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Exploring Subglacial Antarctic Lake Environments

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While subglacial lakes have been suspected, and speculated about, for more than 50 years, recent analyses of historical and new data have shown that liquid water environments are common beneath the vast Antarctic Ice Sheet. Airborne radar surveys have now documented more than 145 subglacial lakes, the largest being Lake Vostok located 4 km beneath the vast East Antarctic Ice Sheet (Figure 1).

The public and scientists alike have been intrigued by the possibility that these environments harbor life in conditions not previously studied on our planet. Planning for the exploration and study of these unique environments has focused international attention on the challenges presented by the way science is conducted in such settings while providing for environmental protection and stewardship. Exploration of subglacial environments will require careful and detailed planning, adoption of environmental protocols, and international cooperation.

The Subglacial Lake Exploration Group of Specialists (SALEGOS; http://salepo.tamu.edu/scar_sale) has made significant progress in developing a plan for the study of subglacial lake environments. The Scientific Committee on Antarctic Research (SCAR) established SALEGOS in 2000 as an international group of scientists with backgrounds needed to address all facets of a possible research program. The group has served as a focal point for organizing and encouraging international planning for subglacial lake environment exploration.

SALEGOS' overarching scientific objectives to guide subglacial exploration and research are to:

- understand subglacial environments and their impact on the origins, evolution, and maintenance of life beneath ice sheets;
- 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
- recover and decipher the climatic information contained in the sediments in lakes and the ice sheet sealing the lakes.

The plan requires substantial human and logistical resources over many years. The proposed programmatic time line (Table 1) is driven in large degree by the sampling methodologies needed and the samples required to conduct key experiments. While some technologies require development, others such as remote sensing are already being applied in ongoing studies. More challenging objectives require lake entry, and the most challenging objectives require sample retrieval.

The deployment of in situ observatories is one possible first step in exploring subglacial lakes, and can be mostly accomplished using current oceanographic technology. Observatories could gather a time series of basic physical and chemical measurements that would be essential to assist in the planning for the more complex components of the program involving sample retrieval. The first phase of observatories could be static or vertically mobile strings of sensors deployed in multiple locations within a lake.

Sample return will focus on the identity and diversity of life forms in a lake, in situ growth and metabolic rates, the presence of unique biochemical and/or physiological processes, and the evolutionary history of subglacial environments recorded in lake sedimentary records. While a major commitment of resources will be necessary to implement an ambitious program of exploration and research, the potential scientific and educational payoff is immense.

Chemical, Glaciological, and Geological Properties of Subglacial Lakes

To date, investigations of subglacial lake environments have been directed at Lake Vostok, owing to the existence of a deep borehole over the lake. Relatively little is known about other subglacial environments. Energy mass

