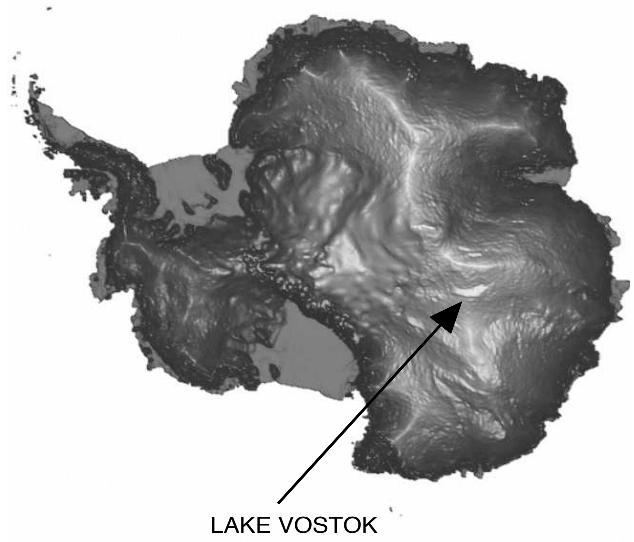
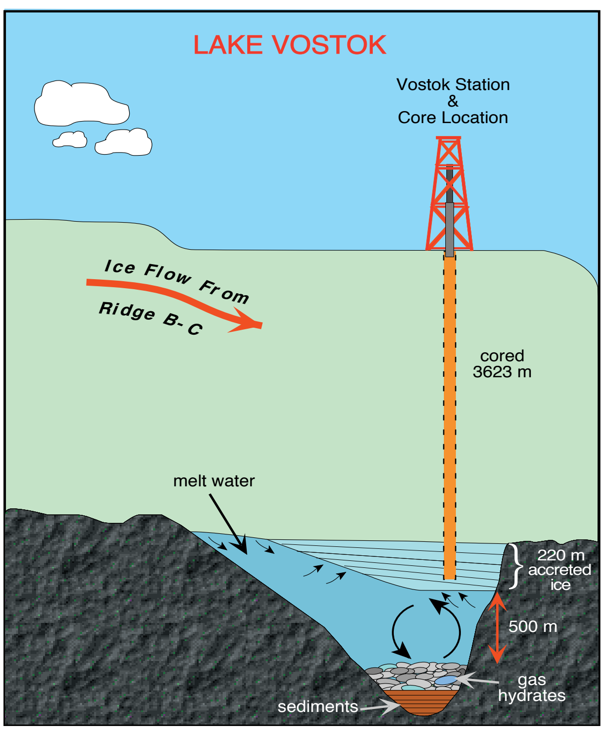
LAKE VOSTOK WORKSHOP



FINAL REPORT

Lake Vostok:
A Curiosity or a Focus for Interdisciplinary Study?



National Science Foundation
Sponsored Workshop

Conveners:

Robin E. Bell
Lamont-Doherty Earth Observatory
of Columbia University

David M. Karl
University of Hawai'i

Washington D.C.
November 7 & 8, 1998

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(1) Executive Summary

Life continues to appear in the unusual and extreme locations from hot vents on the seafloor to ice covered hypersaline lakes in Antarctica (Priscu et al., 1998). The subglacial environment represents one of the most oligotrophic environments on earth, an environment with low nutrient levels and low standing stocks of viable organisms. It is also one of the least accessible habitats. Recently the significance of understanding subglacial communities has been highlighted by discoveries including the thriving bacterial communities beneath alpine glaciers (Sharp et al., 1999), to the evidence from African stratigraphy for a Neoproterozoic snowball earth (Hoffman et al., 1998a, Kirschvink, 1992) to the compelling ice images from Europa, the icy moon of Jupiter. If life thrives in these environments it may have to depend on alternative energy sources and survival strategies. Identifying these strategies will provide new insights into the energy balance of life.

The identification of significant subglacial bacterial action (Sharp et al., 1999) as well the work on permafrost communities (i.e. Gilichinsky et al., 1995) suggests that life can survive and possibly thrive at low temperatures. Neither the alpine subglacial environment nor the permafrost environment is as extreme as the environment found beneath a continent-wide ice sheet as Antarctica today. The alpine subglacial environment has a continual high level of flux of nutrients from surface crevasses. The Antarctic subglacial environment lacks a rapid flux of surface meltwater and subsequently is more isolated. In addition to being more isolated, the Antarctic subglacial environment is a high pressure region due to the overburden of ice.

The Antarctic subglacial environment may be similar to the environment beneath the widespread ice sheets in the Neoproterozoic, a time period from about 750 to 543 million years ago. It has been suggested that during this period the earth experienced a number of massive glaciations - covering much of the planet for approximately 10 million years at a time. The evidence for an ancient ice covered planet comes from thick widespread sedimentary sequences deposited at the base of large ice bodies. These glacial units alternate with thick carbonates units-warm shallow water sedimentary deposits. These paired sequences have been interpreted as representing a long period when the earth alternated between from an extremely cold, completely ice covered planet (the snowball earth) and a hothouse planet (Hoffman et al, 1998b). Some speculate that the extremes of these climates introduced an intense “environmental filter”, possibly linked to a metazoan radiation prior to the final glaciation and an Ediacaran radiation (Hofmann et al., 1990; Knoll, 1992). Portions of the Antarctic continental subglacial environment today, which have been isolated from free exchange with the atmosphere for at least 10 million years, are similar to the environment in this ancient global environment. Understanding the environmental stresses and the response of the microbes in a modern extreme subglacial environment will help us decipher the processes which lead to the post-glacial evolutionary radiation over 500 million years ago.

The third important analogue for modern Antarctic subglacial environments is from the outer reaches of the solar system, the ice moon of Jupiter, Europa. Recent images resembling sea ice, combined with the very high albedo of this moon has lead to the interpretation that this moon is ice covered. Beneath the ice covering Europa is believed to be an ocean. The thick cover of ice over a liquid ocean may be a fertile site for life (Chyba, 1996; Williams et al., 1997). The Antarctica subglacial lakes have similar basic boundary conditions to Europa.

An investigation of Antarctic subglacial environments should target the unique role these lakes may have in terms of the triggers for rapid evolutionary radiation, for understanding the global carbon cycle through major glaciations and as an analogue for major planetary bodies.

Lake Vostok is a large (10,000 km^2) water body located beneath ~4 km of glacial ice at 77^{o}S, 105^{o}E within the East Antarctica Precambrian craton (Kapitsa et al., 1996). Based on limited geophysical data, it has been suggested that the Lake occupies a structural depression, perhaps a tectonically active rift. The water depth varies from approximately 500 m beneath Vostok Station to a few 10's of meters at the northern end of the Lake; the ice sheet thickness also varies by nearly 400 m and is thickest in the north (4,150 m). Ice motion across the lake, freezing and melting at the base of the ice sheet and geothermal heating could establish density-driven flows, large scale circulation and geochemical gradients in Lake Vostok.

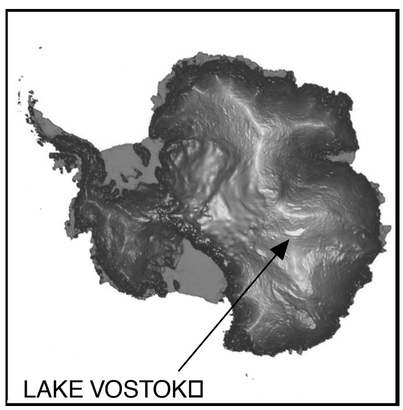

Figure 1: ERS-1 Surface Altimetry indicating location of Lake Vostok

The existence of this lake, and at least 76 others like it, has been documented by extensive airborne 60 MHz radio-echo sounding records that provide coarse sampling coverage of approximately half of the Antarctic ice sheet (Siegert et al., 1996). The majority of sub-glacial lakes are near ice divides at Dome C and Ridge B, East Antarctica. More recently, the European Research Satellite-1 (ERS-1, Figure 1) has provided radar altimeter data which provide unprecedented detail of ice surface elevations. These data have been used to define the physical dimensions of the lake, its drainage basin, and predict lake water density (Kapitsa et al., 1996).

The water body appears to be fresh. Based on considerations of temperature and pressure fields, most of the dissolved gases in the lake would be present as hydrates, which may be segregated in density layers. The unique geochemical setting of Lake Vostok may present an opportunity and a challenge for the development of novel life forms. Lake Vostok, due to its size, is the lake which is most likely to have remained liquid during changes in the Antarctic ice sheet volume and therefore most likely to provide new insights into these subglacial environments. We understand much more about the subglacial processes such as accretion and melting within Lake Vostok than any other lake, and we have a solid local climate record for the last 400,000 years from the overlying ice core (Petit et al., 1999).

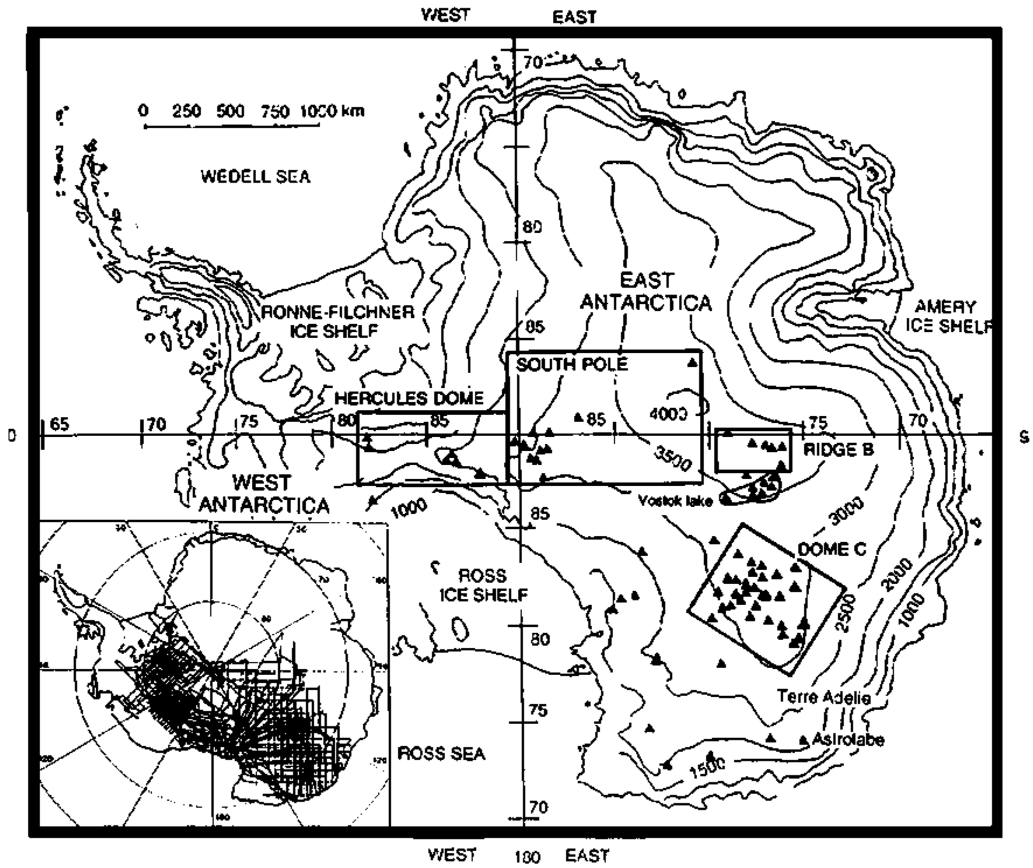

Figure 2: Location of subglacial lakes in Antarctica determined from the NSF/SPRI airborne radar program. The radar flight lines are shown in the inset on the lower left. (adapted from Siegert et al., 1996)

An international team of scientists and engineers has been drilling the ice sheet above Lake Vostok to obtain a detailed record of the past climate on earth. This ice-core program, started in 1989, recently terminated drilling at a 3,623 m depth (approximately 120 m above the ice-water interface at this location). This is the deepest ice core ever recovered. The ice core corresponds to an approximately 400,000 year environmental record, including four complete ice age climate cycles. Below 3,538 m there is morphological and physical evidence that basal ice is comprised of re-frozen Lake Vostok water.

Throughout most of the ice core, even to depths of 2,400 m, viable microorganisms are present (Abyzov, 1993). Previous sampling of ice in the interior of the Antarctic continent has repeatedly demonstrated that microorganisms characteristic of atmospheric microflora are present. Air-to-land deposition and accumulation is indicated, rather than *in situ* growth in the ice (Lacy et al., 1970; Cameron et al., 1972). Cameron and Morelli (1974) also studied 1 million year old Antarctic permafrost and recovered viable microorganisms. Prolonged preservation of viable microorganisms may be prevalent in Antarctic ice-bound habitats. Consequently, it is possible that microorganisms may be present in Lake Vostok and other Antarctic subglacial lakes. However, isolation from exogenous sources of carbon and solar energy, and the known or suspected extreme physical and geochemical characteristics, may have precluded the development of a functional ecosystem in Lake Vostok. In fact, subglacial lakes may be among the most oligotrophic (low nutrient and low standing stocks of viable organisms) habitats on earth. Although "hotspots" of geothermal activity could provide local sources of energy and growth-favorable temperatures, in a manner that is analogous to environmental conditions surrounding deep sea hydrothermal vents (Karl, 1995), it is important to emphasize that without direct measurements, the possible presence of fossil or living microorganisms in these habitats isolated from external input for nearly 500,000 years is speculation.

Lake Vostok may represent an unique region for detailed scientific investigation for the following reasons:

- it may be an active tectonic rift which would alter our understanding of the East Antarctic geologic terrains;
- it may contain a sedimentary record of earth's climate, especially critical information about the initiation of Antarctic glaciation;
- it may be an undescribed extreme earth habitat with unique geochemical characteristics;
- it may contain novel, previously undescribed, relic or fossil microorganisms with unique adaptive strategies for life; and
- it may be a useful earth-based analogue and technology "test-bed" to guide the design of unmanned, planetary missions to recently discovered ice-covered seas on the Jovian moon, Europa.

These diverse characteristics and potential opportunities have captivated the public and motivated an interdisciplinary group of scientists to begin planning a more comprehensive investigation of these unusual subglacial habitats. As part of this overall planning effort, a NSF-sponsored workshop was held in Washington, D.C. (7-8 Nov. 1998) to evaluate whether Lake Vostok is a curiosity or a focal point for sustained, interdisciplinary scientific investigation. Because Lake Vostok is located in one of the most remote locations on earth and is covered by a thick blanket of ice, study of the lake itself that includes *in situ* measurements and sample return would require a substantive investment in logistical support, and, hence financial resources.

Over a period of two days, a spirited debate was held on the relative merits of such an investment of intellectual and fiscal resources in the study of Lake Vostok. The major recommendations of this workshop were:

- **To broaden the scientific community knowledgeable of Lake Vostok by publicizing the scientific findings highlighted at this workshop.**
- **To initiate work on sampling, measurement and contamination control technologies so that the Lake can be realistically and safely sampled.**
- **Both NASA and NSF should prepare separate, or a joint, announcement of opportunity for the study of Lake Vostok, possibly through the LExEn program.**

(2) Introduction

The goal of the workshop was to stimulate discussion within the U.S. science community on Lake Vostok, specifically addressing the question: "Is Lake Vostok a natural curiosity or an opportunity for uniquely posed interdisciplinary scientific programs?" The workshop was designed to outline an interdisciplinary science plan for studies of the lake.

The structure of the workshop was a series of background talks on subjects including:

Review of Lake Vostok Studies	Robin E. Bell
The Overlying Ice: Melting and Freezing	Martin Siegert
Evidence from the Vostok Ice Core Studies	Jean Robert Petit
Tectonic Setting of Lake Vostok	Ian Dalziel
Biodiversity and Extreme Niches for Life	Jim Tiedje
Lake Vostok Planetary Analogs	Frank Carsey
Identification of Life	David White
Mircrobial Contamination Control	Roger Kern

A summary of each of these background talks is presented in this report Section (4) entitled: "Lake Vostok: Background Information."

Following these talks each workshop participant presented a 3 minute, one overhead presentation of why, from their perspective, Lake Vostok was more than a curiosity, and warranted significant effort to study. These presentations ranged from discussion of helium emerging from the mantle, to the unique temperature and density structure which might develop in such an isolated high pressure, fresh water environment as Lake Vostok. Written summaries of these presentations and key illustrations are included in Appendix 1 entitled "Why Lake Vostok?".

Next, the workshop participants as a large group, identified the fundamental aspects of a research program across Lake Vostok with each participant presenting five key ideas. These ideas were synthesized into 6 major themes which became the subject of working groups. The working groups and their members were:

(1)Geochemistry-Mahlon C. Kennicutt II, Berry Lyons, Jean Robert Petit, Todd Sowers
(2)Biodiversity-Dave Emerson, Cynan Ellis-Evans, Roger Kern, José de la Torre, Diane McKnight, Roger Olsen
(3)Sediment Characterization - Luanne Becker, Peter Doran, David Karl, Kate Moran, Kim Tiedje, Mary Voytek
(4)Modeling - David Holland, Christina Hulbe
(5)Site Survey - Robin Bell, Ron Kwok, Martin Siegert, Brent Turrin
(6)Technology Development - Eddy Carmack, Frank Carsey, Mark Lupisella, Steve Platt, Frank Rack, David White

Each group was tasked with developing: a) justification for a Lake Vostok effort; b) the goals of a research effort; c) a strategy to meet the goals; and d) a time-frame for the effort. In addition, the groups were tasked with presenting the single most compelling scientific justification for studying Lake Vostok. The groups worked through the morning of the second day preparing draft presentations. The draft reports were presented in plenary at the conclusion of the workshop. The reports from the working groups are found in Section 6, "Group Reports". The workshop participants debated the justifications and the major obstacles to studying Lake Vostok.

The discussion of the major obstacle to advancing a well developed scientific justification and plan to study Lake Vostok hinged on several major factors including:

- The exploratory nature of the program coupled with the paucity of data about this unknown region making development of a detailed scientific justification difficult;
- the need for technological developments to ensure contamination control and sample retrieval, recognizing that Lake Vostok is a unique system whose pristine nature must be preserved;
- the need for a strong consensus within the U.S. science community that Lake Vostok represents an important system to study, and recognition that international collaboration

is a necessary component of any study;
- the recognition that the logistical impact of a Lake Vostok program will be significant and that the scientific justification must compete solidly with other ongoing and emerging programs; and
- that the lack of understanding of the present state of knowledge of the Lake as a system within the U.S. science community remains a difficulty in building community support and momentum for such a large program.

These obstacles were addressed in workshop discussions and are specifically addressed in the report recommendations, the draft science plan and the proposed timeline. The preliminary science plan and timeline was based on working group reports and is presented below in Section (3) "Preliminary Science Plan and Timeline".

(3) Preliminary Science Plan and Timeline

This preliminary science plan is based on a synthesis of working group reports. The overarching goal of the science plan is to understand the history and dynamics of the Lake Vostok as the culmination of a unique suite of geological and glaciological factors. These factors may have produced an unusual ecological niche isolated from major external inputs. The system structure may be uniquely developed due to stratification of gas hydrates. Specific scientific targets to accomplish this goal include:

- determine the geologic origin of Lake Vostok within the framework of an improved understanding of the East Antarctic continent as related to boundary conditions for a Lake Vostok ecosystem;
- develop an improved understanding of the glaciological history of the lake including the flux of water, sediment, nutrients and microbes into a Lake Vostok ecosystem;
- characterize the structure of the lake's water column, to evaluate the possibility of density driven circulation associated with melting/freezing processes or geothermal heat, the potential presence of stratified gas hydrates, and the origin and cycling of organic carbon;
- establish the structure and functional diversity of any Lake Vostok biota, an isolated ecosystem which may be an analogue for planetary environments;
- recover and identify extant microbial communities and a paleoenvironmental record extending beyond the available ice core record by sampling the stratigraphic record of gas hydrates and sediments deposited within the Lake; and
- ensure the development of appropriate technologies to support the proposed experiments without contaminating the Lake.

Timeline

1999 (99-00) Planning Year
- Modeling studies
- Develop international collaboration
- SCAR Lake Vostok workshop
- Begin technology development

2000 (00-01) Site Survey Year I
- Joint NSF/NASA LExEn Call for Lake Vostok Proposals
- Airborne site survey
- Preliminary ground based measurements
- Preliminary identification of observatory sites

2001 (01-02) Site Identification and Site Survey Year II

- Ground based site surveys
- Complete airborne survey if necessary
- Test access/contamination control technology at a site on the Ross Ice Shelf
- Finalize selection of observatory sites

2002 (02-03) *In Situ* Measurement Year

- Drill access hole for *in situ* measurements
- Attempt *in situ* detection systems to demonstrate presence of microbial life
- Install long term observatory
- Acquire vertical profile of water column
- Acquire microscale profiles within surface sediments
- Conduct interface survey (ice/water and water/sediment)
- International planning workshop (including exchange workshop)

2003 (03-04) Sample Retrieval Year

- Acquire samples of basal ice
- Acquire samples of water and gas hydrates
- Acquire samples of surface sediments
- Stage logistics for second observatory
- International planning workshop (including data exchange)

2004 (04-05) Installation of Second Long Term Observatory

- Installation of second long term observatory
- Analysis of data
- Build new models
- International planning workshop (including data exchange)

2005 (05-06) Core Acquisition Year

- Begin acquisition of long core
- International planning workshop (including data exchange)

In order for this science plan and timetable to be realized, several coordination issues must be addressed including inter-agency and international collaboration, refinement of the scientific objectives, rigorous selection of the observatory and sample locations, and identification of the critical observations. The development of three major groups is envisioned including (1) an inter-agency working group to identify the relative interests and potential roles in a Lake Vostok program, (2) an international working group focused on scientific and logistical coordination for studies of Lake Vostok and (3) a Lake Vostok Science Working group to address refinement of science objectives, site selection and determination of primary objectives.

Inter-agency Working Group: The study of the Lake Vostok system is relevant to the mandate of several agencies, most notably NASA, NSF and the USGS. Active coordination between these agencies will be key to a successful science program focused on Lake Vostok. Other agencies or industrial partners might be sought as well. Due to their role as stewards of Antarctica and providers of logistical support, NSF would be the preferred lead U.S. agency for any Lake Vostok mission.

International Working Group: To date, our understanding of Lake Vostok is the result of integration of diverse data sets from the international research community. A successful exploration of Lake Vostok will require ongoing international collaboration with significant contributions from all participants. International collaboration will broaden the scope of the Lake Vostok studies. The SCAR workshop in 1999 is an excellent venue for developing an international Lake Vostok Working Group.

Science Working Group: Before implementation of the science plan can begin, scientific objectives must be refined, the site selection process defined, and the critical observations defined. Careful review of these issues would best be accomplished by a small team of scientists, engineers, and logistics experts. The creation of this group is a key first step. This group will be tasked with addressing issues such as site selection and development of an observation and sampling strategy.

(4) Lake Vostok: Background Information

REVIEW OF LAKE VOSTOK STUDIES

Robin E. Bell
Lamont-Doherty Earth Observatory, 61 Route 9W, Palisades, NY 10964,
p (914) 365-8827; f (914) 365-8179, robinb@ldeo.columbia.edu

The identification of Lake Vostok in 1996 by Russian and British scientists (Kapitsa et al., 1996) represented the culmination of decades of data acquisition with a broad range of techniques including ground based seismics, star observations, and airborne ice penetrating radar supplemented by spaceborne altimetric observations. These measurements were the result of a long history of investment in Antarctic research by the international science community. The initial discovery was subsequently complemented by results from the Russian-French-American Vostok ice coring program and the Russian Antarctic program. This review outlines the general characteristics of the Lake, beginning with a description of the overlying ice sheet, continuing to the lake itself and on into the sedimentary deposits (Figure 3).

The horizontal extent of the Lake is estimated from the flat surface (0.01 degrees) observed in the ERS-1 ice surface altimetry. The 4 km thick ice sheet floats as it crosses the lake, just as ice sheets become floating ice shelves at the grounding line. The flat ice surface associated with Lake Vostok extends 280 km in the north-south direction and 50-60 km in the east-west direction. Over the lake the ice surface slopes from 3550 m above sea level in the north to 3480 m above sea level in the south. The ice surface is ten times flatter over Lake Vostok than in the surrounding regions. The regional ice flows in from an elevated feature known as Ridge B-C to the west down the slope to the east. The presence of water may significantly alter this flow (Robin, 1998). The flow rates across Lake Vostok have been estimated from star sights at Vostok Station in 1964 and 1972 (Kapitsa et al., 1996) and synthetic aperture radar (SAR) interferonmetric methods (Kwok et al., 1998). The star sights at Vostok Station suggest primarily an easterly ice flow (142 degrees) at 3.7 m/yr . The SAR results indicate a significant component of flow (2.22 m/yr) along the lake axis (Kwok et al., 1998). As the overlying ice sheet is probably the major source of sediments, microbes and gas hydrates in the lake, understanding the trajectory of the ice across the lake will be critical to understanding the lake as a system.

The present understanding of the 3750-4100 m of ice sealing Lake Vostok comes from limited airborne ice penetrating radar data acquired by a joint U.S.-British program in the 1970's, and from the deep ice core drilling at the Russian Vostok Station by an international team of scientists from 1989 - 1998. The radar data, collected as part of a reconnaissance survey of Antarctica, provides cross-sectional images of the bedrock surrounding the lake, the internal layering within the ice, and the base of the ice over the lake for six flight lines. Across the lake the reflection from the base of the ice sheet is strong and very flat. In contrast, reflections from portions of the ice sheet over bedrock are characterized by rugged reflections of varying strength that are dominated by reflection hyperbolas. Radar data indicate that water within the northern half of the lake may be very shallow (~10-30 m) and that several bedrock islands protrude through the lake into the ice sheet. The ice thickness is 4150 m in the north thinning to 3750 m in the south beneath Vostok Station.

The ice core at Vostok Station was drilled to recover a record of global climate changes over the past 400,000 years which is preserved in distinct ice layers. Near the bottom of the core, beginning at a core depth of 3311 m, the ice first shows signs of disruption of the layering by ice dynamics. Generally ice layers become tilted and geochemical climatic signals become difficult to interpret (Petit et al., 1998, Duval et al., 1998). This layer between 3311 m and 3538 m has been interpreted as ice which was part of the continuous ice column but has been disrupted by deformation processes as the ice sheet moves over the underlying bedrock. The randomly distributed moraine particles in the base of this section are interpreted as an active shear layer. Below this layer, changes in ice character are significant with a dramatic increase in crystal size (to 10-100 cm), a decrease by two orders of magnitude in the electric conductivity, the stable isotopic content of the ice and the gas content. These physical and chemical changes continue through the base of the Vostok ice core at 3623 m and is interpreted to represent ice accreted to the base of the ice sheet as it passed over Lake Vostok. The upper 70 m of this large crystal ice includes numerous mud inclusions approximately 1 mm in diameter. These 70 m of "muddy" ice are interpreted to be ice accreted during a repeated melting and freezing cycle along the lake's margin. Below the 70 m of ice containing mud (i.e. below 3608 m) the ice is very clear and is believed to have been formed as accreted ice as the ice sheet floated over Lake Vostok. In this interpretation, the base of the ice sheet consists of a layer of 227 m of disrupted ice, 70 m of ice with mud inclusions and approximately 150 m of clear accreted ice. A freezing rate of several mm per year is required to generate these layers of accreted ice.

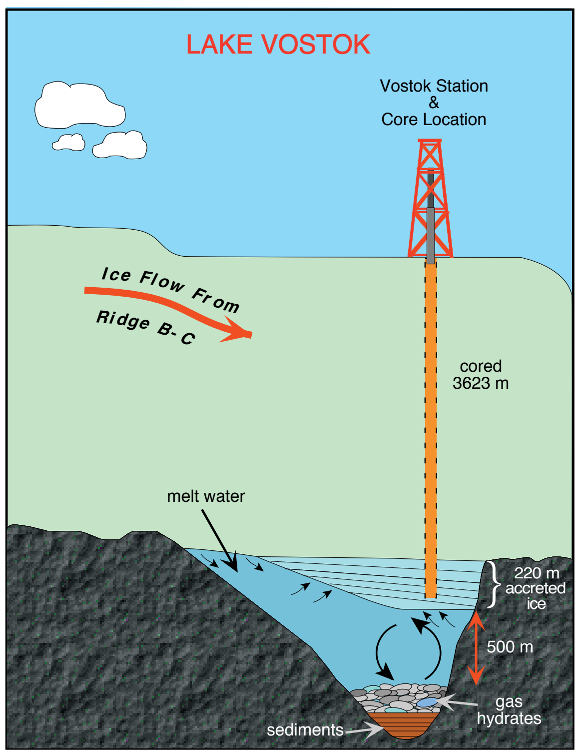

Figure 3: Cartoon of Lake Vostok indicating the ice flow over the Lake near Vostok Station. The melting and accreting processes are indicated at the base of the ice sheet. Arrows also indicate the potential circulation within the lake. The accretion ice is the light blue layered material at the base of the ice sheet. The sediments (orange lined pattern) and hypothesized gas hydrates (pebble pattern) on the lake floor are shown.

The Russian seismic experiments, led by Kapitsa in the 1960's and by Popkov in the 1990's (Popkov et al., 1998), provided insights into the depth of the lake at the southern end of the Lake and the presence of sediments. Interpretation of Kapitsa's 1960's data is that 500 m of water exist between the base of the ice sheet and the underlying rock (Figure 3). These seismic experiments show the base of the lake is 710 m below sea level. This level is close to the estimated level of 600 m below sea level for the northern portion of the lake. Recent seismic experiments have confirmed the early measurement of ~500 m of water beneath Vostok Station and deeper water (670 m) several kilometers to the north. These new experiments also identified 90-300 m sediment layers close to Vostok Station. Sediments were absent 15 km to the southwest. Leichenkov used very limited gravity data to infer as much as 4-5 km of sediments in the central portion of the lake (Leichenkov et al., 1998). Russian scientists (Kapitsa et al., 1996) have suggested that Lake Vostok results from extensional tectonics, inferring that the Lake has an origin similar to Lakes Malawi (Africa) and Baikal (Russia) (Figure 4). This interpretation is based on the long narrow nature of the lake and the bounding topography in some profiles. If the extensional origin is correct, the lake may have thick sequences of sediment, elevated heat flow, and hot springs.

