr. Martin Siegert of the University of Bristol was re-processing the archived seismic records from the 1970s it became apparent that Lake Vostok was not the only subglacial lake. We now know that these features are common beneath thick ice sheets not only today but also in the geological past. The first inventory of subglacial lakes in the late 1990s identified about 140 lakes whereas the latest inventory, in 2012, identified nearly 400 lakes. The more scientists search for lakes, the more they find.

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Slide 6 – International Cooperation

Even in the earliest discussions, it was recognized that science on the scale demanded by subglacial exploration could not be accomplished by one individual, program or nation meaning that international cooperation was essential.

A hallmark of subglacial exploration programs has been international cooperation and coordination and the Scientific Committee on Antarctic Research (SCAR) has played an important role as facilitator of this teamwork since the year 2000. SCAR has had a long-term scientific interest but has also served as a source of authoritative advice in regard to environmental issues surrounding the exploration of these environments. SCAR organized much of the international planning that ultimately lead to the funding of several major exploration programs.

In 1998 in Conception, Chile Dr. Frank Carsey of NASA presented a lecture at the SCAR biennial meetings on the potential use of Subglacial Lake Vostok as a test-bed for technologies to look for life elsewhere in our solar system. This piqued the interest of the attending scientists and contributed to the growing interest in these environments.

Recognizing this growing scientific interest, SCAR formed the Subglacial Antarctic Lake Environments Group of Specialists (SALEGOS) in 2000 in Tokyo Japan which operated until 2004 when a subglacial environment Scientific Research program was proposed. This proposal was approved and the Subglacial Antarctic Lake Environments (SALE) program was created. SALE was a sanctioned International Polar Year 2007-2008 program and a major SCAR contribution to the IPY.

SALE was ultimately replaced in 2010 by the SCAR Expert group - Advancing Technologies and Environmental stewardship for subglacial exploration in Antarctica (ATHENA) which continues to meet today. My co-author, Jemma Wadham is co-convener of ATHENA.

These groups produced a wide range of planning documents and served as the international focus for interests in subglacial environments for over a decade before national subglacial exploration programs were funded.

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Slide 7 – 2. Why Study Subglacial Aquatic Environments?

The cover of the journal Nature in June 1996 announced to the world - "Giant Lake beneath the Antarctic Ice". This created much public and scientific interest. In the 1990s, Subglacial Lake Vostok was mostly seen as a curiosity. At that time, the depiction of a subglacial network of streams and lakes in the center of this this slide would have been seen as fanciful and speculative. We now know that this artist's rendition is an accurate depiction of subglacial environments.

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Slide 8 – An International Focus of Interest

The appearance of Subglacial Lake Vostok on the cover of Nature in 1996 was a catalyst for serious consideration of planning for the exploration of subglacial aquatic environments. Several major international workshops were held. The title of a 1999 workshop report succinctly expresses the state of thinking about subglacial lakes at that time: *"Lake Vostok- A curiosity or a focus for interdisciplinary study?"*

As our understanding of these environments grew over the next decade focus shifted from solely talking about Subglacial Lake Vostok. Over time discussions evolved to speaking of lakes in the plural and phrases such as "lake districts" indicating geographic clusters of lakes were being used more often by scientists. Subglacial hydrological networks of features were recognized and today's most commonly used terminology, which includes all of these features, is Subglacial Aquatic Environments. This evolution in terminology closely followed the evolving understanding of the extent of these environments and a growing appreciation of their importance and role in the Antarctic system.

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Slide 9 - Subglacial Lake Vostok

In the 1990s attention was focused on Subglacial Lake Vostok because it was the one lake we knew at least something about. Also, Subglacial Lake Vostok is a global-scale feature visible from space and comparable in size to some the largest surface lakes on our planet. But even for Lake Vostok, little was known and most of that knowledge came from remote sensing and models. This lack of even the most fundamental knowledge allowed for much conjecture about Subglacial Lake Vostok, particularly speculation about what might be living in the lake and some of the suggestions were rather fantastic!

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Slide 10 – Scientific Themes

Over the years, the scientific justifications for what would surely be challenging and expensive exploration programs expanded to interests in other areas of Antarctic research. While the search for life at its limits has always been a central question other fundamental earth sciences and earth processes questions became part of the dialogue.

