“Subglacial Lake Exploration:

Workshop Report and Recommendations”

Volume II

for the

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in regard to the

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The Antarctic and Southern Ocean Coalition

Lake Vostok: To Drill or Not to Drill?

R. Roura
Antarctic & Southern Ocean Coalition
European Coordination & Campaign Office
44 II P. v.d. Doesstraat
1056 VH Amsterdam
Netherlands
e-mail : ricardo.roura@worldonline.nl

Lake Vostok is to Antarctica what Antarctica is to the rest of the planet: remote, pristine, and unique. For this reason, while this workshop's discussions focus mainly on scientific rather than environmental matters, in our view a basic question remains: whether or not to drill into Lake Vostok? The answer requires consideration of several other questions, including:

1. **Is scientific and technological research a sufficient justification for allowing drilling at Lake Vostok?**

   Research on subglacial environments is clearly a legitimate and important Antarctic scientific activity. But it should not be the only basis for deciding if or when to drill at Lake Vostok (or elsewhere). Under the Madrid Protocol a set of procedural steps must be complied with for each individual proposal. Given the facts in this case, this means preparing a full CEE and going through the other related procedural steps under the Protocol and its Annexes, as well as complying with relevant national laws and regulations.

   A CEE should canvass all options, including (1) distinguishing pure science from technology research and development; (2) the alternative of using other, smaller lakes or the ice-sheet downstream from Lake Vostok, rather than taking risks in sacrificing the values of Lake Vostok, which appears to be the largest lake of its type, and therefore arguably unique; (3) the alternative of a moratorium for the time being (or a stated period) on any drilling into Lake Vostok, given the risks posed - perhaps for a generation or more, and (4) discussion of the merits of the "full protection" option.

2. **Is late 20th century technology, or the technology likely to be developed in the foreseeable future, adequate to conduct intrusive subglacial research at Lake Vostok without risking its unique values?**

   The current framework for technology research and development is based on existing technology. Given this, Lake Vostok can be fully studied at the present time only by using intrusive methods. Some of those methods would be less risky and less contaminating than others, but at present there is no way to drill into the Lake without risking its environment.

Arguably, late 20th century technology, including what can be termed Best Available Technology, will be obsolete within a generation. The unique scientific and environmental values of Lake Vostok warrant that serious consideration is given to the likelihood that technological developments in, say 20-50 years, could significantly reduce or perhaps fully avoid the risk of harmful impacts.

3. **Are the risks to the ultimate scientific and environmental values worth taking, considering that Lake Vostok is unique?**

   Since there are 60+ subglacial lakes in Antarctica, of which Lake Vostok is probably the largest, there are arguments that any scientific drilling should be attempted somewhere else first, starting with lakes outside Antarctica to test the proposed technology, and possibly using a smaller Antarctic lake after that. There appear to be valid scientific reasons to consider drilling into the ice sheet upstream and downstream from Lake Vostok as well. From a scientific perspective, it may be the case that other Antarctic lakes offer a more representative subglacial environment. Drilling into another Antarctic subglacial lake would of course not interfere with continuing non-intrusive scientific research at Lake Vostok, nor would it preclude drilling into the Lake at some time in the future if and when the technology is available to do so with greatly reduced risk.

4. **Is Lake Vostok suitable for use to further technological research and development (e.g., the NASA/Jet Propulsion Laboratory proposal)?**

   In ASOC's view, the answer to this question is "No". A clear distinction should be made between pure science and technology research and development. This is even more true if the latter does not have Antarctic research as a primary purpose but rather would be using Lake Vostok as a "planetary analogue" to test technology to be used elsewhere. Testing new technology at Lake Vostok with ulterior purposes is unacceptable even if one of the results of this test would help further basic science.

5. **Is some form of enhanced protected status under Annex 5 appropriate for Lake Vostok?**

   Yes. There is a case for designating Lake Vostok as a protected area with enhanced protection status under Annex 5 of the Protocol. The Second Protected Areas Workshop in Lima recommended "That in selecting new protected areas, a range of tools be used, including analysis of environmental risk, quality and feasibility" (Rec. 3) - see XXII ATCM/WP37. In the supporting table of indices for that recommendation, several "risks" (human activities and impact; vulnerability; non-Antarctic threats; urgency and time period) and "quality" factors would be applicable to Lake Vostok.

Conclusions

ASOC is concerned that it has been decided *a priori* that something must be “done” with Lake Vostok as soon as technically possible, seemingly foreclosing the option of not drilling at the lake. In the interest of protecting ultimate scientific and environmental values of Lake Vostok, the most appropriate option would appear to be to postpone drilling the lake for the indefinite future - perhaps even for several generations. Scientists interested in subglacial research should consider a range of alternatives to drilling into Lake Vostok, as outlined above. This will require foresight and forbearance.

Does UV Radiation Close the Global Carbon Cycle?
- A Test in Lake Vostok

Maurice A. Lock
School of Biological Sciences
University of Wales, Bangor
Gwynedd, LL57 2UW, UK
e-mail: *bss020@bangor.ac.uk*

Hypothesis

Mopper, Zhou et al. (1991) hypothesised that UV radiation on the oceans may be responsible for the conversion of microbially-recalcitrant oceanic dissolved organic matter to forms which were metabolisable by microbes. In the absence of a mechanism of this type, the carbon cycle would be predicted to ultimately stall. In the oceans, the photo-converted organic matter had a predicted residence time of 500 - 2100 years. With the closure time of Lake Vostok being ~0.5 million years, the absence of light in the lake affords an opportunity to test the hypothesis that the aquatic carbon cycle is closed via photochemical reactions.

Some predicted consequences of the absence of UV radiation in Lake Vostok resulting in an accumulation of microbially recalcitrant organic matter

Prediction 1. The total/proportion of microbially recalcitrant organic matter in the dissolved organic matter pool will be substantially higher than that in the oceans.

- ***Test in-situ*** *Deploy a fiber optic probe (Guay, Klinkhammer et al. 1999) using fluorescence spectroscopy to distinguish these two pools (Mopper and Schultz 1993).*
- ***In vitro*** *Use the broad spectrum of lab based analyses and assays to compare the organic carbon pool within Lake Vostok with those of the oceans.*

Prediction 2. The microbially recalcitrant organic matter may substantially limit bacterial metabolism through direct or indirect inhibitory effects (Freeman and Lock 1992). It is possible that over millennia of isolation, microbial activity within Lake Vostok may have been increasingly inhibited due to a gradual accumulation of recalcitrant organic matter.

- ***Test.*** *Preparation of sterile water samples from Lake Vostok and an appropriate illuminated ice-covered control lake, which then have inorganic/organic nutrient amendments. Amended samples then have reciprocal inoculations of Vostok or control bacteria (- predators) followed by monitoring of bacterial growth /metabolism. Lake Vostok bacteria would be expected to thrive in the illuminated lake water while the bacteria from the illuminated water body would be expected to be inhibited by the Vostok waters.*
-

Prediction 3. Exposure of sterilised Lake Vostok water to standard, natural level and spectral composition of UV radiation would support massive growth of bacteria in comparison with equivalent exposure of a sunlit ice-covered control lake water (cf Benner & Biddanda 1998).

- ***Test.*** *Produce sterile lake waters by gentle filter sterilisation, expose to UV, then add back a natural inoculum of the lake's bacteria. Growth /metabolism of the bacteria followed.*

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The Potentials for Cosmogenic Be^{10} and Inorganic Particles in Deciphering Environmental History of Lake Vostok

Ala Aldahan
Institute of Earth Sciences
Uppsala University
S-752 36 Uppsala
Sweden
e-mail: ala.aldahan@geo.uu.se
web site: http://www.kv.geo.uu.se/aa.html

Background

The primary source of beryllium-10 (half-life 1.5 million years) is the atmosphere which accounts for more than 99% of the total production. This feature and the relatively inert chemical nature of Be makes it a unique tracer of climate/environmental changes during the last 10 Ma. The main carriers of ^{10}Be are Fe-Mn-oxides and hydroxides, and clay mineral particles which are common constituents in dust/aerosol and glacial input. At a lower concentration, ^{10}Be also occurs in water and ice. Another possible and most likely localised (in time and space) source is cosmic particles (cosmic dust and meteoritic fragments).

Proposal

We propose here using ^{10}Be as a tracer for estimating of water inventory (fluxes of melting ice and possibly other sources) to the lake and possible consequences of climatic-environmental changes. ^{10}Be from melting ice may accumulate in the lake water and either adsorbs to and sinks with suspended particles or stays within the lake water body. There is a very good estimate of ^{10}Be concentration in the ice column which can thus provide an acceptable measure for the amount of melted ice. In this context, sampling sediments from the lake will give a valuable opportunity to estimate both the amount of ^{10}Be removed from the water body and the main carrier particles. Sediment horizons containing some amounts of cosmic micro-particles will show high Be-concentration. Additionally, clues on glacial conditions in the lake (advance and retreat of ice masses) can be obtained from ^{10}Be data. For example, deposition during retreat of ice wedges can lead to increased ^{10}Be concentrations and visa versa during ice-wedge advance where sediments are scraped off and eroded. ^{10}Be may also be used as a tool for relative change in sediment budget due to possible diagenetic alteration.