Conceptual models of circulation within the lake have been advanced by Zotikov (1998) and Salamatin (1998). These models are based on the density differentials associated with variable ice thickness across the lake. The poor understanding of the size of the lake, the distribution of the melting and freezing regions and the geothermal flux, limits the applicability of these models.

Finally, in terms of understanding microbes within the lake, the overlying Vostok ice core contains a diverse range of microbes including algae, diatoms, bacteria, fungi, yeasts and actiomycetes (Ellis-Evans and Wynn-Williams, 1996). These organisms have been demonstrated to be viable to depths as deep as 2400 m (Abyzov, 1993).

In summary, these data provide us with a general sense of the horizontal scale of the lake and hints of the nature of the Lake's structure and origin, but many questions remain unanswered.

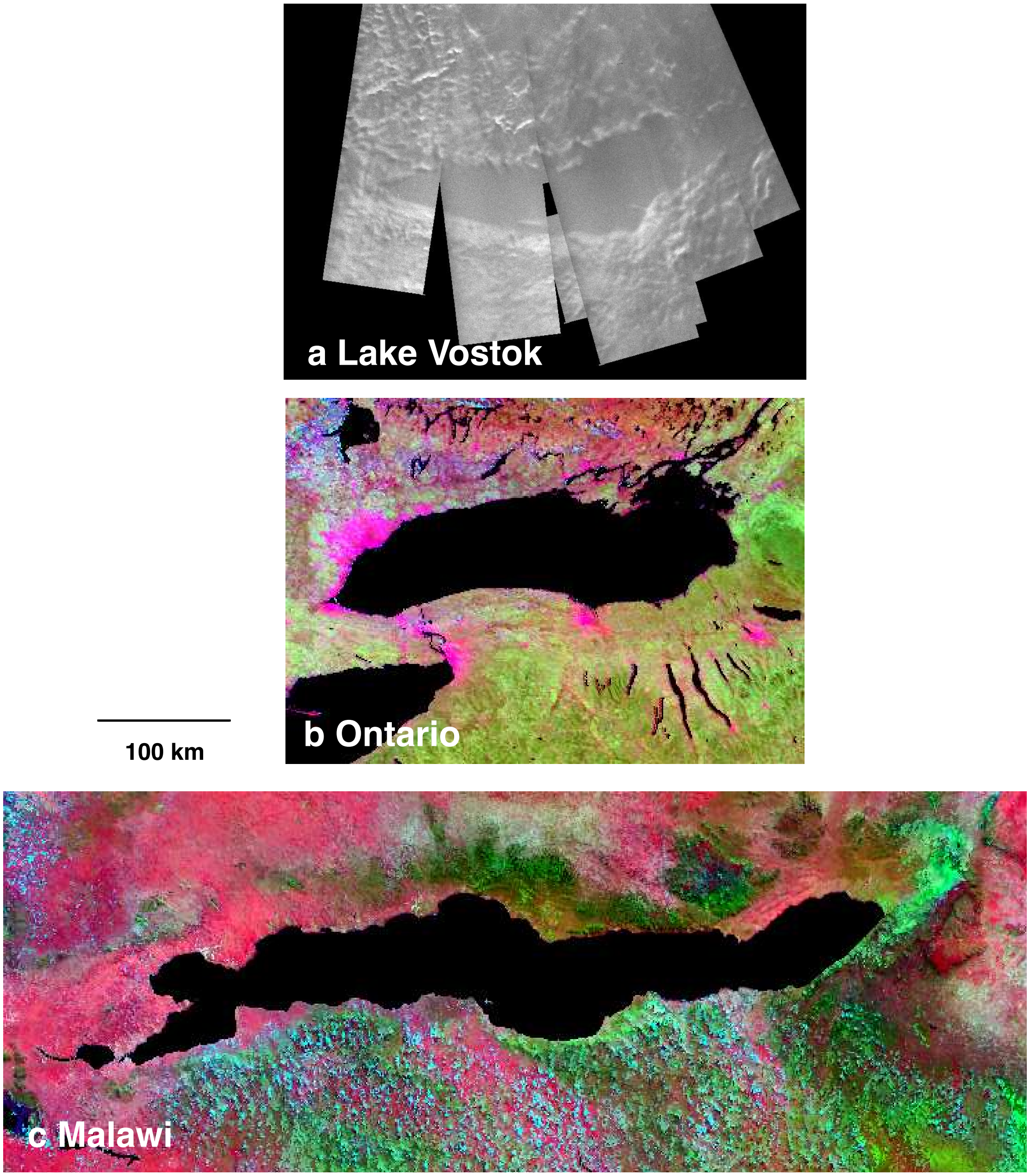

Figure 4: Satellite images of several large lakes shown at the same scale. (a) An ERS-1 image of Lake Vostok (R. Kwok, JPL). Lake Vostok shows as the flat featureless region. In this image north is to the right, and Vostok Station is on the left of the image. Both (b) and (c) are AVHRR false color composite images. Red indicates regions of high thermal emittance, either bare soil or urban areas. Green represents vegetation, Blue primarily indicates clouds and black is water. (b) An AVHRR image of Lake Ontario, a glacially scoured lake in North America. Toronto is the red area at the western end of the lake (left side of image). (c) An AVHRR image of Lake Malawi, an active rift lake from the East African Rift system. North is to the right in this image.

THE OVERLYING ICE: MELTING AND FREEZING

Martin J. Siegert
Bristol Glaciology Centre, School of Geographical Sciences,
University of Bristol, Bristol BS8 1SS, UK,
p. 44-117-928-7875; f. 44-117-928-7878, m.j.siegert@bristol.ac.uk.

The location and extent of Lake Vostok have been determined from ERS-1 altimetry and radar sounding (Kapitsa et al., 1996). The ice thickness over the lake is 3740 m at Vostok Station and 4150 m at the northern extreme of the lake. The ice-sheet surface elevation decreases by ~40 m from north to south, whilst the base of the ice sheet increases by ~400 m. The water depth is about 500 m at Vostok Station (from seismic information) and a few tens of meters at the northern end (from VHF radio-wave penetration through water).

The basal ice-sheet conditions that prevail over the lake have not been previously identified. However, this information is required in order to establish the environment within the lake and, from this, the likelihood of life in the water. A new interpretation of internal ice-sheet layering from existing airborne 60 and 300 MHz radar indicates that as ice flows across the subglacial lake, distinct melting and freezing zones occur at the ice-water interface. These events suggest a major transfer of water between the ice sheet and lake, inducing circulation in the lake and the deposition of gaseous hydrates and sediments into the lake.

The position of one airborne radar line (Fig. 5) is approximately parallel to the direction of ice flow as derived from InSAR interferometry and steady-state ice flow considerations (Siegert and Ridley, 1998). Three individual radar layers, extracted from the raw 60 MHz radar data, were continuously traced across the lake. The change in ice thickness between the top two internal layers, and the change in ice thickness between the lowest layer and the ice-sheet base, were then calculated (Fig. 6).

Generally, over grounded sections of ice sheets, internal layers are observed to converge and diverge in vertical sections as ice gets thinner and thicker, respectively. In contrast, if the grounded ice-sheet base is flat, the internal layers tend to be flat in response. Along a W-E transect across the middle of Lake Vostok, the ice thickness is relatively constant and the ice-sheet base is very flat (Fig. 6). However, along this line, internal radar layers from 60 Mhz radar are (1) approximately parallel to each other and (2) non-parallel to the ice base (Fig. 6). Any loss or gain in thickness between the ice base and the lowest internal layer along the flow-parallel transect probably reflects accumulation or ablation of ice at the ice-water interface. In contrast, 300 MHz radar indicates that compression of layering occurs in the top layers of the ice sheet, where ice density changes cause internal reflections.

Other possible explanations for the pattern of internal radar layering observed in the transect can be discounted. For example, decoupling within the ice sheet (so that ice flow above the internal layers is different from that below) is unlikely because of negligible basal shear stress between ice and water. Further, convergent and divergent flow around the bedrock island (Fig. 6) is not observed in the ice-surface velocity field derived from InSAR interferometry. Divergent flow around the island in lower ice layers would only cause ice thickening in adjacent regions. However, thickening of the ice sheet on either side of the island is not observed in radar data. Furthermore, the internal layers do not reflect ice flow around bedrock upstream of the lake because radar data show that such ice structure involves deeper internal layers diverging with increasing ice depth, whereas the layering in our transect maintains a steady separation of internal layers across the lake.

Assuming that ice does not accelerate across the lake (e.g. Mayer and Siegert, submitted), the ice velocity will be steady at around 2 m yr^{-1} across the transect from west to east (left to right in

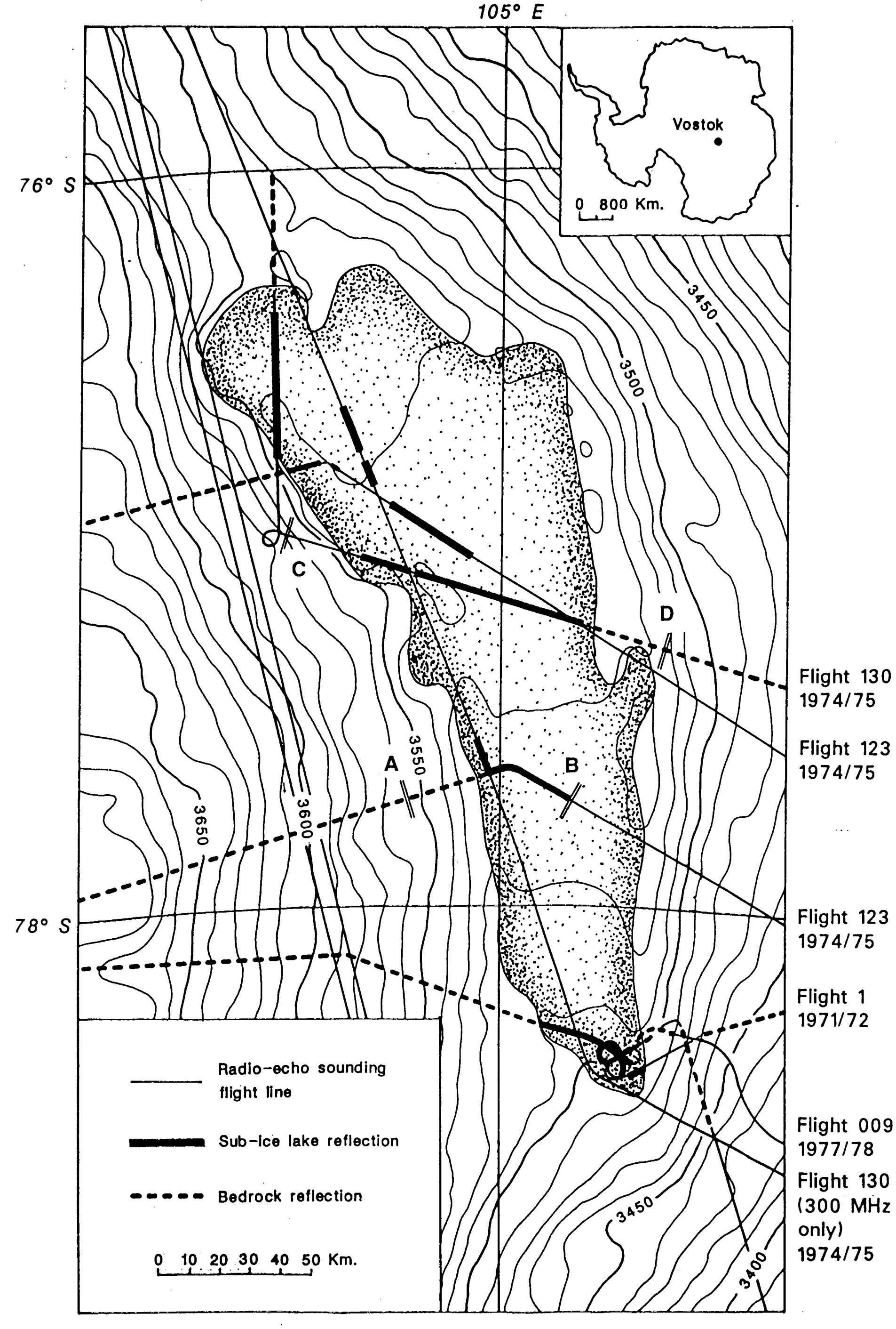

Figure 5: The position of one airborne radar line is approximately parallel to the direction of ice flow as derived from InSAR interferometry and steady-state ice flow considerations.

Fig. 6). The processed 60 MHz radar data can then be used to determine rates of change of ice thickness between the lowest layer and the subglacial interface. Assuming that there is neither lateral flow nor compression of ice in the lower layers, these rates of change of ice thickness may be related directly to rates of subglacial melting or freezing (Fig.6).

Using this method, melting of up to 15 cm yr^{-1} occurs across the first ten kilometers of the ice-

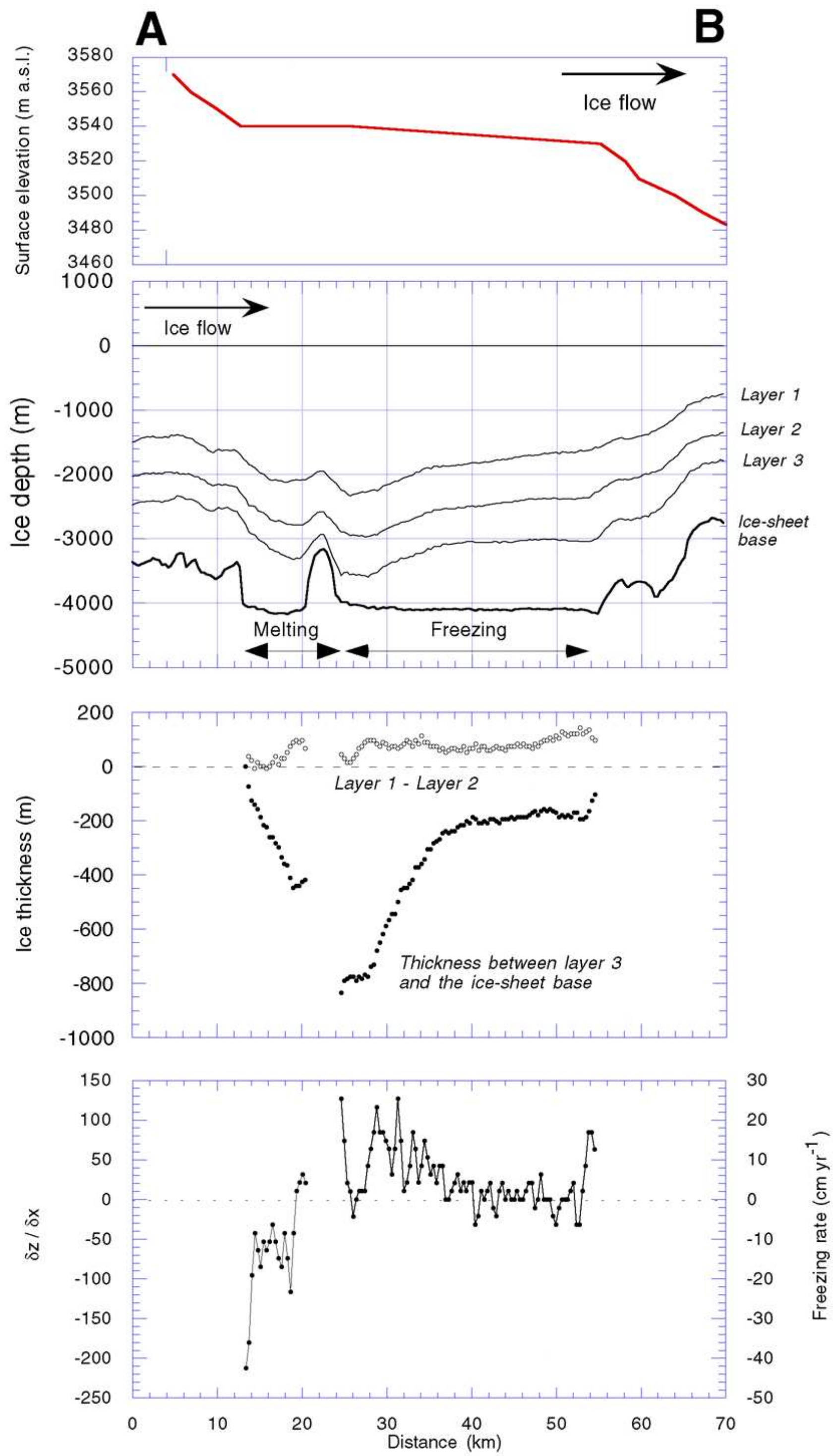

Figure 6: Calculation of the change in ice thickness between the top two internal layers, and the change in ice thickness between the lowest layer and the ice-sheet base.

water interface (Fig. 6d). This zone is followed by a thirty kilometer-long region of net freezing with an accumulation rate of up to 8 cm yr^{-1} (Fig. 6d). These data, therefore, indicate significant release of water from the ice sheet to the lake over the first 10 km of the transect, which is followed by net refreezing of lake water to the ice base.

Using these estimates approximately 400 m of basal ice will be accreted to the base of the ice sheet as it traverses the central portion of Lake Vostok. This compares to the 200 m of refrozen ice observed 100 km to the south at Vostok Station in the narrow portion of the lake (Fig. 5). The melting of the ice sheet as it first encounters the lake provides a supply of water, gas hydrates, biological debris and sediments to the lake. The sediments and gas hydrates will be deposited at the base of the lake, while the water will be refrozen in the base of the ice sheet in the accretion zone. The refrozen or accreted ice appears to be derived from freshwater (J. R. Petit, pers. comm.).

This investigation indicates how basal ice-sheet conditions may be identified from analysis of airborne radar data. However, the present radar dataset is too sparse to provide a detailed analysis of ice-sheet basal melting and freezing for the entire 14000 km^2 area of the lake. New radar data are therefore required to extend this investigation over the full extent of Lake Vostok. Analysis of new surveys will quantify the total volume of water involved in the exchange between the ice sheet and the lake, and allow calculation of the input of non-ice material to the lake. This volume estimate will supplement the glaciological parameters that radar measurements will provide.

EVIDENCE FROM THE VOSTOK ICE CORE STUDIES

J. R. Petit
LGGE-CNRS, BP 96, 38402 St. Martin d'Hères Cedex, France,
p. +33 (0)4 76 82 42 44, fax +33 (0)4 76 82 42 01, petit@glaciog.ujf-grenoble.fr

As part of the long term Russian-American-French collaboration on Vostok ice cores, started in 1989, the drilling of hole number 5G was completed during the 97-98 field season. Ice coring reached 3623 m depth, the deepest ice core ever obtained. The drilling operations stopped 120 m from the ice/water interface to prevent contamination of the underlying lake by kerosene based drilling fluid.

The ice core continuously sampled for paleoclimate studies and discontinuous sections have been sent to selected laboratories in three countries. Below 3350 m depth, one half of the main core was cut as a continuous archive for future studies, and stored at -55°C in an ice cave at Vostok station. The very good quality and transparency of the retrieved deep ice allowed for continuous visual inspection of the ice inclusions, studies of ice crystals, and measurements of electrical conductivity. Preliminary isotopic measurements of the ice, (deuterium, δD), and analyses of the gas and dust content have be performed on selected deep ice samples.

The upper 3000 m of the ice core (88% of the total ice thickness) provides a continuous paleoclimatic record of the last 400,000 years. The preservation of this paleoclimatic record is due to the slow velocities of the glacier ice and the low accumulation rates at Vostok Station (presently 2 cm water equivalent per year). Preliminary studies of the ice have yielded information on; a) the local temperature and precipitation rates (from isotopic composition studies); b) aerosol fluxes of marine volcanic, and terrestrial origin (from chemical, ECM and dust content analyses); c) atmospheric trace gases (in particular the greenhouse gas content [CO_2 and CH_4] and the isotopic composition of this "fossil" air); and d) the physical properties of the ice, including air hydrates, ice crystals. The preliminary results of these studies indicate that the main patterns of the Vostok temperature are well correlated to global ice volume from deep sea sediments, back to the marine stage 11 (circa 400,000 BP) (Petit et al., 1999). The record shows four complete climatic cycles, including four ice age or glacial periods associated with the development of large ice sheets over the Northern Hemisphere, and four transitional warmer interglacial periods (Petit et al., 1998).

Between depths of 3300 m and 3538 m, the layering is disturbed by ice sheet dynamics. For example, at 3311 m depth, three volcanic ash layers 10 cm apart are tilted in opposite directions. Moreover, 10 m deeper, at 3321 m, stable isotope content, gas composition and dust concentrations of the ice, display very sharp and significant variations which cannot be of climatic origin. In these deep layers, the geochemical parameters interpreted as climatic proxies can no longer be interpreted as the glacial-interglacial cycles. The observed values are intermediate between glacial and interglacial levels, suggesting the layers have been mixed. At the base of this ice there is evidence of disruption due to ice sheet dynamics (3460 - 3538 m). The ice contains randomly distributed moraine particles with particle sizes up to a few millimeters in diameter, indicative of an active shear layer.

Beneath these disturbed and apparently mixed layers, (below 3538 m) the ice character changes dramatically: ice crystals are very large (10-100 cm), electrical conductivity drops by two orders of magnitude, stable isotope content of ice shifts, and gas content becomes two orders of magnitude lower. These drastic and related changes, indicate that the basal ice at this location is re-frozen lake water. The accreted ice at the base of the Vostok core is about 220 m thick, or 6% of the total ice thickness.

The ice from the Vostok basin originates from the Ridge B area and flows over the lake in a manner similar to an ice shelf. Temperature in the ice sheet and melting or freezing events at the base are linked to ice sheet dynamics and lake and bedrock heat fluxes. Whilst Lake Vostok exhibits evidence of large scale melting, the flow line passing through Vostok site indicates a significant refreezing event. This provides a constraint that must be taken into account when modeling the ice paths and dating the climatic record.

Sampling the lake and underlying sediments is necessary, but will require the development of "clean" sampling techniques. A continuation of geophysical measurements in the existing bore hole, and complementary studies of deep ice from Vostok, may provide important insights into the ice sheet, regional geology and the lake.

TECTONIC SETTING OF LAKE VOSTOK

Ian Dalziel
Institute for Geophysics, University of Texas, Austin, 4412 Spicewood Springs Rd., Bldg. 600, Austin TX 78759-8500,
p (512) 471.0431, f (512) 471-8844, ian@ig.utexas.edu

Lake Vostok is located at 77°S, 105°E within the East Antarctic Precambrian craton, remote (>500 km) from both the Neoproterozoic rifted Transantarctic margin and the Mesozoic rifted margin south of Australia and India. Its specific geologic setting is completely unknown.

It has been suggested on the basis of limited geophysical data that the Lake occupies a structural depression such as a rift (Kapitsa et al., 1996). Assuming this to be correct, several plausible scenarios can be developed that would explain the tectonic setting of such a depression in central East Antarctica:

Intracratonic Rift associated with Extensional Processes: Given the presence of the extensive Lambert-Amery aulacogen along the Indian Ocean margin of the craton at 69°45'S, 71°00'E, Lake Vostok could occupy an intracratonic rift valley comparable to the lakes of the East African rift. An aulacogen is a rift system penetrating a craton from its margin. This could be either an active rift system, as suggested by Leitchenkov et al. (1998) or an ancient and tectonically inactive rift. Despite the presence of a young volcanic edifice at Gaussberg, also on the Indian Ocean margin at 66°48'S, 89°11'E, there is nothing to directly indicate present tectonic activity in the Lake Vostok area. Gaussberg is >1000 km distant and located at the termination of the Kerguelen oceanic plateau. The Antarctic continent is anomalously aseismic, and only proximity to the Gamburtsev Subglacial Mountains with their unusual 4 km of relief at 80°30'S, 76°00'E might be taken to indicate any local tectonic or magmatic activity. These mountains, which do not crop out, could be like the Cenozoic Tibetsi or Hoggar volcanic massifs of North Africa. Again, however, there is no direct evidence of recent, let alone active, volcanism or tectonism in central East Antarctica. Evidence from sedimentary strata within the Lambert-Amery system suggests that this aulacogen is of Paleozoic age, and may be the southern limb of a rift in India that predates Mesozoic opening of the Indian Ocean basin (Veevers et al., 1994).

Rift Resulting From a Continental Collision: A depression containing Lake Vostok and the Gamburtzev Subglacial Mountains could be in a setting similar to Lake Baikal and the Tien Shan Mountains or Mongolian Plateau, i.e. a rift and intracratonic uplift associated with transmission of compressive stress thousands of kilometers into a continental interior as a result of collision with another continent. Unlike Lake Baikal, however, Lake Vostok is not situated within a craton that has undergone Cenozoic collision like that of Asia with India. Veevers (1994) has suggested that the Gamburtzevs may have resulted from far-field compressive stresses associated with the amalgamation of Pangea at the end of Paleozoic times along the Ouachita-Alleghanian-Hercynian-Uralian suture. Alternatively, uplift and rifting within the East Antarctic craton could have been generated in the latest Precambrian "Pan African" continent-continent collision of East and West Gondwanaland along the East African orogen (Dalziel, 1997). The early Paleozoic Ross orogen along the Transantarctic Mountain margin was a subduction related event which is not likely to have transmitted compressive stress far into the cratonic interior. Consideration of subduction-generated Andean uplifts, however well to the east of the present Pacific margin of South America, demands that this possibility also be kept open.

Hot Spot or Mantle Plume Driven Depression: Plate tectonic reconstructions maintaining the present day positions of the Atlantic and Indian ocean basin "hot spots" such as Tristan da Cunha and Reunion islands, indicate that several of these (notably Crozet-Heard and Kerguelen) could have been beneath East Antarctica prior to the opening of the Southern Ocean basins. The Gamburtzev Subglacial Mountains and an associated Lake Vostok depression could owe their origin to such activity.

Glacial Scour possibly Eroding an Older Feature: An erosional origin for the Lake Vostok depression, i.e. a Lake Ontario-type scenario, is possible, but could also have its origin in tectonism. For example, several of the Great Lakes occupy depressions formed during the development of the North American mid-continent rift system at 1100 Ma that was excavated by the Laurentide ice sheet during Cenozoic glaciation of that continent.

Meteor Impact: Circular depressions in the interior of cratons can form as a result of meteor impact. Even the elongate depression indicated by the shape of Lake Vostok could result from a bolide impact scar modified by subsequent tectonism, as in the case of the elliptical Sudbury basin in Ontario, Canada.

Hence the age of the depression that Lake Vostok appears to occupy could have resulted from a variety of tectonic causes, and could range in age from Precambrian to Recent. At present, there is no evidence to indicate that the setting is tectonically or magmatically active. Several lines of investigation should be undertaken to clarify the tectonic setting, and hence the likely history and possible present activity of the feature:

1. Airborne geophysical survey of the region surrounding the lake;
2. Seismic refraction profiling to ascertain the deep crustal structure beneath the lake;
3. Seismic reflection profiling to determine the shallower structural setting, nature of the sedimentary fill, and relation to overlying present ice sheet and its base;

3. Comparable geophysical studies of the Gamburtzev Subglacial Mountains; and
4. Sampling of the Gamburtzev Subglacial Mountains by drilling - evidence of a young volcanic construct locally would dramatically change the geologic picture.

EXPLORING MICROBIAL LIFE IN LAKE VOSTOK

James M. Tiedje
Center for Microbial Ecology, Michigan State University,
540 Plant and Soil Science Building, East Lansing, MI 48824-1325,
p (517)-353-9021, f (517)-353-2917, tiedjej@pilot.msu.edu

Microorganisms have been on Earth at least 3.7 billion years and during this evolutionary history have developed incredible biochemical, physiological and morphological diversity. Members of the microbial world encompass the three domains of life, the *Bacteria*, the *Archaea*, and the lower *Eukarya*. This diversity encompasses organisms with novel redox couples for production of energy; adaptations to extremes of temperature, salt, and pH; novel energy acquisition mechanisms as well as strategies for withstanding starvation. About 4,200 prokaryotic species have been described out of an estimated 10^5 to 10^6 prokaryotic species on Earth. Many of the extant microorganisms have not been cultured in the laboratory and hence remain unknown because we apparently cannot reproduce their environment in the laboratory.

Conditions in Lake Vostok are not so severe as to make microbial life impossible. Hence, at least some forms of microorganisms should exist in Lake Vostok water and sediment. The founding populations (original inoculum) could come either from the rock or sediment prior to ice cover, or from microbes trapped in the ice that are slowly transported through the ice to the water. In either case, Lake Vostok microbes would have been isolated from their global relatives for at least 1 million years. Some changes in genotype and even phenotype could have occurred during this time, presumably making the organisms more adapted to this cold, dark, oligotrophic environment. The time scale of 1 million years, however, is not long in terms of prokaryotic evolution when compared to their 3.7 x 10^9 year history. As points of reference, the *E. coli-Salmonella enterica* genospecies, which are closely related organisms but differentiated because of their health importance, are considered to have diverged only in the last 100 million years (Lawrence and Ochman, 1998). Hence, species level differentiation may take at least 10-100 million years. Secondly, changes due to mutation (silent mutants) occur at the rate of approximately 5 x 10^{-10} per base pair (bp) per replication (Drake et al., 1998). Assuming an average gene size of 10^3 bp and 10 generations per year, one would expect on average a change in only one base pair per gene in the 1 million years since Lake Vostok microbes have been isolated from their relatives. Other mechanisms of genetic change, especially recombination and mutator genes, could have altered organism phenotype more rapidly allowing for adaptation to Lake Vostok conditions. The above discussion is based on the conservative estimate of biological isolation by the ice cover of 1 million years. If the original inoculum were derived from rocks or sediments that had been sealed from surface microbial contamination pre-Lake Vostok, their age of isolation would have been longer, probably 35-40 million years. It should be noted that this form of isolation is not unique to Lake Vostok rocks.

The major biological questions to be addressed in Lake Vostok would appear to be the following:

1) Who (what taxonomic groups) lives there?
2) How different are the Lake Vostok organisms from what we already know?
3) Who are the Lake Vostok organisms related to and from what habitats do these related organisms arise?
4) Which of the Lake Vostok organisms are metabolically active?

5) How do these organisms live in this unique environment? Where do they get their energy (geothermal?, clathrates [gas hydrates]?, other?), and do Lake Vostok natives have special adaptive strategies for this environment?

