Submitted to EOS, 6 November 2003

Subglacial Antarctic Lake Environments: International Planning for Exploration and Research

While subglacial lakes have been suspected, and speculated about, for more than fifty years, recent re-analysis and collection of new data has resulted in the discovery that subglacial aquatic environments are relatively common under the vast Antarctic Ice Sheet. Airborne radar surveys have now documented more than 100 subglacial lakes with the larges being Lake Vostok. Public and scientific interest has been generated by the possibility that these environments harbor life in conditions not previously studied on our planet. These discoveries have focused international attention on the challenges presented by the way science is conducted in such unique and inhospitable settings within the context of environmental stewardship. Exploration of subglacial environments requires careful and detailed planning, organization and international cooperation. Significant progress in planning subglacial lake environment exploration and research has been accomplished by the Subglacial Lake Exploration Group of Specialists (SALEGOS). SALEGOS was established by the Scientific Committee on Antarctic Research (SCAR) in 2000. The exploration and study of subglacial environments can serve as an example of how interdisciplinary and international science can be brought together to explore the last unexplored frontiers of our planet within a framework of environmental consciousness and protection.

Subglacial lake exploration has occurred in three stages: discovery and serendipity (1955-1984), deliberation and assessment (1994-2001), and action (2001 to present). In the mid-1950's it was suggested that liquid water can exist beneath an ice sheet once the overlying ice burden exceeds the thickness that is needed to create the appropriate temperature and pressure regimes for liquid water. While recognized as a novelty, interest in the lakes was minimal for many years. Attention was again brought to these environments in the early 1990's when compelling re-interpetations of old survey data clearly inferred the existence of a very large lake, Lake Vostok (Figure 1). A re-examination of airborne radar and seismic data, as well as the acquisition of new ice surface altimetry, soon made it clear that Lake Vostok was only one of many lakes under the East Antarctic Ice Sheet (Figure 2).

A period of deliberation and assessment then followed. Several key workshops were held to summarize what was known about subglacial lake environments and to judge whether there was sufficient scientific justification to commit the needed resources for their exploration. Data indicating that Lake Vostok harbors a viable microbial assemblage was presented during a 1999 workshop on subglacial lake exploration (SCAR, 2001). These data stimulated public and scientific interest in subglacial lakes and showed that the scientific knowledge and educational potential of a major subglacial lake environment exploration was significant, and that a research program was warranted.

The 1999 Workshop (SCAR, 2001) developed a draft science plan for subglacial lake exploration, including consideration of the technological challenges. The workshop report established scientific goals for an exploration program, assessed the exploration technologies needed to attain the goals, suggested the stages required for a phased-in exploration program, established guiding principles for subglacial lake exploration, and produced a set of recommendations to facilitate further planning. One outcome of the workshop was the formation of SALEGOS by SCAR to serve as a focal point for organizing and encouraging international planning for a subglacial lake environment exploration program (Table 1).

To understand the complex interplay of biological, geological, chemical, glaciological, and physical processes within subglacial environments an international, interdisciplinary plan for coordinated research and study is essential. The overarching scientific objectives that will guide subglacial environment exploration and research are:

- To understand the formation and evolution of subglacial lake processes and environments;

- To determine the origins, evolution and maintenance of life in subglacial lake environments;

- To understand the limnological record and paleoclimatic history of subglacial lake sediments;

- To determine the form, distribution, and functioning of biological, chemical and physical systems in subglacial environments including the sediments, the water, and the overlying ice; and

These objectives can only be accomplished by integrated and coordinated phases of discovery and hypotheses driven research over at least a ten-year period. The scientific objectives will be addressed through a series of projects which form a comprehensive research program for the exploration of subglacial lake environments. Each research project will be defined by its own scientific objectives and requirements for logistics and technology. Together the portfolio of projects will advance the overall program. The timing of individual projects, while inter-related, will be ultimately determined by the resources and technologies available and the priorities of individual national Antarctic programs. The projects will not necessarily be sequential and several may be pursued in parallel. Below are scientific objectives for the various disciplines involved:

Functional Genomics and Phylogenetics

- Search for extinct and extant life signatures in the overlying ice sheet to determine the possible origins of biotic constituents to the underlying lakes.
- Determine the genetic and functional diversity in the water columns and benthic sediments of the lakes.
- Search for novel organisms that may exist in the lake environments.

Limnology

- Determine biogeochemical processes and their rates in the water columns of the lakes and compare to genomic data.

