# Future Directions in Subglacial Environments Research

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Subglacial Antarctic Lake Environments (SALE) exploration and study is poised to be a major focus of Antarctic science for the next decade or more. The foundation for an intensive period of SALE research and field efforts has been provided by substantial improvement in our understanding of these environments, the establishment of SALE research programs by the International Polar Year (IPY) Program Office and the Scientific Committee on Antarctic Research (SCAR), the funding of several national SALE programs, independent guidance on environmental stewardship issues, and a series of international workshops, meetings, and conferences that have refined SALE scientific objectives. This article summarizes recent developments in subglacial environment exploration and study and describes future research needs.

### *The Fundamentals of SALE Science*

In the 7 years since the report "Subglacial Lake Exploration: Workshop and Recommendations" (SCAR International Workshop, Cambridge, U.K., September 1999), our understanding of subglacial environments has greatly improved. Subglacial environments are continental-scale phenomena that occur under thick ice sheets [*Siegert et al.*, 2005]. The importance and role of subglacial water are now recognized as central to many processes that have shaped the Antarctic continent and its ice sheets today and in the past. Subglacial environments include a range of features that differ in geologic setting, age, evolutionary history, limnological conditions, and size [*Bell,* 2006]. These environments are 'natural' Earth-bound macrocosms that in some instances trace their origins to a time before Antarctica became encased in ice [*Bell,* 2006].

Subglacial environments are isolated from the weather, the seasons, and celestially controlled climatic changes that establish fundamental constraints on the structure and functioning of most other Earth-bound environments. In contrast to these other habitats, where solar energy is a primary influence, processes in subglacial environments are mediated by the flow of the overlying ice, a glaciological boundary condition, and the flux of heat and possibly fluids from the underlying basin, a tectonic control. Recent findings suggest that a third control is subglacial hydrology, which establishes water residence time and enables the delivery of water, materials, and heat to and through subglacial systems.

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The spectrum of types of below-ice environments that occur across the Antarctic continent provides an unparalleled opportunity to explore and study one of Earth's last frontiers and decipher fundamental Earth and life processes. The exploration and study of subglacial environments will advance our understanding of how life, climate, and planetary history have combined to produce the Antarctic continent as we know it today.

### *Life Beneath the Ice*

A first-order question is whether microbial life is present in these environments. Subglacial environments may contain ancient ecosystems, and most evidence suggests that the absence of life would be more unexpected than its presence. Darkness and isolation limit the potential modes of primary production in subglacial environments. Because of a lack of direct inputs of solar energy, microbial metabolism in these systems would rely on metabolic energy and nutrition derived from glacial ice, the bedrock, and/or hydrothermal or geothermal inputs.

An influx of hydrothermal and/or geothermal heat and chemicals would have a profound impact on subglacial microbiology. Whether these environments are 'open' or 'closed' will also be critically important to their ability to sustain life, as carbon and energy may be limiting. For example, are there exchanges among lakes that deliver nutrients and 'microbial seed populations'? If so, on what time frames do these exchanges occur? 'Interconnectedness' will exert a fundamental influence on subglacial physical and chemical characteristics and the capacity of these environments to support life.

As with surface lakes, stability over time will be a determinant of the kinds of ecosystems that might be present. The size, location, and age of below-ice water accumulations are also critical determinants of the physical, chemical, and ecological characteristics of subglacial water and sediment columns. Models of lake water circulation; quantitative water, heat, and biochemical budgets; estimates of water age; and measurement of physicochemical distributions in water and sediments are needed to fully describe subglacial environments.

If life is detected, it will be important to determine the biomass, distribution, and diversity of organisms in subglacial water columns, sediments, and ice. The distribution of bioactive elements in these systems will also indicate whether microbiological communities are, or have been, present. The metabolic and physiological abilities of subglacial residents will lend clues to adaptive strategies for survival and persistence. To unambiguously determine the presence of life in these unique environments, protocols are needed to detect life in highly oligotrophic environments and to recover contaminant-and artifact-free samples. The retrieval and analysis of samples at in situ conditions also presents significant technological challenges.