Microbial exploration of a new ecosystem such as Lake Vostok should include three complementary approaches since each gives unique and vital information: nucleic acid-based methods, microscopy, and the isolation-cultivation approach. The nucleic acid-based methods provide much more comprehensive information on the community than culture-based methods and, through sequencing of small subunit ribosomal RNA genes (SSU rRNA), provide information on the organism's identity. rRNA-based methods such as sequencing of clone libraries, fluorescent terminal restriction fragment length polymorphism (T-RFLP) analysis, denaturing gradient gel electrophoresis/ temperature gradient gel electrophoresis (DGGE/TGGE), fluorescent in situ hybridization (FISH), and quantitative hybridization by phylogenetic group probes, are well proven methods for exploring the microbial community of new habitats such as Lake Vostok. Other phylogenetically important genes such as 23S rRNA, intergeneric spacer regions and *gyr*B may also be useful. Once pure culture isolates are obtained, reverse sample genome probing (RSGP) can be used to quantify the importance of isolated organisms in the total community.

Microscopy remains a powerful exploratory approach because it is the best method for comprehensive observation and quantification of the microbial community. New forms of microscopy such as confocal laser scanning and environmental scanning electron microscopy, as well as coupling microscopy with the use of fluorescent probes of various types can reveal key information both on organism's identity as well as on their activity.

Isolation and cultivation of pure cultures remains the primary means to fully characterize a microorganism, including its metabolic capacity, unique physiology, confirming its taxonomy and for studies at the molecular level. An example of the latter could be to identify genes responsible for adaptation to cold, genes potentially useful to making plants more winter hardy. Strategies that might be useful for cultivating Lake Vostok organisms would be to minimize the shock of warming, matching the ion composition of the medium to the lake water, maintaining oligotrophic nutritional conditions yet stimulating growth, and planning for a long incubation period.

Special challenges for the study of Lake Vostok microbes would likely include the following. Very low densities of microbes, which is probably the case in Lake Vostok, always requires special methodologies to concentrate cells. Furthermore, risk from contamination from outside microbes is more problematic. Determination of the metabolically active cells versus resting or dead forms, is especially difficult at low temperatures because of the low metabolic rate. Isolation and cultivation of oligotrophic microbes is always difficult. The more interesting microbes are likely to be the ones most difficult to cultivate and isolate. It may be difficult to determine whether what is found is really new and unique since so many of the world's microbes remain unknown. To answer this question one may have to seek "Lake Vostok-like" relatives outside of Lake Vostok once the former are characterized.

Abyzov and colleagues have studied microbes in the Vostok ice core by microscopy and cultivation (Abyzov et al., 1998). They find low densities (10^3 cells/ml) of microbes in the ice core extending to ages of 240,000 years, the oldest period on which they have reported. Microbial density fluctuated with ice core age, being higher when the dust particle density is high, which also corresponds to periods of greater atmospheric turbulence. Bacteria were the most prevalent microbial cells, but yeast, fungi, microalgae, including diatoms, were also seen. Thawed ice samples assimilated ^{14}C-amino acids establishing that some of the cells were alive. Most of the organisms that were isolated from the ice core are spore-formers, e.g. *Bacillus*. Attempts to isolate more oligotrophic types apparently have not been made. Organisms from the ice core could be one source of inoculum to Vostok Lake.

Studies on the microorganisms of Antarctica and buried Arctic permafrost soils have relevance to Lake Vostok questions. Culturable strains from 1 million year old buried arctic permafrost soil belong to the *Planococcus, Psychrobacterium, Arthrobacter, and Exigobacterium* groups. It is interesting that the closest relatives of some of these strains are found in Antarctica. Some of the ancient arctic isolates grow relatively rapidly at -4.5°C. Hence, growth rate at the Vostok temperature of -3.2°C would not appear to be a limitation. The major limitation to microbial density in Lake Vostok would be a renewable supply of energy. If clathrates (gas hydrates) were present, the potential microbial use of this energy source would be particularly intriguing.

LAKE VOSTOK PLANETARY ANALOGS

Frank Carsey
California Institute of Technology Jet Propulsion Laboratory
JPL ms 300-323, 4800 Oak Grove Dr., Pasadena CA 91109,
p (818) 354-8163, f (818) 393-6720, Frank.D.Carsey@jpl.nasa.gov

About the time that the true scale of Lake Vostok was generating excitement in the Earth Science community, spacecraft images and other data of the Galilean satellites of Jupiter similarly electrified the Planetary Science community, and for a similar reason: in both cases strong evidence was suddenly provided for large, previously unknown bodies of water which might well be home to unique life forms. As of this writing, large, old, subsurface oceans are suspected on both Europa and Callisto, and water ice is known or speculated to occur in a great number of other sites, including Earth's moon. Meanwhile, the microbiologists are revolutionizing the picture of biodiversity of life on Earth and repeatedly astounding the scientific community and the public with information on microbes thriving in sites long considered untenable for life. These developments are obviously interrelated; it is clear that explorations of Lake Vostok and Europa/Callisto have much in common, including the scientific excitement of exploring a new place.

The chief similarity is in the primary scientific goals at Lake Vostok and the Jovian satellite oceans, the search for life. In the Jovian system, this search must be carried out robotically, and the robotic approach has much to offer in various sites on Earth where such issues as contamination prevention and remoteness make sample removal challenging. Lake Vostok, in particular, is a site in which low temperatures, high pressures, low salinity, isolation, and great age indicate an oligotrophic environment. This suggests that life could occur in highly specialized microbial communities with low populations. This situation may not be representative of Europa or Callisto, as these sites may be prebiotic. However, the exercise of locating and examining life in small numbers is clearly excellent preparation for sites which may have no life forms at all. The scientist will be testing a system trying to establish a negative, which is demanding. Similarly, at both Earth and planetary sites, the issue of evaluating habitat and bioenergy sources will be crucial.

In addition to the physical and scientific similarities, the technologies required for accessing and studying the liquid water domains at Lake Vostok and Europa/Callisto have numerous elements in common, many of them quite challenging. Both sites require vehicles that can move through great distances of ice, 4 to 10 km vertically; both sites require communication of data through the ice and water; both sites require sophisticated instrumentation to locate and describe life and evaluate habitats; and both sites call for exploration with little basic data on site characterization as they are unknown places. In addition, it is worth noting that when a NASA mission goes to a planetary site it can take only the smallest quantity of equipment, yet it must do a sophisticated job. These kinds of capabilities could greatly benefit Earth-bound science, especially in polar regions, as the investment in on-site support could be dramatically reduced, and more of the agency resources could go into science. Additional sites exist on Earth with key similarities to both the deep ice sheet and the oceans of Europa/Callisto, e.g., the deep ocean. Timely and interesting projects that promise multi-use developments for all three sites include observations of clathrates, high pressure habitat characteristics, and microbiological studies.

There is clear benefit in collaborative efforts of U.S. and foreign agencies concerned with cold-region science and operations, aqueous instrumentation and robotics, high pressure/low temperature processes in water and sediment, and extremophile biology. There are programmatic vehicles in place to initiate and coordinate these collaborations, NSF, NASA, the Polar Research Board and the Scientific Committee for Antarctic Research. Communications with and among these agencies should be encouraged.

IDENTIFICATION OF LIFE

David C. White
University of Tennessee, ORNL, JPL, 10515 Research Dr., Suite 300Knoxville TN 37932-2575, p (423) 974-8001, f (423)974-8027, Milipids@aol.com

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Lake Vostok as a pristine, cold, dark, high-pressure, and large lake provides a new extreme environment in which to search for indigenous microorganisms that have been isolated from the rest of the biosphere for a long time. Thus it is of paramount importance to prevent contamination of the lake by organisms from the overlying ice or contaminants introduced by the sampling device during the assessment process. The parallels to the detection of life on the Jovian moon Europa with a thick ice layer provide an excellent venue for monitoring the Planetary Protection technologies' life detection through a thick ice cover. The technologies discussed below were derived for use within the space program, but are applicable to the Lake Vostok exploration project.

The cleaning, sterilization, and validation technologies for extraterrestrial life detection require extraordinary "instrument" protection. Since the life forms that might be encountered may not conform to the rules of life as currently understood, the JPL Astrobiology team under Ken Nealson has defined the criteria for life as having some essential characteristics that form the basis for life detection:

1. Life detection technology will require mapping those localized areas of heterogeneities in the distribution of biomarkers between the putative life forms and the background matrices. These localized areas of putative life forms must also show concentrations of biomarkers and state conditions far from chemical equilibrium in the components of cells, macromolecules, smaller molecules, and/or elements. The system requires mapping in space and time to demonstrate localization of these heterogeneities and their metabolic activities.

2. The system must have an exploitable energy source and this source for extraterrestrial life may be non-traditional. Non-traditional energy sources could be tidal, radiation, heat, wind, or magnetic, not typical of the visible solar or chemosynthetic redox driven energy systems currently understood.

3. Whatever the system, the basic chemistry must be thermodynamically feasible.

These broad constraints indicate that these missions will require much more comprehensive "instrument" cleaning than the Viking standard of 300 viable spores/m^2. This was considered adequate twenty years ago when the entire spacecraft was held at 112° C for a long period so that no cells known on Earth were known to survive the treatment. This was prior to the discovery of the hyperthermophilic Archaea from the deep oceanic hydrothermal vents.

The sterilization technologies currently under examination at JPL utilize hydrogen peroxide under pressure (oxidative sterilization) and low temperature non-oxidative use of supercritical fluid or other solvents that result in cell lysis, leaving no organic residues. The hydrogen peroxide yields water and oxygen. Not only must the critical areas of the spacecraft be sterile they must be cleaned of biomarkers that could interfere with the detection of life. Life detection will be based in part on detection spatial heterogeneities in concentrations of biomarkers.

The JPL efforts in "instrument" cleaning are currently exploring *in situ* destruction techniques utilizing ultra-violet with photodynamic activation and deep ultra-violet delivered in a vacuum. This is used in combination with various types and recovery techniques more effective than the previously employed cotton swab with 70% aqueous alcohol at room temperature and pressure. Whatever the technology utilized for cleaning, the residue left on the "instrument" after cleaning must be analyzed quantitatively, structurally identified, and mapped. Validation of the cleaning will require detection of biomarkers in cells, macromolecules, and small molecules. Cells will be detected and mapped microscopically and live/dead determinations made. These are currently compared to traditional viable culture methods that are required for flight. Nucleic acid macromolecules will be determined by polymerase chain reaction (PCR) of various nucleic acid polymers and enzymes that detect their activity. Small molecule detection will exploit diagnostic lipids. Lipids can quantitatively indicate viable biomass by differentiating the polar phospholipids, which are lysed by endogenous phospholipases during cell stress forming diglycerides. The nutritional/physiological status, as well as the community composition, can be determined by analysis of specific lipid components, which with HPLC/electrospray ionization/ tandem mass spectrometry can be detected at the subfemtomolar levels (approaching detection limits of a single bacterial cell). Spores can be detected in this system by their dipicolinic acid content. Lipid analysis has the potential for automation and speed by the application of enhanced solvent extraction at high pressure saved temperatures. Components like amino acids, carbohydrates, nucleotides can be detected at subfemtomolar concentrations by capillary electrophoresis which has great potential for miniaturization. There is a possibility of using tracer biomolecules labeled with several isotopes at unusual concentrations that can be clearly identified. These techniques would provide a direct estimate of the degree of contamination after the cleaning procedures have been completed.

The JPL program currently utilizes modifications of extant analytical detection methods and equipment to analyze "coupons" exposed on the "instrument". (Coupons or "witness plates" are recoverable surfaces on or around the spacecraft that are exposed and then removed for analysis; they can also be used to test various cleaning methods by putting a known contaminant mixture on them and then analyzing the biomarkers after treatment.) Alternative recovery methods of solvent or adhesive polymers like the Scotch tape 5414 used in forensic investigations are being explored. A proposed second level of analysis would involve direct detection from the "instrument" using soft X-rays, Raman, infrared, or fluorescent detectors that could be mapped on a virtual "instrument" and successively cleaned. The next level would be on-line reporting of *in situ* biosensors built into the "instrument". These would be developed into the *in situ* life detection systems that monitor the extraterrestrial site and validate planetary protection.

Significant research remains to be done and adequate methods need to be in place by 2000 if the new methods are to be used during sample return missions. International collaboration with industries, academia and the government will be required to fulfill the responsibility to protect Lake Vostok from contamination.

MICROBIAL CONTAMINATION CONTROL

Roger G. Kern
Technical Group Lead/Planetary Protection Technologies
Mail Stop: 89-2, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109
p (818) 354-2233, f (818) 393-4176, Roger.G.Kern@jpl.nasa.gov

The Jet Propulsion Laboratory's Planetary Protection Technologies Group is currently assessing the feasibility of entering Lake Vostok without introducing new types of microorganisms into the lake. Since the inception of robotic missions to the Mars surface, Viking Landers 1 and 2 in the mid 1970's, JPL has had an interest in this specialized type of microbial contamination control. The objective of the Vostok microbial contamination protection research is to prevent contamination of Lake Vostok with viable microbes from the Earth's surface while enabling the robotic exploration of the lake.

The Vostok contamination control challenge is composed of three parts: 1) delivery of a clean and sterile probe to the ice surface 4 km above the lake; 2) preventing contamination of the probe as it is lowered down a warm water drilled bore hole to within a few hundred meters of the lake surface; and 3) performing a sterilization event upon entering the ice at the base of the bore hole to enable the melter probe to proceed without introducing viable surface microorganisms into the lake. Microorganisms present in the ice immediately above the lake are constantly raining into the lake as the ice melts, at an estimated rate of 1 to 2 mm per year, and are therefore not considered contamination in this approach. An environmentally benign chemical sterilization is being tested that could take place at the base of the bore hole and would permit entry into the ice above the lake without entraining viable microbes from the surface.

JPL is currently adapting methods under development by the Mars Exploration Technology Program for application to aqueous environments such as Lake Vostok and the suspected Europan ocean. For future exploration of the surface of Mars, JPL is currently evaluating basic decontamination approaches for the efficacy against microbial cells and molecular cell remnants; proteins, nucleic acids, lipids, and carbohydrates. These initial studies have focused on hardware surface cleaning to remove materials of biological origin from all surfaces both inside and outside the probe. Cleaning techniques being evaluated at JPL include: hydrogen peroxide plasma sterilization; 70% sterile ethanol wash; and existing precision cleaning methods. Sterilization techniques being evaluated at JPL include: hydrogen peroxide plasma; gamma irradiation; and a dry heat procedure developed for the Viking mission to Mars.

At present four methods for characterizing biological contamination are being evaluated for use in verifying the level of cleanliness of hardware. The first of these is a viable count assessment based on the ability to remove and culture a single viable organism on tryptic soy agar. The second method does not require microbial growth since it is widely recognized that less than 1% of the total microbial world is currently culturable. Epifluorescent microscopy is being adapted for validating microbial cleanliness. Microbes sampled are transferred to a 0.2 micron filter where cells are suitably stained to enumerate the total population as well as confirm the absence of viability. This allows the assessment of the microbial population independent of ability to culture in the laboratory. PCR techniques are being employed to detect the presence of trace amounts of DNA associated with the sampled surfaces. Recently capillary electrophoresis has been added to JPL's list of approaches for determining the presence or absence of trace biological molecules associated with hardware. This research into cleaning and sterilization methods, as well as techniques to validate cleanliness is ongoing, and new approaches are constantly being evaluated to achieve and assure a level of cleanliness and the absence of viable microbes.

These ongoing planetary protection efforts can be applied to the NASA Vostok Probe (consisting of a cryobot and hydrobot) and instrumentation, and the overall mission design. The current planetary protection technologies research effort will influence the selection of materials compatible with cleaning and sterilization procedures. Recommendations are awaiting results that are expected in 1999. Materials compatibility studies could lead to the co-location of components with similar cleaning and sterilization constraints (i.e. electronics, optics, chemical sensors).

The protection of Lake Vostok presents challenges new to NASA, since the probe does not transverse sterile space, but rather a water column containing viable surface organisms and ice containing a very low level of viable spore forming microbes. The mission sequence will be determined by unique forward biological contamination constraints. The current mission approach calls for a sterile biobarrier capable of permitting pressure equalization, to deliver the probe to the base of a warm water drilled bore hole. Prior to further descent of the probe by ice melting, an antimicrobial oxidizing agent would be employed to kill organisms present at the base of the bore hole.

At present, experiments are underway to assess the application of 30% concentrated hydrogen peroxide (H_2O_2) to sterilize both the water at the base of the borehole as well as the ice surfaces around the probe. Freezing point suppression caused by the release of H_2O_2, results in the melting of ice at the bore hole base and formation of a sterile slush as the H_2O_2 self dilutes to a concentration permitting the solution to freeze. Using this approach it may be possible to execute a surface sterilization event at the base of the bore hole in the ice, hundreds of meters above the lake. A straight forward experimental design to test the efficacy of ice formation *in situ* with respect to H_2O_2 concentration, temperature and time, is planned to evaluate this approach.

The ability to enter the Lake without contamination that could impact either the environment or the scientific goals of the mission, will require stringent cleaning, sterilization and verification methods. The proposed mission sequence for the Vostok melter probe calls for a sterilization event to occur at the base of the bore hole that will enable the already sterile probe to leave its biobarrier, pass through sterilized ice, and proceed to the lake's surface entraining only those living microorganisms that naturally rain into the lake as the glacial ice melts. The only organisms recovered by culture to date from deep drill cores at Vostok station are spore-forming bacteria and actinomycetes although others may be present and as yet not detected.

(5) Group Reports

Each of the five working groups was tasked with developing scientific goals for a program, justifying the program, developing a strategy and time-line to accomplish the goals, and justifying why Lake Vostok is the preferred study site.

GEOCHEMISTRY WORKING GROUP CONCLUSIONS

Group Members: Mahlon C. Kennicutt II (archivist), Todd Sowers, Berry Lyons, Jean Robert Petit

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JUSTIFICATION FOR LAKE VOSTOK STUDIES

Due to the remote location and the complexity and cost of the logistics to mount a study of subglacial lakes, it is imperative that the scientific return from such a study be justified in light of the resources needed to accomplish the program. In particular, it is important to elucidate what it is that makes subglacial lakes a high priority for study, and in particular why Lake Vostok is the preferred site amongst all other possible sites. On the first issue, the “extreme” environment under which the lakes exist suggests that fundamental questions related to an array of scientific issues could be addressed by an interdisciplinary study of subglacial lakes. Life at the extremes is justified in the context of the ongoing LExEn program. From a geochemical standpoint, the subglacial lake systems represent an unique and unparalleled combination of physical and chemical environments. The lakes are unique in the low temperatures and high pressures encountered, the total darkness, the origins of the water in the system (suspected to be fresh), the overlying thickness of ice, and their isolation from the atmosphere for long periods of time. It is hypothesized that this combination of attributes will lead to an unique geochemical system that is duplicated under few, if any other, circumstances world-wide. While individual attributes can be found in various locations (dark, cold, and high pressure in the deep sea) the combination of traits described above is only found in subglacial lakes.

Amongst subglacial lakes, the most obvious characteristic of Lake Vostok that differentiates it from the 60 to 80 other known lakes, is its size. Lake Vostok is believed to be the largest subglacial lake on the Antarctic continent. The size of the lake imparts attributes that make it well-suited for an initial study of subglacial lakes. The size of the lake suggests that Lake Vostok is the most likely site for a fully developed subglacial lake system that might be precluded in other smaller lakes. The varying water depths, the varying and substantial sediment accumulations, the varying thickness of the overlying ice sheet, and the sheer size of the lake suggests that the likelihood of physical and chemical gradients within the lake is high. The physical setting suggests that circulation, stratification, and compartmentalization within the lake is likely. This setting is believed to be the most favorable for supporting a fully developed subglacial lake system and provides the greatest likelihood that biological systems have inoculated and developed within the lake.

GOALS FOR GEOCHEMICAL INVESTIGATIONS

1) The first and foremost goal of any geochemical investigations would be to characterize the structure of the lake's water column. Due to the low temperatures and high pressures it is believed that hydrates of various gases will play an important role in determining the distribution of the lake's geochemical properties. Stratification of the lake in very unusual ways may occur due to density differences between various gas hydrates, some heavier than water and some lighter, and the suspected cycles of thawing and freezing that appear to characterize different regions of the

lake. In a more standard sense, initial studies of the lake would establish the limnological characteristics of the lake both vertically and horizontally including, for example, the distributions of salinity, temperature, major ions, and nutrients.

2) As a follow on to the discussion of hydrates, the gaseous constituents of the lake would also be a high priority for investigation. The physical occurrence of gaseous constituents and the partitioning between free, dissolved and hydrate phases will be important to establish. The origins of these gases should also be explored through the use of stable isotopic analysis of various key elements. It would also be important early in the study of the lakes to determine the distribution of those geochemical properties most directly affected by the presence of biota, in particular microbiota. These properties include, but are not limited to: redox potential, pH, sulfate reduction, methanogenesis, metal and nutrient concentrations.

3) Due to the emphasis on the theme of life in extreme environments, the carbon cycle would be an area of special emphasis for geochemical investigations. The system is expected to be unique in that cold water carbonates and hydrates of hydrocarbon gases may be important reservoirs of carbon. The carbonic acid system may also be unusual at the ambient high pressures and low temperatures. The origins and cycling of organic carbon in the lakes will also be of special interest. The distribution between dissolved and particulate organic carbon and the portions of the pools that are biologically available will be important considerations. The reservoir of carbon in sediments may also be important for sustaining any extant biological systems.

4) Finally, the interaction between the geochemical properties of the lake and the circulation within the lake will be important to characterize. Redistribution of chemicals in the lake and the development and location of physical and chemical gradients may be important in developing and sustaining biological systems.

JUSTIFICATION FOR GEOCHEMICAL INVESTIGATIONS

Geochemical investigations of subglacial lakes are critical to interdisciplinary studies to determine the origins and functioning of subglacial lake systems. Geochemical properties are widely recognized as evidence of the presence of life in systems. It can be argued that some of the more easily measured attributes of a system that provides evidence of biological processes are geochemical distributions and patterns. Biological processes are known to produce and consume various compounds in the process of living and surviving in aquatic systems. The water and the sediments of the lake are also a repository of chemicals derived from various interactions over the lifetime of the lake. As such, geochemical distributions and patterns are keys to understanding the origins of various lake constituents. As previously mentioned, subglacial lakes also represent geochemistry at the extremes of temperature, pressure, light, and isolation suggesting that the study of these lakes will provide insight into geochemical systems in general. Areas of particular interest where geochemical investigations will be key in providing information are the age of the lake and the origin of the water.

The sedimentary record is an important repository of evidence of the history and evolution of the lake. Organic and inorganic geochemical markers of the lake's history may be deposited and preserved in the sedimentary record. Geochemical investigations are fundamental to addressing a wide range of interdisciplinary questions related to the evolution and history of subglacial lakes as well as documenting the functioning of these unique systems.

STRATEGY TO MEET GEOCHEMICAL GOALS

Most of the investigations that are important for the geochemistry component of an interdisciplinary study of subglacial lakes rely on standard and proven technologies. However, if it is proposed that the first entry into the lake will be in a non-sample retrieval mode, appropriate sensors for measuring geochemical attributes of the water column need to be developed. As mentioned above, inferences related to the presence of life can be obtained by measuring specific geochemical characteristics of the lake. Initial establishment of the water column structure and heterogeneity will require real-time *in situ* detection of geochemical properties.

Once the investigations have proceeded to sample retrieval, the methods to be used are readily available and proven. In order to optimize the information return from geochemical investigations, water column profiles at multiple locations will be necessary. Time series measurements will also be important to determine if the lake is static or dynamic on short timeframes (< 1 yr). A range of technologies including continuous measuring sensors left in place, profiling sensors, and discrete samples will be required to address the goals of the geochemical investigations.

TIMEFRAME

Geochemical investigations will be key to an interdisciplinary study of subglacial lakes. A range of characterization activities would be an initial goal including water column structure, the distribution and occurrence of gaseous components, the reservoirs and cycling of carbon, and the biogeochemical processes operating in the lake. The vertical and horizontal distribution of essential chemicals in the lake will reflect interactions with lake circulation and the alteration of these patterns by organisms. Geochemical measurements will be key in determining the age, the origins of various constituents, the history, and the evolution of the lake. Most technologies are currently available but development of remote sensors of geochemical properties will be needed. It is estimated that one to three years will be needed to develop these new technologies.

BIODIVERSITY WORKING GROUP CONCLUSIONS

Group Members: Cynan Ellis-Evans (archivist), José de la Torre, Dave Emerson, Paul Olsen, Roger Kern, Diane McKnight

JUSTIFICATION FOR LAKE VOSTOK STUDIES

The compelling science justification for undertaking research at Lake Vostok is:

1) the unique nature of the environment - permanently cold, dark, high pressure freshwater environment;
2) this lake may lie within a rift valley of as yet undetermined age or activity - this offers the potential for geothermal processes comparable to the hydrothermal vents of the ocean abyss;
3) the spatial scale of the environment - the lake is amongst the top 10 largest lakes worldwide and offers an opportunity to research large scale processes;
4) the temporal scale of the environment - the possibility exists that the lake overlies sediments of an earlier rift valley lake, providing a vertical chronology;
5) information on possible inoculum is available - it is likely to be representative of other sub-glacial lakes but the Vostok ice core has a detailed record for the overlying ice sheet of biota present within that ice sheet;
6) the first opportunity to sample a microbial community isolated from the atmosphere for perhaps a million years or more - possibly uncovering novel micro-organisms or processes, notably the microbiology of gas clathrates (hydrates) in a water column; and
7) possible data on evolution of global biota - data gathered could potentially contribute to the current debate regarding the evolution of global biota.

GOAL FOR BIODIVERSITY STUDIES

Extreme environments have proved a rich source of novel physiological processes and biodiversity. The estimated age of this lake and its isolation from the atmosphere for possibly a million years, may allow the identification and study of novel micro-organisms or processes, notably the microbiology of gas clathrates (hydrates) in a water column. The goal of the biodiversity studies should be to establish the structure and functional diversity of Lake Vostok biota.

JUSTIFICATION FOR BIODIVERSITY STUDIES

Microorganisms are a substantial component of all environments and their significant role in key food web processes is recognized increasingly. The main lineages of life are dominated by microbial forms, and comparative analyses of molecular sequences indicate that all life belongs to one of three domains, *Bacteria*, *Archaea* and *Eukarya*. Microbes are ubiquitous in extreme environments. Recent deep ocean hydrothermal vent studies suggest that such environments may have been sites for the origin of life. Novel environments, such as sub-glacial lakes, may likewise contain unique biota.

STRATEGY FOR BIODIVERSITY STUDIES

At least four biodiversity scenarios exist for the lake:

1) The lake is geologically inactive and only contains till, glacially derived sediments with low organic carbon. No geothermal hot spots exist, and the low organic carbon till, substantially dilutes any input of ice sheet biota. Gas clathrates present in the lake are a potential target for microbial activity.
2) The lake is geologically inactive with old lake sediments buried under recent till. The clathrates are still a target, but retrieval of old lake sediments is a further goal.
3) The lake is geologically active without old lake sediments. The sites of geothermal activity would be a major focus requiring several coring sites.
4) The lake is geologically active and old lake sediments are present. This would be the best case scenario, offering a range of research topics, requiring long cores and possibly multiple sampling sites.

In the absence of detailed data on the lake characteristics this group suggests that the initial starting point for sampling the lake should be in the melting zone of the lake and not the accretion zone. The melt zone will be where the clathrates and ice sheet microflora enter the lake. Both the ice/water interface region and the sediments offer the best opportunity for initially looking for microbes, but it was recognized that clathrates may be distributed through the water column. The accretion zone will not be a source for microbial or clathrate input to the lake.

In light of these four scenarios, the strategy for studying biodiversity in Lake Vostok would involve (a) preliminary activities prior to any field sampling (zero-order activities) to establish the nature of the environment, possible microfloral inputs and relevant technologies and (b) field sampling of Lake Vostok and post-sampling analysis:

(a) Zero-order activities - *(no field campaign needed)*

1 - Physical characterization of the lake (non-invasive)

2 - Technological developments for *in situ* micro- and macro- scale probes, sample retrieval, non-contamination of lake and data relay from within lake. Remote operated vehicle (ROV) to increase the area of lake studied

3 - Development of biogeochemical and ecosystem models

4 - Characterization of the ice sheet microflora using existing cores if possible and both

molecular and cultural methodologies

(B) MAIN SAMPLING ACTIVITIES - *(Field campaign needed)*

1 - Obtain vertical profiles of physical and chemical parameters from the ice/water interface through to sediments. Microscale profiles within surface sediments

2 - Leave monitoring observatories in place with both physical/chemical monitoring and a bio-sensing capability, for detecting life in dilute environments needing long incubation times

3 - Sample retrieval (for chemical and biological purposes) from the ice/water interface, from the water body (may need to filter large volumes to concentrate biota) and from sediments - A suite of molecular, microscopical and activity measurements (see earlier overview by Jim Tiedje) will be required to analyze potential biota. Anti-contamination protocols will feature significantly here (see earlier overview by White/Kern).

4 - May need to consider repeat sampling or further sites, notably if there are geothermal hot spots. Also need to take into account possible heterogeneity, particularly in sediments. An ROV may offer an ability to sample heterogeneity more cheaply than numerous drill holes.

TIME FRAME FOR BIODIVERSITY STUDIES

• Zero order activities - 2-3 years in advance of lake penetration, but continuing afterwards, notably with modeling studies

• Year 1 - Vertical profiling and establishment of long term *in situ* "observatories"

• Years 2 and 3 - Sample retrieval activities at one or more sites

• Year 4 - Sample analysis ongoing and further planning

• Year 5 and 6 - New research initiatives building on data collected to date - could include tackling issues of heterogeneity or perhaps novel biogeochemical processes

*Note 1: The merits of sampling another lake in the vicinity of Lake Vostok need to be considered.

Note 2: The Year 1 work might be best undertaken with the NASA strategy of using both a hot water drill and a modified Philberth probe** to penetrate the lake, deployment of hydrobots beneath the ice and at the sediments and establishment of observatories in the lake. Subsequent years could potentially use alternative drilling technologies to facilitate sample retrieval, once contamination issues have been addressed.

*A hot water drill pushes hot water down a hole to melt the ice.