Recognition of Biomolecules, Past and Present, in Lake Sediments of Lake Vostok by Remote Sensing

Dr. David D. Wynn-Williams,
British Antarctic Survey,
Madingley Road
Cambridge, CB3 0ET, UK
e-mail: ddww@pcmail.nerc-bas.ac.uk

The biologists' need:

To obtain evidence of present or former microbiological life (and its characteristics) in the bottom sediment of Lake Vostok

The problem:

- Lake Vostok is under >4 km of Antarctic ice sheet and is c. 500m deep
- There is concern about contamination during any attempts to retrieve samples under extremely difficult technical conditions

The potential solution:

- Laser Raman Spectroscopy (LRS)

Heritage:

Used to analyse the spatial biomolecules *in situ* in Antarctic endolithic sandstone communities, desert crusts, cyanobacterial mats and lichens. Currently being developed for remote analysis of putative former cyanobacteria-like communities on early Mars.

The technical advantages for LRS use in Lake Vostok (or Europa):

- Based on scattering of laser light from surfaces *in situ.*
- Spectrum depends on the sum of the components of a given molecule.
- The Raman spectrum of a given molecule is therefore unique.
- Corroborative peaks from a given key molecule are detectable in a mixed community of inorganic and organic molecules.
- Diagnoses biomolecules in their natural state and spatial location.
- Has identified ancient derivatives of current pigments (e.g. porphyrins from chlorophyll) and is applicable, for example, to isoprenoids and hopanoids.
- No interference from any water signal (unlike IR spectroscopy).
- Surface reflectivity is not important.
- Laser excitation at 852 nm does not generate major autofluorescence.
- Can be used with a fibre-optic probe and unreeled cable potentially long enough to penetrate the ice and water column.

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Searching for Microbial Sub-Fossils –Enrichment Culture and Electron Microscopy

B.J. Finlay and K.J. Clarke
Institute of Freshwater Ecology,
The Ferry House, Ambleside, LA22 0LP, UK.
e-mail: BJF@wpo.nerc.ac.uk KC@wpo.nerc.ac.uk.

If microbes live in Lake Vostok they will be most abundant, and most easily detected, in the surface layer of the sediment (top 1 cm). We will concentrate on those micro-organisms that leave recognisable remains after the organism has "shut down" or died and the remains have fallen to the sediment. Suitable candidates include the most abundant of biological particles – free viruses and one other group that is relatively abundant in fresh waters – the chrysomonad flagellates bearing siliceous surface scales.

If viruses are found, their hosts (presumably other micro-organisms) must also be present or have been present in the recent past. If chrysomonad flagellates are found, then a functional microbial food web probably exists in the lake. If neither of these groups is detected in surface sediments, there may be fossil remains deeper in the sediment, indicating when life disappeared.

The chrysomonad flagellates will also be used to answer a further question. The genus *Paraphysomonas* is known to compromise 50 species. These are probably all ubiquitous[1], because the astronomical abundance of their natural populations drives large-scale dispersal across the physical barriers that halt migrations of larger animals and plants. This ubiquity is probably responsible for very low rates of speciation and extinction and the low global number of species. Lake Vostok may be unique in having been physically isolated from the rest of the biosphere over a relatively long evolutionary period. It may be the only place in the biosphere where "endemic" microbial species (including new *Paraphysomonas* species) could exist.

The two main tools used to examine the superficial sediment will be direct examination of preparations using transmission electron microscopy[2], and a suite of enrichment culture methods to detect rare micro-organisms[3].

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Micron - Scale Structure of Trace Metals in Pore Waters : A Possible Technique for Investigating Sub-Glacial Lakes.

Gary Fones[1], Bill Davison[1] and Geoff Grime[2]
[1]Environmental Science Department, I.E.N.S.,
Lancaster University, Lancaster, LA1 4YQ.
[2]Microprobe Unit, Department of Nuclear Physics,
University of Oxford, Oxford, OX1 3RH.
e-mail : g.fones@lancaster.ac.uk

Introduction

The technique of **d**iffusive **g**radients in **t**hin films (**DGT**) can be used to measure solutes in situ by concentrating them on an immobilized binding agent, after diffusion through a high porosity hydrogel. Using chelex resin as the binding agent, DGT has been used to measure in situ fluxes and concentrations of trace metals in open waters and in pore waters at mm resolution (Zhang *et al.,* 1995). New smaller in situ assemblies (~ 1 mm total thickness) using SPR-IDA chelating resin (Iminiodiacetate 5%, 0.2 mm bead size, Cetac Technologies Inc.) and ceramic supporting plates have been developed which enable measurements to be made at 100 mm spatial resolution. Traditional pore water measurements made at 1 cm intervals relate to a temporal resolution of 1 day (Davison and Zhang, 1996). Such measurements are incapable of providing mechanistic information about faster processes, such as adsorption/desorption and oxidation/reduction. To reveal the kinetics of such fast processes (minutes), measurements must be made in pore waters at sub-mm resolution.

DGT Rationale

For trace metal measurements, a layer of ion-exchange resin (SPR-IDA) is separated from the pore water by a permeable hydrogel membrane of thickness $\mathrm{D}g$. Any convection within the solution will produce a diffuse boundary layer (DBL), of thickness d, on the surface of the gel layer. If it is assumed that $d \ll \mathrm{D}g$, Fick's laws can be used to define the flux of a given metal ion. Flux = $DC\mathrm{b}/\mathrm{D}g$, the mass per unit area of resin, $M\mathrm{a}$, after time t is then: $M\mathrm{a} = DC\mathrm{b}t/\mathrm{D}g$, measurement of $M\mathrm{a}$, with a knowledge of D, $\mathrm{D}g$ and t, allow $C\mathrm{b}$ to be calculated $C\mathrm{b} = M\mathrm{a}\mathrm{D}g/Dt$.

Sampling and Analysis

A new ceramic pore water gel probe was deployed in situ on the 5th of June 1996 at Sankey Brook, Warrington, Cheshire. Temperature, dissolved oxygen and pH were also measured. The probes were removed after twenty-four hours and thoroughly rinsed with Milli-Q. The gel was dried onto a Millipore filter using a gel dryer. The accumulated metal ions were then measured at 100 mm spatial resolution in rastor mode using proton induced X-ray emission (PIXE) (Grime *et al.*, 1991). At the time of measurement the water above the sediment was characterised by: $DO_2 = 0$, T = 14 degrees C and pH = 7.2. The sediment was covered with a 5 mm thick green layer, shown to be dominated by Oscillatoria spp (Cyanobacteria), but also including Trachelomonas spp, Cryptomonas spp, and Chlorococcum spp.

Results and Discussion

Two modes of PIXE analysis were used in this study. In one, the 1 mm beam was continuously rastered over a 2.5 x 2.5 mm square to produce a two dimensional image of element concentrations. In the other, the beam was rastered over a 100 x 500 mm area for a short time (minutes), to quantify average elemental concentrations for the area. Successive measurements were performed at 100 micron intervals to obtain a continuous vertical concentration profile (Figure 1).

Two dimensional image intensity maps of pore water concentrations reveal pronounced horizontal heterogeneity of, for example Zn and Mn on a sub-mm scale (Figure 2). The continuous vertical profile (Figure 1) shows maximum concentrations of Zn, Mn and As below the sediment water interface and ~ 5mm above it, coincident with the surface of the algal layer. The higher Zn and Mn peaks are exactly coincident, suggesting a similar supply and removal mechanism for these two elements at this location. Within the sediment, however, maxima for Zn, Mn and As are ~ 1 and 2 mm apart, indicating that different chemical processes control their development. The very sharp resolution implies rapid removal mechanisms immediately above and below the spatially well defined source. For there to be removal within < 0.5 mm, a reaction must have a half life of less than three minutes. This is consistent with adsorption processes.

These first measurements of metals at this resolution by DGT have revealed a detailed structure in pore water concentrations on the micron scale. Clearly further measurements and their detailed interpretation will advance significantly our understanding of biological and chemical processes within sediments. This work has shown that the technique of DGT coupled with PIXE analysis can provide 2 dimensional images of trace metal concentrations in pore waters and also pore-water profiles at 100 micron resolution.

Fig 1 Concentrations of Zn, Mn, Fe and As, and fluxes of these elements to the DGT assembly.