- Measure vertical density gradients and use these to model vertical and horizontal water motion.
- Examine the geochemical and isotopic composition of selected lake water constituents to determine their role in biological processes, water column stability, and geological age of the lakes.
- Compute the hydrological budget and hydrological linkages of subglacial lakes.

Geophysics

- Identify and measure subglacial lake surfaces using radio echo sounding.
- Determine the bathymetry of subglacial lakes and sediment thickness from seismic measurements.
- Comprehend the tectonic and ice sheet setting of subglacial lakes through geological analysis of geophysical data.

Glaciology

- Measure the flow of ice over subglacial lakes through direct surface measurements and satellite data.
- Understand the interrelation between ice sheet processes and lake water circulation.
- Identify the formation and evolution of subglacial lakes using numerical models of ice sheet history.

Geology and Cenozoic Paleoclimate

- Understand the origin, transport and deposition of subglacial lake sediment and relate surface sediment in each lake sub-environment to extant processes.
- Use paleoenvironmental data to determine lake and ice sheet histories, and

evaluate temporal changes in Cenozoic paleoclimate relative to those histories determined from Antarctic marginal sequences and global Cenozoic proxy records.

- Examine sediment mineral composition and chemistry, and sample geological bedrock to establish the basinal tectonic setting and its temporal evolution.

The ambitious plan for subglacial lake environment exploration and research will require substantial human and logistical resources over a sustained period of many years. The proposed program time line (Table 2) is driven in large degree by the types of sampling methodologies needed and the types of samples required to conduct the experiments of interest. The most readily available technologies are remote sensing techniques that are already being used in on-going studies. More challenging objectives require lake entry and the most challenging objectives require sample retrieval.

The deployment of *in situ* observatories is seen as an important step in subglacial exploration that it is relatively tractable given current technology. Observatories will be essential to gathering a time series of basic physical and chemical measurements that can be used to plan the more complex program involving sample retrieval. The first generation of observatories are envisioned either as a static or vertically mobile string deployed in selected locations of each lake basin. These observatories would return time-series data on such parameters as temperature, conductivity, redox, and selected gas concentrations. Such data will allow circulation models to be refined and provide important information on redox couples that could potentially support life. Spatial and temporal gradients of bioreactive chemical species may also lend the first clues of what organisms live in subglacial environments. These data are essential for constraining risk and planning for sample return programs. Sample return would focus to a large degree on the identity and diversity of life forms in the lake, *in situ* growth and metabolic rates, the presence of unique biochemical and/or physiological processes, and the evolutionary history of subglacial environments through analysis of their sediment record.

One of the more important issues facing the development of a subglacial lake exploration program is stewardship of the environment. Critical testing, verification and monitoring for potential contamination during all phases of the scientific program will be necessary. This will require a deliberate and careful scrutiny of all of the methodologies employed, from ice drilling to sample recovery, both from an environmental and scientific standpoint. Contamination may arise not only from the possible introduction of chemicals (toxic, nutritive, or otherwise) into the lake but also from the potential for the introduction of non-indigenous microorganisms. Redistribution of water and sediments within the lakes must also be minimized during any *in situ* operations. It is clear that lessons can be learned form the experiences of planetary protection during space exploration that can be adapted to the challenges of subglacial exploration. Analogies drawn between the list of environmental issues encountered by both projects include: cleanliness of equipment and sampling arrays; transfer of material during operations such as the introduction of drilling fluids or microbes into the lake during drilling; the need for monitoring of operations to ensure compliance and quality in all phases of the program; clear guidelines on the decision path and responsibilities when difficulties are encountered; and contingency planning for unforeseen events or developments. Important considerations during planning include: attempts to better understand perceptions of risk; development of a risk communication plan; plans to deal with potential lawsuits and liability issues; and programs for public education and engagement in the project. Complete documentation of and transparency in the decision making process is also essential since the project is certain to attract both scientific and public debate. It is also clear that in projects at the frontiers of knowledge and technology there is uncertainty in the process and unforeseen events will likely occur. It is expected that the project will be highly scrutinized, possibly challenged and perhaps even opposed. Planning must be flexible and allow for incremental decision-making as our understanding of science and the project develops over a period of many years.

The aims and objectives of subglacial studies can only be accomplished by an integrated series of interlocking phases of discovery and exploration. It is envisioned that the program will take at least ten-years to accomplish and will require a period of sustained international coordination of the best scientists and technologists available. While the commitment to such an ambitious program of exploration and research is major, the potential pay-off in scientific and educational returns is immense.