Scientific justifications for exploring subglacial environments broadened to questions regarding the geodynamics of lake evolution; subglacial hydrology, interactions with ice sheet dynamics, the limnology and biogeochemistry of subglacial lakes, unique sedimentary climate records, and what, if any, connections were there between palaeo-outbursts of subglacial waters, local oceanography, and regional climate.

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Slide 11 - Water is Abundant Beneath the Antarctic Ice Sheet

It is now recognized that water is abundant beneath the Antarctic ice sheet with more than half of its bed predicted to be experiencing ice melt. This image depicts rates of basal melting and freezing. Melting is shown in warm colors (red, yellow) and freezing is shown in cold colors (blue). These are unusual environments where water can flow “uphill” due to hydrologic gradients caused by differences in ice sheet thickness counter-acting gravity. We also know that not only is there basal melting of ice but there is basal freezing of water and subglacial water in some locations are subject to super-cooling events. Only a few short years ago we knew little about these processes.

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Slide 12 – A Continent–Wide Feature

As I mentioned, in the 1990s, some speculated that Lake Vostok was a one-of-a-kind feature and not representative of subglacial environments in general. However, based primarily on the work of Martin Siegert at the University of Bristol, it became clear that there are numerous lakes waiting to be identified. As archived geophysical records were re-examined, new records collected, and satellite imagery analyzed - it became apparent that there were hundreds of lakes of varying sizes across Antarctica. Aero-geophysical surveys by Robin Bell, Don Blankenship, and others and utilization of satellite imagery by Helen Fricker steadily increased the number of identified lakes. The latest inventory of subglacial lakes by Wright and Siegert in 2012 identified 397 lakes.

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Slide 13 - Diverse Subglacial Environments

It has also been recognized that all subglacial water accumulations are not randomly distributed across Antarctica. Water accumulations occur in close proximity to ice divides, at the heads of ice streams, in fault generated basins and in depressions etched out of basement rock by ice scouring. This suggests that subglacial lakes differ in age, origins, histories, limnologies, and the extent of isolation signifying that individual lakes may harbor different assemblages of microbes. All subglacial lakes are not created equal.

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Slide 14 - Subglacial Hydrology

The next major advance in understanding occurred in the mid-2000s when it was recognized that subglacial aquatic environments were not static and that some were filling and emptying on time-frames of years or even months to weeks. The analyses of Wingham et al. documented rapid changes in the elevation of the ice sheet surface. These surface fluctuations can only be caused by water filling and flushing events at the base of the ice sheet. This was the first suggestion that a hydrologic system existed beneath the ice though it was recognized several years earlier that lakes occurred in clusters near Dome C that gave an appearance of linkages. This interconnection raises the concern that if one lake or stream was contaminated by entry other downstream water accumulations might be as well.

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Slide 15 - Life in Subglacial Aquatic Environments

As I indicated earlier, the questions of greatest interest, especially among the public, have been about what might be living in these environments.

The darkness, water temperatures, and high pressures in these environments are not so different from conditions in the world's deep ocean basins that cover a majority of our planet. The uniqueness of sub-ice environments is due to the cold, dark, and high pressure conditions in combination with isolation and limited sources of energy, nutrition and carbon. It is this combination of features that suggests that microbes found in these environments will be unique and most likely never seen before.

Early discussions debated whether life was present in subglacial environments at all, but based on finding life essentially everywhere it is looked for on the planet, the consensus is that the absence of life in subglacial environments would be bigger news than if it is found. The interconnectedness previously mentioned suggests that these features may not be as isolated from outside influences as once thought. Subglacial flows of water increases the likelihood that these environments have been seeded with microbes at some point in their history.

Early discussions about life in the lakes were purely speculation until the Russian Federation recovered accreted ice from the bottom of the Vostok borehole in the 1990s. Accreted ice is lake water frozen to the base of the ice sheet as it travels over the lake surface. It was this ice that served as a proxy for *in situ* sampling of the lake which, at the time, was still many years away.