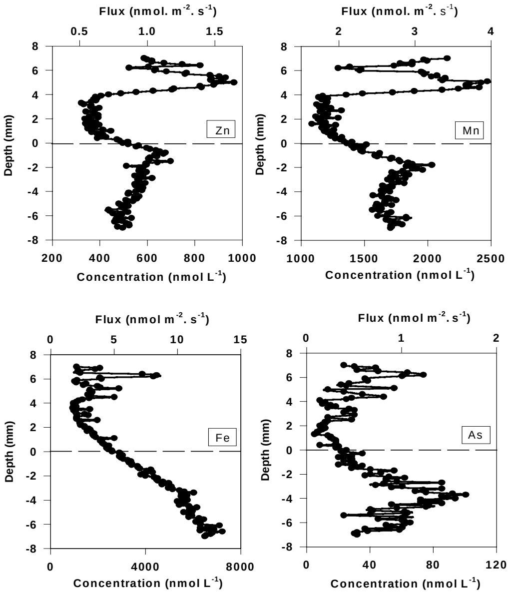
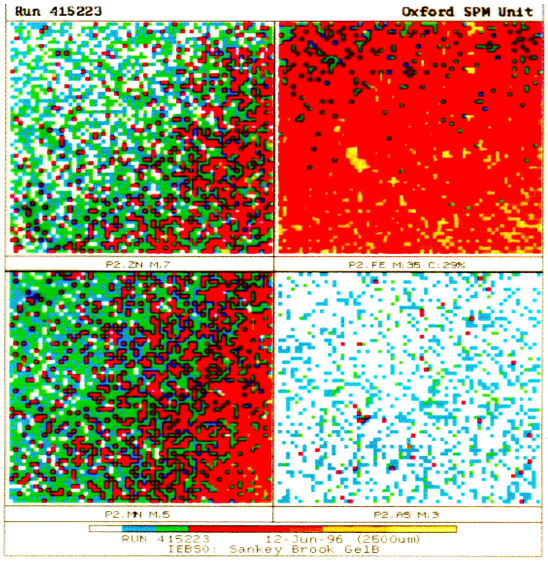


Fig 2 Two-dimensional representation of porewater relative concentrations of Zn, Mn, As and Fein a plane perpendicular to the sediment surface at the sediment-water interface.



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Metal Mobilisation in the Surface cm's of Marine Sediments using DGT

Gary Fones, Bill Davison & John Hamilton-Taylor
Environmental Science Department, I.E.N.S.,
Lancaster University, Lancaster, LA1 4YQ.
e-mail : *g.fones@lancaster.ac.uk*

Introduction

In this study of deep-sea benthic processes a new autonomous benthic lander was used to provide in situ measurements. Using the lander overcomes the problems of temperature and pressure artefacts associated with collecting sediment samples. The new technique of **d**iffusive **g**radients in thin-films (**DGT**) was deployed *in situ* using the benthic lander as well as in collected cores for comparative measurements. Three contrasting sites in the eastern north Atlantic were chosen as experimental sites for the **BENBO** programme (**BE**nthic **BO**undary study) this is a multi-disciplinary, inter-institutional marine benthic biogeochemistry programme funded by NERC. Each site has a different water depth, bottom current speed and input of marine snow. Bottom sediments at Sites A and B comprise of carbonate ooze, while Site C is a fine-grained marl.
Site A: Mouth of Rockall trough ; 52.918 degrees N - 16.917 degrees W (~3600 m)
Site B: Hatton - Rockall Basin ; 57.425 degrees N - 15.683 degrees W (~1100 m)
Site C: Flank of Feni Drift ; 57.100 degrees N - 12.515 degrees W (~1800 m)
In 1998, two three-week process cruises were mounted either side of the spring phytoplankton bloom, the first during April 1998, the second in June-July 1998.

Gel-based techniques for high-resolution pore water measurements

The new procedure of DGT (Davison et al., 1999; Davison et al., 1997; Zhang & Davison, 1996; Zhang et al., 1995) has recently been developed at Lancaster and used to determine fluxes and concentrations of metals in aquatic systems. Metal ions freely diffuse (diffusion coefficient, D) through the filter and gel layer (total thickness Dg) before binding to a chelating resin (either Chelex 100 for high resolution or 5 % SPR-IDA chelating resin - CETAC iminiodiacetate, 0.2 mm bead size for ultra-high resolution) encapsulated in a layer of polyacrylamide gel. The mass of metal, M, in this backing layer (area A) is measured after a known deployment time, t, and used to calculate a mean flux (F) from pore waters to resin during deployment (Eqn. 1, in Fig. 1 legend).

The interpretation of this measured flux in terms of pore water concentrations depends on the availability of metal. Three cases can be considered (Fig. 1):

Sampling & Analysis

A gel deployment system (GDS) was used to deploy DGT *in situ* in deep-sea sediments. This modular unit was bolted to the frame of a benthic autonomous lander. The perspex gel probes are driven into the sediment to a pre-determined depth. The benthic lander is completely autonomous and is fully computer controlled. The lander is brought back to the surface by releasing three ballast buckets from the main lander frame. This is done by using an acoustic release with a back up mechanism of a burn wire controlled by the computer. On-board ship deployments of DGT probes were also undertaken on collected cores from a meg-corer. The DGT probes are then inserted into the cores for periods of up to 36 hours. The cores are kept in the ships cold room at ambient bottom water temperature. Probes were sliced at 1 mm intervals eluted with 1M nitric acid and analysed using ICP-MS.

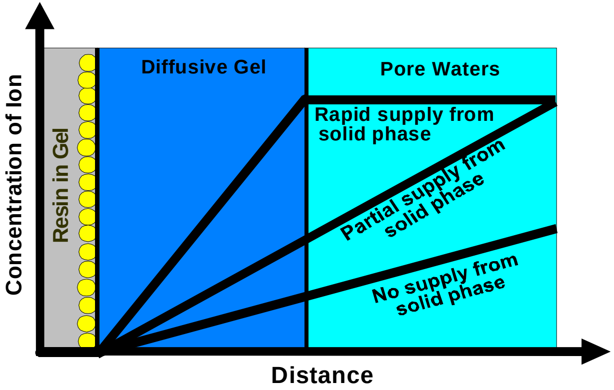


Figure 1: Scematic representation of concentration gradients in a DGT assembly in contact with pore waters where there is rapid, partial or no supply from the solid phase.
$F = M / At$ (Eqn. 1) ; $C = M\Delta g / DAt$ (Eqn. 2)

(1) Sustained: Dissolved metals in the pore waters are locally re-supplied from the solid phase. The concentration in the pore waters is effectively well buffered and can be calculated from the measured mass on the resin (Eqn. 2, in Fig. 1 legend)
(2) Unsustained There is no re-supply from the solid phase. Supply is by diffusion from the pore waters alone.
(3) Partially Sustained: There is some re-supply of metal from the solid phase. The measured flux can be equated to the in-situ flux.

Results and Discussion

Figure 2 shows the trace metal profiles of Cd, Zn, Co and Cu at 1 mm resolution from Site C during CD 113. When the mega cores were collected there was found to be a fluff layer on the surface of the sediment about 2 cm thick. These profiles show clear mobilization of Zn and Cd within the fluff and Co and Cu just below the fluff/sediment interface. Mobilization within the fluff layer is probably associated with biological breakdown of organic material releasing trace metals. Figure 3 shows Mn and Co profiles from the same site before and after the bloom. The profiles clearly show similar profiles indicating that geochemically associated elements will behave the same and therefore produce similar profiles. Profiles from CD 111 show the increase at the sub-oxic boundary while CD 113 profiles clearly show remobilisation in the surface mm's of the sediment just below the fluff layer.

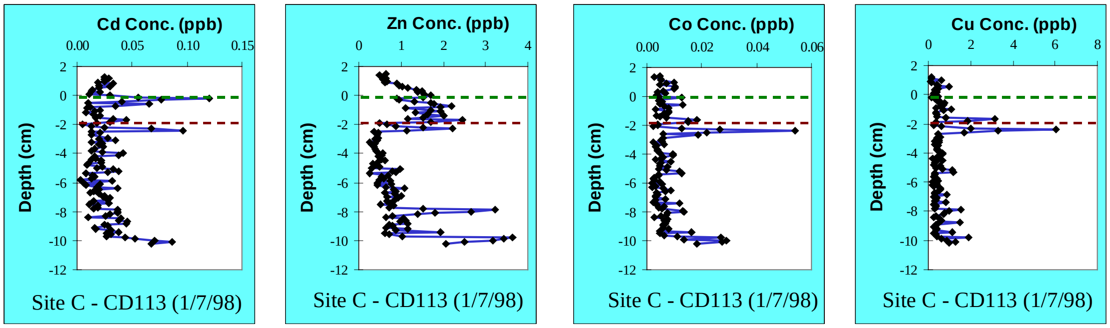
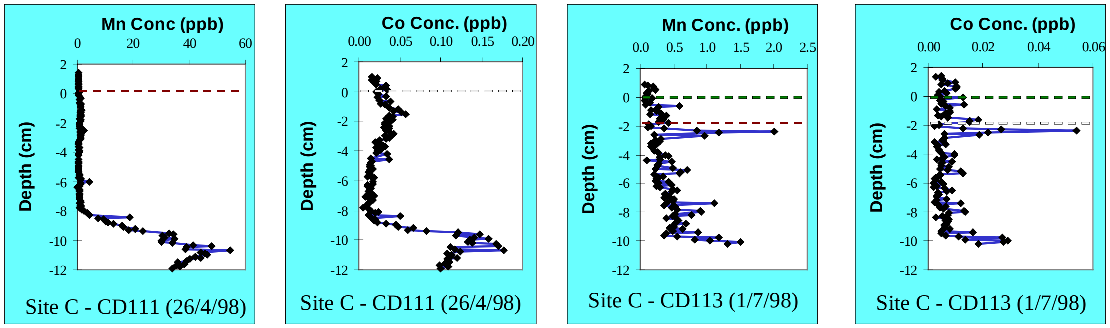