**A Philberth probe is an instrumented cylindrical shaped device that has an electrical heater at its tip. The melting of ice ahead of the probe allows it to drop down through the ice under its own weight paying out cable to the surface as it goes. A device such as this is being proposed as a means of getting through the last 100 m or so of overlying ice sheet. (For more information on this please refer to Appendix (1) "Why Lake Vostok?" write up by Stephen Platt pg. 45.)

SEDIMENTS WORKING GROUP CONCLUSIONS

Group Members: Peter T. Doran (archivist), Mary Voytek, David Karl, Luanne Becker, Jim Tiedje, Kate Moran

JUSTIFICATION FOR LAKE VOSTOK STUDIES

The existing ice core from Lake Vostok can provide us with unique background information on the Lake which is not available to us from any other subglacial lakes in Antarctica. The size and estimated age of the lake offers the best potential for a long continuous sedimentary record.

GOALS FOR SEDIMENT STUDIES

The sediments of Antarctic subglacial lakes have the potential to be significant for the following reasons:

1. *Extant microbial communities*. Microbial communities often favor interfaces as habitats, so that the ice/water and sediment/water interfaces will be prime targets in the search for life. Along with sediment deposition at the bottom of the lake, chemical energy required by the microbes may be focused on the bottom, i.e., if geothermal energy flux is significant in this habitat. Therefore, the search for extant life in Lake Vostok should not end at the sediment/water interface, but should extend into the sediment column. Measurements of chemical profiles (including dissolved, particulate and gas phases) in the sediment can also be used for life detection (past and present) and for mapping of metabolic processes.

2. *Storehouse of paleoenvironmental information.* The sediment column in Lake Vostok has been estimated to be ~300 m. This thickness of sediment could contain an unparalleled record of Antarctic paleoenvironmental information, extending beyond the limit of ice core records. The record contained in the sediments may reveal information on past geochemical processes, microbial communities, and paleoclimate. Interpretation of this record will require a thorough understanding of the modern lake depositional environment.

The gas geochemistry in Lake Vostok has the potential to be unique, with hydrated gas layers accumulating in the water column based on density stratification. In particular, CO_2 hydrates are expected to sink upon entering the water column and collect in the bottom sediments, potentially creating a continuous record of atmospheric CO_2 in the lake sediments.

3. *Direct measurement of geothermal heat flow.* Any sediment borehole created can be used to determine geothermal heat flux through direct temperature measurements. This information will contribute to models of the lake's origin, possible circulation and maintenance.

4. *Extraterrestrial material capture*. The lake sediments undoubtedly contain a large number of meteorites, micrometeorites and cosmic dust (e.g. interplanetary dust particles and cometary debris) given that all “coarse” material that moves into the lake and melts out of the ice will be focused in the sediments. In this way the sediments offer an extraordinary opportunity to measure extraterrestrial flux over possibly several million years. The flux of extraterrestrial material can be monitored by measuring helium-3 in very small grains (<50 μm) in bulk sediments. In fact, it has been suggested that periodic changes in the accretion rate of extraterrestrial material is due to a previously unrecognized 100,000 yr periodicity in the Earth's orbital inclination which may account for the prominence of this frequency in the climate record over the past million years. Measurements of the extraterrestrial flux of material to the Vostok sedimentary record coupled with the possible presence of CO_2 clathrates may provide a record of climate change that could only be preserved in this unique setting.

JUSTIFICATION FOR SEDIMENT STUDIES

The sedimentary analysis of Lake Vostok is of particular interest among Antarctic subglacial lakes by virtue of its size, thickness of sediments, and because of the background information already available. The ice core record collected at Vostok Station will be valuable in conjunction with the historical sediment record for reconstruction of the paleoenvironment of the lake. This is particularly true for the accretion zone at the base of the ice core. Furthermore, Lake Vostok's size makes it the best candidate for the existence of a stable microbial community and a long, continuous sediment record.

SEDIMENT SAMPLING STRATEGY

Information that can be gained by *in situ* measurements at the sediment/water interface will be limited. Therefore, its strongly encouraged that a strategy based on sample return be pursued. Initial survey measurements can be accomplished remotely and by *in situ* instruments, but in order to fully implement the science plan, return of samples to the surface will be essential. The largest technological obstacle to the collection and return of 300 m of sediment core will be creating and maintaining an access hole through the deep ice. The Ocean Drilling Program (ODP) has already developed many of the techniques necessary for collecting and sampling cores of this length, and from this depth (in the ocean). Some technology development would be required to utilize lake water as drilling fluid to minimize lake contamination. A suite of ODP standard procedures currently used could be applied to Lake Vostok sediments including: acquisition 300+ m of sediment core in pressurized ten (10) meter sections for sampling; sampling of gas hydrate formations; pore water sampling; down-hole logging; establishment of long-term benthic monitoring observatories; casing of the bore-hole for later re-entry if desired; and established sampling and repository protocol.

It is recommended that methodology for investigating the lake sediments proceed as follows:

1. remote site survey (e.g. thickness of sediments, stratigraphy, etc.);
2. *in situ* sediment/water interface survey (use of resistivity probes, video, sonar, particulate sampling);
3. surface sample "video grab" and return to the surface;
4. establishment of long-term *in situ* sediment-water interface experiments;
5. collection of long cores;
6. down-hole logging (e.g. geothermal heat flux, fluid flow); and
7. cap hole for future re-entry if desired.

CONTAMINATION ISSUES

Disturbance of the lake and contamination of the lake and samples can be kept to a minimum through a number of initiatives:

1. sterilization of all equipment entering the lake to greatest degree possible;
2. collection of the cores in sealed canisters so that there is no loss of sediment on removal or contact of the sample with upper strata as it is being raise through the water column; and
3. use of benthic lake water as drilling fluid to reduce introduction of foreign fluids.

NUMERICAL MODELING FOCUS GROUP CONCLUSIONS

Group Members: Christina L Hulbe (archivist) and David Holland

JUSTIFICATION FOR LAKE VOSTOK STUDIES

Lake Vostok is an unique physical environment which offers the opportunity for new development of information, and a better understanding of subglacial lakes. The study of closed lake circulation is new and therefore allows us to test and refine existing models, and develop new models and theories. Furthermore, available information suggests that Lake Vostok may be an analogue for ice-covered planetary bodies.

NUMERICAL MODELING GOALS

Numerical modeling of ice sheet and lake behavior should begin early in a Lake Vostok initiative and form a close collaboration with other research communities before and after the direct exploration of the lake. Models will provide the best *a priori* characterization of the lake environment, offer advice for drilling site selection, and constrain the interpretation of observations made within the lake. Existing ice sheet/ice shelf models need little modification to meet the requirements for such studies. However, the exploration of Lake Vostok poses a new challenge for modelers of lake circulation. The lake has no free boundaries, a unique physical environment on Earth that may be an analogue for ice-covered oceans on other planetary bodies.

The primary goal of an ice sheet flow/lake circulation modeling effort is characterization of the lake environment. Simulations of the modern ice sheet can provide three-dimensional views of temperature in the ice and lake sediments, and of ice velocity. Those results can then be used to predict the thermal environment of the lake and the pathways and delivery rates of sediments through the ice sheet into the lake. Because basal melting is widespread under the thick East Antarctic Ice Sheet, the lake probably receives water and bedrock-derived sediments from the surrounding area. The flow of water and sediments at the ice/bed interface, both to and from the lake, should also be modeled. Another important use of the results of ice sheet simulations will be in the prescription of boundary conditions for lake circulation models. Lake circulation will be influenced by gradients in ice temperature and overburden pressure (due to gradients in ice thickness), and by meltwater flow into and out of the lake along the ice/bed interface. The pattern of ice melting and freezing predicted by a lake circulation model will in turn be used to refine modeled ice flow over the lake. Lake circulation models will resolve the patterns of water temperature, salinity, and clathrate (gas hydrate) distribution. Together, the simulations will define the habitats in which lake biota exist and can also be used to evaluate the constancy of those habitats over time.

Because the present state of the lake depends in part on past events, it will be important to conduct full climate-cycle ice sheet simulations. A coupled grounded ice/floating ice model that incorporates basal water and sediment balance can estimate past changes in lake water and sediment volume, including the possibility of periodic sediment fill-and-flush cycles. The proximity of the Vostok ice core climate record makes Lake Vostok an ideal setting for such experiments. Investigating the full range of time since the lake first closed to the atmosphere is more challenging and may best be accomplished by a series of sensitivity studies, in which lake volume and meltwater flow are predicted for extreme changes in ice sheet geometry, sea level, and geothermal heat flux. Sensitivity experiments can also be used to speculate about the likelihood of modern hotspot activity, given what is known about lake extent and volume. Perspectives on past lake environments may be used to determine the best sites for lake sediment coring and will aid in understanding present-day lake habitats and biota.

NUMERICAL MODELING JUSTIFICATION

Numerical modeling of Lake Vostok will be interactive with the other areas of research undertaken at Lake Vostok, and will provide valuable support information for these research objectives. The modeling will provide valuable information on lake circulation characterization/ ice sheet flow, the role of past events such as changes in lake water and sediment volume, and the possibility of periodic sediment fill-and -flush cycles.

NUMERICAL MODELING STRATEGY

The first stage in meeting the modeling objectives for the exploration of Lake Vostok should be model development. Models of whole ice-sheet systems must be constructed to properly characterize ice flowing into the Vostok region. Nested models should be used to provide the high resolution needed for detailed studies of flow in the region. Existing models of grounded ice sheet and floating ice shelf flow are sufficient for those tasks, provided grounding-line flow transitions can be accommodated. Basal water and sediment balance models should be coupled to the ice flow model. Full climate-cycle simulations should incorporate bedrock isostasy accurately but in a computationally practical manner. New lake circulation models must be developed to meet the challenge of Lake Vostok's unique physical setting, in which there is no free boundary and clathrates (hydrates) are likely to be present in the water column. New equations of state, that account for the lake's low-temperature, high-pressure, low-salinity setting, must be developed. The optimal model will be three-dimensional, nonhydrostatic, resolving both vertical motions and convection, and must be of fine enough resolution to capture details of what is likely to be a complicated circulation pattern. Biological and chemical models that use the products of ice sheet and lake circulation models to simulate the lake’s biogeochemical cycles should also be developed, although the final nature of such models cannot be determined until lake waters are sampled (for example, does the lake have a carbon cycle?).

The second stage of a Lake Vostok modeling effort should be the integration of new data sets into the models. Regional topography, especially lake bathymetry, will be essential for the fine resolution needed to fully characterize the lake environment. Radar profiling of ice internal layers would promote studies of grounding line dynamics. Simulations of the present-day system can make use of existing ice sheet Digital Elevation Models and measurements of surface climate. The Vostok ice core climate record is ideal for driving longer-time simulations of ice sheet and lake behavior. Improved knowledge of regional geology will be important, both rock type -- for model studies of lake sedimentation -- and geothermal heat flux -- for ice thermodynamics. Such regional data sets should be developed before the drilling program begins, to give modelers ample time to describe the lake environment, discuss preliminary results with other project scientists, refine the models, and finally aid in drill site selection. Lake circulation models, in particular the development of an appropriate equation of state, will benefit from the products of drilling and lake water sampling. Interaction between modelers, biologists, limnologists, and the borehole site selection group will be vital as models are developed and tested.

In a final stage, the fully-developed and tested models can be used to link together observations made at discrete locations and to develop a robust history of lake evolution. The unique physical setting of the lake and its remoteness for observation demand an interdisciplinary approach to this stage of the modeling effort, including theoretical, numerical, and observational components.

NUMERICAL MODELING TIMEFRAME

Any time schedule proposed for a Lake Vostok initiative must accommodate time in the pre-drilling phase for model development, analysis, and interaction with other project scientists. That development can proceed in tandem with preliminary geophysical surveys of the Vostok region.

Model simulations should be analyzed, in conjunction with geophysical surveys, prior to drilling site selection in order to identify areas of special interest (for example, likely sites of thick sediment deposits). Once sampling has begun, lake circulation models can be tested and improved and biogeochemical models can be developed. Finally, modelers can work with biologists, geochemists, and limnologists to develop a comprehensive understanding of the lake's unique physical and ecological systems.

SITE SURVEY GROUP CONCLUSIONS

Group members: Brent Turrin (archivist), Ron Kwok, Martin Siegert, Robin Bell

JUSTIFICATION FOR LAKE VOSTOK STUDIES

Lake Vostok provides a rare opportunity for an interdisciplinary study of an extremely cold, dark, high pressure aqueous environment. The chance to study the synergy between geologic/ geochemical processes and biologic/biochemical processes that define this distinct aqueous system may lead to new fundamental understandings.

SITE SURVEY GOALS

The primary goal of a site characterization study at Lake Vostok is to acquire the critical regional information both across Lake Vostok and the surrounding area to constrain the flux of material across and into the Lake, and to provide insights into the geologic framework for the Lake. These improved datasets will provide critical insights into selecting sites for installing observatories and acquiring samples. Site selection would best be facilitated by generation of a high-resolution 3-D geophysical image of the ice-sheet, water body, the lake sediment package, and bedrock. This 3-D image would address ice-sheet thickness and structure as well as dynamics; water-depth and aerial extent; lake sediment thickness and distribution; and bedrock topography, structure, and lake bathymetry. These data sets will also provide input for ice sheet and water circulation models.

SITE SURVEY JUSTIFICATION

Lake Vostok is the largest subglacial lake yet discovered. Because of its size, Lake Vostok will have a greater influence on ice dynamics than a smaller subglacial lake. Therefore, it provides a superior natural laboratory for studying the phenomena of ice dynamics such as grounding/ungrounding and the associated stress/strain regime and mass balance considerations, in both the transition and upstream-downstream environs.

In addition to providing an occasion to study ice dynamics, the drilling of Lake Vostok will also provide an opportunity to sample a distinct extreme (cold, dark, high pressure) aqueous environment. Biologic and biochemical sampling of Lake Vostok could lead to the discovery of new organisms and enzymes with potentially invaluable societal relevance.

Geologic, geochemical and geophysical studies will lead to a better understanding of (1) the geology of Antarctica and (2) how geologic/geochemical processes interact with biologic and biochemical processes that define this distinct aqueous system

SITE SURVEY STRATEGY

The site survey strategy is broken down into two components: airborne studies; and ground-based studies. The airborne studies consist of collecting aerogravity data, aeromagnetic data and coherent radar data. These data sets would be enhanced by ground-based seismic studies, and by the installation of a passive seismic and Global Positioning Satellite (GPS) network around Lake

Vostok. The seismic studies should be further broken down into two phases. First, a preliminary pilot study, where data collection is concentrated mostly in the Lake Vostok area proper, and second, a high-resolution seismic study in which the seismic lines are tied into the existing regional seismic data.

SITE SURVEY TIME FRAME

The group feels that the necessary data can be collected and evaluated in two years/field seasons. In year one four separate teams would be needed. Team one, would be responsible for the airborne geophysical studies; gravity, magnetics, and radar. Team two, would conduct the pilot seismic study. The third team would install the passive seismic and GPS nets. The fourth team will conduct radar 3-D imaging studies on and around Lake Vostok.

Year two, would be devoted mostly to a collaborative international project collecting high-resolution seismic data, tied to existing regional data.

TECHNOLOGY DEVELOPMENT WORKING GROUP CONCLUSIONS

Group members: Frank Carsey (archivist), Steve Platt, David White, Mark Lupisella, Frank Rack, Eddy Carmack

JUSTIFICATION FOR LAKE VOSTOK STUDIES

Why should we study Lake Vostok? The lake is unique and interesting because of its immense size, isolation, high pressure, low temperature, estimated age, water thermodynamics, contamination concerns, habitat, biota, sediments, geological setting and possible planetary analogue.

TECHNOLOGY GOALS

The broad goal of Lake Vostok exploration is to access the lake water and sediments in a noncontaminating fashion, obtain certain physical, chemical and biological measurements, as well as retrieve water and sediment samples for study in the laboratory. Numerous aspects of this program have never been done and have no documented approaches. The areas which require technologic development are detailed below.

1. *Site Selection*. The lake is large. Presently the satellite altimeter and limited airborne radar data point to the presence of numerous, varied interesting sites but rigorous site selection requires improved regional data. Well-planned airborne geophysics and seismic programs are necessary to complete the specification of the lake, its ice cover, and its sediments. In this regard, ice penetrating radar is a key means of observing the ice, providing estimates of ice ablation and accretion over and near the lake. The technology of sounding radar has developed rapidly in recent years. To generate accurate data on ablation and accretion as it varies in the lake environs, optimized radar configurations should be employed in the site survey.

2. *Entry Means.* The emerging scientific goal requires robotic, observatory installation and sample-return programs. These approaches necessitate different means of obtaining access to the lake water, ice surface, lakefloor, and sediment. None of these approaches has ever been demonstrated through 3700 m of ice or within a lake of this pressure-depth.

3. *Contamination Prevention.* Access to the lake, activities within the lake, withdrawal from the lake, any equipment abandoned in the lake, and possible unplanned experimental difficulties in the course of studying the lake must be proven to be safe with respect to contamination by living microbes.

4. *Sampling Requirements.* Preliminary scientific goals point to physical, chemical, and biological observations of the ice above the lake, the lake water, the lakefloor, and the sediments, at several sites. To understand the three dimensional system within the Lake several *in situ* robotic, observatory installations and sample-return efforts will be necessary. On the whole, these campaigns require accessing the lake in at least two different ways, one way for robotic vehicles and observatory installations and another for coring operations. Contamination issues are significant for both approaches. In addition, some means of sampling within the lake is required, e.g. something simple such as a vertical profile to the lake floor from the entry point, or something more complex such as an autonomous submersible vehicle. The sediments must be sampled; it is probable that *in situ* sampling of the pore water and structure of the upper sediment layers will precede sample return of sediment cores. The lake floor itself should be observed, both the sediment and basement rock areas, for paleoenvironmental and sedimentation studies. Finally, the water, ice, and sediment must be observed and analyzed *in situ* for composition, microbial populations, stratification, particulate burden and nature, circulation, and related characterizations.

In situ Observations and Robotics. In the past few years the capability for robotic activity and *in situ* measurements with micro-instrumentation has grown immensely; in coastal oceanography it has significantly changed spatial data gathering, and the Ocean Drilling Program is now interested in this kind of data acquisition at depth. Also, NASA has undertaken a significant program of *in situ* development for solar system exploration. The goals of Lake Vostok exploration have much in common with those of oceanographic and planetary work, and this overlap of interests provides an avenue for economy and creative collaboration which the Lake Vostok exploration can utilize.

TECHNOLOGY JUSTIFICATION

Technology development is a resource investment, and an appropriate question in a discussion of it concerns its inherent value, i.e., the importance of its immediate use and its applicability to other uses.

To address the first issue, the question “Why Lake Vostok?” is posed. Lake Vostok is scientifically unique and interesting because it is large and deep, essentially isolated, at high pressure and low temperature, old, fresh (as nearly as can be determined), the site of interesting water thermodynamics and dynamics, underlain by deep sediments of biological and geological promise, in an interesting geological setting, characterized by several unusual sorts of habitats, strongly influenced by the overlying ice sheet, and analogous to interesting planetary sites. Taken together, the pressure and temperature regimes and the ice sheet processes give rise to another interesting aspect; they indicate that the gases present will be in clathrate (gas hydrate) form, and this provides a key biological question regarding the ability of microbes to utilize gas clathrates.

The second category addresses whether the technologies of Lake Vostok exploration are of use in other pursuits. Clearly they are. The tools and techniques needed for Lake Vostok site survey and *in situ* campaigns are applicable to ice sheet and permafrost studies, *in situ* water and sediment composition analysis, device miniaturization, sterilization and sterile methods development, biological assessments, seafloor characterization, radar surveys in other sites and even other planets, and similar problems.

TECHNOLOGY STRATEGY

The pathway of activity to lead from this workshop to the actual initiation of Lake Vostok campaigns is complex, with some elements that can, in principle, be conducted in parallel. Technology development precedes field deployments; thus, with the exception of procedural and legal issues related to contamination control, the technology will come first and determine the earliest date that performance data or testing results can be available. Clearly, the technology time frame is of crucial importance; what controls it? The following approximate high-level sequence of activities is suggested.

1. *Interagency International Interest Group.* The science and technology of Lake Vostok, and similar sites, is relevant to several agencies and a number of national Antarctic programs, and possibly industrial supporting partners. A group representing interested agencies should be formed to outline possible lines of support.

2. *Science Working Team.* Before any implementation can begin, a working team of scientists, engineers, and logistics experts must be appointed to establish science requirements for the first campaign, and a general sequence for future campaigns.

3. *Site Survey and Selection Team.* A working group on site selection issues and information needs, should meet immediately to set forth what data should be sought.

4. *Observation and Sampling Strategy.* A strategy of measurement and sampling needs can be constructed as project scenarios, flexible enough to adapt to varying success rates for the development activities.

5. *Technology Plan.* A plan is needed for technology development and testing, including subsystem level functional units as well as integrated systems and including contamination prevention procedures and validation at each step. This will include documentation of requirements, priorities, constraints, information system roles, and phasing of deployment and integration. The plan should be viewed as a roadmap and a living document, and its architecture is not specified here as there may be effective web-based methods for its implementation.

6. *Technology Implementation.* Development of implementation teams to obtain funding and perform the functional unit development. Selection and recruitment of these specialists groups are key tasks. Actual development of technologies will follow, and coordination of developments is needed.

7. *Testing.* The subsystems, the integrated systems, and the contamination prevention techniques all require realistic testing. These testing regiments are demanding and can be expensive, but they are not as expensive as failure during a campaign. The testing of a given subsystem, e.g. an instrument to obtain chemical data from the lake water, may well call for deployment in an analogous environment, e.g. an ice-covered lake, and this deployment could be costly unless it is collaborative with other investigations of ice-covered lakes. To optimize the testing process, planning, coordination and collaboration are essential.

TECHNOLOGY TIMEFRAME

1. *Summary of Actions.* From above, the actions required for a Lake Vostok program include interagency communications, science and engineering team definition work, development of technology requirements and project scenarios, system definition, subsystem development (including integration and test), system level test, the first Lake Vostok entry, and the subsequent review of status to determine future directions.

2. *Crucial Technologies.* While much of the technical work required for a successful Lake Vostok exploration is challenging, most of the technologies are seen to be within reach, and many of the tasks have several candidate approaches. An exception is contamination control; this technology is challenging in both development and validation, and it should be developed and proved before any *in situ* examination of the lake can be addressed. Apparently, this work has begun within NASA, and at the earliest opportunity an estimate of the time required for its completion should be requested.

3. *Other Timetable Considerations.* In assessing the technology timeframe it is necessary to

understand the overall schedule constraints, e.g. contamination prevention, development of consensus on scientific objectives and requirements, logistical resources and commitments, site surveys, international participation, etc. From an initial assessment, it appears that site surveys may be addressable as early as in the 00-01 field year (but maybe later), and this seems to be the schedule driver. From the perspective of participating scientists, the field work could begin in the field season of the year following the site survey, assuming that site survey data can be made widely available.

(6) Appendices

Appendix 1 Presentations on: "Why Lake Vostok?"

3-5 MINUTE PARTICIPANT PRESENTATIONS

Geochemical Overview of the Lake

Berry Lyons
Department of Geology, University of Alabama, Box 870338,
Tuscaloosa AL 35487-0338, U.S.A.,
p (205) 348-0583, f (205) 348-0818, blyons@wgs.geo.ua.edu

Lyons discussed how the major ion chemistry of the lake might have evolved based on the French research on the chemistry of the Vostok ice core. Because the hydrogen ion is a major cation in the ice during interglacial times, the lake's water could be acidic. This might lead to enhanced leaching of particulate matter within or at the sediment-water interface of the lake. In addition, he described the possible N:P ratios of the water (again, based on the ice core results), and suggested that the lake could be very P deficient.

1. What is the overall geochemistry of the lake waters?

glacial times ice: from: Legrand and Mayewski, (1997)

Na > Ca = H > Mg

$Cl \geq SO_4 = NO_3$ "seawater like" waters

interglacial ice:

H > Na > Mg "acid waters"→would enhance "weathering" the subsurface geology

$SO_4 >> Cl = NO_3$

2. How do nutrient ratios affect life?

Glacial times ice = NO_3 = 1.35 μmol L^{-1}

interglacial ice = NO_3 = .38 μmol L^{-1}

P values calculated using Al data (De Angelis et al., 1987) and Al:P of Wedepohl (1995)

glacial times ice = 1.4×10^{-2} μmol L^{-1} (values as high as 3.5×6^{-2})

interglacial ice = 8.4×10^{-4} μmol L^{-1}

N:P ratios:

Glacial times ice = 96

interglacial ice = 452

3. Gas geochemistry

Lyons will make a comparison as to how Lake Vostok might compare and contrast to the ice-covered lakes in Taylor Valley.

Handout: Lyons

Technologies for Access Holes and Thermal Probes

Stephen R. Platt
Snow & Ice Research Group (SIRG), Polar Ice Coring Office, Snow & Ice Research Group, University of Nebraska-Lincoln, 2255 W Street, Suite 101, Lincoln, NE 68583-0850, U.S.A., p (402) 472-9833, f (402) 472-9832, srp@unl.edu

The Snow & Ice Research Group (SIRG) at the University of Nebraska-Lincoln has conducted a comprehensive analysis of the technological challenges associated with delivering a cryobot-hydrobot transporter vehicle to the surface of Lake Vostok, and has developed a plan that we believe has the highest chance of success and lowest cost consistent with logistical, technical, and time constraints. The proposed course of action uses a hot water drill to produce a 50 cm diameter access hole approximately 3700 m deep. An instrument carrying thermal probe (the cryobot) will then be deployed from the bottom of this hole to penetrate the final few hundred meters of ice and deliver a hydrobot exploration vehicle to the surface of the Lake.

A division of SIRG, the Polar Ice Coring Office, has a proven capability for drilling 2400 meter deep access holes in ice using a hot water drilling system at the South Pole. The current drill design can be modified to achieve depths of 3500-3700 m. Hot water drilling will not produce a permanent access hole because the hole will begin to refreeze as soon as the water stops circulating. Once the access hole freezes over, the lake would remain sealed from the outside world, even as the probe entered it. However, because the drilling fluid for this technique is water, the risk of contaminating the Lake is greatly reduced compared to alternative drilling techniques. Furthermore, this is the fastest method for producing large, deep access holes in the ice. Once the drill equipment is assembled on-site, 3700 m deep holes can be drilled in less than two weeks

SIRG has also developed thermal probes for making in-situ measurements of the properties of the Greenland and Antarctic ice sheets. A thermal probe is an instrumented cylindrical vehicle that melts its way vertically down through an ice sheet. At Lake Vostok, a thermal probe would be lowered to the bottom of the access hole created by the hot water drill, where it would start its descent in to the lake. The probe can be configured to house instruments which measure parameters indirectly through windows in the outer wall of the vehicle, or directly by using melt-water passed through the probe. This approach is fundamentally different from other means of sampling the physical parameters of ice sheets which usually rely on recovering ice cores. A cable housed within the upper section of the probe unwinds as it moves down through the ice. This cable is used for both data and electrical power transmission between the probe and the support equipment on the surface of the ice sheet. The probe can only make a one-way trip down through the ice because the melt-water re-freezes behind the probe so it is not recoverable. SIRG is currently doing the preliminary design work for modifying existing probes for use as instrument delivery vehicles, and for integrating in-situ measurement techniques for physical, chemical, and biological phenomena with the cryobot-hydrobot delivery platform.

Helium isotopic measurements of Lake Vostok

Brent D. Turrin
Lamont-Doherty Earth Observatory, Columbia University, Route 9W
Palisades New York, 10964, U.S.A.,
p (914) 365-8454, f (914) 365-8155, bturrin@ldeo.columbia.edu

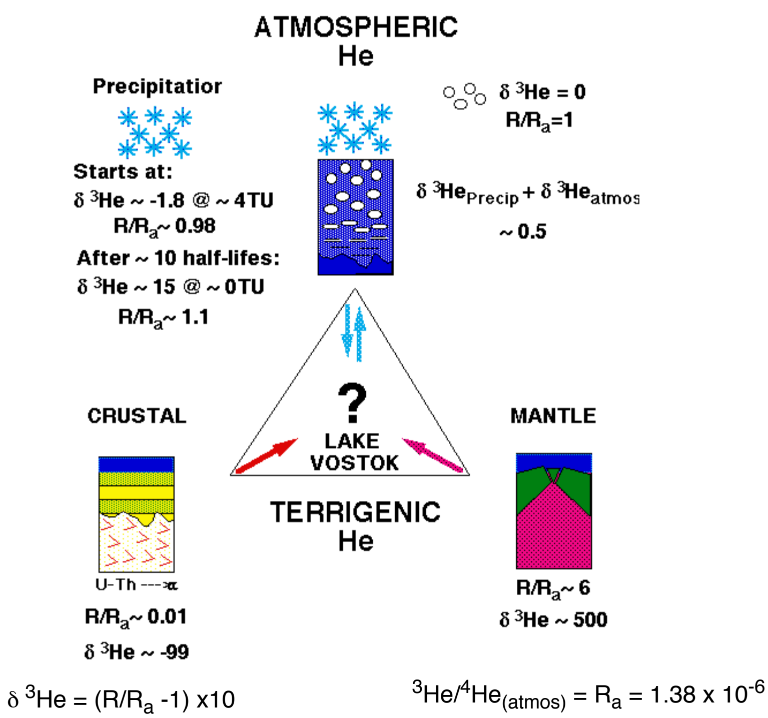
Helium isotopic measurements will help provide information on the tectonic environment of Lake Vostok. The input of He into Lake Vostok will come from three discrete sources, atmospheric, crustal, and mantle. These sources of He have distinctly different isotopic signatures. Atmospheric He, accounting for the decay of natural tritium to ^3He, will have a R/R_a between 1 to 1.5. Atmospheric He enters the lake via melting ice at the ice-water interface.

If Lake Vostok is located on old stable continental crust, the measured He will have a R/R_a of 0.01. Because crustal He is dominated by a large input of ^4He from radioactive decay of U and Th. On the other hand, if Lake Vostok is located in an active rift environment, the flux of mantle He (R/R_a=6) into the lake would increase the measured He R/Ra to values significantly greater than one.

The He sampling protocol must sample a profile thorough the water column. This is necessary to determine the mixing structures between different He sources.