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Slide 16 - Subglacial Lake Vostok: Accretion Ice

In 1999 a series of papers reported analyses of Subglacial Lake Vostok accretion ice in the journal Science. These papers and others generated great interest in the scientific community and the press. While the results were tantalizing, there were discrepancies in results amongst laboratories and questions about the integrity of the accreted ice samples. Recovery of samples through a borehole with techniques not designed to be contamination-free raised questions about whether non-indigenous microbes had been introduced to the samples.

While these results remain controversial, microbes were detected in the accretion ice and the study by Karl et al. indicated that not only were microbes present but they were viable. Accreted ice was found to be chemically pure and contain very low densities of cells raising even more questions about the origins of the cells that were detected. The microorganisms recovered appeared to use chemical energy for growth as expected in environments isolated from the Sun.

Questions about these conclusions persist and can only be answered by the analysis of samples retrieved and processed under clean conditions and protocols. The very early results from *in situ* samples of subglacial aquatic environments are just now being reported and will be discussed in a few minutes.

Slide 17 - Latest Scientific Results

Now I highlight a few of the more intriguing, recent research results to illustrate how broadly subglacial waters may be exerting an influence.

It has been hypothesized that subglacial water outflows at ice margins affect oceanic productivity by adding nutrient, in particular iron. A mounting body of data shows that melt water generated at the ice sheet bed exits via channels at the ice margin. This is illustrated by satellite data which has recorded traces of channels in the surface of ice shelves. Very high levels of iron found in the Pine Island polynia in the Amundsen Sea and are thought to be linked to an iron in the melt water emanating from the ice stream and the Pine Island Glacier. Recent numerical modelling studies have shown that iron derived from the melting of the ice sheet could have a significant impact on primary productivity in the coastal Southern Ocean. Further studies will be needed to better define the importance of this novel nutrient pathway to the coastal ocean.

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Slide 18 - Latest Scientific Results

It has also been speculated that subglacial environments are a major, unrecognized reservoir of greenhouse gases. Beneath the ice sheet there are vast thicknesses of subglacial sediments that are in part relict marine sediments from former high sea level stands in the past. It is likely that anoxic conditions have developed in these sediments. If this is true, it would be expected that resident microbes could produce methane that would accumulate as gas hydrate. This process would create one of the largest methanogenic wetlands on our planet. Only further research will be able to ascertain if this unrecognized reservoir of methane is significant on a global scale and how stable it might be in future warmer climate.

In summary there are strong scientific justifications for investments in exploring subglacial aquatic environments based on the potential for significant new and fundamental scientific knowledge in many areas of Antarctic research, much of which has global significance.

However, scientific value and return is balanced against potential environmental harm and this is particularly true when the targets of exploration are unique and pristine environments that will be accessed by humans for the very first time.

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Slide 19 – 3. Envionmental Stewardship

Concerns about the environmental consequences of drilling into, entering and sampling these environments has been the subject of intense international debate since serious consideration of exploring subglacial environments began. First, adequate levels of cleanliness have to be agreed and then procedures must be developed to attain these standards of cleanliness to protect these environments from being biologically or chemically contaminated.

Second, concerns about contamination or alteration of retrieved samples with non-indigenous microbes and chemicals are important from a scientific standpoint procedures must be adopted that ensures the integrity of any samples that are collected. In reality, the scientific requirements for cleanliness may far exceed those wished for from an environmental stewardship perspective. Modern biological and chemical analytical techniques can often detect chemicals and organisms at levels far lower than those known to cause environmental issues. Once the integrity of samples has been questioned it is impossible to determine if the resultant scientific data are reliable and artifact-free. Samples must be recovered, processed, stored and analyzed under near-sterile conditions if the results are to be believed.

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Slide 20- ATPs/ATCM/CEP

As unique Antarctic environments there has been great interest, concern and debate about how best to protect subglacial environments. These issues have been on the agenda of the Antarctic Treaty Parties, the Committee Environmental Protections ATCM and CEP for more than a decade. As mentioned before SCAR has played an important scientific advisory role over the years as well.