Fig. 2: Remobilization in the surface sediment and marine snow



Site C - CD111 (26/4/98) Site C - CD111 (26/4/98) Site C - CD113 (1/7/98) Site C - CD113 (1/7/98)

Fig. 3: Geochemically similar elements (Mn/Co)

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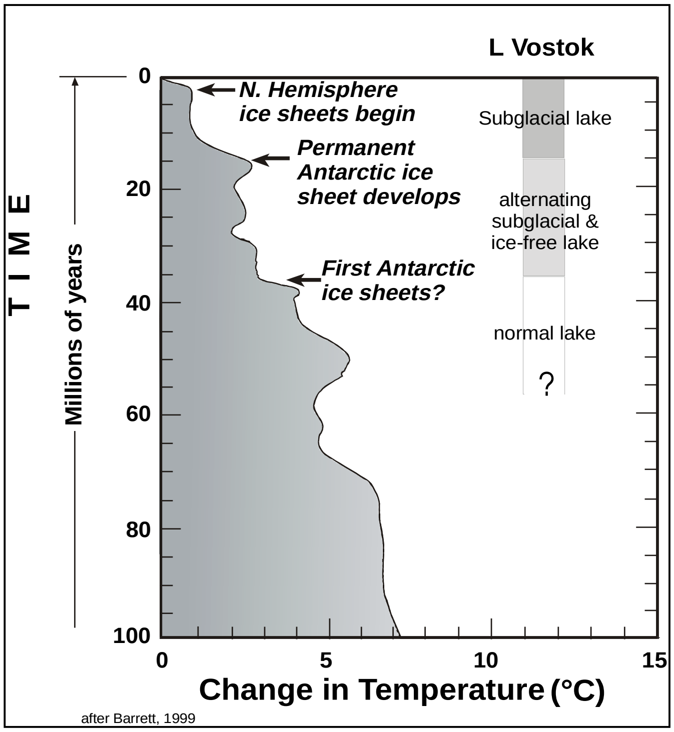
How Old is Lake Vostok?

Peter Barrett
School of Earth Sciences,
Victoria University of Wellington,
PO Box 600, Wellington, New Zealand
e-mail: *peter.barrett@vuw.ac.nz*

Interest in life forms that might be found in Lake Vostok stems from their evolution in the most extreme and isolated environment on earth, thus providing an analogue for harsh environments on other planetary bodies. A key question for those interested in the origins of the biota in the lake will be its age, and especially the time span for its existence as an ice-covered water body isolated from light and atmosphere. We can consider the geological history of the Vostok basin in terms of 4 phases, the first two tectonically controlled, and the latter two distinguished by climate:

- development of a topographic basin in the area of Vostok through tectonic processes probably related to the development of the Lambert Graben and the formation of the nearby Gamburtsev Mountains
- the initiation of sedimentation in a stream-fed lake, collecting water and sediment from the surrounding "pre-glacial" landscape
- the formation of an ice cover, first by annual freezing of lake waters, but later by the advance of an ice cap centred on the Gamburtsev Mountains, the highest land in the region. Sedimentation continues during glacial episodes through sub-glacial melting and circulation of lake waters beneath the ice, but the ice cap periodically melts, leaving the lake ice-free on a regular basis.
- the formation of a permanent ice sheet, almost completely isolating the lake from the atmosphere.



after Barrett, 1999

There is not yet a basis for estimating the time at which the Vostok basin developed, though if it is linked in age with the Lambert Graben and the Gamburtsev Mountains at its head, the age is likely to be at least 30 and more likely 50+ million years old. Some idea of the age of the mountains could come from coring a transect from mid level to summit of the central Gamburtsev Mountains, i.e. from 2000 to1000 m below the ice surface at Dome Argus 800 km west of Lake Vostok. If the rocks are not volcanic, then fission track ages could provide a chronology for their uplift. If the mountains are of volcanic origin, the time of last effusion of the lavas could be established directly from radiometric dating the core. Geophysical surveys could also provide data to resolve this issue from magnetic and gravity signatures of the mountains and the Vostok Basin.

From current knowledge of Antarctic glacial history (Barrett, 1996), we can expect a transition from a green ice-free Antarctica to a continent with an episodic ice sheet cover at around 34 Ma, followed by continental ice sheets waxing and waning, probably on Milankovitch frequencies (phase iii above). The current majority view is that the continental ice sheet became a permanent feature a little less than 15 million years ago, though it still varied significantly in size – perhaps by as much as a third of its volume. Throughout this period Lake Vostok would have been covered with thick ice (phase iv above).

The only means of assessing the age of the basin and lake sediments, both pre-glacial and glacial in age, is by sampling the sediments, said to be several hundred metres thick, to the floor of the lake basin. Even relatively low resolution (± 1 My) dating of the sediment is likely to be difficult and would require a wide range of methods, including radiometric dating of any volcanic ash layers, the stable isotopic record of oxygen in penecontemporaneous minerals, and magnetostratigraphy. The strata themselves are, of course, an archive for the biota that evolved throughout the existence of the lake, and may well record the passage of time, though provide a means of measuring it. They would represent the longest-running experiment in the harshest environment on earth.

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Food Webs in Lake Vostok?
Hypotheses About a Hidden Ecosystem

Roland Psenner & Birgit Sattler
University of Innsbruck
Institute of Zoology and Limnology
A-6020 Innsbruck, Austria
e-mail:* *Roland.Psenner@uibk.ac.at*   *Birgit.Sattler@uibk.ac.at

Introduction

The following arguments are based on different lines of thinking with which we tried to reconcile existing knowledge about the history and development of the lake:

1. a (hypothetical) budget study of organic carbon and nutrients based on the suggested water renewal time of 50,000 years (Kapitsa et al. 1996) and the chemical/microbiological composition of the ice cap over the lake;
2. a comparison of life conditions in other extreme lakewater, groundwater or ice ecosystems; general considerations about food webs in oligotrophic aquatic systems.

Since Lake Vostok is such a special or unique case, we took the liberty to create a few **new concepts** (“glacial diet” etc.) which may be revised or omitted in the course of the exploration. But also common concepts such as “pelagic” etc. must be used with care, for the following conclusions are derived from extant, though extreme, ecosystems; new life cycle strategies and specific adaptations are not known and cannot be inferred. Thus our vision is an **extrapolation** from existing to potential ecosystems.

Outline

1. Lake Vostok has a long history, possibly up to 40 million years, the last million years thereof are peculiar and without paradigm. We assume that Lake Vostok – before reaching the current state – has undergone a transition from a warmer and more eutrophic level through an arctic-alpine state, characterized by low concentrations of DOM (typical for high mountain lakes), low temperatures, oligotrophic conditions, long ice duration, with low density, biomass and productivity of pelagic and benthic organisms. During the last phase, i.e. before it switched to the present conditions of a light-less, heterotrophic and/or lithotrophic system, it may have been comparable to the Dry Valley lakes with permanent ice cover. Looking at the actual situation, Lake Vostok resembles more a thick glacier-bed or a groundwater ecosystem than a normal lake. However, unlike a typical **glacier bed ecosystem** supported with organic carbon and oxygen by meltwater from the surface, the input to Lake Vostok seems to be restricted to ice melt at the base of the glacier which entails extremely low flux rates and the absence of anthropogenic contaminants, nutrients etc. Lake Vostok differs also from a typical **groundwater** system by having a large “pelagic” zone, and also a comparison with a **cave** system is not very appropriate.
2. This means, that Lake Vostok may have harboured in its **past a diverse pelagic, littoral and benthic community** but has undergone a long “**glacial diet**” from a normal lake situation, characterized by the exchange of matter and energy with its environment (photoautotrophy, tributaries, dust and organic debris from surrounding soils and long-range transport, atmo-

spheric depositions), to a sealed, dark system. Thus the principal question regarding the actual trophic status of Lake Vostok and its possibility to sustain a food web must consider whether there is a substantial input of organic and inorganic material: Which redox-couples exist, what is their concentration and how is the redox potential re-established? We consider the following possibilities:

- **Organic matter** (dissolved and particulate, living and dead organisms), nutrients and gases resulting from melting at the bottom of the **glacial ice** cap; this is the main supposed input and we will base our principal arguments (see. Table 1) on those facts (and hypotheses). However, other sources of matter and energy should not be omitted, such as:
- **Freshly weathered material** (basic cations, silica, phosphorus, hydrogen carbonate) and liquid water (produced by friction) **from the glacier bed**. This process could not only deliver some alkalinity to the supposedly acidic lake water (see Legrand & Mayewski 1997) but also organic carbon from **palaeosoils** or rocks. If this matter is delivered in relatively high concentrations, e.g. as a slurry of ground rock and glacial flour, it can increase the supposed low flux resulting from melting ice at the lake surface. Geothermal heating (perhaps ~50 mW m^{-2}) could enhance inputs from this source.
- The release of organic matter and reduced substances (H_2S, Fe^{2+}, NH_4^+, CH_4, fatty acids etc.) from **ancient lake sediments** could also retard the effect of the "glacial diet". It is difficult to say how large this supposed contribution may be because after a million years of reduced inputs, these sediments may have been covered by thick layers of virtually inorganic material (rock debris from the glacier bed). In this case, the organic sediments will not be accessible and may not contribute to the influx of organic matter and reduced substances – but they may still function as a repository of organisms such as diatoms, chrysophytes and other indicators, i.e. they are a highly interesting object for palaeo-limnology.
- **Gas hydrates** could be a source of organic (methane) and inorganic carbon (carbon dioxide), and other gases, but they are generally not easily accessible unless temperature increases or pressure decreases.
- **Hydrothermal vents** may be another source of chemical energy in the form of reduced susbtances. In contrast with the situation in Oceans, however, the input of **oxidized redox partners** will then be the limiting step.