References

Dowdeswell, J.A. and M.J. Siegert. 2002. The physiography of modern Antarctic subglacial lakes. *Global and Planetary Change* 35: 221-236.

Popov, S.V., V.N. Masolov, V.V. Lukin and A.N. Sheremetiev. 2002. Central part of East Antarctica: Bedrock topography and subglacial lakes. *Scientific Conference: Investigation and environmental protection of Antarctica* (Abstract). St. Petersburg. AARI, 84-85.

SCAR 2001. *Subglacial lake exploration: workshop report and recommendations*, Cambridge, England, September 1999.

Siegert, M.J., J.A. Dowdeswell, M.R. Gorman and N.F. McIntyre. 1996. An inventory of Antarctic subglacial lakes. *Antarctic Science* 8:281-286.

Studinger, M., R.E. Bell, G.D. Karner, A.A. Tikku, J.W. Holt, D.L. Morse, T.G. Richter, S.D. Kempf, M.E. Peters, D.D. Blankenship, R.E. Sweeney, and V.L. 2003. Rystrom, Ice Cover, Landscape Setting, and Geological Framework of Lake Vostok, East Antarctica, *Earth Planet. Sci. Lett*., 205 (3-4), 195-210.

Tabacco I.E. A. Forieri, A. Della Vedova, A. Zirizzotti, C. Bianchi, P. De Michelis, A. Passerini . 2003. Evidence of 14 new subglacial lakes in DomeC-Vostok area. *Terra Antartica Reports* 8, 2003: 175-179.