Reviewing the record of the ACTM and the CEP there have been 26 papers submitted over the last 13 years, including three at this ATCM, that reference subglacial environments. Seven have been Working Papers, 18 Information Papers and 1 Background Paper. The papers were submitted by the Russian Federation, SCAR, the United States, the United Kingdom and the

Netherlands. Most of these papers were submitted by the Russian Federation (18) and provide yearly reports of scientific investigations at Vostok Station and progress toward entering Subglacial Lake Vostok, These papers also include Initial and Comprehensive Environmental Evaluations of the Subglacial Lake Vostok, the Whillans Ice Stream and the Subglacial Lake Ellsworth programs and responses to questions posed at ATCMs about the IEEs/ CEEs.

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Slide 21 - SCAR/CEP and Subglacial Aquatic Environments

Within the context of the ATCM and CEP, SCAR provided expert scientific commentary on the Russian Federation plans to enter Subglacial Lake Vostok, presented a SCAR science lecture on subglacial lakes in 2004, provided updates on scientific advances related to subglacial environments, and developed a code of conduct for the exploration and research of subglacial aquatic environments.

Environmental issues engendered much international debate and lead to the establishment of guiding principles and environmental protocols for subglacial aquatic environment exploration. While drilling at Subglacial Lake Vostok was the continuation of long-term program at the site and proceeded by deepening the existing bore hole, other national programs have funded and begun to implement major subglacial exploration programs in the last five years that have addressed these important environmental issues.

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Slide 22 – Guiding Environmental Principles

Two important reports suggesting guiding principles and laying out a framework for clean technology best practice for use by subglacial exploration programs are the U.S. National Academies "Subglacial Aquatic Environments: Environmental and Scientific Stewardship" and SCAR's Code of Conduct for the exploration and research of subglacial environments". Both of these documents provide explicit guiding principles for those that may be considering subglacial environment exploration programs. Excellent examples of the applications of these principles are the WISSARD and Subglacial Lake Ellsworth programs.

Important conclusions of the National Academies report included:

- international cooperation is essential;
- exploration targets should be well characterized remotely before entry is attempted;
- subglacial aquatic environments intended for research should be designated as Antarctic Specially Protected Areas to ensure that all scientific activities are managed;
- acceptable levels of biological, chemical, and other contaminants should tailored to the specifics of each site and program;

The SCAR Code of Conduct recommendations are similar to the U.S. report include but are not limited to:

- subglacial exploration programs should comply with the Environmental Protocols,
- all programs should undergo environmental assessment,
- IEEs and CEEs should be conducted as applicable,
- exemplar subglacial aquatic environments should be designated ASPAs for long-term conservation,
- it should be assumed liquid water will be encountered and that living organisms will be present,
- drilling fluids and equipment that will enter the subglacial aquatic environment should be cleaned to the extent practicable,
- the total amount of any contaminant added to these aquatic environments should not be expected to change the measurable chemical properties of the environment,
- water pressures and partial pressures of gases in lakes should be estimated prior to drilling in order to avoid down flow contamination or destabilization of gas hydrates,
- sampling plans and protocols should be optimized to ensure that one type of investigation does not accidentally impact other investigations adversely, and
- sampling systems and other instruments lowered into subglacial aquatic environments should be meticulously cleaned.

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Slide 23 – Program Design and Environmental Protection

The first exhortation to the subglacial scientists is to - Do no harm! The scientific teams have risen to the occasion and I discuss the approach used by the WISSARD program to illustrate how multiple approaches have been adopted to meet stringent cleanliness requirements.

For hot water drilling the drilling fluid is water and the WISSARD water treatment system has utilizes a combination of filtration, UV irradiation and pasteurization (heating). To clean hoses and cables all equipment is cleaned with high pressure water and air and UV. And finally science instruments and samplers are disinfected with hydrogen peroxide. All equipment and tools must be able to sustain these types of treatments without significant degradation in materials or performance. In most instances the WISSARD team performed these procedures on site in clean laboratory facilities.

The Subglacial Lake Ellsworth team took a slightly different approach while using the same basic approaches to cleanliness of chemical cleaning, UV irradiation, and heating. Cleaning instruments was conducted in UK-based laboratories off the ice and equipment was hermetically sealed. These sterile packages were only opened in the field when it was time for deployment. Instruments and samplers were to be deployed only once and retrieval the instruments and samplers were to be re-sealed for transport back to the U.K.-based laboratories for processing under ultra-clean conditions.