3. Based on these considerations, it is crucial to figure out the "**limiting nutrient**": is it organic carbon and/or the availabity of oxidized redox couples (such as oxygen, nitrate, nitrite, sulphate, iron, manganese etc.) or rather the availability of CO_2 – if the system is driven by chemolithotrophic reactions? If organic carbon is not limiting, phosphorus and nitrogen may be the classical limiting nutrients. It seems to us that in all of these cases, the renewal time of water and the resulting renewal times of crucial elements (oxygen, carbon, nutrients) play a central role for existence and magnitude of a hypothetical food web in Lake Vostok.
4. A general consideration regarding the existence, structure and **functioning of food webs** is: "Do these inputs support life at concentrations (**densities**, numbers, biomass per ml or cm^2) allowing the existence of grazing, competition, exchange of metabolic products, lateral gene transfer, symbiosis, parasitism, viral infections?" Certainly, if the whole input is evenly

distributed and diluted in 1,800 km^3 of lake water, one can hardly expect the density and biomass necessary for "normal" ecological interactions as depicted above. To support bacterivorous protists, for instance, the density of bacteria should reach a limit of 10^5 to 10^6 ml^{-1}, as known from oligotrophic lakes. It may be possible to reduce this number under very slow growth conditions, but one has to consider that bacterivores then have to swim or filter for much longer periods to gain their prey. Eventually, the "soup" could become too thin for particle feeders. This problem could be circumvented, if **biological activities are concentrated at certain sites**, even a small influx of organic matter and energy can be sufficient to support an oligotrophic, though **functioning,** and – very important – measurable **food web**. This could happen at the site where fresh material comes in, i.e. immediately beneath the ice or at the sediment-water interface where a richer communitiy comprising ciliates, flagellates and possibly also meiofauna (rotifers, nematodes?) may exist. Other possibilities are hydrothermal vents; gas clathrates and the glacier bed.

- This point is of utmost importance in another respect: - a food web, whatever it may look like, will increase the recycling of nitrogen, phosphorus and carbon, and consequently increase total productivity. If a food web is established, the chances to sustain it are enhanced (positive feedback). This means that if Lake Vostok had been an ordinary lake, there is a good chance that it may still contain a functioning food web.

6. Which **organisms** may do the job? The simplest assumption is: those who lived in the lake before it froze but which have been **selected** in the course of millions of years, adapted to survive under high pressure, low temperature and low supply of nutrients and organic matter. The latter two conditions may have been quite common in a lake which has an arctic-alpine history. The constant "**contamination**" of the lake by microorganisms from the melting ice cap may be of lower importance because they derive from long-range transport, are more ubiquitous (Abyzov 1993, Abyzov et al. 1998) and thus are generally not adapted to Lake Vostok conditions. In addition, only a small percentage seems to be viable. The situation was presumably different before Antarctica had been covered by ice, as in the Dry Valley lakes, a large portion of the organisms may have originated from soils in the catchment. Nonetheless, this mechanism seems to be the only one to bring in new traits and new phylogenetic and physiological diversity. It is also a point which should be considered for sampling, because we may increase this *natural contamination* and thus find more organisms from the ice cap in the lake water.

- We should be prepared to find some **new adaptations** – not primarily in bacterial metabolism (Olsen 1999, Strous et al. 1999) but in certain bacterivorous protists which have to cope with a thin prey suspension; moreover, even some bacteria may have adapted to feed on others (*Bdellovibrio*-style). We do not expect more than **2 trophic levels** (bacteria and bacterivores). The presence of metazoa can not be ruled out: If they managed to survive, they can be expected at the sediment-water interface (rotifers, nematodes) or other **interfaces** where the biomass of bacteria reaches a threshold concentration. There may be only psychotrophic bacteria and there could be some interesting adaptations in metazoa (if they survived the glacial transition of the lake), e.g. as observed in cave-dwelling organisms.

7. So in principle we have **two options** – or a **combination** thereof:

a) Lake Vostok is a **heterotrophic** system depending on the supply of organic carbon and oxygen or other electron acceptors such as NO_3, SO_4, Fe^{3+} etc. (*Scenario A*)
b) Lake Vostok is a **chemolithotrophic** system, e.g. fuelled by hydrothermal vents rich in reduced substances (H_2, H_2S) and depends thus on the supply of electron acceptors (O_2, NO_3, NO_2, SO_4, Fe^3) and CO_2 (biomass production). It is assumed that chemolithotrophy increases productivity 10 times (*Scenario B*).

In both cases, nitrogen and phosphorus can become the limiting nutrients.

- Has Lake Vostok become **anaerobic**? The absence of light and the thick ice cap may suggest that, but only if oxygen consumption processes by heterotrophs are higher than the oxygen input through melting ice, the glacier bed etc. It is thus conceivable that Lake Vostok was partly or completely **anaerobic at the beginning of its icy phase** but that it has returned to aerobic conditions after most organic carbon originating from the former, open lake situation has been consumed. Are other electron acceptors available? If there are hydrothermal vents then the consumption of oxyenated compounds (sulphate, nitrate, ferric iron) must have been higher and the lake has turned into an anoxic system, however only if the inflow of reduced substances from vents (H_2, H_2S, etc.,) exceeds the input of oxygen and other electron acceptors. An interesting aspect in the history of dissolved gases is the moment when the ice cup became thick enough to allow for the build-up of clathrates.

The concept

Inputs

Based on a simple **budget approach** with 2 scenarios the following considerations give a framework of theoretical solutions to the problem of productivity and food webs. If the lake water volume is exchanged every 50,000 years as supposed by Kapitsa et al. (1996), we need a flushing rate of 0.036 km^3 or 36 million m^3 of water per year (Table 1).

Table 1. Lake morphology and hydrolgoy

Lake volume	1800 $km^3 = 1.8 \cdot 10^{12}$ m^3
Residence time	**50000 years**
Annual inflow	$36 \cdot 10^6$ m^3 yr^{-1}

This water contains $3.6 \cdot 10^{16}$ organisms from the melting ice (Abyzov 1998, but only few of them are viable), 36-360 metric tonnes of oxygen (assuming a concentration of 1-10 mg l^{-1}) and 3.6 tonnes of organic carbon per year, assuming an average concentration of 0.1 mg l^{-1} in the ice cap (Table 2). The composition of the melting ice (Legrand & Mayewski 1997) is assumed to be constant, however, during the – relatively short – interglacial periods, nitrate and phosphate concentrations were much lower than during glacial times. Ammonium concentrations are very low (we assumed the same level as in Greenland ice) and the ice is slightly acidic, thus we assumed no additional hydrogen carbonate except dissolved $CO_2 + H_2CO_3$ in air equilibrium (ca. 10 µMol l^{-1}). The inoculum of microorganisms is calculated from Abyzov et. al. (1998).

Table 2. Inflow composition (melting ice)

Total microorganisms	1000 ml^{-1}
Viable microorganisms	10 ml^{-1}
Total organic carbon, TOC	0.1 mg l^{-1}
NO_3	1 •mol l^{-1}
NH_4	0.1 •mol l^{-1}
PO_4	0.01 •mol l^{-1}
O_2	1 mg l^{-1}
CO_2	10 •mol l^{-1}

For a lake containing nearly 2 x 10^{12} m^3 of water, the delivery of 3.6 x 10^6 grams of organic carbon is a very low amount (Table 3). In order to reach a higher metabolism, the lake must harbour lithotrophs which can use chemical energy and CO_2 to produce biomass. But what if other substances are limiting? Can we calculate, roughly, the input of essential nutrients?

Table 3. Annual inputs from melting ice (*Scenario A*)

	Whole lake	**Per litre**
Viable microorganisms	$3.6 \cdot 10^{14}$	0.2
TOC	$3.0 \cdot 10^{5}$ mol	$1.67 \cdot 10^{-10}$ mol = 2 ng
NO_3	$3.6 \cdot 10^{4}$ mol	$2.0 \cdot 10^{-11}$ mol
NH_4	$3.6 \cdot 10^{3}$ mol	$2.0 \cdot 10^{-12}$ mol
PO_4	$3.6 \cdot 10^{2}$ mol	$2.0 \cdot 10^{-13}$ mol
O_2	$2.25\text{-}22.5 \cdot 10^{6}$ mol	$1.3\text{-}13 \cdot 10^{-9}$ mol
CO_2	$3.6 \cdot 10^{5}$ mol	$2.0 \cdot 10^{-10}$ mol

The carbon:nitrogen:phosphorus ratio (Table 4) suggests that both N and P may be limiting nutrients. The oxygen input would be high enough for the oxidation of organic carbon, the inorganic carbon is of the same magnitude as the organic one.