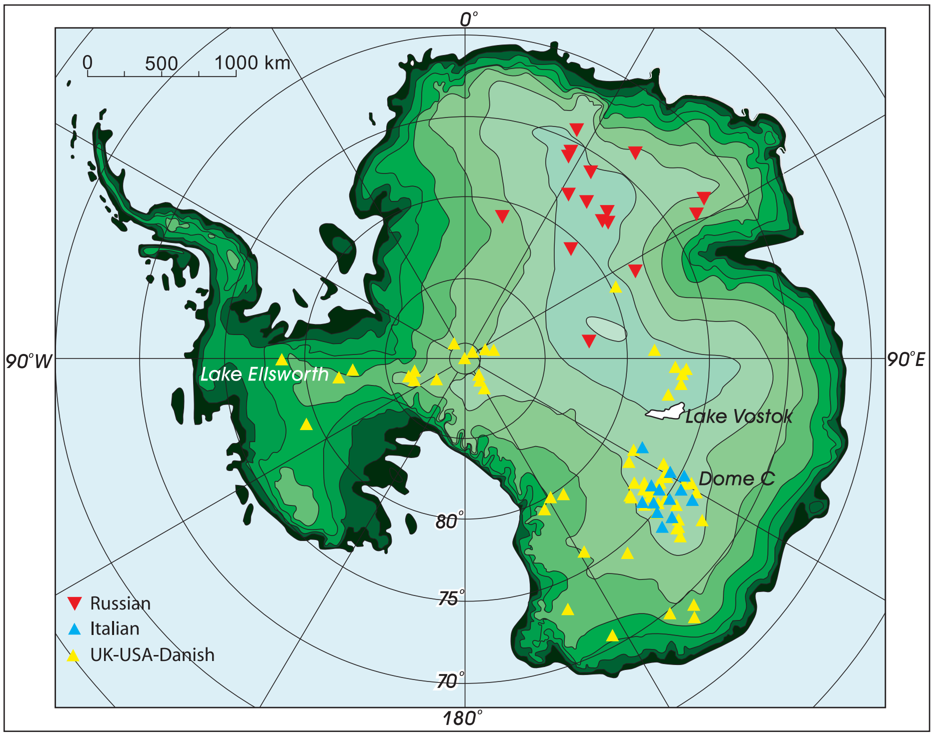

Fig. 1. Locations of Antarctic subglacial lakes. Highlighted are lakes discovered by Italian (blue triangles), Russian (red triangles), and U.K.-U.S.-Danish (yellow triangles) teams. Lake Vostok is shown in outline. The ice sheet surface is contoured at 500-m intervals. Compiled from Siegert et al. *[2005] and* Tabacco et al. *[2003].*

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Table 1. SALEGOS Assessment of the Timing of Subglacial Lake Exploration and Key Technological Milestones[a]

Time	Milestone
Short (0–3 years)	existing technologies, modeling, and other non-field-related activities
Medium (3–6 years)	lake entry and observatory deployment; possible sample return from West Antarctic lakes
Long (6–9 years)	water/shallow sediment retrieval
Very long (9+ years)	sediment deep coring

[a]*Note that the environmental requirements increase in complexity as the activities increase in complexity.*

balance considerations constrain speculation about ice melting and accretion at the lake/ice sheet interface capping Lake Vostok. Ice sheet melting occurs at the northern end of the lake, whereas lake water is freezing to the glacier base over the remainder of the lake surface, resulting in removal of water from the lake by lateral ice sheet motion.

Accreted ice most likely forms by a mechanism similar to frazil ice (which forms from small, randomly oriented spherically crystals that float on water), followed by consolidation via interstitial water freezing. Sediment inclusions in accretion ice are older than 1.5 Ga, and presumably originate from erosional contact of the ice sheet with the surrounding basement rocks. The sedimentary inclusions contain gypsum particles and are enriched in soluble sodium chloride, and magnesium and calcium sulphate, suggesting the presence of an evaporite deposit upstream of the lake that was emplaced before the onset of Antarctic glaciation [*De Angelis et al.,* 2004]. The ionic content of clear, accreted ice is 5–50 times lower than observed in glacier ice implying that it originates from lake water with a salinity of 0.1‰ or less.

Models of gas hydrate formation and stability predict that the lake water is supersaturated with respect to nitrogen and oxygen. Overpressure and high levels of these gases have important practical ramifications for sampling efforts and may limit life in the lake. The physical/chemical properties of water in Lake Vostok inferred from accretion ice analyses and the tilted lake-glacier interface, suggest that thermohaline circulation occurs in the lake. Recent aero-geophysical surveys of Lake Vostok by Russian and U.S. scientists have mapped the lake in great detail, confirming the presence of two basins and morphologically complex shoreline and basal features. Circulation, combined with the lake's complex morphology, suggests the likelihood of horizontal and vertical chemical and physical gradients in the waters within the lake. The latest estimates of the residence time of water in Lake Vostok vary widely between 13,000 and 80,000 years [*Petit et al.,* 2003; *Studinger et al.,* 2004].

Life Beneath the Ice

Probably the most tantalizing, and the most controversial, studies concern the likelihood of life in Lake Vostok. Studies of bacterial isolates and DNA clones (a section of DNA that has been inserted into a vector molecule, such as a plasmid or a phage chromosome, and then replicated to form many identical copies) recovered from accreted ice have been used to infer the presence of life in the lake. Microbiological studies have shown how microbes might make a living and what the "seed" populations might be that established life in these dark, cold, high-pressure, and ultra-low nutrient level environments.

The nature of the samples, the unknowns of how the accretion process fractionates components from its source waters, the integrity of microbes in these settings over long time periods, the possibility of contamination from the drilling and recovery processes, the very dilute biological solutions, and the limited availability of the samples all suggest that caution should be exercised when interpreting these preliminary results.