Slide 24 - 4. Subglacial Aquatic Environment Programs

I will now report the latest developments from the three major, on-going subglacial exploration programs.

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Slide 25 - A Continent-wide Network of Study Sites

As scientific discussion progressed and scientific objectives were broadened to a larger community, it became clear that the full promise of subglacial lake exploration could not be accomplished at a single location or by any single entry and sampling. International thinking about a comprehensive program quickly evolved to the necessity for a number of study sites across the Antarctic continent.

The 3 on-going subglacial exploration efforts include programs by the Russian Federation at Subglacial Lake Vostok, the United Kingdom at Subglacial Lake Ellsworth, and the United States along the Whillans Ice Stream.

Before we discuss the current status of these subglacial environment exploration programs, I want to recognize the essential role that National Antarctic Programs play in supporting subglacial exploration programs both by funding the science but also by supporting the logistical needs.

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Slide 26 - The First Challenge: Getting There

Cooperation and consultation between scientific teams and National Antarctic Programs logistics and support personnel that enable these ambitious and difficult experiments and field programs is essential. In no other scientific endeavor in Antarctica is this partnership and integration of logistics and science so critical to success. One of the first challenges faced by those that wish to study subglacial environments is simply getting to the sites of interest which by their nature are located in some of the most remote and hostile locations on Earth. Deployment of people and equipment to the field is critically dependent on support personnel, ground and air transport, and traverse capabilities. These types of campaign require months if not years of careful planning and close cooperation between scientists, technologists, logisticians.

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Slide 27 - The Next Challenge: Access and Sampling

Once on site subglacial explorers require provisioning, laboratory and sample processing facilities, power, equipment to gain access to the base of the ice sheet such as hot water or mechanical ice drills, and various sampling devices. The design, fabrication, and deployment of complex sensor arrays, probes, and observatories require highly, technically qualified support personnel. As with all remote deployments, support personnel and scientists have to be nimble, able to cope with unforeseen failures and improvise as the situations calls for it.

Now an update of the major, on-going subglacial exploration programs.

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Slide 28 - Subglacial Lake Vostok

The Russian Federation has a long and distinguished history of scientific research at Vostok Station. As previously mentioned one of the most famous efforts is the 400,000 year ice core record of past climate.

In more recent years the recovery of accreted lake ice and the determined effort to enter and sample Subglacial Lake Vostok was a major focus for the Russian Antarctic Expedition. In 2011/2012 the Russian team successfully completed the first ever entry into a subglacial environment, a major technological feat many years in the making that garner wide-spread international attention and acclaim.

The Russian Federation has been providing detailed and thorough yearly updates on their scientific programs at Subglacial Lake Vostok for a more than decade and interested parties are referred to those ATCM/CEP documents.

What I wish to highlight today are the first preliminary results from a truly amazing technological feat, the first ever entry into a subglacial environment. We greatly appreciate our Russian colleagues for allowing these results to be presented and providing the materials I will present.

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Slide 29 - Subglacial Lake Vostok - *In situ* Samples

Samples of frozen lake water recovered during the 2012-2013 field season appear to confirm this finding. New insight was gained about the geochemistry of lake water as well. Seven DNA clones of this new species of bacteria have been found. Phylogenetic analyses suggest that the new species is outside of the main taxonomic categories of microorganisms. While these results are preliminary, they suggest that unique microbial residents do live in Subglacial Lake Vostok.

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Slide 30 - Subglacial Lake Vostok

In the 2011-2012 field season the surface of Subglacial Vostok was penetrated. Drilling into the lake under-pressured allowed lake water to rise in the bore hole and was left in place to freeze during the ensuing winter. The objective of the 2012-2013 was to core the frozen lake water in the bore hole. On average each day more than 10 meters of frozen lake water were recovered during coring operations and 122 meters of ice were recovered. The first signs of frozen lake water in the hole were observed 575 m above the lake. A preliminary examination of the frozen water sample retrieved on the drill bit after Lake Vostok unsealing in 2011-2012 revealed traces of unique microbiota.