Table 4. Molar ratios of inputs (*Scenario A*)

C:N:P	• 1000:100:1
Oxygen : organic carbon	• 10:1 to 100:1
TOC:TIC	• 1:1

Cell production

Assuming on average **10 fg C per cell and a growth yield of 0.1**, we find an annual production of **$2 \cdot 10^4$ cells l^{-1} yr^{-1}** produced from the assumed input of $2 \cdot 10^{-9}$ g TOC l^{-1} yr^{-1}. For the whole lake, this amounts to $3.6 \cdot 10^{19}$ cells yr^{-1} or $3.6 \cdot 10^5$ g C yr^{-1}.

The presence of oxygen would allow a higher productivity. In this case, however, the extremely low input of phosphorus may be the limiting step (even if there is recycling by bacterivores). Additional inputs from the glacier bed, from ancient sediments and from hydrothermal vents may increase the input/production of organic carbon by an order of magnitude. If so, other limitations must be considered, for instance the availability of oxygen or electron acceptors in general, of phosphorus, nitrogen, CO_2 etc. Under the assumption that other sources of matter and energy are one order of magnitude larger than the input from melting ice, we come to the following numbers (Table 5).

Table 5. Annual cell and carbon production

SCENARIO	Whole lake	Per litre
A. Heterotrophic (supported from melting ice)	3.6×10^{19} cells	2×10^4 cells
	360 kg C	0.2 ng C
B: Heterotrophic & chemolithotrophic	3.6×10^{20} cells	2×10^5 cells
	3600 kg C	2 ng C

Assuming 10 generations per year under these constraints (i.e. Scenario B), it requires a cell density (**standing stock**) of **$2 \cdot 10^4$ cells l^{-1}** or $3.6 \cdot 10^{19}$ cells per lake. With only 2 generations per year we find a theoretical standing stock of **~10^5 cells l^{-1}**. Even the highest densities under *scenario B* with 1 generation per year are ca. 3 orders of magnitude too low for the functioning of a simple food web consisting of bacteria and bacterivorous protists as we know it from existing examples in oligotrophic systems. Therefore we assume **locally high densities of bacteria and bacterivores**.

The alternative

- is to leave Lake Vostok untouched. The first, obvious, reason is that there is no method available to sample that lake without the risk of contamination. Recent attempts to study the accretion ice of Lake Vostok have clearly demonstrated that it is even extremely difficult to decontaminate ice samples, while the collection of uncontaminated water from Lake Vostok is actually impossible. To develop a sampling strategy – and to test it under real conditions – will take years. If there is even a minimum risk of contamination, sampling makes no sense. The second reason, which is not so obvious – at least for natural scientists – is a more principal or philosophical one: even if a “relatively secure” sampling strategy can be developed, we may decide to keep Lake Vostok untouched as a source of intuition and speculations for coming generations. We have detected, explored – and spoiled – almost all sites of the world, and we are going to do so with extraterrestrial systems. Why not leave Lake Vostok in the mythical darkness?

Summary

- We assume that Lake Vostok has undergone a glacial diet from a “normal” lake situation to its present “sealed” condition; it now resembles more a glacier bed or a groundwater ecosystem than a lake. If, on the contrary, the lake has no limnological history, the conditions for organisms may be even more extreme (species, abundance, resources).
- If Lake Vostok has been once a lake, it may harbour organic material originating from its limnetic past, but also (micro-)organisms which have adapted to the new conditions of extreme oligotrophy and darkness. In addition to bacteria and Archaea, viruses, protists (flagellates, ciliates) and possibly also meiofauna (rotifers, nematodes) can be expected. The lake is continually “contaminated” by organisms resulting from the melting ice cap.
- Actual inputs of organic and inorganic substances are extremely low, e.g. less than a metric ton of organic carbon per year – unless there are other sources (palaeosoils, sediments, vents, clathrate deposits etc.). A crucial point is the importance of gases, especially oxygen and carbon dioxide: are they available or permanently trapped as clathrates? If the food web of Lake Vostok does not solely depend on heterotrophy, the input of CO_2, P, N or O_2 may become limiting. Under these constraints, a tenfold increase in productivity is assumed, i.e. ca. 4 t of organic carbon per year.
- Growth rates must be extremely low, 1 to 10 generations per year are expected. Consequently, also the abundance of organisms is expected to be low, thus food webs can exist only at interfaces (ice/water or sediment/ water).
- The transition from the (putatively) open to its actual, closed state should be studied by means of palaeo-ecology.
- Sampling should only be considered, if a clean technology is available (and previously tested under real conditions).

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Ice Coring in the Context of Antarctic Subglacial Lake Exploration

Jean Robert Petit
LGGE-CNRS BP 96
F-38402 St Martin d'Hères Cedex
France
e-mail: petit@glaciog.ujf-grenoble.fr

Background

Ice cores from Greenland and Antarctica provide a wealth of paleoclimate information
Ice is unique by its entrapped bubbles containing fossil air.

Amongst ice cores, the Vostok core has provided the longest climate record (420 Ky) and:

- Confirmed the influence of the solar forcing
- Evidenced the importance of greenhouse gases in climatic changes

1. Ice Sheets and the Sub-Glacial Environments (bedrock and lake)

Ice sheet, bedrock and lake are in a dynamic and thermal equilibrium
Exchange of material (rocks, water, gases, aerosols, microbes) through melting/freezing/advection

2. Are new Ice records important?

Antarctic is large(14x10^{16} cm^2). To date only a small number of ice records are available: We need to know the geographical significance of these records.

The Vostok area is particularly significant because **no other site on the polar ice caps will give both**:

- a very long atmospheric record and at the same time
- the highest resolution for >200 Ky BP period

The northern Lake Vostok area with 4100m ice thickness is particularly attractive

3. Questions in climate studies

- 450 Ky ago, the solar forcing influence was low. How to explain the Glacial to Interglacial climate change (stage 12/11 transition)? What about the greenhouses gases?
- Could the Anomalous long Interglacial Stage 11 be an analogue for future climate?

4. Recommendations

Ice records are important to document climate studies
In the context of Lake Vostok exploration : northern lake area is unique for long record.

The adaptation of existing ice coring technologies to be compatible with lake exploration is highly encouraged.

Food Webs and Ecosystem Evolution in Lake Vostok

Roland Psenner & Birgit Sattler
University of Innsbruck
Institute of Zoology and Limnology
A-6020 Innsbruck, Austria
e-mail: Roland.Psenner@uibk.ac.at Birgit.Sattler@uibk.ac.at

We suggest to study **food webs and physiology**, considering also the **historical perspective**. Our proposal fits neatly into plans of other groups to study the *biogeochemistry* (what is the chemical basis for life?), *physics-hydrology-glaciology* (what are the time periods, flux rates and physical forces?), and *phylogenetics* (which organisms – or which genomes – are there?).

Questions

1. Is there a food web? This means: are there active cells of bacteria and protistan bacterivores exceeding a critical density? Is the critical density achieved at certain sites? How large is the overall diversity (morphotypes, size, "behaviour")? Can we measure physiological (and other) characteristics, i.e. are some species culturable? Are there some pathways favoured? Can we address "pure" psychrotrophs? Can microbes evolve into cold-loving bacteria during 1 million years of isolation? Can additional nutrients compensate for low temperatures? Which nutrients are limiting? Is there a chance for eukaryotes? For meiofauna?
2. How did the lake evolve before and after ice cover? What happened during the transition to the present day situation? Up to now, we have seen mostly the reverse, namely oligotrophic natural ecosystems switching to eutrophic and hypertrophic states, contamination, introduction of alien species etc.

Approach

1. To study the presence of known morphologies and overall taxonomic and phylogenetic affiliation of viruses, bacteria, Archaea, flagellates, ciliates and possibly meiofauna (rotifers, nematodes), quantification of size, volume, DNA and RNA content of single cells. Calculation of biomass and cell densities. Depending on the sampling strategy and field facilities: attempt to measure activity with fluorescent and non-fluorescent markers and ^{3}H or ^{14}C labelled substances. Attempt to bring certain species into cultures. Determination of optimal temperatures for maximal growth rates, comparison of the pelagic zone with the interfaces ice/water and sediment/water. Also the influence of nutrient additions should be checked.
2. Reconstruction of the major conditions (pH, alkalinity) by analysing diatom and chrysophycean remains ("lake" phase). Test for other biomarkers in the absence of light. Comparison of pH and alkalinity reconstructions with the history of depositions (ice cores and sediment geochemistry). Investigate any major changes during the transition (organisms, biogeochemistry) from the "lake" phase to the actual conditions.