Not unexpectedly, these limitations have led to differing opinions and, in some cases, contradictory results. While the origins of the microbes isolated from accreted ice are difficult to ascertain unequivocally, some of them may originate from contamination during the sample collection, retrieval and processing procedures and some appear to be indigenous to the ice (or the lake) [*Priscu and Christner,* 2004]. DNA signatures indicate that ice-entombed microbes include phylotypes similar to known thermophilic and yet unclassified phylotypes [*Bulat et al.,* 2004] as well as mesophilic bacteria with diverse physiologies and different habitat preferences, including a hot spring [*Priscu et al.,* 1999; *Karl et al.,* 1999; *Christner et al.,* 2001].

Fundamental to lake ecosystem processes is the ability of organisms to survive and function within these unusually dilute chemical environments. On the basis of varying and limited evidence, researchers have arrived at differing conclusions. An intriguing question is whether alternative sources of energy, such as geothermal inputs, are present in subglacial environments. The geochemical composition of the accreted ice samples has been interpreted as indicating a hydrothermal contribution to Lake Vostok with a source somewhere upstream from the Vostok drill site [*Souchez et al.,* 2003]. Resolution of this question awaits more direct evidence that can only be obtained from lake sampling.

The Latest Developments

Recent developments include a proposal by Russian and French scientists to select a site and drill a deep hole above the northern part of Lake Vostok in the time frame of the International Polar Year (IPY) 2007–2008; a provocative suggestion of a second large lake in East Antarctica [*Leitchenkov et al.,* 2003]; intriguing details of ice accretion and melting dynamics discovered by Italian scientists in subglacial systems at Dome-C, located on the east Antarctic plateau approximately 560 km from Lake Vostok [*Tabacco et al.,* 2003]; and expansion of the inventory of subglacial lakes to 145 features [*Siegert et al.,* in press].

Scientists from the United Kingdom now have evidence supporting the existence of Lake Ellsworth, a subglacial lake in West Antarctica, from radar sounding of the lake surface and numerical modeling of the ice sheet thermal regime [*Siegert et al.,* 2004]. The British Antarctic Survey acquired new transects over the lake in the austral summer of 2004–2005, which confirm the position of the lake across the subglacial foothills of the Ellsworth Mountains.

A U.K.-led team of over 25 scientists, from 12 institutions and five nations, met for the third time at the British Antarctic Survey during March 2005. The purpose of the meeting was to plan in situ exploration of Lake Ellsworth; a proposal to secure funding for the first steps of exploration, geophysical surveys for the lake, has been tentatively approved and awaits scheduling (www.ggy.bris.ac.uk/ellsworth).

At its 28th Meeting in Bremerhaven, Germany (October 2004), the Scientific Committee on Antarctic Research designated Subglacial Antarctic Lake Environments (SALE) as a major Scientific Research Program (*Eos, 86*(9), 90, 2005; http://vpr-zope.tamu.edu/scar_sale). An Expression of Intent entitled the "SALE – Unified International Team for Exploration and Discovery (SALE-UNITED)" was identified by the International Council of Science (ISCU)/World Meteorological Organization (WMO) Joint Committee for the IPY 2007–2008 as a potential "core" program during IPY 2007–2008 (http://salepo.tamu.edu/sale_united). Finally, a U.S.-SALE program and office have recently been formed to organize and coordinate U.S. interests in this area (contact m-kennicutt@tamu.edu, http://vpr-zope.tamu.edu/us_sale).

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MEETINGS

Paleoceanography and Paleoclimatology of the Southern Ocean

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Among the greatest successes of the Ocean Drilling Program were the concerted drilling efforts and exciting results recovered from the Southern Ocean (SO) surrounding Antarctica. Scientific drilling in the SO and on the Antarctic margin has recovered material from hundreds of sites for scientific analysis. The dynamic nature of ice sheet development and ice/margin interactions through time has been observed, as has the role that the SO plays in the development and persistence of Antarctic glaciation. The SO has been documented as a sensitive mixing pool of global water masses that is at times a locus of high biological sedimentation. Also, the SO has been found to contain high-resolution records of climate forcing and response, and as such it may hold clues to future climate.

These results from scientific drilling over the past several decades have significantly increased the understanding of Cenozoic to decadal processes affecting oceanography and climatology of the SO and Antarctica. Now, it is important to mine these results from scientific drilling over the past several decades, and also to provide a scientific, framework for future expeditions in this region to solve unanswered questions. What, for example, was the role of iron as a biolimiting nutrient through time? How does sea ice cover relate to ventilation of the SO and thus to gas fluxes of carbon dioxide on glacial timescales? Was Antarctic glaciation related to the opening of ocean gateways, to decreases in atmospheric carbon dioxide, or to some other factor?