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Slide 31 – Whillans Ice Stream Subglacial Access Research Drilling – WISSARD

The Whillans Ice Stream Subglacial Access Research Drilling project is an integrative study of ice sheet stability and subglacial geobiology in West Antarctica, funded in 2009 by the Antarctic Integrated System Science Program of U.S. National Science Foundation. There are 13 Principal Investigators (PIs) at eight different US Institutions, with additional US and International collaborators. . The study area is the downstream part of the Whillans Ice Stream on the Siple Coast, specifically Subglacial Lake Whillans and the grounding zone the lake discharges into. The program is commonly called WISSARD.

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Slide 32 – WISSARD: An Update

WISSARD Antarctic field work began in austral summer 2010/11 and will continue through the 2013/14 season. The WISSARD science program has three integrated projects. The first project focuses on the role of active subglacial lakes in determining how fast the West Antarctic ice sheet loses mass to the global ocean and influences global sea levels using satellite remote sensing, surface geophysics, borehole sensors and analysis of subglacial water, sediment, and basal ice samples. The second project is studying the stability of the fast flowing Whillans Ice Stream using surface geophysical surveys with borehole and subglacial sampling and measurements. The third project is using a combination of biogeochemical/ genomic measurements to study metabolic and phylogenetic biodiversity and the biogeochemical transformation of major nutrients beneath the Whillans Ice Stream. The 2012/2013 field season was just successfully completed.

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Slide 33 - Subglacial Lake Whillans – *In Situ* Samples

In the 2012-2013 field the program successfully drilled into Subglacial Lake Whillans and recovered water and sediments from the base of the ice stream. Preliminary results have shown that colonies of bacteria from lake water can be grown in the laboratory and cells have been identified by transmission electron microscopy. It is too early to draw conclusions about what types and amounts of microbes reside in Subglacial Whillans.

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Slide 34 – Subglacial Lake Ellsworth

The Subglacial Lake Ellsworth consortium was funded by the Natural Environment Research Council (NERC) as a partnership between two of NERC's Centers of Excellence - British Antarctic Survey and the National Oceanography Centre - and the UK university sector. Over 30 scientists and engineers have been involved since 2004.The program has a dual mission of observing and sampling life at the extremes to determine the presence, origin, evolution and maintenance of life in an Antarctic subglacial lake. The collection and analysis of water samples will determine the presence or absence, origin, evolution and maintenance of life in an Antarctic subglacial lake. This will answer questions about whether, and in what form, microbial life exists in Lake Ellsworth. The second mission is to unlock secrets in the subglacial sediments by recovering the lake bed sedimentary record of the palaeo-environment and glacial history of the West Antarctic Ice Sheet (WAIS). Lake-floor sediments hold clues about the past environment and glacial history of the West Antarctic Ice Sheet. Analysis will determine the date of the last decay of the ice sheet - critical for assessing the present-day stability and the likely consequences for future sea-level rise

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Slide 35 - Subglacial Lake Ellsworth – An Update

In the early hours of Christmas Day 2012) the mission to drill to subglacial Lake Ellsworth was suspended. Drilling was stopped after the team was unable to properly form the water-filled cavity 300 meters beneath the ice. The cavity was to link the main borehole with a secondary borehole used to recirculate drilling water back to the surface. The program is currently convening a panel to analyze the failed attempt and provide recommendations for a future second attempt to reach Lake Ellsworth.

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Slide 36 - 5. Technological Challenges

As you can see from the update just given, technology has been critical for subglacial exploration and technological advances are essential to accomplishing the scientific goals. Technology development is driven by scientific necessity and tempered by environmental concerns. These programs challenge the limits of technology in several areas including cleanliness; drilling and access tools; sampling devices for ice, water and sediments; and deployment of sensors, probes and observatories.

Next I discuss the various technological challenges that subglacial exploration programs face and also provide a glimpse of new technologies that are being developed.

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Slide 37 - Unique Technological Requirements

Subglacial exploration programs face a set of unique challenges including sampling ultra- dilute chemical and biological solutions, designing equipment to work at low temperatures and high pressures, remoteness of study sites, and deployment of equipment through a restricted diameter bore hole. And, all of this must be accomplished while adhering to stringent standards of cleanliness.