Author Information

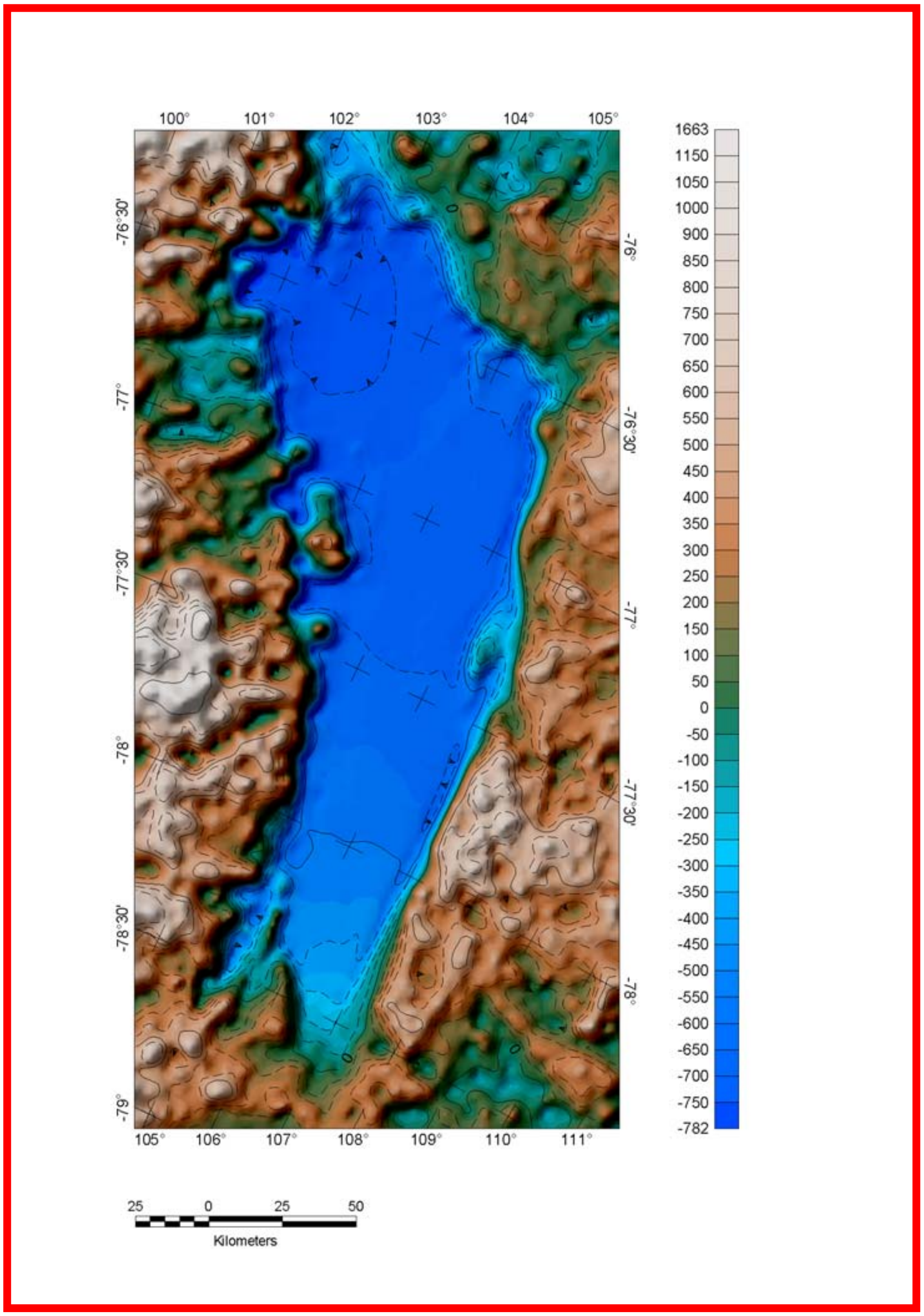
J. C. PRISCU, Department of Land Resources & Environmental Sciences, Montana State University, Bozeman, Montana, USA, jpriscu@montana.edu; M.C. KENNICUTT II, Geochemical and Environmental Research Group, Texas A&M University, College Station, Texas, USA, mck2@gerg.tamu.edu; R. E. BELL, Lamont-Doherty Earth Observatory, Palisades, New York, USA, robinb@ldeo.columbia.edu; S. A. BULAT, Division Molecular & Radiation Biophysic, Petersburg Nuclear Physics Institute, Russia, bulat@omrb.pnpi.spb.ru; J. C. ELLIS-EVANS, British Antarctic Survey, Cambridge, UK, jcel@bas.ac.uk; V. V. LUKIN, Arctic and Antarctic Research Institute, St. Petersburg, Russia, lukin@raexp.spb.su; J-R PETIT, LGGE-NCRS BP96, Cedex, France, petit@glacog.ujf-grenoble.fr; R. D. POWELL, Department of Geology, Environmental Geosciences, Northern Illinois University, DeKalb, Illinois, USA, ross@geol.niu.edu; M. J. SIEGERT, Bristol Glaciology Center, School of Geographical Sciences, University of Bristol, Bristol, UK, m.j.siegert@bristol.ac.uk; I. TABACCO, DST-Geofica, Via Cicoconara 7, 20129 Milano, Italy, ignazio.tabacco@unimi.it

