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Subglacial Antarctic Lake Environments (SALE) in the International Polar Year 2007-2008

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Introduction

1. In the seven years since the Cambridge workshop there have been major advances in our understanding of subglacial environments. While public attention focuses on possible unique forms of life in these environments, it is now clear that subglacial environments are important continental-scale phenomena. Subglacial environments are a wide spread phenomena under thick ice sheets and include a spectrum of geologic settings, ages, evolutions, and limnological conditions. There appear to be interconnected systems that serve as hydrological conduits for water transport at various spatial and temporal scales. Evidence suggests that subglacial lakes may be linked to the onset of ice streams influencing the dynamics of overlying ice sheets. In the past, outbursts of fresh water from subglacial environments may have been an important geomorphic agent of landscape change. There is also speculation that these freshwater discharges influenced past global climate.

2. Subglacial environments are "natural" earth-bound macrocosms. In some instances these environments trace their origins to more than 35 million years before present when Antarctica became encased in ice. As opposed to other habitats on Earth, where solar energy is a primary influence, processes in subglacial environments are mediated by the flow of the overlying ice – a glacial boundary condition and the flux of heat and possibly fluids from the underlying basin – a tectonic control. Recent findings suggest that a third control on these environments is subglacial hydrology, which will influence water residence time and the delivery of water, materials, and heat to and through subglacial systems. Owing to the lack of solar energy, any microbiological metabolism in these systems must rely on energy and nutrition derived from glacial ice, the bedrock, and/or hyrdo- and geothermal sources. For millions of years, many Antarctic subglacial environments have been insulated from weather, the seasons, and celestially controlled climatic changes that establish fundamental constraints on the structure and functioning of most other ecosystems. Subglacial environments provide an opportunity to advance understanding of how life, the environment, climate, and planetary history combine to produce the world as we know it today.

The science of SALE

3. This IP summarizes the discussions, recommendations and conclusions of an international community of scientists and technologists with interest and expertise in subglacial Antarctic lake environments research and exploration.

4. **Geodynamics of Lake Evolution -** Subglacial lake environments rest at the intersection of continental ice sheets and the underlying lithosphere. The distribution of subglacial lakes is determined by the distribution of water and the availability of basins to collect water. While surface water distributions are closely linked to climate cycles, the distribution of water in subglacial environments is related to surface temperature, accumulation rates, ice thickness, ice velocities, and geothermal flux. The vast majority of subglacial lakes identified to date are within 100 km of an ice divide and are less than 20 km in length. The volume of water in known Antarctic subglacial lakes is approximately 25% of the water in world-wide surface lakes. Important scientific questions related to the geodynamics of lake evolution are:

- What role does lithospheric structure play in the origin and evolution of subglacial lakes?
- What role do lithospheric processes play in determining the temporal and spatial stability of subglacial environments?
- Does the geographic distribution of subglacial lakes of differing origins follow trends observed in surface lakes?
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- How do lithospheric processes affect or alter the physical, chemical and biological character of subglacial environments?
- Do subglacial lake processes modify landscapes and how important is this process in the evolution of Earth's surface?

5. To address these questions the lithosphere structure and morphology of Antarctica must be assessed with geophysical surveys at regional and continental scales. Space borne observations must be integrated with field measurements and the bed rock sampled. I*n situ* and remote lithosphere heat flux measurements must be made. A continent-wide campaign to systematically define large-scale subglacial lake systems with targeted regional scale geophysical experiments addressing lake processes is needed. Studies of the geodynamics of subglacial lake environments will improve our understanding of lithospheric controls on ice sheet stability, Antarctic geology and the role of subglacial lake outburst floods in reshaping the earth's surface.

6. **Subglacial Hydrology -** The distribution and setting of subglacial lakes beneath ice sheets suggests that hydrologic processes play an important role at the basal interface of ice sheets. The interconnectedness of these environments exert a fundamental influence on subglacial physical, chemical, and ecological environments; the degree of isolation; and the evolution and maintenance of life. Important scientific questions related to the subglacial hydrology are:

- How does subglacial hydrology influence the distribution and stability of subglacial environments?
- How does subglacial hydrology control or transform the physical, chemical and biological characteristics of subglacial habitats?
- Is interconnectedness a fundamental characteristic of subglacial environments and if so, how has this affected the origins and metabolic strategies of organisms living in these environments?
- What is the role of groundwater in subglacial systems?