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Slide 38 – Drilling and Access

Thermo-mechanical and hot water drilling techniques have been successfully utilized at ice streams. Drilling through glacial ice, liquid water and into deep lake sediments and sedimentary basins has NOT been accomplished. There is a need to couple hot water drilling (lake/ice stream bed access) and sediment coring capabilities in order for this to happen. Significant technological challenges including addressing environmental issues associated with the possible need to use drill fluids in some instances, potential lake water disturbances caused by coring and retrieval operations, and the difficulty of collection of water, sediments, and microbes at *in situ* conditions

NEXT SLIDE PLEASE

Slide 39 - Water and Sediment Sampling

Collection and return of water, sediments, and microorganisms is an essential element of all three of the current subglacial exploration programs. In the future this may change as sensors, probes and observatories become more sophisticated for making in situ measurements and I will discuss these technologies in a moment. However, assuming sample collection and return is the primary mode of data collection there are a series of challenges including: while not always possible or necessary there are reasons maintain in situ conditions during sample and retrieval as decompression and warming can create artifacts in samples and potential be fatal to micro-organisms. There are some lessons to be learned from those that have devised ways to sample the deep sea at *in situ* pressures and temperatures using pressure devices.

Due to the ephemeral nature of some properties of samples there can be a need for on-site processing of samples that require ultra-clean conditions. If samples are preserved and returned to off-continent laboratories there is still a need for clean sample processing environments.

Retrieval of sediment cores through the lake water column can cause disturbances such as suspension of sediments not otherwise low particulate lake water columns and in these low energy environments these re-suspended sediments may persist for long periods of time altering water column properties. As most corer devices cause some type of disturbance on pull-out but devices such as piston corers can minimize these effect.

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Slide 40- *In Situ* Sensing

An increasingly viable technology is the deployment of various sensors. These sensors can sense a range of environmental variables both chemical and biological depending on the scientific questions be addressed. An advantage of sensors is collection of real-time time data and in many cases time series of data can be provided. Sensors can also be deployed in a wide variety of ways including sensor strings, as part of probes, and on semi-autonomous or autonomous vehicles or observatories.

Advantages to sensor deployment are the possibility of long-term deployments to define temporal variability in environmental properties and if the sensors are on vehicles that are mobile spatial variability can be addressed as well. The challenges are that sensors and sensor packages or strings must be deployment through narrow bore ice holes, they need a source of power, and if they generate large data streams onboard storage or real-time transmission of data streams through ice or up a tether is necessary.

The potential for what sensors might measure is nearly limitless, current technologies are generally restricted to basic chemical properties such as temperature, salinity, pressure, pH, dissolved oxygen, and others; biological properties such as fluorescence, cell counts, and possibly DNA; and proxies for various biogeochemical processes such as major ions, nutrients, and dissolved gases. In general the range of sensors available for water for exceeds those available for sensing sediment properties which is often technologically challenging,

The deployments of sensors and observatories have their own set of associated environmental issues. For example, environmental concerns include possible contamination associated with power supplies, for example batteries, and some sensors use chemical reagents that may be deleterious to environment. Finally, loss of sensors due to accidents and dispensable sensors or observatories that are not intended to be retrieved by design are abandoned at the study site.

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Slide 41 - In situ Sensors

Given the range of sensors that can be imagined for subglacial exploration, there is also a technological challenge to bundle sensors together for ease of deployment while miniaturizing and ensuring one sensor's operation does not interfere with or compromise the functionality of other sensors. One approach that has great potential is to adapt sensor platforms already in development for the exploring the world's oceans. An example is presented funded by the U.K. National Environment Research Council the" DEveLopment and Validation of chemical sensors for icy Ecosystems" (DELVE) project. DELVE aims to adapt chemical sensors for application in icy ecosystems. Wet chemistry analysers such as the nitrate analyser shown here are good candidates for adaptation. These sensors are miniaturized Lab-on-Chip versions of bench top chemical laboratory instruments. In this case the Lab-on-Chip Nitrate Sensor is a complex lab-based chemical analysis process that has been miniaturized and automated. The Lab-on-a chip uses a small sample size, low reagent usage, faster results at reduced cost, and these chips can be mass produced

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Slide 42 – Probes and Observatories