R_a = atmospheric ratio of $^3He/^4He = 1.384 \times 10^{-6}$

R = measured $^3He/^4He$ ratio

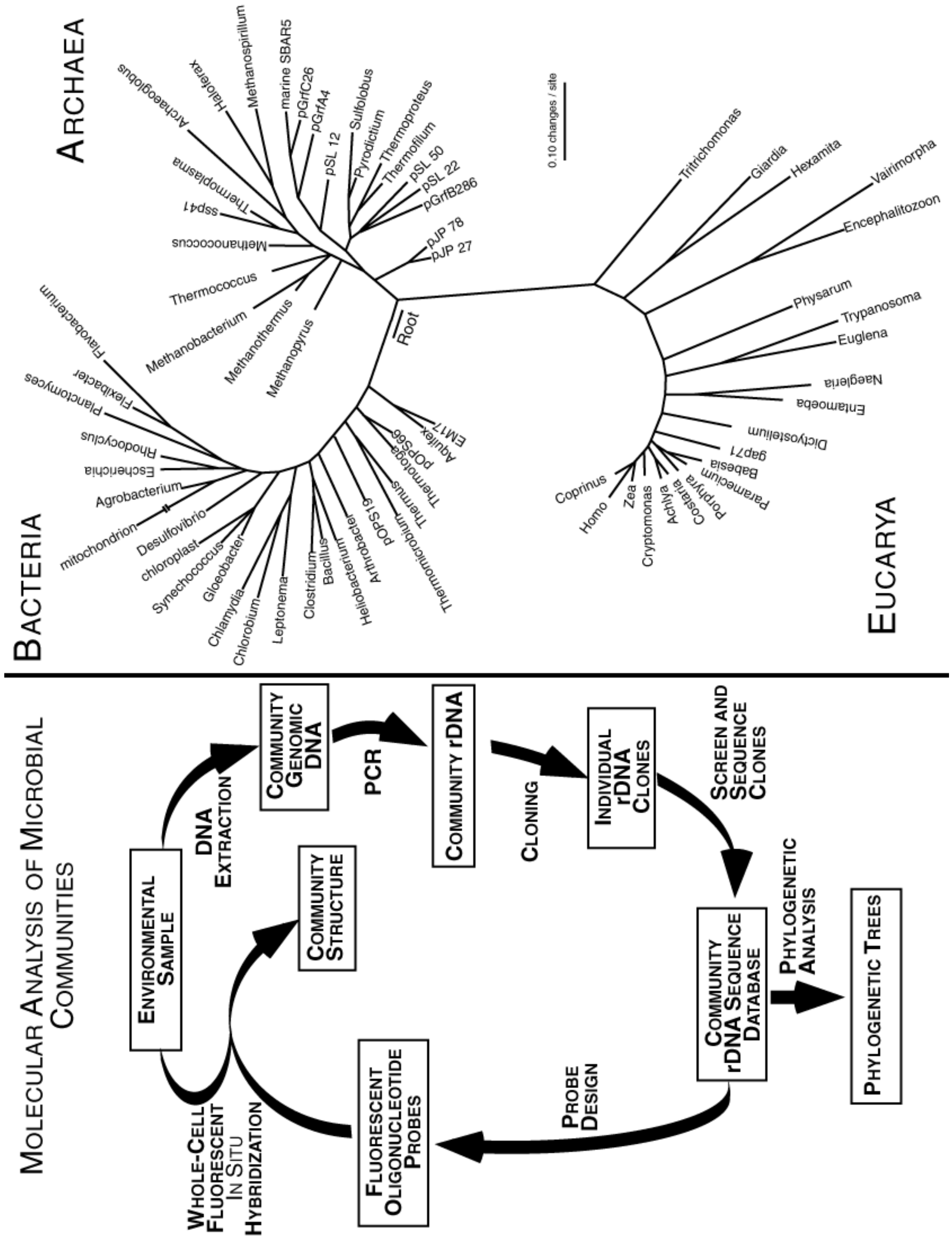


Handout: Turrin

Molecular Characterization of Microbial Communities

José R. de la Torre & Norman R. Pace
Department of Plant and Microbial Biology, University of California Berkeley,
Berkeley, CA 94720-3102 U.S.A.,
p (510) 643-2572, f (510) 642-4995, jtorre@nature.berkeley.edu

It has recently become accepted that microbial organisms thrive in habitats previously deemed too extreme to support life. Lake Vostok represents a new and unexplored habitat, subglacial lakes, which may contain untold biodiversity despite the challenges presented by the physical environment: extreme pressure, darkness, cold and presumably few available nutrients. The use of molecular techniques in studying microbial populations presents several advantages over traditional survey methods. Most importantly, these methods eliminate the need for laboratory cultivation, since the vast majority (>99%) of microorganisms are refractory to laboratory cultivation using standard techniques. This molecular approach is based on the use of ribosomal RNA (rRNA) sequences to identify population constituents, and to deduce phylogenetic relationships. This sequence information is obtained by either directly cloning environmental DNA, or by cloning amplified polymerase chain reaction (PCR) products generated using oligonucleotide primers complimentary to either universally conserved or phylogenetic group specific sequences in the rDNA. Comparison of these cloned sequences with those of known rRNA genes reveals quantifiable phylogenetic relationships, independent of morphological and physiological variations, between constituents of the studied community and previously characterized organisms. These data allow the inference of physiological and metabolic properties based on the properties of known relatives within particular phylogenetic groups. This sequence information can also be used to design fluorescently-labeled oligonucleotide probes to examine the morphology and physical distribution of the novel organisms in the environmental setting.



Handout: de la Torre

Contributions of Ice Sheet Models to Understanding Lake Vostok

Christina L Hulbe
Code 971, NASA Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.,
p (301) 614-5911, f (301) 614-5644, chulbe@ice.gsfc.nasa.gov

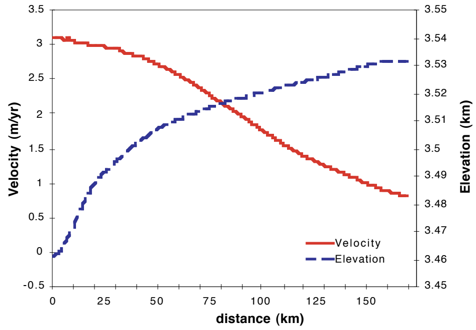
Dynamic/thermodynamic numerical models of ice sheet flow should play a role in several aspects in the exploration of Lake Vostok. First, models can be used to characterize the present-day physical environment of the lake. For example, by providing a 3-dimensional view of ice temperature and age, estimating the influx of debris carried by ice flow, and estimating the horizontal flux of ice sheet basal meltwater into the lake. When coupled with a numerical model of lake water circulation, an ice sheet model can predict the spatial pattern and rate of melting and freezing above the lake. Second, numerical models can investigate the climate-cycle history of the lake. Changes in ice sheet mass balance over the time since the lake was isolated from the atmosphere are likely to have affected Lake Vostok's areal extent, its sediment content, and meltwater flux. To perform such computations, ice sheet models will need accurate, well-resolved basal topography of the region around the lake and as much information about basal geology and geothermal heat flux as possible. Other input data, such as present-day surface elevation and the local climate record, are available. Indeed, the closeness of the Vostok ice core climate record is ideal. Numerical-model studies of both present and past lake environments would be useful in both site-selection prior to direct contact with the lake and in interpretation of data retrieved from lake exploration.

Implications of Ice Motion Over Lake Vostok

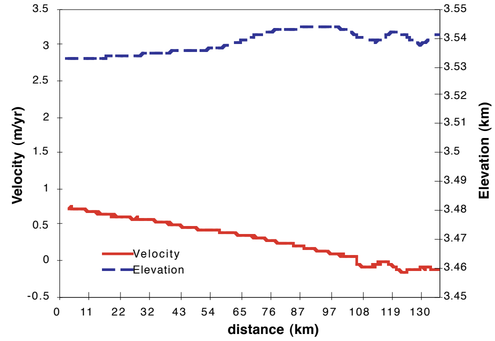
Ron Kwok
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr.,
Pasadena, CA 91109, U.S.A.,
p (818) 354-5614, f (818) 393-3077, ron.kwok@jpl.nasa.gov

Ice motion estimates show that the subglacial lake exerts considerable control over the regional ice dynamics. As the ice flows pass the grounding line, there seems to be a pronounced southward component of motion with a profile which increases slowly at the northern tip of the lake and then rather rapidly starting at approximately 100 km along the length of the lake. Critical to the understanding of past trajectories of the ice recently cored at Vostok Station, and the interpretation of internal layers of the ice sheet from radio echo sounding measurements, the characteristics of the ice motion of the ice sheet as it flows over the lake are important. If flow is normal to the contours over the center of the lake, ice from the lower parts of the Vostok ice core spent on the order of 100,000 yrs traveling down the length of the lake. In this case, dating core layering should be regular and accurate. If there was a westward component, the age-depth relation in the previously grounded ice core would be less regular than for transport down the lake. The ice motion field also raises numerous interesting questions concerning thermal and mechanical processes in the ice sheet. It will help in the modeling of bottom melt and accretion; processes which might help localize areas where ecosystems could most likely exist

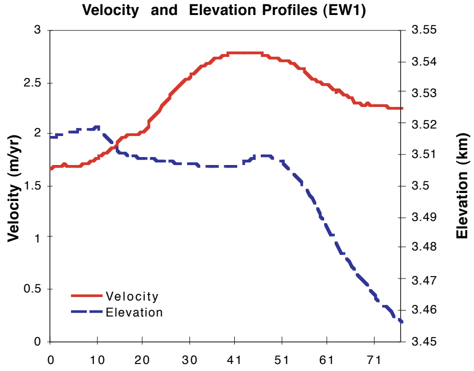
Velocity and Elevation Profiles (NS1)



Velocity and Elevation Profiles (NS2)



Velocity and Elevation Profiles (EW1)



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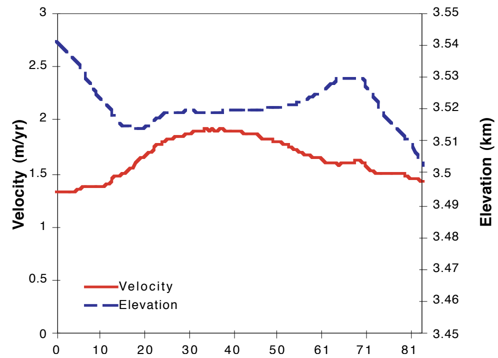
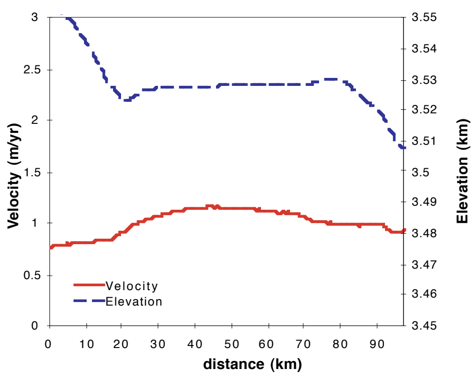
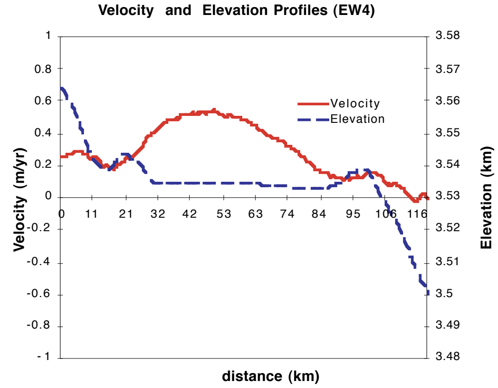


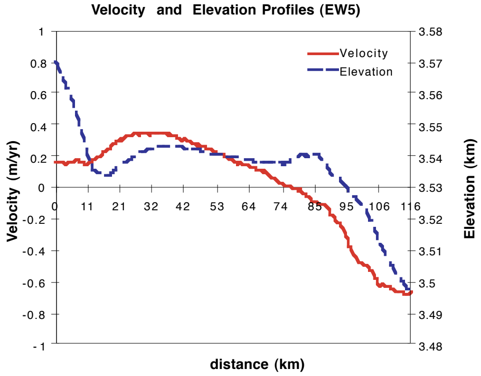
Velocity and Elevation Profiles (EW3)



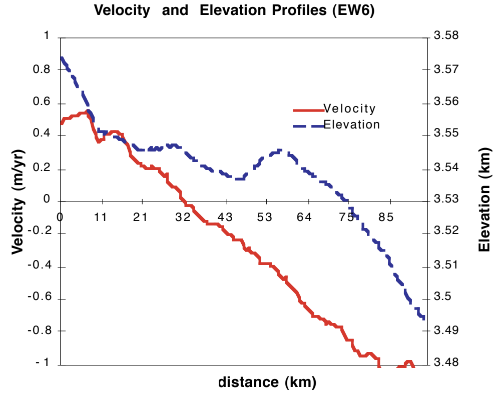
Velocity and Elevation Profiles (EW4)

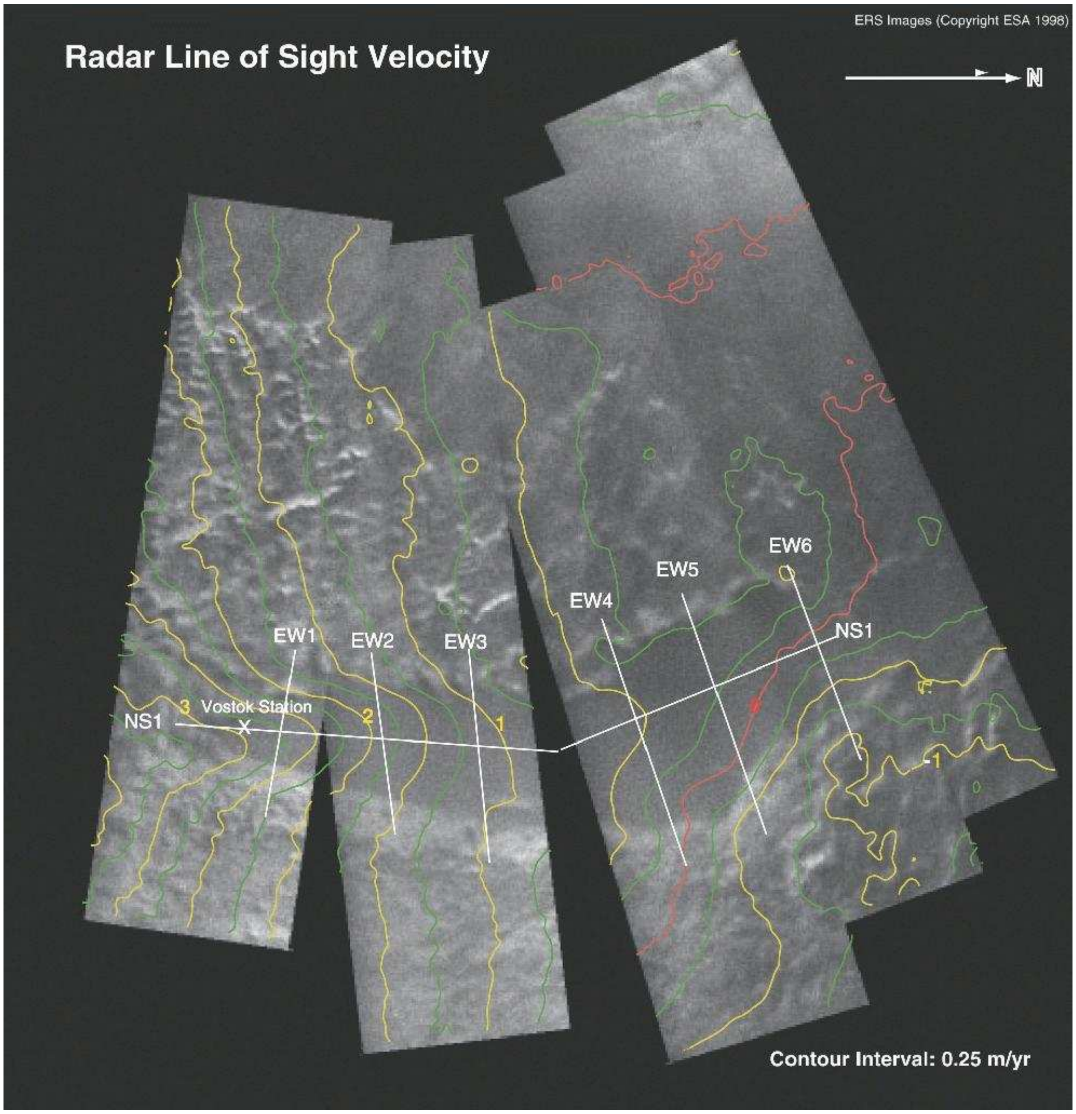


Velocity and Elevation Profiles (EW5)



Velocity and Elevation Profiles (EW6)





Handouts: Kwok

The Study & Evolution of an Ancient Ecosystem & Its Evolution

Todd Sowers
Penn State University, Geosciences Dept., 447 Deike Bldg., University Park, PA, 16802 U.S.A., p (814) 863-8093, Lab 863-2049 or 863-3819, f (814) 863-7823, sowers@geosc.psu.edu

Why study the Lake?

One fascinating aspect of the lake involves the notion that we may be able to study an ancient ecosystem that has evolved for millions of years. This ecosystem has been effectively isolated from almost every aspect of the biosphere as we know it. As such, the organisms which inhabit the lake have adapted to a very different environment compared to most of the near-surface ecosystems studied to date. In my mind, the most important reason to study the lake is to document the evolution of the biota within the lake. The results will not only shed light on evolutionary biology here on Earth, but it will also help in the search for life on other (cold) planets.

In terms of my specific contribution to the study of Lake Vostok, I'd be very interested in looking at the isotope systematics of the lake. Specifically, I'd like to look into the stable isotopic composition of O_2, N_2, and Ar clathrates which are liable to be floating near the water/ice interface. There are two interesting aspects of such a study which will need to be considered in parallel; 1) the possibility of dating the lake and 2) providing some constraints on the biogeochemical cycling of O_2 and N_2 within the lake.

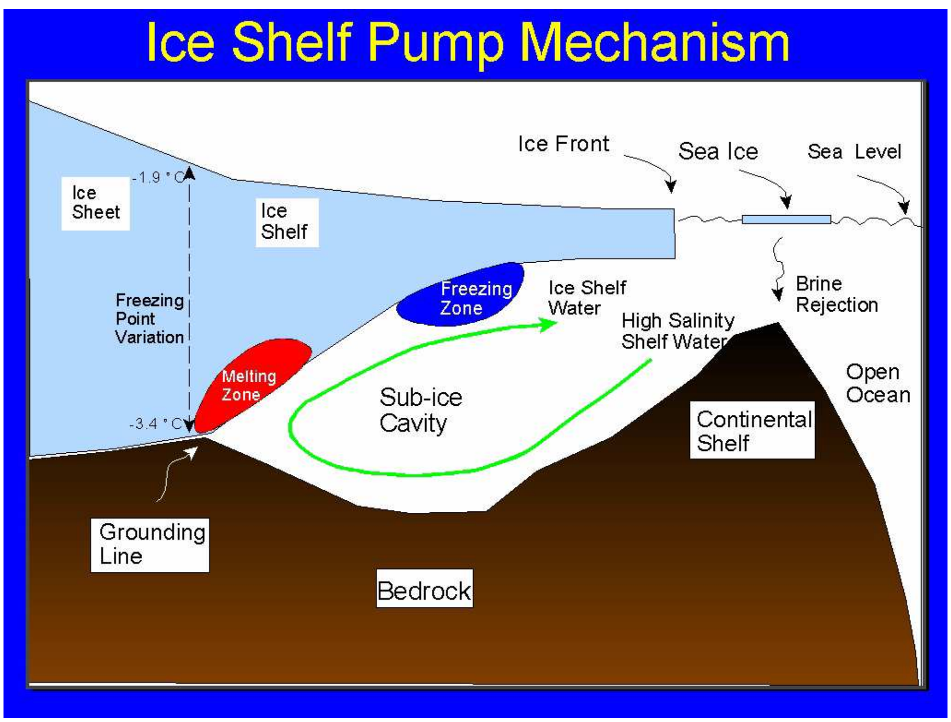
1) The $^{18}O/^{16}O$ of O_2 in the lake may provide some information regarding the age of the lake. To use the $d^{18}O$ of clathrate O_2, we must first assume that the $d^{18}O$ of paleoatmospheric O_2 has followed the $d^{18}O$ of sea water as it apparently has (to a first approximation) over the last 400,000 years (Bender et al., 1994; Jouzel et al., 1996; Sowers et al., 1993). Then, using the $d^{18}O$ of benthic forams covering the Tertiary (Miller et al., 1987) as a proxy for the $d^{18}O$ of sea water (and paleoatmospheric O_2), we may be able to ascertain the youngest age of the lake by analyzing the $d^{18}O$ of clathrate O_2 from the lake. If the $d^{18}O$ of O_2 is within 1‰ of the present day value, then we can safely say that the lake is probably less than 2.2 myr old. If, on the other hand, the d18O of O2 is between 1 and 3‰ lower than today, then we can say that the clathrates (and lake) are probably between 2.2 and 50 ma (myr before present). Values which are lower than 3‰ could be interpreted as signaling clathrates which are more than 50 myr old.

2) By studying the stable isotope systematics of O_2, N_2, and Ar, we may be able to learn something about the biogeochemical cycling of these bioactive elements within the lake. Assuming organisms can be cultured and incubated under conditions approaching Lake Vostok, (and the organisms use/produce O_2 and N_2 as part of their metabolic activity), we can determine the community isotope effect for these gases using laboratory incubations. Having this data in hand, along with the isotope measurements on the air clathrates from the lake, we may be able to provide some qualitative estimates of the longevity of the ecosystem via simple isotope mass balance.

Modeling the thermal forcing of the circulation in Lake Vostok

David Michael Holland
Courant Institute of Mathematical Sciences, 251 Mercer Street, Warren Weaver Hall, 907,
New York University, MC 0711, New York City, New York, 10012 U.S.A.,
p (212) 998-3245, f (212) 995-4121, holland@cims.nyu.edu

Lake Vostok is situated at the base of the huge Antarctic Ice Sheet. The isolation and remoteness of the lake imply that it will have a circulation driven by the heat and freshwater fluxes associated with phase changes at the ice sheet - lake surface boundary. While geothermal fluxes would also play a role at the lake bed interface, the nature of these important, but poorly known fluxes for Lake Vostok, are not considered in the present discussion. A hierarchy of formulations that could be used to describe the heat and mass transfer processes at the lake surface are presented. The main difference between them is the treatment of turbulent transfer within the lake surface boundary layer. The computed response to various levels of thermal driving and turbulent agitation in the upper layers of the lake is discussed, as is the effect of various treatments of the conductive heat flux into the overlying ice sheet. The performance of the different formulations has been evaluated for the analogous environment of an oceanic cavity found beneath an ice shelf. In an effort to understand what the physical circulation is in the lake and subsequently of what relevance it might be to chemical and biological activity in the lake, the following investigation is proposed: An investigation of the details of the thermal interaction between the lake and the overlying ice sheet could be pursued by building on existing theoretical and modeling studies of other cold liminological/oceanographical environments.



Handout: Holland

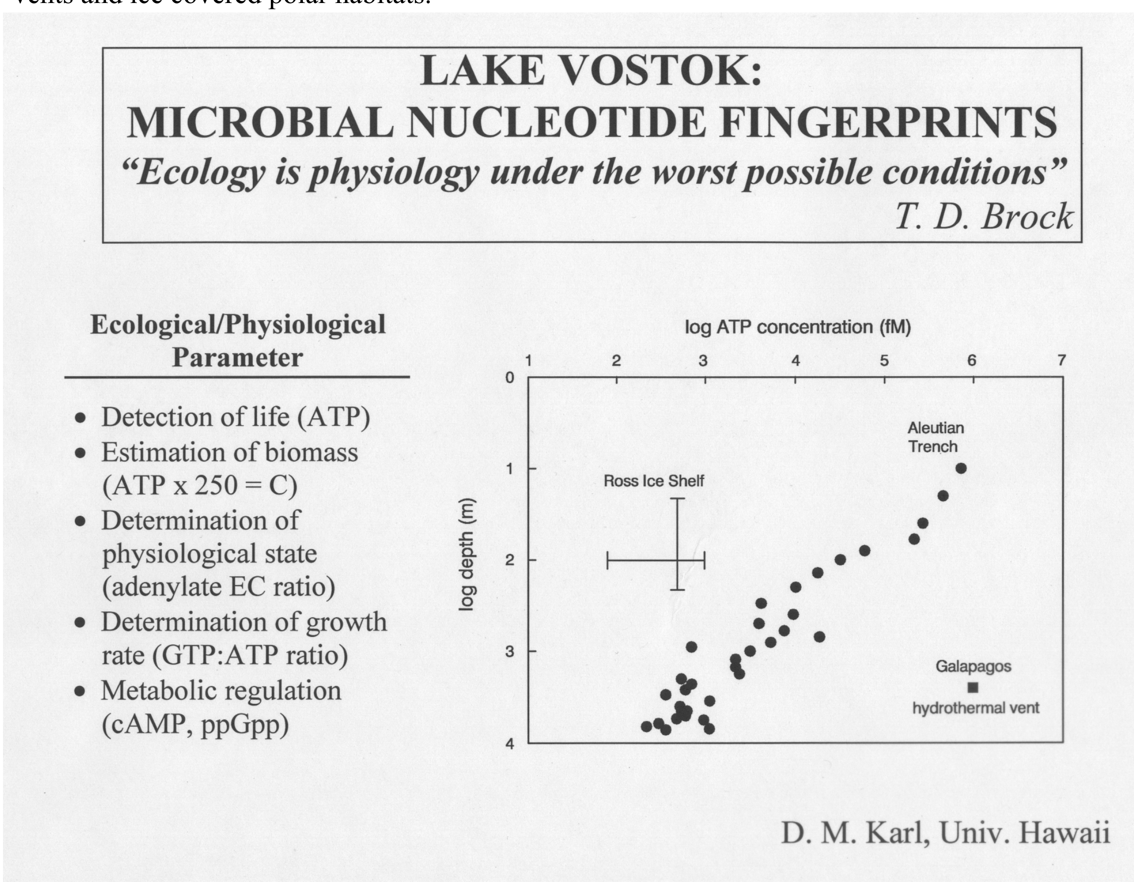
The detection of life: Nucleotide fingerprints

David M. Karl
School of Ocean and Earth Science and Technology, University of Hawaii,
Honolulu, HI 96822, U.S.A.,
p (808) 956-8964, f (808) 956-5059, dkarl@soest.hawaii.edu

Perhaps the first question that one should ask about “life” in Lake Vostok is...is there any? If the answer is yes, then one needs to ask how much life is there, how rapidly is the crank turning and what kind of life forms are present. Although there are numerous methods available to address these fundamental ecological questions, only a relatively few have the sensitivity required for the detection of low standing stocks of microorganisms that might occur in the hyperoligotrophic Lake Vostok.

Adenosine 5'-triphosphate (ATP) is present in all living cells where it functions as an essential link between energy generation and biosynthesis and as a precursor for RNA and DNA synthesis. Furthermore, in concert with related cellular nucleotides (e.g., ADP, AMP, GTP, cAMP, ppGpp), ATP also serves to regulate and direct cellular metabolism. In addition, ATP and associated nucleotide biomarkers can be extracted from cells and measured *in situ*; hence sample return is not mandatory, although it is desirable.

ATP has already proven to be useful in many ecological studies of remote and extreme environments including the deepest portions of the Aleutian Trench (>7500m), hydrothermal vents and ice covered polar habitats.



Handout: Karl

Alternative Mechanisms for Organic Syntheses and the Origin of Life: Lake Vostok as a Case Study

Luann Becker
University of Hawaii, Manoa, 2525 Correa Rd., Honolulu, HI 96822, U.S.A.,
p (808) 956-5010, f (808) 956-3188; lbecker@soest.hawaii.edu

One of the more exciting new fields of research that is emerging within the deep-sea drilling program is the search for a subsurface biosphere. This field has developed as a result of the study of extreme environments and their possible link to the first living organisms that inhabited the early Earth.

Recent experimental data show that amino acids can be activated under plausible 'Prebiotic' geologic conditions [nickel, iron (Ni,Fe) sulfide (S) and carbon monoxide (CO) in conjunction with hydrogen sulfide (H_2S) as a catalyst and condensation agent at 100^oC, pH 7-10 under anaerobic, aqueous conditions; Huber and Wachtershauser (1998)]. These findings support a thermophilic origin of life and the early appearance of peptides in the evolution of a primordial metabolism.

Other research efforts have focused on identifying alternative energy sources available in hydrothermal regimes as supporting a deep subsurface biosphere. For example, it has been suggested that hydrogen produced from basalt-ground-water interactions may serve as an energy source that supports the existence of microorganisms in the deep subsurface of the Earth (Steven and McKinley, 1995). However, Anderson et al., (1998) have demonstrated experimentally that hydrogen is not produced from basalt at an environmentally relevant alkaline pH. Furthermore, geochemical considerations suggest that previously reported rates of hydrogen production couldn't be sustained over geologically significant time frames. Nevertheless, results from the Anderson et al., (1998) study do not rule out the possibility that reduced gases emanating from deeper in the Earth could fuel deep subsurface microbial ecosystems (Gold, 1992). Finally, the hypothesis that a reducing lithosphere on the early Earth would have resulted in an ammonia-rich atmosphere was tested experimentally by using a mineral catalyst to reduce N_2, NO_2^- and NO_3^- to ammonia (NH_3) under typical crustal and oceanic hydrothermal conditions (Brandes et al., 1998). Results of this study showed that oceanic hydrothermally derived ammonia could have provided the reservoir needed to facilitate the synthesis of these compounds on the early Earth.

All of these studies indicate that a <u>direct</u> evaluation of the subsurface biosphere ecosystem is needed to assess the plausibility that organic syntheses capable of supporting life can occur in this environment. A planned program to sample water, porewater and sediment samples for the detection of organic components (i.e. amino acids, peptides etc.) is necessary to ascertain the mechanism of formation (abiotic or biotic) and further determine whether the organic components detected are capable of supporting or synthesizing a subsurface biosphere. These samples can be collected and examined on board using conventional organic geochemical approaches (i.e. HPLC, PY-GCMS, etc.). In addition, a planned re-entry program will allow us to measure for organics *in situ* downhole (e.g. state-of–the-art fiber-optic fluorescence or micro-Raman approaches). The use of fluorescence for the detection of organic compounds is an extremely versatile and sensitive technique (detection at the sub-femtomole level).