7. To answer these questions subglacial hydrology must be studied at a continental-scale. Studies must include: (i) remote and field-based surveys; (ii) mapping and modeling of subglacial hydropotential; (iii) evaluation of former drainage events; (iv) mapping of subglacial water; (v) quantification of subglacial discharges; (vi) recovery of geologic records of past hydrologic events; and (vii) assessment of the impact of hydrological events on sediment distribution, landscape evolution, and biological evolution. These studies will improve our understanding of subglacial systems and their importance in a global context while discerning the implications for ice sheet stability and fast glacier flow. These studies will also inform reconstructions of the history of the Antarctic ice sheet and decipher the climate history of the Antarctic interior.

8. **Limnology and Biogeochemistry -** Currently little is know about *in situ* limnological conditions in subglacial envrionments. The size, location, and age of lakes will influence physical, chemical, and biological processes within the water column and sediments. Knowledge of the limnological processes operating within subglacial lakes will be essential to understand the presence and structure of microbiological communities. Important scientific questions relating to limnology and biogeochemistry are:

- Which subglacial environments exhibit internal circulation and how does this effect water and heat budgets, vertical stratification, biogeochemical gradients, and the conditions that support life?
- Do the spatial and temporal distributions of inorganic species, dissolved organic carbon, and other bioactive chemicals in subglacial environments indicate the presence of life?
- Are dissolved organic carbon (DOC) levels sufficient to support heterotrophic life and or is life based on chemolithoautotrophic production of new organic carbon?
- How do nutrients (e.g., carbon, nitrogen, phosphorus, sulfur and others) cycle in these environments?
- Are gas hydrates present, and if so, what gases are involved and do they support microhabitats for living microorganisms?
- What is the biogeochemical role of sediment in these environments and how do sediments affect limnological conditions?
- Do sediments contain a record of previous lake environments and a history of the evolution of life in the lakes?

9. These questions can be addressed with a combination of models, field observations, *in situ* experiments and monitoring, and laboratory measurements. It is critically important to know if these environments are "open" or "closed" systems, i.e., is there exchange among lakes within a certain geographical area and on what timeframes. To model circulation; construct water, heat, and biochemical budgets; and estimate the age of the water; the basin topography and salinity, temperature, density, and current distributions must be known. Biogeochemical studies also provide data about the presence of metabolic activity. The amount and distribution of bioactive elements in subglacial environments will indicate the presence of biological production and suggest how microorganisms meet metabolic needs. The spatial and temporal distribution of various elements in water columns and sediments lend clues to elemental cycles. Information on potentially toxic elements lend clues to the habitability of subglacial environments. Chemical profiles in sediments will establish if chemical gradients are present suggesting biological activity.

10. **Microbiological Life, Evolution and Adaptations -** The darkness and isolation of subglacial lakes, adds constraints on energy and resources that likely limit primary productivity more than in other habitats. If geothermal heat and chemicals are present they will have a profound importance on subglacial microbiology. Subglacial lakes are thought to be relatively stable environments that may contain ancient ecosystems. As with surface lakes, the stability of lakes over time will be a major determinant of the kind of ecosystems that are present. Important scientific questions related to microbiological life, evolution, and adaptations are:

- Is there microbial life in subglacial environments?
- What types of microbiota are present and what metabolic processes do they rely on to survive and propagate?
- What are the intra- and inter-lake microbial distributions (biomass) and how diverse is the microbial life?
- How long has microbial life in subglacial environments been isolated?
- Do subglacial environment micro-organisms express unique metabolic adaptations, especially adaptations to toxic environmental conditions such as high oxygen concentrations?
- Does subglacial microbiology exhibit the characteristics of a community and/or an ecosystem?
- Do syntrophic consortia exist among microorganisms within lakes?

11. The first order question is whether microbial life is present in these environments Protocols must be developed to detect life in very dilute environments. If life is unambiguously detected, it will then be important to establish the amount (biomass), distribution, and diversity of organisms in subglacial lake environments. This will require sampling of water columns, sediments, and ice. Retrieval and analysis of samples at *in situ* conditions will present special technological challenges. The metabolism and physiological capability of subglacial microorganisms will lend clues to special adaptive strategies for surviving in these harsh conditions. The study of life in subglacial environments will contribute new information on life at the edges of survivability, furthering our understanding of the diversity of life on Earth, its evolution, and its response to environmental processes over geological time.

12. **Ice Sheet Dynamics -** Subglacial reservoirs (lakes and ground water) and water fluxes between reservoirs impact ice sheet and ice stream dynamics, but the details are poorly understood. The connection between the location of subglacial lakes and ice domes is poorly understood and further study will test the association through empirical observations and models. Important scientific questions related to ice sheet dynamics are:

- What is the interplay between subglacial lakes and ice sheet dynamics?
- What is the role of ice domes and ice divides in subglacial systems?
- Do ice sheet dynamics exert fundamental controls on the location and stability of subglacial environments?
- How and why do pro-glacial lakes evolve into subglacial lakes under an expanding ice sheet?
- What is the interplay between climate, ice sheet development and history, and the origins, evolution, and microbiological inhabitants of subglacial lakes?