Being able to better capture the temporal and spatial complexity of processes in subglacial requires the development of new probes and observatories. The current time is an exciting one and the last 5 years has witnessed significant investment by national programs in technology development for subglacial science. These include the down-borehole remotely operable probes such as the "Micro-submersible Lake Exploration Device (MSLED)" funded by the NASA Jet Propulsion Laboratory and the National Science Foundation in the United States to autonomous devices such as Environmentally Non-Disturbing Under-ice Robotic Antarctic Explorer – ENDURANCE and "Very-deep Autonomous Laser-powered Kilowatt-class Yo-yoing Robotic Ice Explorer" (VALKYRIE) also funded by NASA in the United States, and Cryo-Egg funded by U.K.NERC and IceMole being developed at the Aachen University of Applied Sciences in Germany. Some of these programs are motivated also by National Space Programs and the search for life on other icy planets, VALKYRIE is developing technologies to drill into the sub-ice oceans of Europa.

The MSLED device is the only technology of its kind to be deployed in a subglacial lake to date, and was used in Lake Whillans earlier this year to image the lake bed and to provide data that later helped inform the deployment of the water sampling probe. The device transmits real-time data via fiber-optic cables. Plans are underway to make it semi-autonomous and ultimately, autonomous.

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Slide 43 - Autonomous vehicles

This slide shows two autonomous vehicles under development in the UK - Cryo-Egg) and the US - VALKYRIE. The former relies on passive transport beneath the ice, collecting data and transmitting them back to the ice surface wirelessly. The latter is a laser powered melting probe.

The Stone Aerospace VALKYRIE project is a laser-powered melter for Europa and subglacial exploration. Funded by NASA "cryobot" is slated for a future landing by NASA on Europa. A very thin fiber optic cable delivers the power, and can also be used for communications. It will have autonomous navigation, through-ice obstacle avoidance capability and suite of sensors to detect the presence of life. It will undergo field tests on the Matanuska Glacier (Alaska) and on the Greenland ice sheet in 2014 with later deployment in Antarctica.

Cryo-Egg is a NERC funded programme, which aims to develop mini egg-like wireless sensor platforms for ice sheets. Cryo-eggs are autonomous, move freely beneath the ice in water features and transmit data from to the ice surface through water/sediment and ice. The long term goal is to integrate chemical sensors into this package, to create subglacial observatories. They are currently being tested in Greenland.

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Slide 44 - 6. Summary

Current sampling missions are centered on sample collection and return but future investigations will rely much more heavily on sensors, probes and observatories. These technologies require development and have their own special set of environmental issues related to abandonment of instruments, chemical reagent usage and others issues.

There is great potential for adapting technologies from other fields of science to subglacial lake exploration and subglacial exploration programs should investment in technology development as well.

Future studies should build on the successes and knowledge of predecessor programs and mutual benefits will accrue by increased data and geographical coverage, beginning to establish baselines and tine series data collections, and integrating results across the diverse subglacial environments.

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Slide 43 - 6. Summary (Cont.)

Exploration of subglacial Aquatic environment exploration has greatly benefitted from international cooperation and coordination and this is a hallmark that will continue into the future.

These programs have also been interdisciplinary in scope and this will be essential for realizing the ambitious scientific goals of subglacial exploration.

There is great synergy in coordinated continent-wide approach to subglacial environment exploration and entry, sampling, and observing multiple study sites over a number of years will be required to fully realize the potential of this science frontier.

The Scientific Committee on Antarctic Research (SCAR) has an important role to play in facilitating international partnerships, verifying best practice and conduct, and providing sound scientific advice to support the ATS and the CEP.

From the earliest discussions and planning for subglacial exploration programs environmental stewardship and “Do no harm” have been guiding principles and this will continue into the future The Antarctic Treaty Parties (ATPs) and the Committee on Environmental Protection (CEP)have important oversight roles to ensure that the highest environmental standards and best practice are adopted by future subglacial exploration programs.

NEXT SLIDE PLEASE

Slide 45 – Thanks to:

As you can imagine, the work presented today is many years of work by a large community of subglacial aquatic environment explorers and we especially thank them for sharing their insights, presentations and knowledge. This has allowed us to present the very latest developments related to their exciting work! It is deeply appreciated!

NEXT SLIDE PLEASE

Slide 52 - THANK YOU FOR YOU ATTENTION AND ARE THERE ANY: QUESTIONS??