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List of Participants

LAKE VOSTOK WORKSHOP, LUCY CAVENDISH COLLEGE, CAMBRIDGE
26-28 SEPTEMBER 1999

NAME	ADDRESS	TELEPHONE	FAX	E-MAIL
ADAMS, ED	CIVIL ENGINEERING DEPT. MONTANA STATE UNIV. BOZEMAN, MT 59717, USA	001-406-994-6122	001-406-994-6105	EDA@CE.MONTANA.EDU
ALDAHAN, ALA	INSTITUTE OF EARTH SCIENCES VILLAVAGEN 16, S-752 36 UPPSALA SWEDEN	00-46-18-4713095 00-46-18-4712342	00-46-18-55520	ALA.ALDAHAN@GEO.UU.SE
ANANDAKRISHNAN, SRIDHAR	UNIVERSITY OF ALABAMA, DEPT. GEOLOGY BOX 870338 TUSCALOOSA, AL 35487-0338, USA	001-205-348-9097	001-205-348-0818 001-205-348-5095 (DEPT.)	SAK@UA.EDU
BARRETT, PETER	SCHOOL OF EARTH SCIENCES VICTORIA UNIVERSITY OF WELLINGTON, PO BOX 600, WELLINGTON, NEW ZEALAND	00-64-4-471-5336	00-64-4-495-5186	PETER.BARRETT@VUW.AC.NZ
BECK, CHRISTIAN	UNIVERSITE DE SAVOIE LGCA/CISM CNRS UMR 5025 CAMPUS SAVOIE-TECHNOLAC 73 376 LE BOURGET DU LAC, FRANCE	+33 04 79 75 87 05	+33 04 79 75 87 77	Christian.Beck@univ-savoie.fr
BELL, ROBIN	LAMONT-DOHERTY EARTH OBSERVATORY OF COLUMBIA UNIVERSITY, PO BOX 1000, 61 ROUTE 9 W. PALISADES, NY 10964-8000, USA	001-914-365-8598	001-914-365-8179	R.Bell@ldeo.columbia.edu
BLANKENSHIP, VICTOR (DON)	INSTITUTE FOR GEOPHYSICS THE UNIVERSITY OF TEXAS AT AUSTIN, 4412 SPICEWOOD SPRINGS ROAD AUSTIN, TEXAS TX 78759, USA	001-512-471-0489	001-512-471-8844	blank@ig.utexas.edu
CARSEY, FRANK	JPL ms 300-323, PASADENA CA 91109, USA	001-1-818-354-8163	001-1-818-393-6720	f.carsey@jpl.nasa.gov

NAME	ADDRESS	TELEPHONE	FAX	E-MAIL
CHIANG, ERICK	NATIONAL SCIENCE FOUNDATION, 4201 WILSON BLVD. ARLINGTON, VA 22230 USA	+703 1045 X7305	+703 306-0645	echiang@nsf.gov
CLARKE, KEN	INSTITUTE OF TERRESTRIAL ECOLOGY, WINDERMERE LABORATORY THE FERRY HOUSE, AMBLESIDE, CUMBRIA LA22 OLP	+44 015394-42468	+44 015395-46914	k.j.clarke@ife.ac.uk
CLARKSON, PETER	SCAR EXECUTIVE OFFICE SCOTT POLAR RES. INST. LENSFIELD ROAD CAMBRIDGE CB2 1ER, UK	00-44-1223-362061	00-44-1223-336549	execsec@scar.demon.co.uk
COLLINS, TONY	LABORATOIRE DE BIOCHIMIE INSTITUT DE CHIMIE B6A UNIVERSITE DE LIEGE 4000 LIEGE BELGIUM	00-32-4-366-33-46	00-32-4-366-33-64	tcollins@student.ulg.ac.be
DALZIEL, IAN	INSTITUTE FOR GEOPHYSICS UNIV. OF TEXAS AT AUSTIN, 4412 SPICEWOOD SPRINGS RD. BLDNG. 600, AUSTIN, TEXAS 78759-8500, USA	+512 232 3231	+512 471 8844	ian@utig.ig.utexas.edu
DELBART, FRANCK	IFRTP, TECHNOPOLE BREST-IROISE, BP 75, 29280 PLOUZANE, FRANCE	+33 2 98 05 65 56	+33 2 98 05 65 10	Franck.Delbart@ifrtp.ifremer.fr
DELONG, EDWARD	MONTEREY BAY AQUARIUM RESEARCH INST. 7700 SANDHOLOT RD. MOSS LANDING, CA 95039, USA	001-831-775-1843	001-831-775-1645	delong@mbari.org
DORAN, PETER	UNIVERSITY OF ILLINOIS AT CHICAGO, DEPT. OF EARTH AND ENVIRONMENTAL SCIENCES, 845 W. TAYLOR ST., CHICAGO, ILLINOIS 60607-7059, USA	001-312-41307275	001-312-413-2279	pdoran@uic.edu new e-mail

NAME	ADDRESS	TELEPHONE	FAX	E-MAIL
EDWARDS, HOWELL	DEPT. OF CHEMICAL & FORENSIC SCIENCES, UNIV. OF BRADFORD RICHMOND ROAD, BRADFORD BD7 1DP WEST YORKSHIRE, UK	+44 (0)1275 233798	+44 (0)1275 235350	h.g.m.edwards@bradford.ac.uk
ELLIS-EVANS, CYNAN	BRITISH ANTARCTIC SURVEY HIGH CROSS, MADINGLEY ROAD CAMBRIDGE CB3 OET, UK	+44 (0)1223-221555	+44 (0)1223 362616	jcel@bas.ac.uk
FINLAY, BLAND	INST. OF FRESHWATER ECOLOGY, WINDERMERE LABORATORY, THE FERRY HOUSE, AMBLESIDE, CUMBRIA LA22 OLP, UK	+44 (0)15394 42468	+44 (0)15394 46914	b.finlay@ife.ac.uk
GRIKOROV, GARRICK	VNII OKEANGEOLOGIA 1 ANGLIISKY AVE. 190121 ST. PETERSBURG RUSSIA	00-7-812 114 3113	00 7 812 114 1470	grikurov@mail.lanck.net
HAMILTON, GORDON	BYRD POLAR RESEARCH CENTER, THE OHIO STATE UNIVERSITY, 1090 CARMACK RD. COLUMBUS, OH 43210-1002, USA	001 614 688 3793	001 614 457 3248	hamilton@iceberg.mps.ohio-state.edu
HOJ, LONE	DEPT. MICROBIOLOGY UNIVERSITYOF BERGEN JAHNEBAKKEN 5 PO BOX 7800, 5020 BERGEN NORWAY	+47 555 82 662	+47 555 89671	Lone.Hoj@im.uib.no
KARL, DAVID	PROFESSOR OF OCEANOGRAPHY, SCHOOL OF OCEAN & EARTH SCIENCE & TECHNOLOGY, UNIVERSITY OF HAWAII, HONOLULU, HL 96822, USA	+808 956 5059	+808 956 5059	dkarl@soest.hawaii.edu
KENNICUTT II, CHUCK	DIRECTOR, GEOCHEMICAL & ENVIRONMENTAL RES. GROUP, TEXAS A & M UNIVERSITY 833 GRAHAM RD. COLLEGE STATION, TX 77845, USA	001 409 862 2323	001 409 862 2361	mck2@gerg.tamu.edu

NAME	ADDRESS	TELEPHONE	FAX	E-MAIL
LEICHENKOV, GERMAN	VNII OKEANGEOLOGIA 1 ANGLIISKY AVE., 190121 ST. PETERSBURG RUSSIA	00 7 812 312 3551	00 7 812 114 1470	leichenkov@mail.lanck.net
LIESACK, WERNER	MAX-PLANCK-INSTITUTE FOR TERRESTRIAL MICROBIOLOGY KARL-VON-FRISCH-STR. D-35043 MARBURG GERMANY	+49 6421 178720	+49 6421 178809	liesack@mailer.uni-marburg.de
LOCK, MAURICE	SCHOOL OF BIOLOGICAL SCIENCES, UNIVERSITY OF WALES, BANGOR, GWYNEDD LL57 2UW, UK	+44 (0)1248 382310	+44 (0)1248370731	bss020@bangor.ac.uk
LUKIN, VALERY	ARCTIC & ANTARCTIC RESEARCH INSTITUTE, BERING ST., 38, 199397 ST. PETERSBURG, RUSSIA	+812 352 22 46	+812 352 26 88	lukin@raexp.spb.su
LYONS, BERRY	DEPT. GEOLOGY UNIVERSITY OF ALABAMA ALABAMA, USA	001 205 348 0583	001 205 348 0818	blyons@wgs.geo.va.edu
MASOLOV, VALERY	HEAD OF ANTARCTIC DIVISION, PMGRE, 24 POBEDY ST. LOMONOSOV, 189510 ST. PETERSBURG, RUSSIA	+ 7 812 423 18 58	+ 7 812 423 19 00	ice@polarex.spb.ru
MAYER, CHRISTOPH	ARZLER STR. 50 A-6020 INNSBRUCK AUSTRIA	+43 512 202095	-	-
MELLES, MARTIN	ALFRED-WEGENER-INST. FOR POLAR & MARINE RESEARCH RESEARCH UNIT POTSDAM TELEGRAFENBERG A43, D-14473 POTSDAM GERMANY	+49 331 288 2116	+49 331 288 2137	mmelles@awi-potsdam.de
MEYER, MIKE	ASTROBIOLOGY DISCIPLINE SCIENTIST, CODE SR, 300 E. ST., SW WASHINGTON, DC 20546, USA	001 202 358 0307	001 202 358 3097	mmeyer@hq.nasa.gov