The development of an 'Organic Probe' that we can attach to a re-entry device to detect organic components 'real-time' in the Lake Vostok aqueous and sedimentary environment is needed. These measurements are critical to the assessment of contamination that may be introduced during the sampling program. Thus, the instrument implementation and the results obtained will be important to future investigations of life in extreme environments on Earth and perhaps beyond (e.g. Europa).

Hypotheses about the Lake Vostok Ecosystem

Diane McKnight
INSTAAR, University of Colorado, 1560 30th St., Boulder, CO 80309-0450, U.S.A.,
p (303) 492-7573, f (303) 492-6388, Diane.McKnight@Colorado.edu

Lake Vostok allows us an opportunity to extend our knowledge of ecosystem processes to a new extreme environment; one in which there has been sufficient time for microorganisms to adapt. Our approach should be to develop ecosystem hypotheses based upon current knowledge. Our current knowledge of environments of this type is based on the Dry Valley ecosystem characteristics.

Dry Valley ecosystem characteristics:

1. Autotrophs in lakes and streams are adapted to use low energy, e.g. photosynthesis begins with sunrise.
2. Relict organic carbon sustains ecosystems at a slow rate over long periods, e.g. soil system runs on old algal carbon.
3. All landscape components - lakes, streams, soils - have a food web, e.g. "microbial loop" in lakes.
4. In the lakes, viable organisms persist through winter and mixotrophs become abundant.

Hypotheses about the Lake Vostok ecosystem:

1. Autotrophic microorganisms exist and use chemical energy sources at very low fluxes.
2. The Lake Vostok ecosystem will be primarily heterotrophic, with organic compound deposited with snow on plateau as an organic carbon source.
3. The Lake Vostok ecosystem will have a microbial look, including mixotrophs and grazers.

*Even if DOC of glacier ice is 0.1 mg C/L, this DOC may be a greater energy source than those available to support autotrophic processes. One could hypothesize that humics in Lake Vostok water would have a different signature than humics in overlying glacier ice because of microbial processing.

Plan for discoveries, for unexpected observations

It should be noted that studies in the Dry Valleys began in the 1960s, and were not conducted with a focus on avoiding the introduction of exotic microorganisms. Although there is not evidence of introduced algal species becoming abundant, we have not assessed introductions as an ecological factor. For isolated inland locations, introductions should be a concern because equipment or food could transport species that do not survive long range aeolian transport.

A Terrestrial Analog

Mark Lupisella
NASA Goddard Space Flight Center, Greenbelt Rd., Mailstop 584.3, Building 23, Rm. W207, Greenbelt, MD 20771, U.S.A.,
p (301) 286-2918, f (301) 286-2325, Mark.Lupisella@gsfc.nasa.gov

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A key challenge for a human mission to Mars will involve assessing and minimizing adverse impacts to the indigenous environment, where “adverse” means anything that could compromise the integrity of scientific research-especially the search for life. Due to the extreme surface conditions of Mars, signs of Martian life, if they exist at all, are likely to be under the surface where there is thought to be a layer of permafrost. It is also possible that sub-glacial lakes exist under the polar caps of Mars. Humans on Mars will eventually have to drill for many reasons, including the search for life, so Lake Vostok should be considered as a terrestrial analog for understanding how humans might conduct such drilling activities on Mars-particularly regarding issues of contamination control.

Microbial Sample Characterization and Preservation

David Emerson
American Type Culture Collection, 10801 University Blvd., Manassas, VA 20110-2209, U.S.A.,
p (707) 365-2700, f (707) 365-2730, demerson@gmu.edu

Characterization and preservation of samples of microbes that are returned from Lake Vostok will be a vital aspect of any attempt to study the life that lives in the Lake. The American Type Culture Collection (ATCC) houses the world's most diverse collection of microorganisms, and includes large collections of prokaryotes, fungi, and free-living protists. Members of all these groups are likely to be found in Lake Vostok waters. ATCC scientists are well versed in the methods of cryopreservation and lyophilization of microbes, and microbe containing samples, as well as in isolation and characterization of the microbes themselves. Recently, the ATCC has acquired the ability to carry out more extensive genomic analysis of isolates, including sequencing of SSU rRNA genes, DNA fingerprinting, and hybridization technologies. In addition, the ATCC has a strong bioinformatics group with experience in developing databases concerning specific groups of microorganisms. The ATCC would be a willing participant in efforts to preserve and characterize samples returned from Lake Vostok.

Some of the issues regarding sample handling from the Lake would involve returning unfrozen samples through the ice sheet for culturing. It is known that one freeze/thaw cycle can significantly diminish the number of viable organisms in a sample and can be especially hard on the protists. An alternative would be to inject cryopreservatives into samples *in situ* so freezing upon return would be less deleterious, although some protists will not tolerate any freezing at all. Once samples are returned to the surface, it will be important to have the logistical support in place to insure that they remain close to ambient temperature (assuming the ambient temperatures are near 0°C, and not from a 'hot spot') during any transport and handling back to the laboratories where they will be processed. In addition, assuming samples are returned unfrozen, it would be wise to preserve a subset of samples with different cryopreservatives for archival maintenance.

In terms of cultivating microbes, and especially novel prokaryotes from Lake Vostok samples, the most interesting habitat from a physiological perspective would be the putative gas clathrates that exist in the Lake. While methane clathrates are known to exist at cold seeps in the Gulf of Mexico, and other deep-sea environments, relatively little microbiological work has been done with these, and environments suitable for life containing other types of gas clathrates are even less known. These unusual chemical conditions are most likely to lead to unusual metabolic/

phylogenetic types of microbes. Understanding and reproducing the conditions whereby it might be possible to culture these organisms will be important, and will require collaboration between chemists and microbiologists to establish the best methods. It would be best to have the protocols for these methods worked out prior to sample return; for cultivation studies it is best to use 'fresh' samples and there may be a relatively narrow window of a few weeks to have the highest rate of success for cultivation. Finally, from a culture collection perspective, it would be ideal to have thorough documentation procedures in place for any biological samples collected from Lake Vostok. This would include a WWW accessible database that would catalog where samples were taken, how they were preserved, where they were distributed, and a summary of the results obtained for each sample, including the ultimate deposition of any isolated microbes from the samples with a major culture collection. Ready access to this information would insure the widest participation of the whole scientific community in what is likely to be a highly unique and exciting, though costly, endeavor.

Motivation for Sampling Hydrates and Sediments

Peter T. Doran
University of Illinois at Chicago, Department of Earth and Environmental Sciences,
845 W. Taylor St., Chicago, Illinois, 60607-7059, U.S.A.,
p (312) 413-7275 f (312) 413-2279, pdoran@dri.edu, pdoran@uic.edu

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The impetus to study a deep subglacial lake such as Lake Vostok will undoubtedly be driven by the investigation of life's extremes on this planet. Extremes for life in Lake Vostok will include high pressure (for a freshwater environment), low nutrient levels, absence of light, and all gases being in hydrated form. Lake Vostok is analogous to the bottom 500 m of a 4 km deep freshwater lake with a 3.5 km perennial ice cover. The motivation for studying Lake Vostok is similar to the motivation for studying other unique and extreme habitats such as Antarctic Dry Valley lakes, hydrothermal vents, and the deep Earth. Defining modern life's extremes is critical to understanding the origins and evolution of life on this planet and others. Having said this, science at Lake Vostok should not be limited to the search for life. If no life exists in Lake Vostok we will want to know why, which will require a detailed biogeochemical sampling of the lake. Furthermore, the water column and sediments of Lake Vostok should offer new and exciting sources of paleoenvironmental information (e.g. CO_2 clathrate record, extraterrestrial flux), even in the absence of a viable lake community. The sediment record could conceivably extend well beyond ice core records. The first stage of any Lake Vostok study should be exploration with *in situ* instruments, but *in situ* monitoring will fall short of answering the key science questions (particularly in the sediment record). Samples will need to be brought to the surface, which appears feasible with some technology development. Access and retrieval technologies should be tested in a smaller, logistically convenient subglacial lake or analogous environment prior to going to Vostok.

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Some Factors Influencing Circulation in Lake Vostok

Eddy Carmack
Institute of Ocean Sciences, Institute of Ocean Sciences, 9860 West Saanich Rd.,
P.O. Box 6000, Sidney BC V8L4B2, Canada,
p (250) 363-6585, f (250) 363-6746, CarmackE@pac.dfo-mpo.gc.ca

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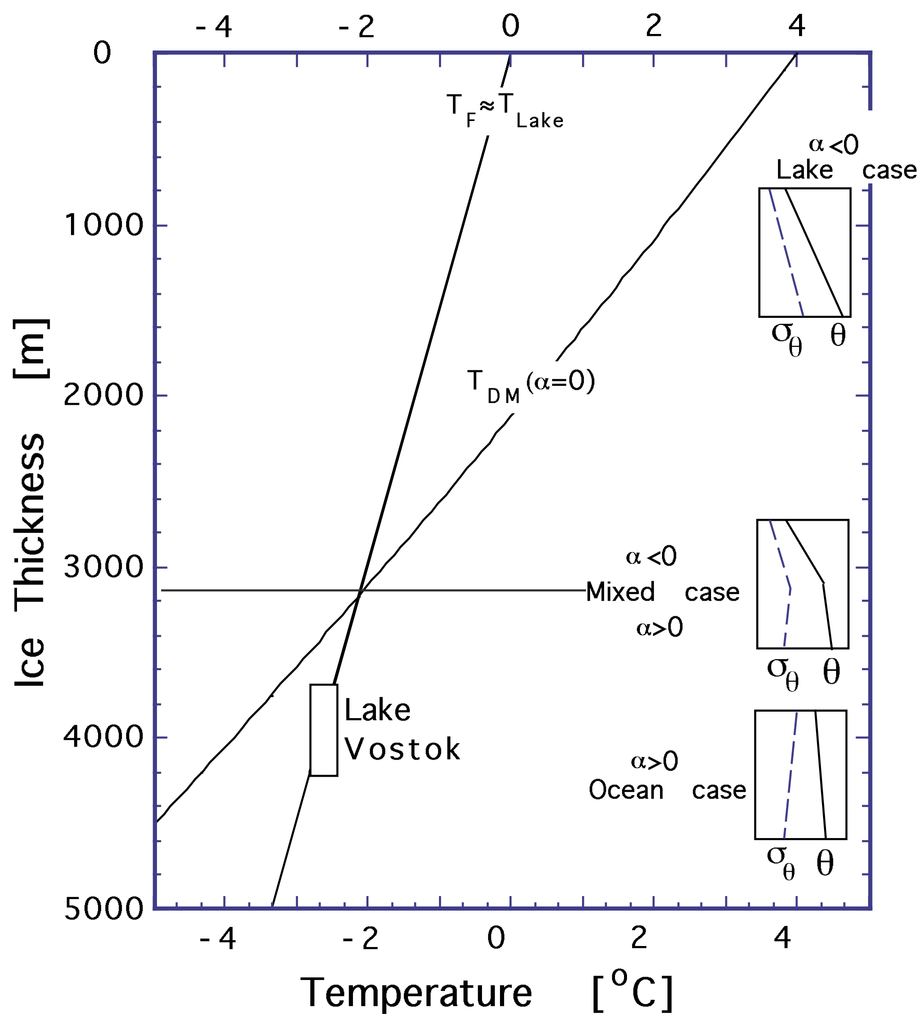
Density-driven flows are likely to dominate water motion within Lake Vostok. Hence, consideration must be given to (1) the equation of state of fresh water; (2) the effect of pressure on freezing point; (3) potential material flux from the overlying ice; and (4) geothermal heating from below. In turn, these factors may be modified by sloping boundaries, e.g. along the ice-water interface (ceiling) and water-sediment (floor) of the lake. Some simple constraints follow from basic thermodynamic considerations. The depression of the temperature of maximum density (TMD) with pressure is given by TMD(S, p) = TMD(0, p) - 0.021p, where p is pressure in bars or 105 Pa (Chen and Millero, 1986). The depression of the freezing temperature (TFP) with pressure is given by TFP(S, p) = TFP(S, 0) ñ 0.00759p (Fujino et al., 1975). Taking TMD(0, 0) ~ 4 ^{o}C and TFP(0, 0) ~ 0 ^{o}C we see that the two lines cross at a critical pressure (pcrit) of about 305 bars, which corresponds to an overlying ice thickness of about 3350 m. Above this critical pressure TMD > TFP and the system is stable when (T/(Z > 0); that is, it behaves as a lake. Below this pressure TMD < TFP and the system is stable when (T/(Z < 0); that is, it behaves as an ocean. It appears that pressures with Lake Vostok place it in the “ocean” category. Other Antarctic lakes, for example the one at South Pole, may fall into the “lake” category. An interesting situation would arise if pcrit were to lie internal to the lake, yielding bimodal flow conditions. External sources of buoyancy to the system include geothermal heating (perhaps ~ 50 mWm^{-2}) and particle fluxes (unknown, but, if existent, likely to be highly localized). Lateral gradients of buoyancy may also arise from boundary conditions at the sloping ceiling (required to be at the local TFP) and bottom (derived from either geothermal effects or solute flux). It is noted that examples are found elsewhere in nature where extreme pressures affect water stratification and motion; for example in the oceans off Antarctic ice shelves (Carmack and Foster, 1975) and in deep lakes such as Baikal (Weiss et al., 1991). Prior to *in situ* measurements of circulation in Lake Vostok, possible scales of motion should be explored with simple models. Also, field experiments could be carried out to see if flow can be detected in similar but less extreme high pressure and low temperature situations (e.g. beneath the Ward Hunt Ice shelf off Ellsmere Island (Jefferies, 1992).



Handout: Carmack

Figure Caption

Concerning water column stratification, three types of lakes under ice can be expected in Antarctica, depending on whether the ice thickness is larger or less than the depth, where freezing temperature T_F and the temperature of maximum density T_{MD} are identical (3170 m ice). Lake Vostok, where T_F (lake temperature = -2.7°C) is warmer than T_{MD} (-4°C), thermal expansivity α is positive and subsequently density σ_Θ decreases with depth, as typical under convective instability

Appendix 2 Workshop Program

Lake Vostok Workshop
"A Curiosity or a Focus for Interdisciplinary Study?"
An NSF Sponsored Workshop
Washington D.C.
November 7 & 8, 1998

Conveners

Robin E. Bell, Lamont-Doherty Earth Observatory, Oceanography, Rt. 9W, Palisades, New York 10964, Phone: 914-365-8827, E-mail: robinb@ldeo.columbia.edu

David M. Karl, School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, HI 96822, Phone 808-956-8964, E-Mail: dkarl@soest.hawaii.edu

WORKSHOP GOAL

The goal of the Lake Vostok workshop will be to stimulate discussion within the US science community on Lake Vostok specifically addressing the question: "Is Lake Vostok a natural curiosity or an opportunity for uniquely posed interdisciplinary scientific programs?" The workshop will attempt to develop an interdisciplinary science plan for studies of the lake.

WORKSHOP STRUCTURE

The workshop will open with a series of short talks setting the background on Lake Vostok. Prior to the meeting a package of information on Lake Vostok will be distributed to ensure that the group has adequate background. Following the background talks, each participant will be provided an opportunity to share their focused thoughts on Lake Vostok, and critical information or research directions they would like to see pursued. In the following day and a half the group will break into cross disciplinary groups to develop a sequence of key science objectives and a strategy to carry them out. Each group will present its plan to the full workshop group and the results will be discussed.

PROGRAM

Saturday 11/7/98

8AM - 8:45 AM Continental Style Breakfast at AGU facilities

9:00	Welcome and Introduction	(Robin Bell & David Karl)
9:15	NSF Charge	(Julie Palais)
930	Overview talks on Lake Vostok	
	Review of studies to Date	(Robin Bell)
	The Overlying Ice	(Martin Siegert)
	Possible Lake Samples - Basal Ice	(Jean Robert Petit)
1030	Break	

1045	Geologic Framework	(Ian Dalziel)
	Biodiversity Questions	(Jim Tiedje)
	NASA & Lake Vostok	(Frank Carsey)
	How to Identify Life	(David White/Roger Kern)

12:30 lunch break (lunch provided for group)

1:30 PM session

1:30	*Why Lake Vostok? 3-5 minute - 1 overhead presentations from participants (see section labeled "Why Lake Vostok" for more information)
3:30	Break
3:45	Break into Discipline Based Groups to Develop List of Key Questions
4:45	Present Key Questions & Discuss linkages
6:00	Reception at AGU

Sunday 11/8/98

8:00-845	Continental Style Breakfast @ AGU facilities
9:00	Review Linkages Break into Interdisciplinary Groups to (1) Develop Questions (2) Research Plan
12:00	lunch break (lunch provided for group)
1:00	Groups Present Summaries Discussion
4:00	Adjourn

APPENDIX 3 WORKSHOP PARTICIPANTS

Name	*Affiliation*	*Address*	*phone, fax, e-mail*
Becker, Luann	University of Hawaii, Manoa	University of Hawaii 2525 Correa Rd. Honolulu, HI 96822	p.808.956-5010 f.808.956-3188 lbecker@soest.hawaii.edu
Bell, Robin	LDEO	Oceanography Rte. 9W Palisades NY 10964	p.914.365-8827 f.914-365-8179 robinb@ldeo.columbia.edu
Cameron, Mary Ellen	NSF	4201 Wilson Blvd. Arlington VA 22230	p.703-306-1030 f.703-306-0645 Mcameron@nsf.gov
Carmack, Eddy	Institute of Ocean Sciences	Institute of Ocean Sciences 9860 West Saanich Rd. P.O. Box 6000 Sidney BC V8L4B2 Canada	p.250-363-6585 f.250-363-6746 CarmackE@pac.dfo-mpo.gc.ca
Carsey, Frank D.	JPL/NASA	JPL ms 300-323 4800 Oak Grove Dr. Pasadena CA 91109	p.818-354-8163 f.818-393-6720 Frank.D.Carsey@jpl.nasa.gov
Dalziel, Ian	Institute for Geophysics University of Texas, Austin	4412 Spicewood Springs Rd. Bldg. 600 Austin TX 78759-8500	p.512-471-0431 f.512-471-8844 ian@utig.ig.utexas.edu
de la Torre, José	U.C. Berkeley	Department of Plant & Microbial Biology 111 Koshland#371 University of California Berkeley, CA 94720-3102	p.510-643-2572 f.510-642-4995 jtorre@nature.berkeley.edu
Doran, Peter	University of Chicago	University of Illinois at Chicago Department of Earth and Environmental Sciences 845 W. Taylor St. Chicago, Illinois, 60607-7059 USA	p.312-413-7275 f.312-413-2279 pdoran@dri.edu pdoran@uic.edu

Duguay, Linda	NSF Office of Polar Programs	4201 Wilson Blvd. Rm. 755 Arlington VA 22230	p.703-306-1045 X7375 f.703-306-1039 lduguay@nsf.gov
Ellis-Evans, Cynan	Terrestrial and Freshwater Life Sciences Division British Antarctic Survey	Terrestrial and Freshwater Life Sciences Division British Antarctic Survey High Cross Site Madingley Road Cambridge CB3 0ET Cambs., England	p.+44 (0)1223-221555 f. +44 (0)1223-362616 jcel@nerc-bas.ac.uk
Emerson, David	American Type Culture Collection	10801 University Blvd. Manassas, VA 20110-2209	p.707-365-2700 f.707-365-2730 demerson@gmu.edu
Guthridge, Guy	NSF Office of Polar Programs	4201 Wilson Blvd. Arlington VA 22230	p.703-306-1033 f.03-306-1039 gguthid@nsf.gov
Holland, David M.	Courant Institute of Mathematical Science	251 Mercer St. Warren Weaver Hall, 907 New York University, MC 0711 New York City, NY 10012	p.212-998-3245 f.212-995-4121 holland@cims.nyu.edu
Hulbe, Christina	NASA Goddard Space Flight Center	Code 971 NASA Goddard Space Flight Center Greenbelt MD 20771	p.301- 614-5911 f.301-614-5644 chulbe@ice.gsfc.nasa.gov
Jatko, Joyce	NSF Office of Polar Programs	4201 Wilson Blvd. Arlington VA 22230	p.703-306-1032 f 703-306-0139 jjatko@nsf.gov
Karl, David	University of Hawaii	Dept. of Oceanography 1000 Pope Rd. University of Hawai'i Honolulu, HI 96822	p.808-956-8964 f.808-956-5059 dkarl@soest.hawaii.edu
Kennicutt II, Mahlon (Chuck)	Director Geochemical & Environmental Research Group	Director Geochemical & Environmental Research Group Texas A&M University 833 Graham Rd. College Station, TX 77845	p.409-862-2323X111 f.409-862-2361 mck2@gergl1.tamu.edu

Kern, Roger	JPL/NASA	Group Leader of Biological Technologies, Chemical & Biological Technologies Science & Technologies Development Section, Mail Stop: 89-2 Jet Propulsion Laboratory 4800 Oak Grove Drive Pasadena, CA 91109	p.818-354-2233 f.818-393-4176 Roger.G.Kern@jpl.nasa.gov
Kwok, Ron	JPL/NASA/Cal Tech	Radar Science & Engineering 4800Oak Grove Dr. M/S: 300-235 Pasadena CA 91109-8099	p.818-354-5614 f.818-393-5285 ron@rgps1.jpl.nasa.gov
Lupisella, Mark L.	NASA Goddard Space Flight Center	NASA Goddard Space Flight Center Greenbelt Rd. Mailstop 584.3 Building 23, Rm. W207 Greenbelt, MD 20771	p.301-286-2918 f.301-286-2325 Mark.Lupisella@gsfc.nasa.gov
Lyons, W. Berry	University of Alabama	Dept. of Geology University of Alabama Box 870338 Tuscaloosa AL 35487-0338 p205-348-0583 v205-348-0818	p.205-348-0583 f.205-348-0818 BLyons@wgs.geo.ua.edu
Marinelli, Roberta	NSF Office of Polar Programs	4201 Wilson Blvd. Arlington VA 22230	p.703-306-1033 f.703-306-1045 rmarinel@nsf.gov
McKnight, Diane	INSTAAR/University of Colorado	INSTAAR 1560 30th St. Boulder CO 80309-0450	p.303-492-7573 f.303-492-6388 Diane.McKnight@Colorado.edu
Metcalf, Altie	NSF Office of Polar Programs	4201 Wilson Blvd. Rm 755 Arlington VA 22230	p.703-306-1030 f.703-306-0645 ametcalf@nsf.gov

Moran. Kathryn	Director, Ocean Drilling Program	Director, ODP Joint Oceanographic Institutions, Inc. 1755 Massachusetts Ave. NW, Suite 800 Washington DC 20036	p.202-232-3900X217 f 202-232-8203 kmoran@brook.edu
Olsen, Paul E.	LDEO	Geoscience Rte. 9W Palisades NY 10964	p.914-365-8491 f.914-365-2312 polsen@ldeo.columbia.edu
Palais, Julie	NSF Office of Polar Programs	4201 Wilson Blvd. Arlington VA 22230	p.703-306-1033X7351 f.703-306-1039 jpalais@nsf.gov
Peacock, Dennis	NSF Office of Polar Programs	4201 Wilson Blvd. Arlington VA 22230	p.703-306-1033 f.703-306-1041 dpeacock@nsf.gov
Penhale, Polly	NSF Office of Polar Programs	4201 Wilson Blvd. Arlington VA 22230	p.703-306-1033X7348 f 703-306-1039 ppenhale@nsf.gov
Petit, Jean Robert	Senior French Scientist on the Vostok Station Ice core	LGGE-CNRS BP96 38402 St. Martin d'Heres, Cedex France	p. 33 4 76 82 42 44 f. 33 4 76 82 42 01 petit@glaciog.ujf-grenoble.fr
Platt, Steve	University Nebraska Lincoln/Polar Ice Core Office	Polar Ice Coring Office University of Nebraska-Lincoln 2255 W Street, Suite 101 Lincoln, NE 68583-0850	p.402-472-9833 f.402-472-9832 srp@unl.edu
Rack, Frank	Ocean Drilling Program	Assistant Programs Director Joint Oceanographic Institutions, Inc. 1755 Massachusetts Ave. NW, Suite 800 Washington DC 20036	p.202-232-3900X216 f.202-232-8203 frack@brook.edu
Siegert, Martin	Bristol Glaciology Centre	School of Geographical Sciences, University of Bristol Bristol BS8 1SS, UK	p.+44 117 928 8186 f.+44 117 928 9000 m.j.seigert@bristol.ac.uk

Sowers, Todd	Penn State University	447 Deike Building Dept. of Geosciences Penn State University University Park, PA, 16802	p.814-863-8093 f.814-863-7823 sowers@geosc.psu.edu
Tiedje, Jim	Center for Microbial Ecology Michigan State University	540 Plant & Soil Science Michigan State University East Lansing, MI 48824-1325	p.517-353-9021 f.517-353-2917 (Lisa Pline 517-353-90210 tiedjej@pilot.msu.edu
Turrin, Brent	LDEO	Rte. 9W Palisades NY 10964	p.914-365-8454 f. 914-365-8155 bturrin@ldeo.columbia.edu
Voytek, Mary	USGS	USGS MS 430 12201 Sunrise Valley Dr. Reston VA 20192	p.703-648-6894 f.703.648-5484 mavoytek@usgs.gov
White, David	University of Tennessee, ORNL, JPL	10515 Research Dr., Suite 300 Knoxville TN 37932-2575	p.423-974-8001 f.423-974-8027 Milipids@aol.com

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A copy of this report can be accessed on the World Wide Web at:
http://www.ldeo.columbia.edu/vostok/
The ERS-1 image was obtained from the Glaciology Home Page of the University College London at:
http://msslsp.mssl.ucl.ac.uk/orgs/cp/html/glac/topog.html
Additional hard copies of the report may be requested from Margie Turrin (mkt@ldeo.columbia.edu).

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Microflora of the Deep Glacier Horizons of Central Antarctica

S. S. Abyzov, I. N. Mitskevich, and M. N. Poglazova

Institute of Microbiology, Russian Academy of Sciences, pr. 60-letia Oktyabrya 7, k. 2, Moscow, 117811 Russia

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Abstract—Microorganisms were detected in samples taken from different horizons of the glacier of Central Antarctica (at depths of 1500–2750 m), whose age is over 240 000 years. Microscopic studies of microorganisms from thawed water samples taken from the center of the glacier core (precipitated on membrane filters and stained with fluorescent dyes) revealed that they contained a wide variety of microorganisms. Bacteria prevailed, although yeasts, fungi, and microalgae also occurred. Some horizons also contained the pollen of higher plants and dust particles of various origins. Consumption of ^{14}C-labeled organic compounds by most thawed samples testified to the presence of viable cells in them. The total microorganism number at depths of 1500–2750 m was 0.8×10^3 to 10.8×10^3 cells/ml. Fluctuations in the number of microorganisms throughout the glacier correlated with changes in the number of mineral particles detected by glaciologists in the respective glacier horizons, which, according to their calculations, depended on alternations of warm and cold periods on Earth.

Key words: Antarctic continent, glacier, microorganisms, anabiosis.

This paper concerns itself with the investigation of the microflora of the deep horizons of the Antarctic glacier and forms part of a series of studies on the ice-bound continent [1, 2].

Due to specific conditions characteristic of this continent (low temperatures, dry climate, enhanced radiation level), many researchers consider the Antarctic continent a model in the quest for extraterrestrial life forms and the development of quarantine systems for planets (including Earth) in connection with interplanetary contacts. It is also viewed as Nature's successful attempt to solve the problem of long-term anabiosis and other global ecological problems [3–5].

The Antarctic ice sheet represents an ideal object for diverse scientific studies, based on: (1) its location far away from regions with intense anthropogenic influence; (2) the stability of its subzero temperature level; and (3) the protection provided by glacier horizons formed in the geological past against the subsequent effects of environmental factors.

Research on the ice core of the glacier, extracted at the Vostok station, won worldwide recognition [6]. Antarctic glaciers had not received attention from microbiologists for a long time. Nevertheless, a number of researchers [7, 8] believe that the ice fields of Antarctica and Greenland serve as a natural trap for precipitations and airborne particles. Their sediments in the glacier represent a unique historical record of both cosmic and earthly events. Research on inclusions of terrestrial and extraterrestrial origin (ancient air bubbles, volcanic ash, extraterrestrial dust, microalgae, pollen of ancient plants, etc.) accumulated over the course of many millennia and their quantitative analysis can provide valuable information for solving many important problems of modern science [9–12].

The goal of this work was to detect microorganisms in ancient glacier horizons located at depths of 1500 to 2700 m, to study their morphological diversity, quantity, and viability. This work was also aimed at comparing the number of microbial cells with that of dust particles and clarifying the possible relationship between their oscillations in different horizons of the glacier section tested and paleoclimatic data.

MATERIALS AND METHODS

The samples of the ice core used in our microbiological studies were taken at the Vostok station (78°28′ S, 106°48′ E, 3488 m above sea-level). The glacier thickness was 3700 m, and the temperature in the glacier thickness was –53 to –55°C. The samples were extracted from the glacier at depths of 1500 to 2750 m.

The method of drilling the glacier was described in detail in earlier papers [1, 13]. Samples from the core (the inner part) of the ice extracted from the glacier were taken using a device constructed for this purpose. A detailed description of this device and the sample-taking technique are available in our earlier works [2].

The thawed samples were placed in sterile flasks, which were sealed immediately thereafter and stored in the refrigerator of the research vessel. After the flasks were delivered to the laboratory, they were opened in a sterile chamber, and their contents were inoculated into various nutrient media.

Part of the thawed samples (150–200 ml) was passed through a filter to precipitate microflora, other organisms, and various particles whose size exceeded the filter pore diameter. We used polycarbonate nuclear filters preliminarily quenched with saturated alcohol solution of Sudan Black B. The filter pore diameter was 0.2 μm. The filter-precipitated cells were fixed with 96% ethanol and dried. The filters could be stored for several months before subjecting them to subsequent treatment. The filter-precipitated cells were stained with the fluorescent dye fluorescamine. It does not emit light per se, but its complexes with proteins and amino group–containing compounds, which result from a reaction involving NH groups, are characterized by an extremely high fluorescence level. The staining method was described in detail earlier [14]. The stained filters were used to determine the total microbial cell number by a direct count in a luminescent microscope in 20–30 fields and subsequent calculation of the cell concentration in the specimen according to a conventional formula [15]. The same filters were employed to research the morphological diversity of microorganisms and to preliminarily determine their group affiliation. The specimens were examined in a LYUMAM-I-2 luminescent microscope (Russia). Blue–violet exciting light (using an FS-1-4 filter) was employed. The specimens were photographed with an 100× objective lens and an 5× ocular lens.