13. Important linkages between ice sheets and underlying subglacial environments will be assessed through: (i) observations of the surface manifestation of hydrologic processes; (ii) borehole observations of basal

water; and (iii) numerical modeling of ice sheet evolution. Hydrologic and thermodynamic controls can be tested by model simulations. The role of water circulation, the hydrologic cycle, ice dynamics, and sedimentation in paleoenvironments and paleoclimate will be addressed in a variety of ways. Studies will include: (i) identification of the spatial and temporal distribution of free water at the ice-bed; (ii) observation and modeling of the rates of water and sediment transport through subglacial environments; (iii) observation and modeling of ice sheet interactions with subglacial water, and (iv) modeling of the turnover time of subglacial lakes. Regional geophysical site survey data must be integrated to develop models of subglacial drainage and sedimentation at a variety of temporal and spatial scales. Critical components of predictive climate models need to be improved to account for subglacial interactions. Research on ice sheet dynamics will increase our understanding of subglacial hydrological systems on local, regional, and global scales; explore the relationship between ice sheet stability and fast glacier flow; and assist in reconstructing the development of the Antarctic ice sheet.

14. **Paleoclimate Records –** The key to understanding the origins and evolution of subglacial lake environments is likely to be recorded in subglacial sedimentary sequences. These lakes are thought to contain sedimentary records that document how they and life evolved through time, and possibly the only records of glacial and paleoclimatic Cenozoic history of the interior of Antarctica. Too little is known about ice sheet history to fully assess its role and significance in global Cenozoic climate. The history of the Antarctic interior is totally unknown for times beyond ice cores and it is these interior environments that may contain the key to understanding critical thresholds of ice sheet initiation, growth and decay rates, and volume change. Important scientific questions related to paleoclimate are:

- Do subglacial lakes contain decipherable records of past climate?
- Do subglacial sedimentary records fill gaps in the history of Antarctica's interior and the evolution of ice sheets?
- What biological, chemical, and geological proxies can be used to interpret the timing of paleoenvironmental and climatic change and their timing from sedimentary records in subglacial environments?
- What role has Antarctica's interior played in the glacial and paleoclimatic history of its margins and globally through the Cenozoic?
- What does the history of subglacial lakes tell us about the response of microbiological systems to climate change?
- What are the tell-tale signs of life's evolution in icy environments that would inform the search for life elsewhere in our solar system?

15. Proxies need to be identified that are indicators of subglacial sedimentation processes. Proper interpretation of the geological record requires an understanding of the mechanisms that disrupt or destroy stratigraphic chronologies. Methods need to be developed to estimate the maximum age of subglacial lakes. Chronological tools must be developed for dating subglacial lake records. The key to understanding the origins of subglacial lake environments may well be at the bottom of sedimentary sequences. The information recorded in cores is the best way to constrain the nature of the pre-glacial to subglacial transition. If subglacial lakes persist during glacial/interglacial transitions, subglacial lacustrine and hiatus-free deposition may have occurred over several million or even tens of millions of years. If subglacial lakes are unstable they may cease to exist for a period of time and such cessation events should leave distinct sedimentary. Recognizing subglacial lake cessation events is important because these events affect how life is expressed over time. If substantial sedimentary records can be recovered and decoded, paleoclimate records will an invaluable aid in reconstructing the development of the Antarctic ice sheet and the paleoenvironmental history of the Antarctic interior.

16. **Global Climate Connections** – Emerging evidence that Antarctic subglacial lakes can 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. The linkage of subglacial lakes with the onset of rapid ice flow indicates that subglacial lakes and the associated hydrologic systems may be an important factor in the drainage and collapse of ice sheets. Important scientific questions related to global climate are:

- What is the impact of subglacial water on Southern Ocean circulation?
- What is the impact of subglacial water on deep-water formation?

- What is the impact of subglacial melt water floods on continental shelf sedimentation and marine biological productivity?

17. These questions will be addressed by deciphering the historical record in cores collected around the continental margins to assess the spatial and temporal distribution of outburst deposits. These events would then be linked to onshore and offshore landforms suggestive of erosion due to outburst floods. Sedimentary records will be used to estimate freshwater inputs and their impact on ocean circulation. Oceanic sensitivity to subglacial hydrological processes such as dramatic outbursts floods as well as steady state fluxes across grounding zones will be tested using models. In addition, the response of subglacial lakes to changes in ice thickness and vice versa will be modeled. Of particular interest is the threshold conditions required to drive these changes. The recovery of terrestrial, marine, and oceanographic records of outburst floods is a key need. Further definition of the role of subglacial water in global climate will improve our understanding of how these processes affect the global cryosphere and climate system. The importance of freshwater outbursts and their effect on Southern Ocean circulation, deep-water formation, shelf sedimentation, and biological productivity will be clarified.