NAME	ADDRESS	TELEPHONE	FAX	E-MAIL
MILLER, HEINZ	ALFRED-WEGENER-INSTITUT COLUMBUSSTRASSE D-27568 BREMERHAVEN GERMANY	+49 471 4831210	+49 471 4831149	miller@awi-bremerhaven.de
OVREAS, LISE	DEPT. MICROBIOLOGY UNIV. BERGEN JAHNEBAKKEN 5 PO BOX 7800 5020 BERGEN, NORWAY	+47 555 82 662	+47 555 89 671	Lise.Ovreas@im.uib.no
PALAIS, JULIE	OFFICE OF POLAR PROGRAMS, NATIONAL SCIENCE FOUNDTN, 4201 WILSON BOULEVARD, ARLINGTON,USA	001-703-306-1033	001-703-306-0139	j.palais@nsf.gov
PEACOCK, DENNIS	NATIONAL SCIENCE FOUNDATION, OPP, 4201 WILSON BLDV. ARLINGTON, VA 22230, USA	001 703 306 1033	001 703 306 0139	dpeacock@nsf.gov
PENHALE, POLLY	PROGRAM MANAGER ANTARCTIC BIOLOGY & MEDICINE, OFFICE OF POLAR PROGRAMS, NSF, 4201 WILSON BOULEVARD, ARLINGTON, VA 22230, USA	001 703 306 1033	001 703 306 0139	ppenhale@nsf.gov
PETIT, JEAN ROBERT	LGGE-CNRS BP 96 F-38402 ST. MARTIN D=HERES CEDEX FRANCE	+33 4 76 82 42 44	+33 4 76 82 42 01	petit@glaciog.ujf-grenoble.fr
PLATT, STEPHEN	THE SNOW & ICE RESEARCH GP. UNIVERSITY OF NEBRASKA-LINCOLN 2255 W. STREET, SUITE 101 LINCOLN, NE 68583-0850 USA	001 402 472 9833	001 402 472 9832	srp@unl.edu
PRICE, BUFORD	PHYSICS DEPT. UNIVERSITY OF CALIFORNIA BERKELEY, CA 94720 USA	001 510 642 4982	001 510 643 8497	bprice@uclink4.berkeley.edu
PRISCU, JOHN	PROFESSOR OF ECOLOGY DEPT. OF BIOLOGY MONTANA STATE UNIV. BOZEMAN, MONTANA 59717 USA	001 406 994 3250	001 406 994 5863	ubijp@montana edu

NAME	ADDRESS	TELEPHONE	FAX	E-MAIL
PSENNER, ROLAND	UNIV. OF INNSBRUCK INST. OF ZOOLOGY & LIMNOLOGY, TECHNIKERSTR. 25 A-6020 INNSBRUCK, AUSTRIA	+43 512 507 6130	+43 512 507 2930	roland.psenner@uibk.ac.at
RAPLEY, CHRIS	BRITISH ANTARCTIC SURVEY HIGH CROSS, MADINGLEY RD CAMBRIDGE CB3 OET, UK	+44 1223.221524	+44 1223 363616	C.Rapley@bas.ac.uk
RAYNAUD, DOMINIQUE	DIRECTOR, LGGE BP 96 38402 SAINT MARTIN D=HERES, CEDEX, FRANCE	+33 4 76 82 42 45	+33 476 82 42 01	domraynaud@glaciog.ujf-grenoble.fr
ROBIN, GORDON G. DE Q	SCOTT POLAR RES. INST. LENSFIELD ROAD CAMBRIDGE CB2 1ER, UK	+44 1223 336550	+44 1223 336549f	
ROURA, RICARDO	ANTARCTIC & SOUTHERN OCEAN COALITION EUROPEAN COORDINATION & CAMPAIGN OFFICE P.V.D. DOESSTRAAT 44 11 1056 VH AMSTERDAM, NETHERLANDS	+31 20 683 8133	-	Rroura@yahoo.com
RUTFORD, ROBERT	THE UNIVERSITY OF TEXAS AT DALLAS, PO BOX 830668, RICHARDSON, TEXAS 75083-0686, USA		001 214 690 2237	Rutford@utdallas.edu
SATTLER, BIRGIT	UNIV. OF INNSBRUCK INST. OF ZOOLOGY & LIMNOLOGY, TECHNIKERSTR. 25 A-6020 INNSBRUCK, AUSTRIA	+43 512 507 6130	+43 512 507 2930	birgit.sattler@uibk.ac.at
SHEREMETIEV, ALEXA	LEADER OF ANTARCTIC GP PMGRE 24 POBEDY ST. LOMONSOV 189510 ST. PETERSBURG RUSSIA	+7 812 423 18 58	+7 812 423 19 00	Vicaar@mail.wplus.net
SIEGERT, MARTIN	BRISTOL GLACIOLOGY CENTRE, SCHOOL OF GEOGRAPHICAL SCIENCES, UNIVERSITY OF BRISTOL, BRISTOL BS8 1SS, UK	+44 0117-928-8902	0117-928-7878	m.j.siegert@bristol.ac.uk new e-mail
SMELLIE, JOHN	BRITISH ANTARCTIC SURVEY HIGH CROSS, MADINGLEY ROAD CAMBRIDGE CB3 OET, UK	+44 1223-221417	+44 1223 362616	J.Smellie@bas.ac.uk

NAME	ADDRESS	TELEPHONE	FAX	E-MAIL
SOWERS, TODD	ASST. PROFESSOR OF GEOSCIENCES, PENN STATE UNIVERSITY, UNIVERSITY PARK, PA 16802-2714, USA	001 814 863 8093	001 814 863 7823	sowers@geosc.psu.edu
STACKEBRANDT, ERKO	DSMZ, MASCHERODER WEG 1B 38124 BRAUNSCHWEIG GERMANY	+49 531 2616 352	+49 531 2616 418	erko@dsmz.de
STOREY, BRYAN	BRITISH ANTARCTIC SURVEY HIGH CROSS, MADINGLEY ROAD CAMBRIDGE CB3 OET, UK	+44 1223 221417	+44 1223 362616	B.Storey@bas.ac.uk
STUDINGER, MICHAEL	LAMONT-DOHERTY EARTH OBSERVATORY OF COLUMBIA UNIVERSITY, PO BOX 1000, 61 ROUTE 9 W, PALISADES, NY 10964-8000, USA	001 914 365 8598	001 914 365 8179	mstuding@ldeo.columbia.edu
TABACCO, IGNAZIO	DST.GEOFISCA VIA CICOGNARA 7 20129 MILANO ITALY	+39 02 23698404	+39 02 749 0588	ignazio.tabacco@unimi.it
THOMSON, MICHAEL	BRITISH ANTARCTIC SURVEY HIGH CROSS, MADINGLEY RD CAMBRIDGE CB3 OET, UK	+44 1223 221444	+44 1223 362616	M.Thomson@bas.ac.uk
TIEDJE, JIM	DIRECTOR, CENTER FOR MICROBIAL ECOLOGY MICHIGAN STATE UNIV. 540 PLANT & SOIL SCIENCE BUILDING, EAST LANSING, MI 48824-1325, USA	001 517 353 9021	001 517 353 2917	plinel@pilot.msu.edu
VOYTEK, MARY	US GEOLOGICAL SURVEY 12201 SUNRISE VALLEY DRIVE RESTON, VA 20192, USA	001 703 648 6894	001 703 648 5484	mvoytek@usgs.gov
VERKULICH, SERGEY	STATE SCIENTIFIC CENTRE OF RUSSIA, ARCTIC & ANTARCTIC RESEARCH INSTITUTE, BERING ST., 38, 199397 ST. PETERSBURG, RUSSIA	+7 812 352 22 46	+7 812 352 26 88	savat@aari.nw.ru
WUEST, ALFRED	EAWAG, CH-8600 DUBENDORF SWITZERLAND	+41 1 823 55 44	+41 1 823 52 10	Wuest@eawag.ch

NAME	ADDRESS	TELEPHONE	FAX	E-MAIL
WYNN-WILLIAMS, DAVID	BRITISH ANTARCTIC SURVEY, HIGH CROSS, MADINGLEY RD CAMBRIDGE CB3 OET, UK	+44 1223-221554	+44 1223-362616	D.Wynn-Williams@bas.ac.uk
ZOTIKOV, IGOR	INSTITUTE OF GEOGRAPHY RUSSIAN ACADEMY OF SCIENCES 29 STAROMONETNY STREET 109017 MOSCOW, RUSSIA	+7 095-1298285	+7 095-9590033	geography@glas.arc.org