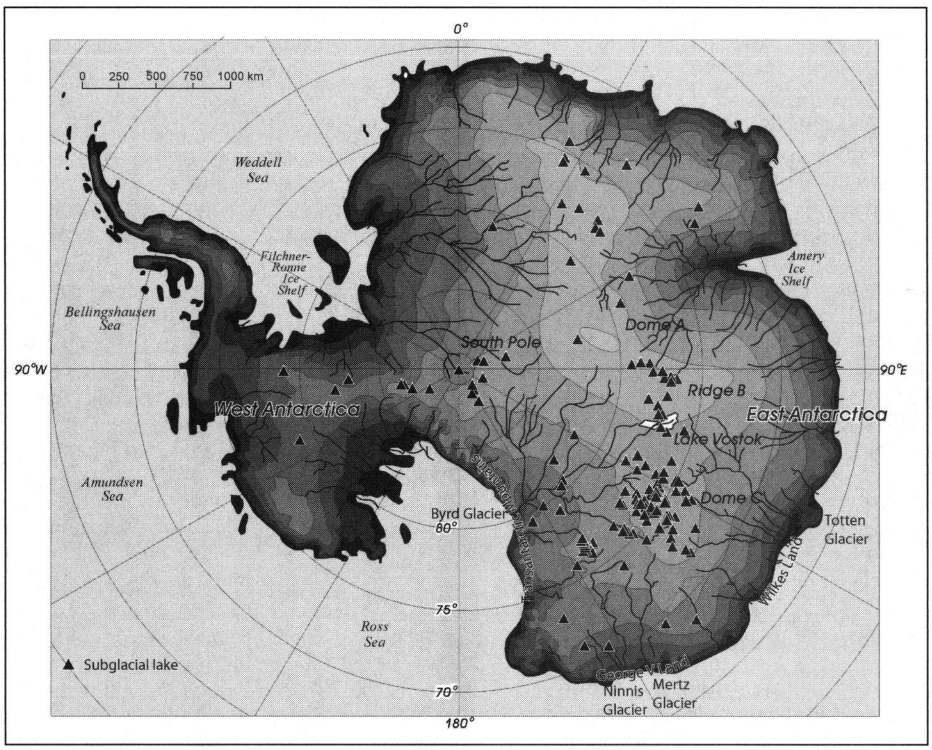


*Fig. 1. The location of 145 known Antarctic subglacial lakes, ice-sheet surface elevation, and large-scale flow paths of subglacial water. Ice surface contours are in 500-meter intervals [from* Siegert et al., 2007*].*

## *Sub-Ice Hydrology*

The distribution of subglacial lakes beneath ice sheets suggests that hydrologic processes play an important role at the basal interface of ice sheets [*Wingham et al.,* 2006; *Clarke,* 2006]. There is increasing evidence that these environments are connected by below-ice hydrologic systems, and recent observations suggest that subglacial lakes are linked to the onset of ice streams influencing the dynamics of overlying ice sheets [*Siegert and Bamber,* 2002; *Wingham et al.,* 2006] (Figure 1).

The geographic distribution of subglacial lakes is foremost determined by the availability of water and basins for it to collect in. It has been observed that subglacial lakes are usually located within 100 kilometers of ice divides. Other controls on the distribution of liquid, below-ice water include surface temperatures, accumulation rates, ice thickness, ice velocities, and hydrothermal/geothermal fluxes. An understanding of subglacial hydrology on a continental scale is needed to establish subglacial water distribution and the effects of subglacial water movements on the overlying ice sheet.

The connection between subglacial lakes and ice domes is poorly understood, and further studies are needed to explore the significance of this association. The spatial and temporal distribution of free water at the ice bed, rates of water and sediment transport through subglacial environments, and quantification of ice sheet interactions with subglacial water are needed to more fully and accurately describe these systems. Regional geophysical survey results can inform models of subglacial drainage and sedimentation over a range of temporal and spatial scales.