Technological Challenges

18. The study of subglacial environments requires a diverse set of technologies that include: (i) entry, (ii) observatories, (iii) sample collection and return, and (iv) methodologies tailored to the environmental conditions of subglacial environments. An essential element for accomplishing the science objectives is the establishment of protocols for environmental stewardship and standards for minimizing the contamination of these unique environments. These protocols must be applicable to the wide range of scientific investigations outlined above. Environmental are tw –fold: (i) protecting these environments by minimizing alterations and (ii) retrieving uncompromised samples for scientifc investigations. Given the potentially low biomass and dilute chemistries expected in these environments, both aspects will pose challenges for current technologies.

19. Once standards are agreed on, the main phase of subglacial access and sampling can begin in earnest. The scope of the research agenda will require the study of mutiple sites across the Antarctic continent. The range of subglacial lake environments, provides added power to experimental designs that can now be formulated to test hypothesis across sites that have experienced differing histories and environmental conditions. The adoption of a muti-site exploration framework entails a number of additonal requirements for subnglacial environment exploration and study. Access drilling and sampling technologies must be developed that can arrive on site, rapidly access the lake, retrieve and process artifact-free samples, and depart for the next location in a timely manner. The establishment of inter-laboratory methodological comparisions is needed to facilitate data comparisons and integration across multiple laboratories. Agreed decontamination protocols for all devices and observatories should be developed. Protocols for aseptic sample handling in the field and in laboratory studies should be agreed on. Technologies for fast, clean access to large volumes of water and sediment samples must be developed. There is also the need for a central archive to maintain the integrity of samples for future investigations and provide for wide dissemination.

21. Advancement in the our understanding of the distribution origin, stability and physical, chemcial, and biological dynamics of subglacial environments will require the systematic integration of existing data from surface experiments, airborne campaigns and satellite sensors. The development and deployment of programs that focus on the full range of subglacial environments that consider the potential for lake environments to change over time. Numerical models must be integrated with empirical data to address impotant questions concerning the origins and evolution of subglaial envrionments. Models must be integrated with analyses of global climate, sea level change, ice sheet stability, and hydrologic and chemical cycles. To better understand subglacial environments as hydrological systems a methodical inventory and characterization of sub-ice watersheds and regional geomorphology is needed.

A Vision for the Future

22. We stand at the beginning of what may be the next major focus of Antarctic Science for the next decade or more. The ultimate outcomes from a fully implemented subglacial envrionment research and explaration program have the potential to be far reaching producing major advances in our understanding of Antarctica and its role in the Earth system. Scientific objectives include developing a better understanding of the geological evolution of the planet's 5th largest continent through surveys, measurements and advanced modeling. Understanding of subglacial environment evolution will provide a holistic view of the fundamental forces that have shaped Antarctic over the millenia. Subglacial sedimentary records will provide unique information about Antarctic paleoclimate, ice sheet history and stability, and the evolution of the interior of the Antarctic continent. The next generation of coupled ice sheet models will incorporate subglacial environments as an important element of the system. These models will be refined and improved until they accurately portray the comlex interplay of tectonics, ice sheet dynamics and climate.The role of large volume subglacial discharges on past ocean circulation and deep-water formation, past and future climate change, geomorphic alteration of landscapes, and material exchange and biological diversity among subglacia environments will be discerned. As we access these environments, the phylogenetic and metabolic diversity of subglacial organisms will be established including their evolutionary position in the "Tree of Life". Microbiological and genomics studies will: 1) improve our understanding of how orgainsms live, propogate, and evolve in harshest environments; 2) explore the limits of the environmental tolerances of life 3) lend clues to the seed organisms for these environments; 3) reveal special adaptations generated by the interplay of tectonics, geology, and climate; and 4) serve as test-beds for the search for life elsewhere in the solar system As is the course in the exploration of new frontiers, the most dramatic breakthroughs are likley to be unpredicted and unforseen. A major outcomes of this program will be the attraction of the next generation of scientists and engineers to polar science by igniting people's imagination about these unique environments. Subglacial envrionment research and exploration will be a furtile training ground for future polar researchers.

For More Infromation go to:

SALE Program Office web site at http://salepo.tamu.edu/

SCAR SALE web site at http://salepo.tamu.edu/scar_sale

SALE 2006 Workshop web site http://salepo.tamu.edu/saleworkshop2006

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