Figure Captions

Figure 1. Subglacial Elevation in Lake Vostok Region from Studinger et al. (2003) illustrating rugged topography to west of the subglacial lake and smoother topography to the east. Blue delineates the approximate shoreline of the Lake.

Figure 2. Locations of Antarctic subglacial lakes. Lake discovered by Italian (blue triangles), Russian (red down white triangles) and UK-US-Danish (yellow triangles) teams are included (Lake Vostok is shown in outline). The ice-sheet surface is contoured at 500 m intervals. Compiled from Siegert et al. (1996), Dowdeswell and Siegert (2002), Popov et al. (2003) and Tabacco et al. (2003).

Figure 1



100° 101° 102° 103° 104° 105°
-76°30' -77° -77°30' -78° -78°30' -79°
-76° -76°30' -77° -77°30' -78°
105° 106° 107° 108° 109° 110° 111°
1663 1150 1050 1000 900 850 800 750 700 650 600 550 500 450 400 350 300 250 200 150 100 50 0 -50 -100 -150 -200 -250 -300 -350 -400 -450 -500 -550 -600 -650 -700 -750 -782
25 0 25 50
Kilometers

Figure 2

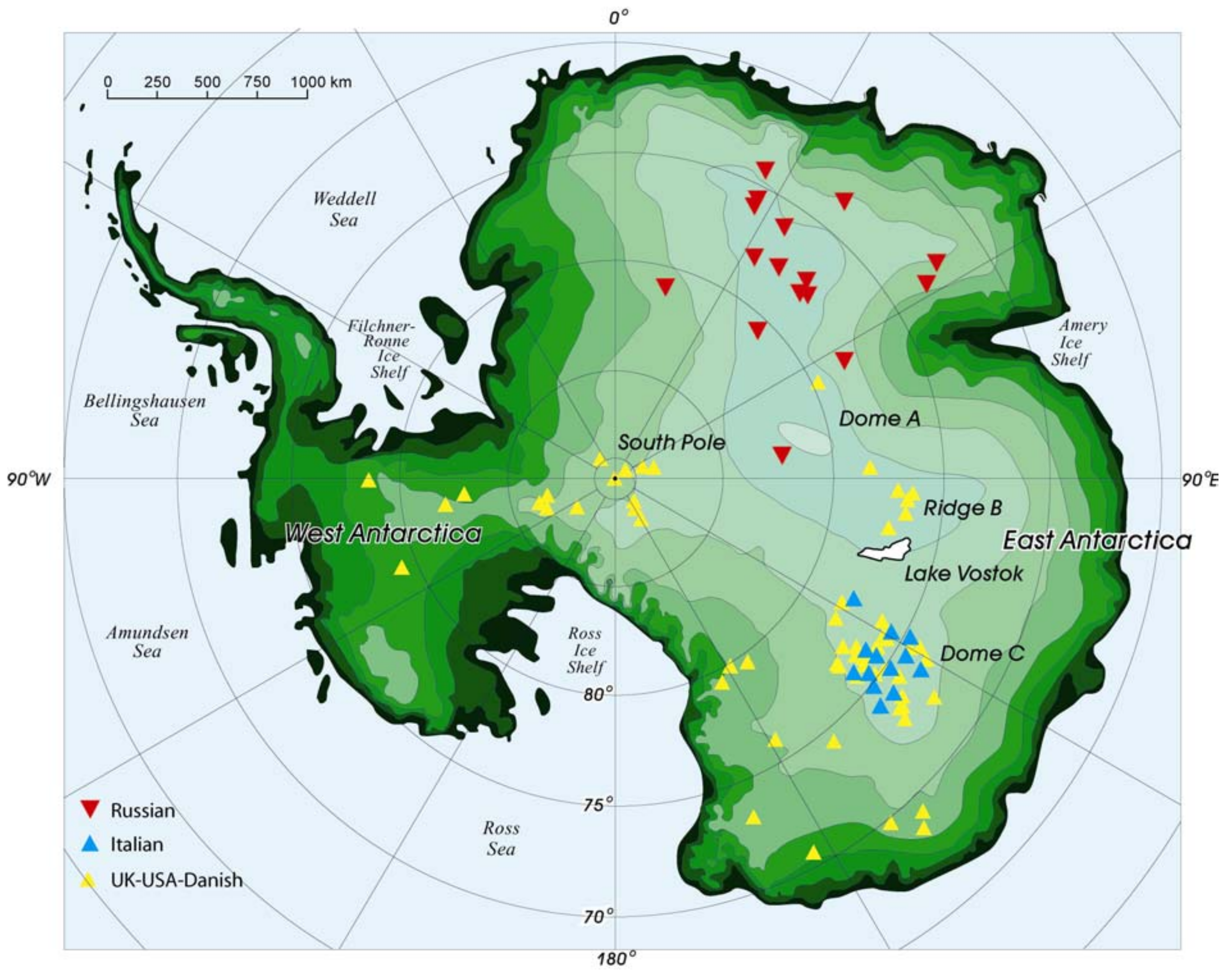

0°
0
250
500
750
1000 km
Weddell Sea
Filchner-Ronne Ice Shelf
Amery Ice Shelf
Bellingshausen Sea
Dome A
South Pole
90°W
90°E
Ridge B
West Antarctica
East Antarctica
Lake Vostok
Amundsen Sea
Dome C
Ross Ice Shelf
80°
75°
Ross Sea
70°
180°
Russian
Italian
UK-USA-Danish

Table 1. Interdisciplinary and international membership in the SCAR Subglacial Antarctic Lake Exploration Group of Specialists (SALEGOS). Website: http://salegos-scar.montana.edu/

J. C. Priscu, USA, Convener (limnology)	M.C. Kennicutt, USA, Secretary (geochemistry)
R. Bell, USA (geology)	J.R. Petit, France (glaciology)
S. Bulat, Russia (molecular biology)	R. Powell, USA (sedimentology)
J.C. Ellis-Evans, UK (limnology)	M. Siegert, UK (glaciology)
V. Lukin, Russia (glaciology)	I. Tabacco, Italy (glaciology)

Table 2. SALEGOS assessment of the timing of subglacial lake exploration and key technological milestones. Note that the environmental requirements increase in complexity as the activities increase in complexity.

---

1. Short (0-3 years)

- *Existing technologies, modeling and other non-field related activities*

2. Medium (3-6 years)

- *Lake entry and observatory(s) deployment*

3. Long (6-9 years)

- *Water/shallow sediment retrieval*

4. Very long (9+ years)

- *Sediment deep coring*