## *Records of the Past*

It has been speculated that the origins and evolution of subglacial environments are recorded in subglacial sedimentary sequences. Studies of lake sediments in nonglaciated continents have made significant contributions to understanding paleoenvironments. Subglacial lakes are also expected to contain sedimentary records of past changes and might be expected to shed light on the Cenozoic evolution of the Antarctic continent and the associated ice sheets. The continental geological record of Antarctica's paleoclimate and ice sheet history is currently being addressed by cores from the continent's edges. Few boreholes have accessed the records stored beneath Antarctica's ice sheets. Subglacial sediments would be expected to record a history of geological processes occurring at the base of ice sheets.

The sedimentary records may inform us about the thresholds for ice sheet initiation, the growth and decay rates of ice sheets, changes in ice sheet volumes over time, the nature of the preglacial to subglacial transition, and whether subglacial environments survive glacial/interglacial transitions. Subglacial sediments may also contain a record of how life has evolved in response to these events.

A complete and accurate interpretation of these unique geological records will require an understanding of the mechanisms that disrupt or destroy stratigraphic chronologies in these settings. Subglacial lake cessation events are expected to have profound effects on the expression of life in these environments. Chronological tools are needed to date subglacial lake records and estimate the age of subglacial water accumulations.

## *Sub-Ice Water as an Agent of Change*

Emerging evidence that Antarctic subglacial lakes catastrophically drain and that they are linked to the onset of ice streams suggests that these features are an integral part of the global cryosphere and climate system [*Lewis et al.,* 2006]. Outbursts of fresh water from Antarctic subglacial environments have been invoked as an agent of landscape change in the past, and there is speculation that these discharges influenced past climate. The linkage of subglacial lakes with the onset of rapid ice flow indicates that subglacial lakes and the associated hydrologic systems may be important factors in the drainage and collapse of ice sheets. Historical records in cores collected around the continental margins will retain a record of the spatial and temporal distribution of outburst deposits and can be used to map onshore and offshore landforms suggestive of erosion due to these flood events. Freshwater inputs and their impact on ocean circulation are also expected to be recorded in the sedimentary record. Oceanic sensitivity to subglacial hydrological processes can be tested using models to explore the importance of subglacial water in the global climate system.

## *The Way Forward*

Building on many years of discussions and meetings, the scientists and technologists assembled in Grenoble in 2006 laid out an ambitious and exciting plan to advance our understanding of subglacial environments. As the central role and importance of water beneath the massive Antarctic ice sheets have been recognized, the scope of SALE research has expanded to include basic questions across a range of scientific disciplines. If the advances of the past few years are an indication of the discoveries and knowledge to come, the study and exploration of subglacial environments hold great promise for furthering our understanding of our planet's fifth-largest continent and its ice sheets, their evolution over geologic time, and how these global forces have influenced the expression of life on Earth, and for lending clues to the presence of life elsewhere in our solar system.

## *Acknowledgments*

At an international gathering in Grenoble, France, in April 2006, participants presented their latest scientific findings about subglacial Antarctic lake environments (see http://salepo.tamu.edu/saleworkshop2006). The group expanded plans for future SALE exploration and study, concluding that a continent-wide campaign at multiple locations, to (1) systematically map subglacial lake systems and their environs and (2) enter, instrument, and sample ice, water, sediments, and potential microbiological residents, was essential to accomplish the interdisciplinary goals of SALE. SALE scientific objectives address fundamental questions about the geodynamics of lake evolution; subglacial hydrology; ice sheet dynamics; microbiological life, evolution, and adaptation; limnology and biogeochemistry; paleoclimate; and global climate connections. The authors wish to recognize the workshop International and Local Steering Committee and the 84 workshop attendees. Financial support for the workshop was provided by the U.S. National Science Foundation Office of Polar Programs, the Scientific Committee on Antarctic Research (SCAR), and the Centre National de la Recherche Scientifique (CNRS).

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