To this end, 26 researchers from five countries attended a synthesis workshop on the campus of the University of Colorado, Boulder, in January. The workshop, funded by the U.S. Science Support Program of Joint Oceanographic Institutions, Inc., focused on Southern Ocean paleoceanography and paleoclimatology. It began with plenary overview talks about the critical aspects of SO development, and continued with poster presentations and discussions in breakout groups, by the group as a whole, and over social events.

The underlying themes of the discussions focused on extracting what is and is not known about a number of critical processes, including ice sheet development, tectonics, ecosystem dynamics, biogeochemical responses, and SO thermal structure, on various timescales. After the discussions, what seemed like a good idea before the workshop (i.e., conducting a synthesis workshop on a regional or topical theme) now seems a must-do for a number of fields related to scientific drilling. Although often the push to recover more samples from critical places is what necessarily drives much of the science, workshop attendees agreed that mining the physical and intellectual archive left from decades of scientific drilling results is also an important activity that should be encouraged and funded as a priority mission of the program.

As summarized by the plenary speakers, several decades worth of scientific drilling in the sea and on land have provided many answers and questions. Peter Barker (British Antarctic Survey) presented the Cenozoic context to SO development, with several aspects of Antarctic glaciation that are well-known: (1) Significant glaciation started ~34 Ma, and cooling intensified from 16 to 13 Ma and in the late Pliocene; (2) except for glacial/interglacial changes there has likely been little change over the past 9–10 Myr in Antarctic ice sheet volume; and (3) atmospheric carbon dioxide is not the whole answer to Antarctic glacial history. Several important questions were also presented: (1) How glaciated was Antarctica during the Oligocene, and how deglaciated was it during the early Miocene? (2) What caused end-Oligocene warming and mid-Miocene cooling? (3) How did high-latitude cooling operate before glaciation?

In addition, Barker focused on the development of the Antarctic Circumpolar Current (ACC), noting that: (1) ACC transport occurs in narrow but meandering frontal jets, (2) the ACC may not have caused glaciation, and (3) increased primary production alone is not a safe ACC indicator. Several unanswered questions remain: (1) When did a deep-reaching ACC begin? (2) How did the ACC evolve? (3) What was SO circulation before the ACC?

Carlota Escutia (University of Grenada) focused on geomorphology and ice dynamics in Antarctica, highlighting an Integrated Ocean Drilling Program (IODP) proposal to drill the Antarctic Wilkes Land margin. The Wilkes Land is the only known Antarctic margin where the unconformity separating pre-glacial strata below from glacial strata above in the continental shelf can be traced to the abyssal plain, allowing sequences to be linked. Because strata below and above the "glacial onset" unconformity can be sampled at relatively shallow depths, the record of the onset of glaciation can be obtained from (1) the shelf foreset section, which provides a direct record of occurrence of grounded ice but one that is less continuous and hard to date, and (2) the abyssal plain hemipelagic (distal continental sediment) section, which provides an indirect record of glaciation but one that is more continuous and easier to date.

Kathy Licht (Indiana University–Purdue University Indianapolis) discussed the dynamics of ice-sediment interactions from Antarctica to the SO from the Last Glacial Maximum (LGM) to the present. She reported that LGM conditions in Antarctica are reasonably well constrained—for example, ice sheet extent is well defined in most places and indicates that an equilibrium configuration was not achieved. Deglaciation records to date show that the ice sheet did not retreat until well after 18 ka, and therefore had a complex response to global sea level rise. Additionally, chronological data of the ice marginal positions do not show evidence of catastrophic retreat of the West Antarctic ice sheet in the Ross Sea. Licht noted that several aspects of ice-sediment dynamics are not as well known, most notably the fate of sediment transported to the continental slope and the role of ice shelves; these unknowns reduce the certainty about the relationship between ice margin fluctuations and SO sedimentation.

Bernard Diekmann (Alfred Wegener Institute Potsdam) presented a summary of Pleistocene sedimentation patterns in the SO. During glacial stages, the locus of prominent opal deposition is shifted to the north in response to a wider extension of seasonal sea ice and a displacement of the polar front to the north, but little quantitative data and proxies exist for calculating the spatial and temporal mass budget of opal deposition. Terrigenous (continentally-derived) fluxes are mostly enhanced during glacial stages, particularly in the Atlantic sector of the SO, but little quantitative information is available to assess the individual effects of stronger glacial input, eolian sediment