Scanning electron microscopy was performed using thawed samples (100–200 ml) passed through nuclear filters with a pore diameter of 0.2 μm. The filters were subsequently treated with 2% glutaraldehyde for 6 h, and thereafter consecutively incubated for 10 min in 30, 50, 70, and 96% ethanol and finally in acetone in order to dehydrate the specimens [15].

After this treatment, the specimens were shadowed with gold and examined in a Jeol Jsm-T-300 scanning electron microscope (Japan) at a magnification of 5000–20 000×.

Consumption of the organic substrate in thawed ice samples was determined using a radioactive label. The thawed ice core was aseptically placed into sterile 100-ml vessels. A solution of carbon-labeled protein hydrolysate (50 μg ^{14}C per liter) was added to each vessel with a sterile syringe. Control vessels were supplemented with 2 ml of 40% formaldehyde solution. The vessels were stored in the dark at 12 and 18°C for different time periods (4 to 40 h) and thereupon fixed with formaldehyde. Each specimen was passed through membrane filters with 0.23 μm pores. The filters were subsequently washed to remove the adsorbed radioactive isotope and dried. The radioactivity of filter-precipitated material was measured with a Rackbeta liquid scintillation counter (Sweden). The rate of ^{14}C hydrolysate consumption in each vessel was calculated using the formula $C_{org} = \frac{rS}{Rt}$, where C_{org} is the amount of organic substance consumed by the microflora, μg/(l/h); S, the amount of substrate added, μg/l; R, the initial radioactivity of the organic substance in each vessel, cpm; r, the radioactivity of the biological material in the filter-precipitated specimen, cpm, and t, incubation time, h.

In contrast to the standard method [15] envisaging sample incubation with the radioactive label for 1 h, microflora in our experiments was in contact with labeled carbon for a longer time (4 to 40 h).

RESULTS AND DISCUSSION

This paper presents the results of an analysis of the glacier microflora revealed at a depth of 1500 to 2750 m; these data are more complete and they have been analyzed in this work in more detail than in the earlier works [1, 2].

Using the epifluorescence method and scanning electron microscopy, we detected microorganisms belonging to different taxonomic groups and characterized by considerable morphological diversity. Prokaryotic microorganisms (bacteria of various shape and sizes) we found throughout the whole layer tested. They included cocci, diplococci, rods of different length and width (straight or curved), and oval cells (Fig. 1a). Actinomycetes were also frequently encountered (Fig. 1b). Eukaryotic organisms were represented by diverse yeast species (budding or dividing cells), which were dominated by the genus *Saccharomyces* with the classic budding pattern, although other yeast, e.g., *Saccharomycoides* (with buds attaching to a broad base) also occurred (Fig. 1c). Some samples contained mycelial fragments of various fungi, whose hyphae were partially or completely lysed (Fig. 1d, upper row). In contrast to mycelium, fungal conidia were in good condition (Fig. 1d, lower row). Based on conidium morphology, an important taxonomic criterion, sickle-shaped conidia with three transverse septa presumably belong to fungi of the genus *Fusarium*, whereas double-celled oval-shaped conidia with a tiny central septum probably relate to the genus *Trichothecium*. Small round conidia, occurring in abundance in some samples, may belong to fungi of various genera (*Mucor, Penicillium, Aspergillus*, etc.).

Importantly, virtually no bacterial spores were revealed in the tested horizons. From the figures, it is evident that the specimens were dominated by vegetative bacteria cells (Fig. 1a). However, this does not rule out the possibility that spore-forming bacteria occurred among the surviving microorganisms. It had been shown earlier that the microflora of the more ancient glacier horizons (below 1500 m) chiefly consisted of spore-forming bacteria (based on results from inoculating the samples into nutrient media) [2]. Possibly, the vegetative cells of spore-forming bacteria, which represent the majority of gram-positive bacteria, are especially cold-resistant and capable of long-term anabiosis (with vital functions retained).

Temporary transition of microbial cells to the dormant state, which involves biochemical, physiological

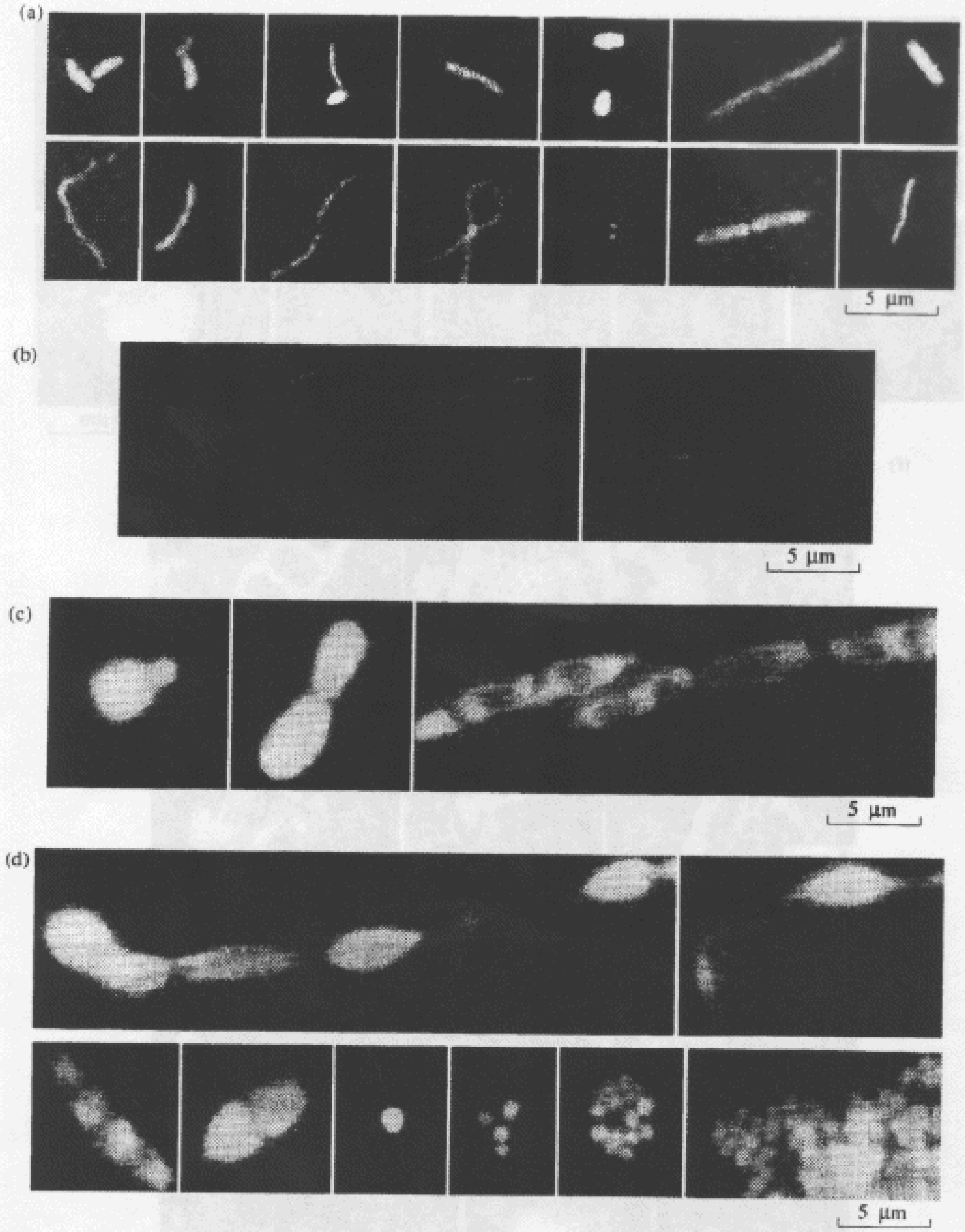

Fig. 1. Microflora of the ancient ice horizons of Central Antarcyica., (a–e), (g) fluorescent and (f) electron microscopy: (a) bacterial cells; (b) fragments of actinomycete cells; (c) budding and dividing yeast; (d) partially lysed hyphae of fungi (upper row) and conidia of various fungi (lower row); bar, 5 µm; (e) and (f) microalgae; (g) dust particle–adsorbed bacteria.

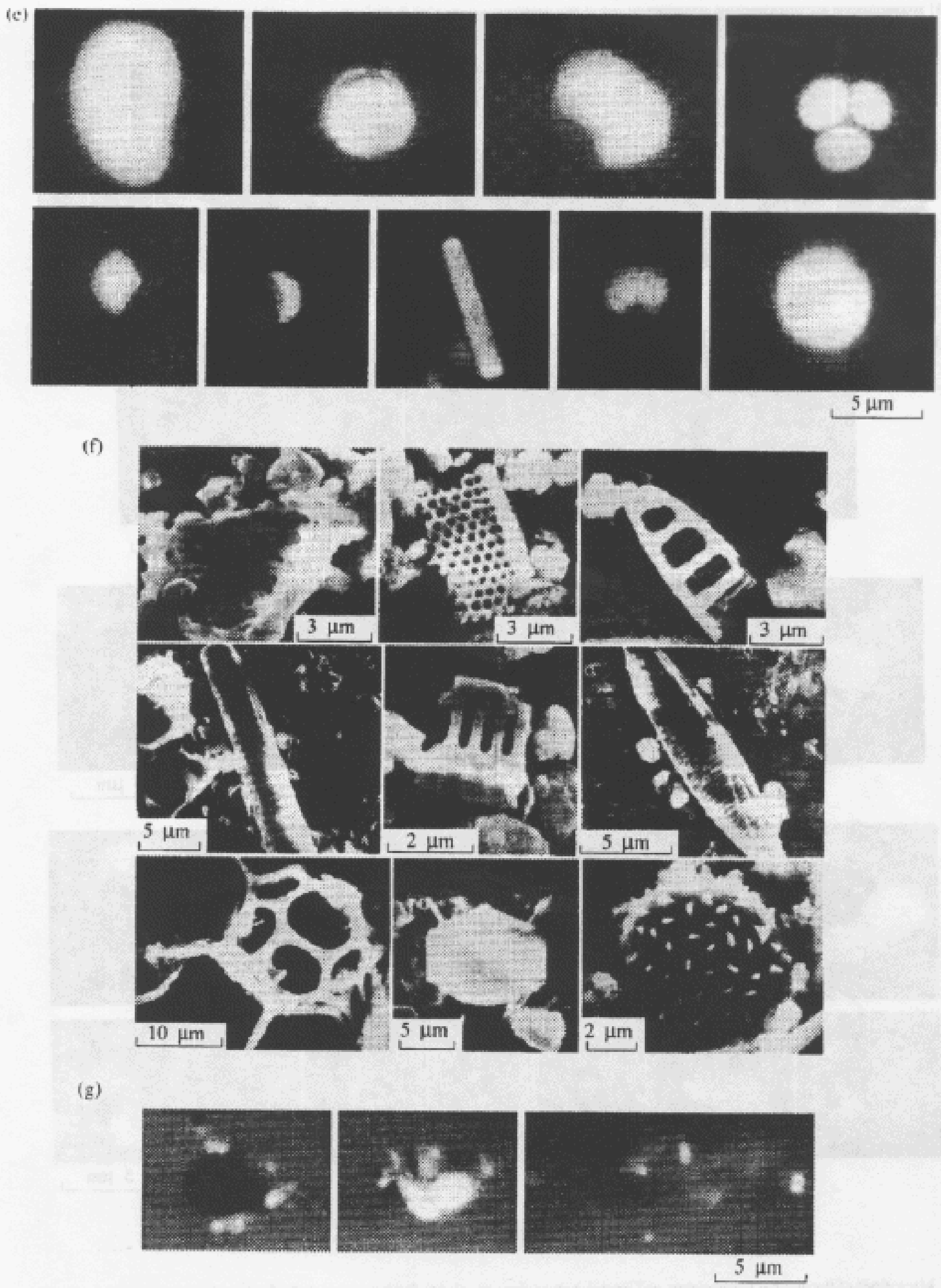

Fig. 1. (Contd.)

[16], and ultrastructural changes, including DNA supercoiling [17], is the most widespread mechanism developed by organisms in the process of evolution to promote species survival under extreme conditions. Undoubtedly, this mechanism possesses an advantage over spore formation, which requires more sophisticated structural alterations, specific conditions, and a relatively long time.

The pollen of higher plants was abundant in some horizons. It was characterized by the emission of yellow-green light. A wide variety of microalgae was detected using a fluorescent microscope (Fig. 1e). Scanning electron microscopy revealed diatomic algae, whose number was particularly great in the samples from the 2035 m deep horizon (Fig. 1f).

Microscopic studies also demonstrated that some horizons contained a large number of dust particles. These particles were copiously precipitated on membrane filters. Bacteria attached to mineral particles or partially decomposed organic remnants were clearly visible (Fig. 1g).

A subsequent series of studies determined the bacterial cell number in the tested glacier layer by a direct count in a luminescent microscope on membrane filters after staining the cells with fluorescent dyes. All cells were taken into account, although their fluorescence brightness was different. The difference in cell fluorescence was due to varying protein contents in the cells, since fluorescamin specifically interacts with proteinaceous substances. Therefore, the difference in fluorescence enables us to evaluate (to some extent) the state of the cells in terms of their degree of lysis.

The microbial cell number in different horizons varied between 0.8×10^3 and 10.8×10^3 in 1 cm^3 of ice. Based on the data in Fig. 2b, it seems that there is no definite law underlying the quantitative distribution of microorganisms among the horizons. However, a comparison of the results of the direct count of microorganisms in different horizons and glaciological studies of the distribution of dust particles from the atmosphere in the same horizons indicates that the two patterns are analogous (Fig. 2b, 2c). The fluctuations in particle concentration depend on the climatic conditions in the respective periods, as a comparison of the data in Fig. 2a and Fig. 2b reveals. During these periods (240 to 110 thousand years ago, Fig. 2a upper scale), the glacier section under study was formed. These periods include the penultimate climatic cycle with one glacial and two interglacial periods.

The data on climate changes and temperature oscillations presented in this work were obtained in glaciological studies, based on changes in the isotope composition of the ice and other physical parameters; they were described in detail in published papers [19–21].

Detailed analysis of the data of microbiological and glaciological research showed that the maximum dust and microorganism concentrations fall on the periods of global temperature decrease on Earth. From Fig. 2b and 2c, it is evident that the points characterized by the maximum dust particle and microbial cell numbers correspond to the horizons located at depths of approximately 2000–2150 and 2300–2400 m. Importantly, scanning electron microscopy of the samples from these horizons demonstrated that they contain the maximum amounts of diatomic algae (Fig. 1f) and pollen of higher plants.

According to glaciological data, the periods of maximum temperature decline, which make possible the conservation of the largest number of dust particles and organisms, were characterized by the expansion of arid territories (corresponding to the dried up parts of the World Ocean shelf), an increase in wind intensity, and the meridional transfer of air masses [12]. In all likelihood, these factors promoted intense diffusion of biological and mineral particles in the atmosphere, and their subsequent migration and transfer to the surface of glaciers, especially since the size of most microbial cells (0.4–1.5 μm^3) and microalgae (15–30 μm^3) approximately equals that of small dust particles. The adhesion of bacteria to dust particles that we observed (Fig. 1g) also substantiates the suggestion that the migration of both microparticles and microorganisms in the circumterrestrial space is determined by the same factors.

Our final series of experiments was concerned with determining the viability of the microbial cells conserved in the ice core. In contrast to earlier studies in which viability was determined by inoculating the samples into nutrient media [2], we used a radioactive label in these studies. The table gives data on the consumption of labeled carbon by the microbial cells contained in the samples from horizons of the 1500–2750 m layer of the glacier.

Since the microbial cells contained in the samples had spent hundreds of millennia in the ice core, the incubation times of the samples were increased in comparison with the standard method. Owing to the limited quantity of experimental material available, the incubation time for the samples from different horizons was different. Thus, this study represents an attempt to find optimum conditions for attaining the goal of this work, and the experiments can be partly regarded as preliminary. The table shows that an 18–40 h incubation does not result in any increase in labeled carbon consumption in comparison with a shorter incubation, suggesting that the samples lack reproducing cells. Incubating the samples for a relatively short time (4–7 h) proved sufficient for cell reactivation and the onset of labeled carbon consumption (a manifestation of vital functions).

Analysis of the data obtained reveals an underlying pattern, even though there were some differences in the techniques used for investigating different samples. The table indicates that, irrespective of the initial bacterial cell number in 1 ml of a sample (determined by the direct irrespective of the incubation time: count of

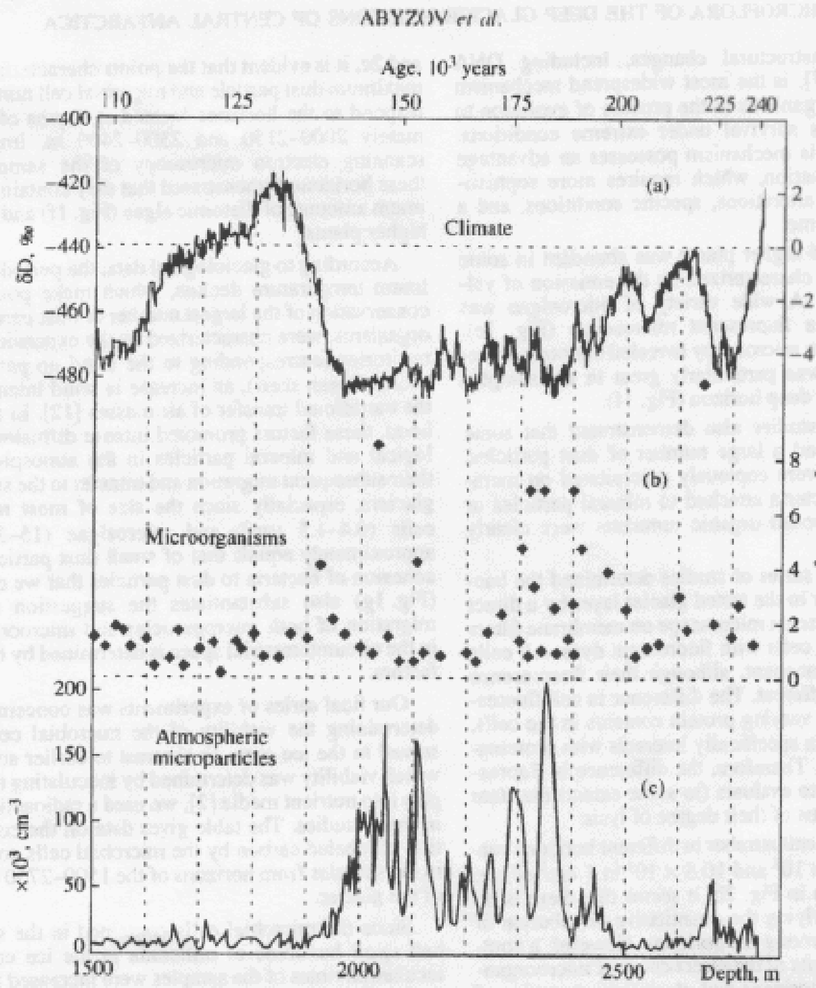

Fig. 2. Quantitative distribution of microorganisms in dust particles in the glacier of Central Antarctic during different geological epochs: (a) changes in climatic conditions based on glaciological data; (b) microbial cell concentration at different depths in the glacier; (c) dust particle concentration at different depths in the glacier.

cells), consumption of labeled carbon tends to decrease if the depth increases. It was $1.0–4.4 \times 10^{-3}$ μg C/(l h) in samples from the 1665–2425 m deep horizons and became lower by one order of magnitude in most samples from deeper horizons irrespective of the incubation time: $1.0–6.0 \times 10^{-4}$ μg C/(l h). A similar regularity was shown earlier when samples from the higher glacier layers were inoculated into nutrient media [2]. According to the table, the data on the samples from 2035–2115 m deep horizons are inconsistent with the general pattern, since their carbon consumption was zero. The corresponding period was characterized (see Fig. 2a) by a global temperature decrease. Along with other factors, it could exert a negative influence on the viability of mesophile cells and only promoted the survival of psychrophile organisms, which were reactivated at 12°C (table).

From the data obtained, we can conclude that microbial cells that occur at a depth of 1500–2750 m have remained viable for 110000–240000 years. It was established for the first time that anabiosis (with vital functions retained) can continue for this long of a time in Antarctic ice. The number of viable cells decreases with increasing depth and does not correlate with the total number of intact cells in the respective horizons.

The total and viable cell numbers, therefore, appear to depend on different factors. The total cell number in various horizons is primarily determined by the cli-

Consumption of radioactive substrate (^{14}C protein hydrolysate) by thawed samples of the ice core taken at the Vostok Station

Horizon, m	Age, 10^3 years	Incubation time, h	Carbon consumption, μg/(l h)		Cell number in 1 ml of the sample
			at 18°C	at 12°C	
1665	118	4	4.4×10^{-3}	7.0×10^{-4}	1.6×10^3
2035	147	24	0	3.0×10^{-4}	8.3×10^3
2115	155	24	0	1.0×10^{-4}	4.1×10^3
2376	187	18	1.3×10^{-3}	1.0×10^{-4}	2.5×10^3
2425	192	24	1.0×10^{-3}	–*	4.6×10^3
2500	202	24	6.0×10^{-4}	–	2.5×10^3
2570	217	24	2.0×10^{-4}	6.0×10^{-4}	1.2×10^3
2626	220	7	1.4×10^{-3}	0	1.8×10^3
2673	227	40	5.0×10^{-4}	0	2.0×10^3
2719	236	40	1.0×10^{-4}	0	2.5×10^3
2750	242	20	2.0×10^{-4}	0	1.2×10^3

* No data.

matic conditions that influence cell transfer to the surface of Antarctica. Subsequent cell conservation on the surface of the ice and within the ice is made possible by low temperatures, which prevent cell lysis. The viability of anabiotic cells depends on a number of circumstances, including interspecies differences, the conditions used to resuscitate anabiotic cells, and a number of factors acting before or during the process of anabiosis.

In summary, this work presents, for the first time, data on ancient glacier horizons (1500–2750 m deep). These studies could be conducted because the ice core-drilling and sampling techniques have been considerably improved [2, 13, 21]. A combination of microscopic and physiological methods, in conjunction with glaciological approaches, made it possible to characterize the glacier section studied in greater detail than in the case of the upper horizons.

Direct microscopy of the glacier samples with the help of fluorescent and scanning electron microscopes allowed a more correct evaluation of ancient microflora than the inoculation techniques used earlier, which only provided information on viable microorganisms. It was established in these studies that the microflora of the glacier layer at 1500–2750 m depth chiefly includes extant microbial species. The data obtained provide only a general insight into the diversity of the ancient representatives of Earth's microbial population. Nevertheless, such research represents a necessary stage of, and its results are prerequisite for, the investigation of the species composition of the microorganisms isolated from the glacier and the evaluation of the similarities and differences between ancient and modern species by examining their ultrastructural organization and characterizing their genome. These data would promote the solution of some problems concerning biological evolution.

Of paramount importance are the data on viable cells in ancient glacier horizons whose formation started 110 000–240 000 years ago. These data provide evidence that vital functions can be retained after long-term anabiosis at low temperatures.

In this work, a relationship between dust particles and microbial cell distribution among glacier horizons and climatic conditions during the corresponding periods was established. In light of these results, we can feel moderately optimistic about the prospects for the possible re-establishment of the ecological conditions under which microorganisms have spread on Earth during various periods of geological history.

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A large deep freshwater lake beneath the ice of central East Antarctica

A. P. Kapitsa*, J. K. Ridley†, G. de Q. Robin‡, M. J. Siegert§ & I. A. Zotikov||

* Faculty of Geography, Moscow State University, Moscow, Russia
† Mullard Space Science Laboratory, University College London, Dorking, Surrey, RH5 6NT, UK
‡ Scott Polar Research Institute, University of Cambridge, CB2 1ER, UK
§ Centre for Glaciology, Institute of Earth Studies, University of Wales, Aberystwyth, Dyfed SY23 3DB, UK
|| Institute of Geography, Russian Academy of Sciences, Moscow, Russia

In 1974–75, an airborne radio-echo survey of ice depths over central East Antarctica led to the discovery of a sub-ice lake of unknown depth and composition, with an area of about 10,000 km^2 and lying beneath ~4 km of ice[1]. In 1993, altimetric data from satellite measurements[2] provided independent evidence of the lake's areal extent, thus confirming it to be the largest known sub-ice lake by an order of magnitude. Here we analyse new altimetric and radio-echo data, along with existing seismic data[3], to show that the lake is deep (mean depth of 125 m or more) and fresh, and that it has an area that exceeds previous estimates by about 50%—dimensions comparable with those of Lake Ontario. We estimate that the residence time of the water in the lake is of the order of tens of thousands of years, and that the mean age of water in the lake, since deposition as surface ice, is about one million years. Regional ice-dynamics can be explained in terms of steady-state ice flow along and over the lake.

The satellite ERS-1, launched in 1991, was the first to be specifically programmed for altimetric surveys of large polar ice sheets. An analysis of the initial fast delivery data gave mean surface elevations every 6.7 km along the satellite track[2]. These defined areas of level ice, which roughly matched the lake boundary indicated by radio-echo sounding (RES), but differed by up to 30 km on the north-west of the lake and did not include Vostok, the Russian ice-drilling station (Fig. 1*b*).

The new lake boundary (Fig. 1*b*) is based on changes of surface slope derived from the waveform product[4] using the latest altimeter data. This agrees with the lake boundary shown by RES profiling (Fig. 1*a*) to within 5 km (maximum error in aircraft position from the inertial navigation[5]).

Owing mainly to the high noise level, seismic shooting studies of the ice cover of central Antarctica produced no evidence, before 1993, of the meltwater lenses beneath the ice sheet that had been suggested by Kapitsa[6] on morphological grounds. Although increasing shot depths[7,8] and higher frequency filtering[8] helped to reduce seismic noise levels, the only major reduction of noise on the Antarctic plateau had been achieved once by Kapitsa and Sorochtin[3] in 1964 by using a vertical seismometer spread from 2.5 to 49 m depth in a borehole at Vostok (Fig. 2). This clearly confirmed the ice depth as 3,700 m for the important ice-coring programme at Vostok, whereas a later echo was then interpreted as a sedimentary layer.

Confirmation of the ice depth and the presence of a water layer by RES profiling (Fig. 3*a*) led to reinterpretation of the seismic data shown in Fig. 2. The absence of any significant energy return between reflections from the ice–water interface and the lake floor on seismometers below 10 m depth, identification of the later echoes as P waves (Fig. 2), together with evidence from RES and altimetry, all confirm the presence of a deep water layer. Assuming 1,450 m s^{-1} as the P-wave velocity in water gives the water thickness as 510 m and the lake bed at 710 m below sea level.

Along RES flight lines, the depth of floating ice changes slowly. The lake bed is around 700 m below sea level near both ends of the lake. Assuming this applies over the whole lake bed, the mean water thickness beneath the south–north profile of flight 130 is 125 m and the total volume of water 1,800 km^3. The bedrock topography around the lake is similar to the topography around the rift valleys, especially of the deglaciated Lake Baikal, Siberia. Similar lake bathymetry would considerably increase the estimated volume of the sub-ice lake.

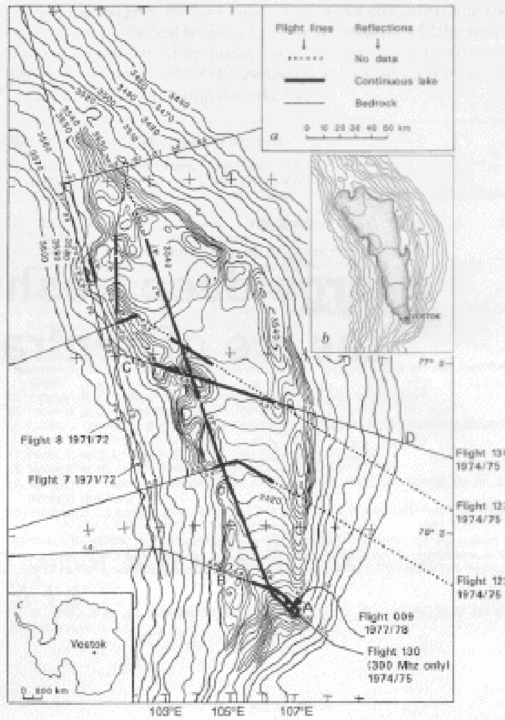


FIG. 1 Surface topography. ERS-1 waveform product (WAP) altimeter maps of the Vostok region. The improved altimetry comes from two 168-day repeat cycles of satellite orbits. The WAP analysis[4] gave 600,000 mean surface elevations over circles of 3 km diameter. Repeated and overlapping measurements gave an r.m.s. deviation of 20 cm and a maximum relative error in contours of 50 cm for the first time. This can now be extended over all inland ice north of 82° S. *a*, Contours over and near the lake boundary at 2-m intervals, with 10-m contours over steeper slopes. Figures along flightlines show bedrock elevations in kilometres above or below (−) sea level. Unpublished data now included come from flight 009 of 1977/78 and spot soundings every 2.4 km along the south-to-north flight 130 of 1974/75, which was not covered by continuous profiling (Fig. 3*a*). *b*, Shaded area shows the extent of the sub-ice lake, based on 2-m contouring but with 10-m contours over the entire area. This shows the low surface slope over the lake compared with the surrounding surface topography. *c*, Location of Vostok station.

With a surface accumulation of 2.7 g cm^{2} yr^{-1}, an ice thickness of ~3,700 m and a geothermal flux of ~50 mW, steady-state theory[9,10] predicts basal melting of ~1 mm yr^{-1}. Glacier dynamic theory indicates that the time taken for ice deposited on the surface to melt at the base is ~10^6 years. These estimates are in broad agreement with the age of the ice core at Vostok[11], shown by isotope profiling to a depth of 2,700 m.

Under steady-state conditions, a water input of 1 mm yr^{-1} from floating ice and a water layer 125 m thick gives a residence time of 1.25×10^5 years. Increasing the water input from basal melting of surrounding grounded ice and increasing the volume of the water in the same proportion leaves the residence time unchanged. With

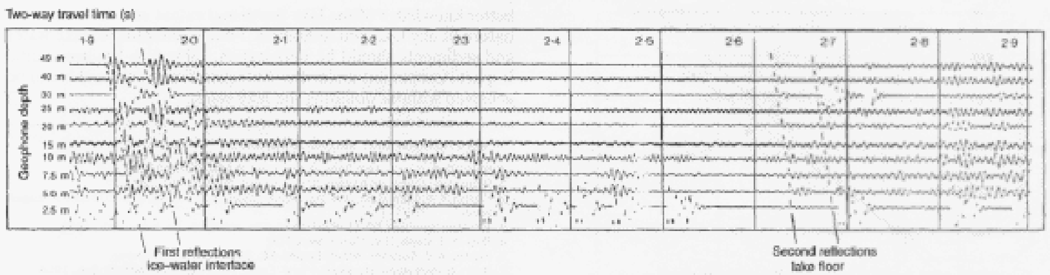


FIG. 2 Section of 24-channel seismic record from Vostok relevant to the sub-ice water layer. This records movement over a vertical line of seismometers from 49 m to 2.5 m depth in a borehole 180 m from the explosion. It covers a period from 1.85 to 2.9 seconds after the explosion of 5 kg of TNT at 39 m depth and 180 m from the vertical seismometer line. A conventional horizontal spread of twelve seismometers at 20-m intervals recorded the same echoes (not shown) at ~1.92 and ~2.65 s against a much higher background noise. The echo from the base of the floating ice reaches the deepest (49 m) seismometer first at ~1.91 s. It then travels up the seismometer line to the surface where it is reflected down to pass the 49-m seismometer ~50 ms later. This has a mean velocity of ~2,200 ms^{-1}, typical of compression (P) waves in the top 50 m of firn in this region[12]. About 45 ms after the first arrival, a second wave train of similar intensity and duration follows as a result of the initial surface reflection of the explosion at 39 m depth. There is no significant return of energy between ~2.00 and ~2.63 s, when a weaker wave train passes up and down the seismometer line at the same velocity. This confirms that they are compressive (P) waves, the only waves that travel through water, and not transverse (PS) waves, which are sometimes recorded from shots on ice shelves.

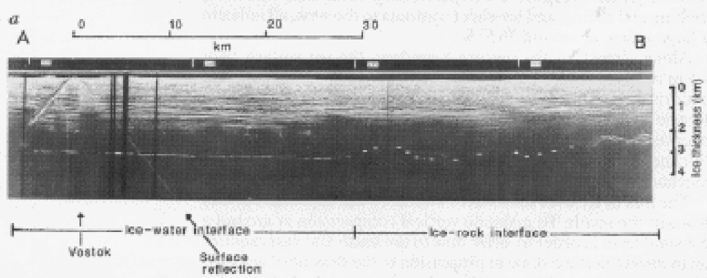
both likely, our best estimate of the residence time of the lake water is of the order of 50,000 years.

Other features of the water mass can be deduced from the relationship between surface elevation and thickness of floating ice (Fig. 4). The close scatter of points around the freshwater line (Fig. 4) indicates a hydraulic pressure equivalent to a head of water close to 3,140 m above sea level over the whole lake. It also confirms the presence of relatively fresh water in the lake. Any difference between the mean slope of plotted points and the freshwater line could be due to residual effects from boundary stresses, to errors of ice thickness and/or to the effect of limited salinity on water density within a range of 0.00 and 0.05‰.

The decrease of ice thickness of ~500 m from north to south of the lake means that the ice–water contact temperature will be 0.4 °C lower at the north than at the southern end. This may be sufficient to drive slow circulation of sub-ice water and affect basal heat flow distribution over the lake, but not the total heat flux.

Ice cores from Vostok contains micro-organisms[12,13] carried by air to Antarctica on dust particles from low latitudes. Melting of basal ice will release these microorganisms into lake water around one million years after deposition on the ice surface. Sediments on the lake bed may be several million years older, an exceptional environment that should provide useful information to the biological community and to geologists.

The lake occupies the lower part of a basin or rift (Figs 1, 3*b*). Unlike grounded ice, basal drag is negligible over an ice–water



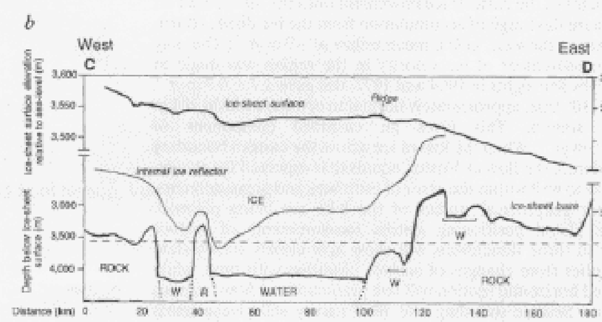


FIG. 3 Two-dimensional vertical profiles. *a*, Continuous RES profile from flight 009, 1977–78, along line A–B in Fig. 1*a*. Strong ice–water reflections beneath Vostok and for ~30 km give way to weaker echoes from ice–bedrock further west. White dots have been added to show the location of weak bedrock echoes where they are not clearly visible. The near-horizontal layering in the upper 2 km is due to higher-conductivity layers of ice resulting from widespread deposition of volcanic material over the ice sheet[17]. Slanting echoes show reflections from surface buildings as the aircraft passed over Vostok. *b*, Cross-section along line C–D in Fig. 1*a*, showing deepest continuous RES layer. The vertical scale of the surface profile is increased to 100 times that of the deep profiles. Surface valleys around 30 and 50 km near the western boundary are due to downslope motion over steeply falling bedrock, opposed by horizontal compression that continues over the lake. After the ice crosses a rock ridge approximately parallel to the lake boundary at 40 km, a deeper valley is formed. The surface and reflecting layer then rise from 50 to 70 km, apparently above faster, southward-moving ice. From 70 to 94 km the surface is almost level, with slight ice thickening probable, until the lake boundary is crossed. A flow component to the east is then indicated by the similarity of the profile in *b* to that across the Doake Ice Rumples[18] (77.7° S, 66.6° W) to the Ronne Ice Shelf. Upslope flow appears to be initiated and driven by vertical pressure in both cases. The alternative to this flow pattern would be an ice divide, with static ice below an almost flat surface for at least 10 km to either side.

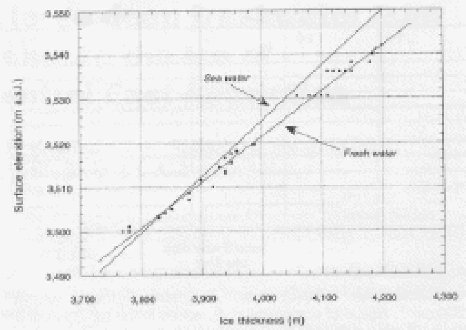


FIG. 4 Thickness (h) of floating ice by RES plotted against surface elevation (E) at locations clear of boundary effects along and across the lake on flight 130. Elevation of corresponding points is interpolated from satellite altimetry (Fig. 1). Also shown are computed slopes for ice in the same thickness range given by $dE/dh = (1 - \rho_{ice}/\rho_{water})$, where ρ denotes density. The lines shown apply to pressures from 30 to 40 MPa (ref. 19), salinity of sea water[20] of 35‰, and a mean density of ice of 0.913 g cm^{-3} from the borehole at VS (J.-R. Petit, personal communication). Resultant slopes are 0.105 for fresh water and 0.127 for sea water. Relative errors in ice thickness measurements should not exceed 30 m.

interface. Away from boundary effects, ice is compressed vertically and expands horizontally in directions offering least resistance. This produces a low surface slope normal to the surface contours as on ice shelves[14,15]. At Vostok[16], flow is normal to local contours. In general, contours show flow along the length of the lake, starting eastwards at 76.5° S and swinging southwards by 77.0° S. The near-parallel tilt of the deep reflecting layer to the valley walls (Fig. 3b) is also typical of flow in the direction of a long valley[17].

The above flow requires a high influx of ice over the northwest boundary. Here steep surface slopes, thick grounded ice with basal melting and sliding, and ice-sheet contours to the west, all indicate a large inflow at around 76.5° S.

Along almost all the eastern boundary, the ice surface rises ~8 m in 10 km before falling at the regional slope to the east, still over rising bedrock (Fig. 3b). This is similar to profiles across the Ronne Ice Shelf rumples[18]. In both cases, the initial rise extends over three times the ice thickness (h). Although magnitudes of ice thickness, slopes and velocities differ considerably, the same basic mechanism driven by vertical compression seems to apply.

The loss of ice over the eastern boundary will decrease velocity towards the south. To maintain vertical compression at around a constant level in order to drive flow to the south and east requires an increased surface slope in proportion to the slowing of velocity. Narrowing of the lake southwards, as with ice shelves, also requires increased surface slope.

Estimates of the easterly ice movement onto the lake, based on steady-state discharge of accumulation from the ice divide (dome B) 240 km to the west, give a mean inflow at ~3 m yr^{-1}. The only direct measurement of ice velocity in the region was made at Vostok[16] by star sights in 1964 and 1972. this gave 3.7 ± 0.7 m yr^{-1} at $142 \pm 10°$ true, approximately normal to contours within 20 km of the station. This gives an eastward component of 2.3 ± 0.5 m yr^{-1}. When the loss of ice across the eastern boundary is considered, the flow at Vostok equals that expected for steady-state flow to well within the error of estimates and measurements.

Further geophysical studies of the lake are being planned. Satellite global positioning system measurements of surface velocity in three dimensions will show how closely steady-state flow applies from changes of surface elevation with time, while measured horizontal motion will test predictions of flow from ice dynamics. Seismic sounding and RES survey will give a much better knowledge of the lake depth and extent and determine the nature of any lake bed sediments. Finally, sampling of lake water and sediments should be undertaken, subject to Environmental Impact Assessment under the Antarctic Treaty, when this can be achieved without polluting the lake water. □

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CORRESPONDENCE and requests for materials should be addressed to M.J.S (e-mail: mas@aber.ac.uk).

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An inventory of Antarctic sub-glacial lakes

M.J. SIEGERT[1], J.A. DOWDESWELL[1], M.R. GORMAN[1] and N.F. MCINTYRE[2]

[1]*Centre for Glaciology, Institute of Earth Studies, University of Wales, Aberystwyth, Dyfed SY23 3DB, UK*
[2]*Earth Observation Sciences Ltd, Broadmede, Farnham Business Park, Farnham, Surrey GU9 8QL, UK*

Abstract: An extensive analogue database of 60 MHz radio-echo sounding records of Antarctica (covering 50% of the ice sheet) is held at the Scott Polar Research Institute, University of Cambridge. This database was analysed in order to determine the presence and location of Antarctic sub-glacial lakes. In total, 77 sub-glacial lake-type records were identified, 13 more than detected in previous studies. An inventory of these sub-glacial lakes includes geographical coordinates, minimum length and overlying ice thickness for each lake. Information concerning the location of these lakes indicates that the majority (~70%) are found in the proximity of ice divides at Dome C and Ridge B within East Antarctica.

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Key words: Antarctic ice sheet, radio-echo sounding, RES

Introduction

Lakes beneath the Antarctic ice sheet were first reported from airborne radio-echo sounding (RES) records by Oswald & Robin (1973). Several other studies of Antarctic 60 MHz RES data, acquired as part of the SPRI-NSF-TUD (Scott Polar Research Institute, University of Cambridge, UK; National Science Foundation, USA; Technical University of Denmark) joint research programme between 1967 and 1979 (Drewry 1983) (Fig. 1), have identified up to 64 areas of bright, mirror-like reflections (Fig. 2), interpreted as representing water beneath the ice sheet (Robin *et al.* 1977, Steed 1980, McIntyre 1983). The lakes identified in these studies were discovered during the reduction of radio-echo sounding data from several regions of Antarctica.

In this contribution, we present an inventory of Antarctic sub-glacial lakes which is derived from a systematic re-analysis of the entire SPRI-NSF-TUD Antarctic RES dataset, undertaken with the specific aim of identifying the full set of sub-glacial water bodies present along these ~400 000 km of RES flight track over the Antarctic ice sheet (Fig. 1). Geographical coordinates, ice thickness and length of mirror-like reflections are presented for the set of Antarctic sub-glacial lakes for the first time.

RES and characteristics of sub-glacial water bodies

Airborne RES at 60 MHz has been used successfully to penetrate to the base of ice over 4 km thick in Antarctica (e.g. Robin *et al.* 1977, Drewry 1983). This is possible because ice is relatively transparent to radio waves at this frequency (Johari & Charette 1975), especially when it is several tens of degrees below freezing, as is the case for most of the Antarctic ice sheet.

The strength of reflection from the bed depends to a first order upon the difference between the dielectric properties of the ice (dielectric constant $\varepsilon = 3.2$), and the dielectric properties of the sub-ice material. As the dielectric constant of water ($\varepsilon = 81$) is very different from typical bedrock ($\varepsilon =$ 4–9), a much stronger reflection is obtained from an ice-water interface compared with an ice-rock interface. This difference is further increased by the relatively rough character of an ice-bedrock interface, which scatters energy and further reduces echo strength.

Sub-glacial lakes are identified on 60 MHz RES records by the presence of the following characteristics (Fig 2.):

(i) strong reflections from the ice sheet base, which appear bright on film records and are typically 10–20 dB stronger than adjacent ice-bedrock reflections,

(ii) echoes of constant strength along the track, indicative of an interface which is very smooth on the scale of the RES wavelength, and

(iii) a very flat and virtually horizontal character, with maximum slopes typically less than 1%.

This last property arises from hydrostatic and ice flow mechanisms (Oswald & Robin 1973). Such 'lake' reflections are, thus, highly distinctive, and therefore pose relatively few problems concerning identification (Fig. 2).

It should be noted that accumulations of water-saturated basal sediments may also yield relatively strong electro-magnetic wave returns, in some cases similar to those observed from an ice-water interface. Conceivably, such returns may be observed on the RES record as flat horizontal reflections. As a consequence, we do not preclude that some of the 'lakes' identified in this inventory may comprise pockets of water-saturated sediments at the ice-sheet base.

Analysis of Antarctic RES records

RES data from flights over about 7 million km² of the Antarctica Ice Sheet (Fig. 1) (Drewry 1983) were recorded in

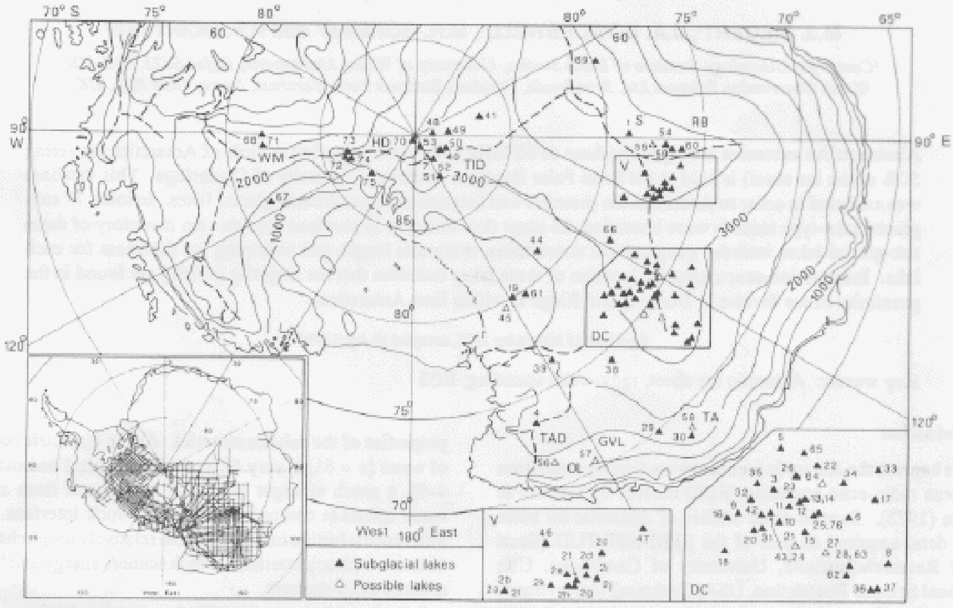

Fig. 1. Locations of subglacial lakes determined from the SPRI-NSF-TUD airborne RES data. The RES flight-lines are inset. The identifying numbers, associated with each lake location, are referred to in Table I. Abbreviations to place names are as follows: DC (Dome C); GVL (George V Land); HD (Hercules Dome); OL (Oates Land); RB (Ridge B); S (Sovetskaya Station); TA (Terre Adelie); TAD (Talos Dome); TID (Titan Ice Dome); V (Vostok Station); WM (Whitmore Mountains).

analogue form on 35 mm negative film as a time-continuous, or Z-scope, record of the received signal (Fig. 2). The full set of film records was examined four times by two individuals working independently over a period of several months. The locations of all possible radar reflections from sub-glacial lakes were noted, using the criteria defined above. Any section of RES film that was found to indicate a relatively flat, bright return (indicative of a radio wave reflection off a basal water layer) was enlarged onto photographic paper. A third person then examined the photographic prints of each possible sub-glacial water body, and a final inventory was agreed after discussion.

The locations of the lakes were then determined using records of the airborne navigation. During the field seasons of 1967–69, the navigation relied upon aircraft avionics and compass inputs, with occasional solar and ground fixes, to determine the location of the aircraft. The records of aircraft navigation during these seasons are analogue recordings of aircraft avionics, log books and flight maps. However, between 1971–79, an inertial navigation system was used on flights, which provided an automatic record of time, latitude and longitude. This system, while subject to a drift of *c.* 1–2 km hr^{-1}, provided very much more accurate and systematic navigation than the previous scheme. Navigation errors in absolute lake locations are a maximum of 5 km and are often considerably less, depending on the distance from the nearest reliable position fix (Drewry *et al.* 1982). These lake locations were compared with the maps of Antarctic sub-glacial lakes prepared by earlier workers (Oswald & Robin 1973, Steed 1980, McIntyre 1983), and any further discrepancies were investigated by further inspection of RES data.

The locations of the 77 sub-glacial lakes, identified as a result of these procedures, are plotted in Fig. 1. It should be noted that the large sub-glacial lake of about 10 000 km^2, located close to Vostok Station in East Antarctica (Fig. 1), was observed on several different RES flights (Oswald & Robin 1973, Robin *et al.* 1977, Kapitsa *et al.* 1996). Similarly, where two observations of sub-glacial lakes are plotted within a few kilometres of one another in Fig. 1, we cannot distinguish whether they are independent water bodies or parts of a single, larger lake (e.g. lakes 25 and 76 (Table I) may well originate from the same sub-glacial lake). For lakes of diameter greater than 10–20 km the presence of a

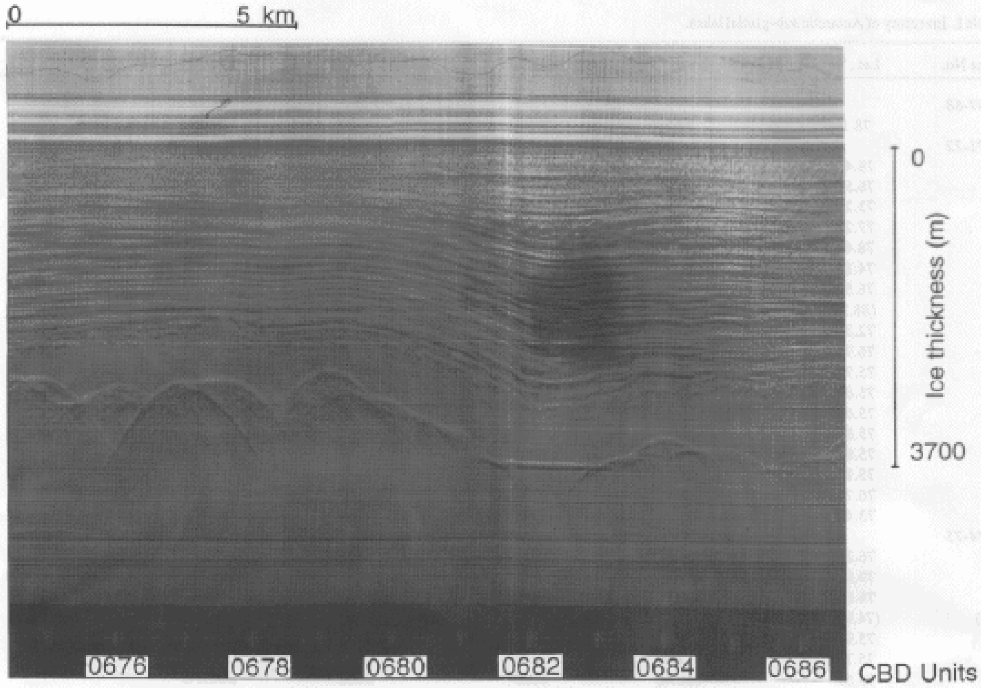

Fig. 2. Sub-glacial lake No. 46, from Flight No. 121 (1974-75) at time 0682. Note the strong, flat, 6.5 km-long reflection off the lake compared with the weaker, undulating signal returned from the surrounding bedrock. Strong downward folding of the ice sheet internal layering is observed directly over the lake. Time is given in CBD units, which are set to zero at aircraft take-off, recording 1 CBD every 15 seconds in the flight thereafter.

continuous, flat and smooth ice-surface, derived from satellite radar altimetry, would provide an independent assessment of this problem (cf. Cudlip & McIntyre 1987, Ridley *et al.* 1993). Consequently, lake records 30 and 58 (Table I), located close to a relatively flat ice-surface in Terre Adélie (identified from Seasat altimeter observations), may also correspond with the same sub-glacial lake (Cudlip & McIntyre 1987).

In addition to information on the latitude and longitude of the set of sub-glacial lakes derived from RES, the length of water body and the thickness of overlying ice were also measured (Table I). Lengths of the sub-ice lake records were calculated by assuming a constant aircraft speed of 300 km hr^{-1}, and may be considered as representing minimum values for water-body dimensions. Ice thicknesses can be measured directly both from the Z-scope data, and individual pulse (A-scope) recordings, by measuring the one-way travel time of the basal reflection and multiplying by the e/m wave velocity within ice (168.5 m ms^{-1}, Glen & Paren 1975). The error in such measurement of ice thickness from RES methods is up to 1.5% of ice thickness (Drewry 1983).

Inventory of sub-glacial lakes

The results of our systematic re-analysis of radio-echo sounding records from approximately half of the Antarctic ice sheet for the presence of sub-glacial lakes are summarized in Table I. This table provides an inventory of data on the latitude and longitude, minimum length and overlying ice thickness for the 77 lake reflections identified from the analogue RES records. The locations of these sub-ice water bodies are shown in Fig. 1.

It is clear from Fig. 1 that the majority of the observed lakes are situated in relatively close proximity to ice divides, where both the surface slope and ice velocity are small. Two clusters of lakes, accounting for 70% of the total lake inventory, are in regions of Dome C and Ridge B in East Antarctica (Fig. 1). In addition, the ice divide stretching from West to East Antarctica (which runs close to the South Pole), has several sub-ice lakes along its length in the areas of Hercules Dome and Titan Dome (Fig. 1).

Although approximately half of the Antarctic ice sheet was sounded by the SPRI-NSF-TUD survey (Fig. 1), flight-line spacing of 50–100 km over much of this area implies that

Table I. Inventory of Antarctic sub-glacial lakes.

Lake No.	Lat., °S	Long., °E	Length, m	Ice thickness, m	Locale
1967-68					
1	78.1	88.5	35 000	4200	Sovetskaya Station
1971-72					
2a	78.48	106.87	5000	3741	Lake at Vostok Station
3	76.57	124.80	5000	3621	Dome C
4	73.28	157.28	3500	2827	Talos Dome
5	77.20	119.27	10 000	3835	Dome C
2b	78.48	106.87	n/a	3741	On ground at Vostok Airstrip
6	74.13	124.58	10 000	4094	Dome C
2c	76.51	101.13	5000	4184	Lake at Vostok Station
(7)	(88.3)	(150)	(5000)	(2807)	(Titan Dome)
8	72.31	123.94	10 000	3254	E of Dome C
9	76.94	129.40	5000	3811	W of Dome C
10	75.94	127.41	5000	3449	W of Dome C
11	75.81	126.56	8500	3860	W of Dome C
12	75.65	125.60	5000	3399	W of Dome C
13	75.87	122.66	5000	3364	W of Dome C
14	75.84	122.82	2000	3490	W of Dome C
15	75.14	126.98	2000	3447	W of Dome C
16	76.75	129.82	2000	3661	W of Dome C
17	73.45	119.54	15 000	3924	E of Dome C
1974-75					
18	76.28	135.31	8040	3214	W Dome C
19	79.93	148.27	8375	2333	E of Byrd Gl. & Transantarctic Mts
20	76.63	129.92	1843	3009	W Dome C
(21)	(74.91)	(128.90)	(670)	(3890)	(Dome C)
22	75.97	124.95	3685	3168	Dome C
23	75.78	125.97	3015	3162	Dome C
24	75.69	126.48	4188	3650	Dome C
25	74.96	124.61	1340	3360	Dome C
26	75.61	120.39	2680	3057	Dome C
(27)	(73.4)	(126.90)	(6700)	(4010)	(W of Dome C)
28	73.17	128.35	15,075	4148	W of Dome C
29	69.71	140.95	2848	2269	George V Land
30 (58)	68.44	136.87	2680	4011	Terre Adelie
31	75.82	129.03	3015	3069	W of Dome C
32	76.40	126.03	2881	3500	W of Dome C
33	74.03	118.50	8543	4092	E of Dome C
34	74.46	119.37	6700	3932	E of Dome C
35	77.12	126.30	8375	3741	W of Dome C
36	71.81	128.35	1340	2994	NE of Dome C
37	71.79	128.2	1340	3021	NE of Dome C
38	74.04	139.92	1608	3285	W of Dome C
39	75.73	148.86	6700	3010	W of Dome C
40	88.5	120	3350	3100	Titan Dome
41	87	075	3183	2943	W of Titan Dome
42	76.19	125.18	4958	3881	W of Dome C

Inventory of sub-glacial lakes includes geographical coordinates, observed length and the thickness of overlying ice. The order of lake entries is chronological, based on the date of the flight from which each is recorded. Parentheses indicate that the RES record may contain a sub-ice lake reflection, but identification is not certain. It should be noted that this inventory represents RES returns from single flight-lines over lake surfaces, and that some of these data may correspond to the same sub-glacial lake (e.g., reflection no. 25 & 76 may represent reflections off the same sub-glacial lake).

Lake No.	Lat., °S	Long., °E	Length, m	Ice thickness, m	Locale
43	76.20	125.30	10,050	3886	W of Dome C
44	81.84	133.47	2680	2641	E of Transantarctic Mts
(45)	(79.43)	(154.13)	(6700)	(2036)	(E of Transantarctic Mts)
46	77.4	100.4	2412	3709	W of Ridge B
47	76.8	97.5	1608	3715	W of Ridge B
48	88.73	64.52	3350	2997	S of Titan Dome
49	88.36	70.54	5360	3027	S of Titan Dome
50	88.37	112.68	3350	3068	Titan Dome
51	87.61	148.62	8040	3062	Titan Dome
52	88.71	136.88	1876	3070	Titan Dome
53	88.42	144.50	1675	2741	Titan Dome
54	77.1	92.5	3350	3784	Ridge B
2d	77.0	104.5	43,550	3812	Lake at Vostok Station
55)	(78)	(99)	(11,725)	(3399)	(Ridge B)
2e	77.6	105.0	26,800	3805	Lake at Vostok Station.
(56)	(71.13)	(155.68)	(10,050)	(2347)	(Oates Land)
(57)	(70.47)	(151.60)	(1675)	(2418)	(Oates Land)
2f	77.18	104.82	30,150	3800	Lake at Vostok Station
2g	77.12	103.99	3350	3857	Lake at Vostok Station
2h	77.4	102.80	3350	3883	Lake at Vostok Station
2i	76.70	102.10	6700	3842	Lake at Vostok Station
2j	76.56	102.13	15,075	3911	Lake at Vostok Station
58 (30)	68.8	136.2	43,550	4224	Terre Adelie
59	77.1	92.5	1340	3481	Ridge B
60	76.8	93.5	1340	3426	Ridge B
61	79.15	144.3	5025	2580	W of Transantarctic Mts
62	72.74	129.41	2010	3828	Dome C
63	73.14	128.41	20,010	4171	Dome C
(64)	(75.76)	(119.71)	(2512)	(3574)	(Dome C)
65	76.07	118.11	5025	3733	Dome C
66	78.00	118.60	14,070	3341	S of Dome C
67	81.4	119.0 W	2010	3200	W of Whitmore Mts
2k	77	102	241,200	n/a	along length of Lake at Vostok Station
1977-78					
68	82.06	98.95 W	1675	2894	Whitmore Mts.
21	78.48	106.87		3741	Aircraft circling over Vostok Station
69	79.04	67.73	6700	2500	Dome A
1978-79					
70	89.97	161.56 W	50,250	2778	South Pole
71	82.99	94.92 W	1340	3200	Whitmore Mts
72	86.36	106.17 W	1675	2814	Hercules Dome
73	86.43	105.56 W	1340	2906	Hercules Dome
74	86.77	111.26 W	1675	3960	Hercules Dome
75	87.77	125.30 W	5025	2315	Hercules Dome
76 (25)	74.92	124.65	3484	3360	Dome C
77	74.92	124.19	1943	3225	Dome C

some additional lakes may be present between existing flight-lines. Similarly, no data were available for the remainder of the ice sheet. Analysis of high-accuracy satellite radar altimeter data will be used in future investigations (during the next two years) of larger sub-glacial lakes over the remaining portion of Antarctica (J.K. Ridley, personal communication 1995).

Our inventory provides important information for several pieces of further work. First, the inventory provides coordinates for the locations of sub-glacial lakes, and an indication of the minimum size of the lake. This may be useful for the identification of ice surface topographical features, using satellite radar altimetry, associated with sub-glacial lakes. Secondly, Antarctic sub-glacial lakes provide an important boundary condition for the thermal analysis of the ice sheet, in that the basal temperature of the ice sheet over sub-glacial lakes may be assumed to be at pressure melting point (Siegert & Dowdeswell in press). Thus, the location of sub-glacial lakes may be important to the understanding of heat flow at the base of the Antarctic ice sheet.

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