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Circulation in Lake Vostok: A laboratory analogue study

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[1] The waters of sub-glacial Lake Vostok are thought to represent a unique biological habitat that has been out of contact with the atmosphere for millions of years. Although the water circulation within the lake will determine how nutrients are redistributed and hence where life may exist, the handful of existing studies conflict regarding whether the lake is stratified or well mixed, whether there is a clockwise or anti-clockwise circulation, or whether the sloping roof leads to a flow intensified along the eastern boundary. Here, an experimental analogue model of Lake Vostok is used to show a qualitatively different mode of circulation than described previously. The dominant mode of dispersion, and hence bio- and chemical redistribution, is controlled by the presence of columnar vortex structures that arise from rotating convection. This form of circulation does not occur in any other lake on Earth. We estimate that a water parcel takes 20–30 days to travel from the base to the roof of Lake Vostok and will experience minimal lateral mixing during this time. As the nutrient supply to the lake via melting ice is predicted to be less than that required for active growth within the entire lake, we speculate that this form of slow columnar convection would lead to the presence of thin biological boundary layers within the waters of the lake. This has important implications for the interpretation of any direct water samples taken near the roof of Lake Vostok.

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1. Introduction

[2] The world's largest sub-glacial body of water is Lake Vostok, which lies below approximately 4 km of glacial ice in Antarctica, at 77°S and 108°E (Figure 1a). The lake is 250 km × 50 km (oriented north to south) with a maximum depth of 800 ± 250 m at the southern end [*Tikku et al.*, 2004; *Studinger et al.*, 2004]. Recent aerogravity surveys indicate that a sill divides the lake into northern and southern basins, so that the chemical and biological composition of the basins may differ due to the limited water exchange [*Studinger et al.*, 2004]. Ice coring has penetrated to 3623 m, terminating within 100 m of the bottom, where ice of thickness from 150 to 220 m has formed by direct freezing of Lake Vostok [*Siegert et al.*, 2003]. Survey data combined with isostatic equilibrium assuming the entire depth of the ice above the lake has a constant density of 0.913 g cm^{-3} leads to the inference that the salinity of the lake is less than 0.1% [*Kapitsa et al.*, 1996]. Viable bacteria have been found in this accreted ice, indicating an aquatic ecosystem that has been out of contact with the atmosphere for several million years [*Christner et al.*, 2006]. A principal motivation for understanding the circulation in Lake Vostok is to discern the physical constraints on one of the most isolated biological aquatic systems on Earth and to guide future exploratory studies.

[3] Although Lake Vostok is comparable in size to many of the Great Lakes, its isolation from surface winds and seasonal variations in temperature constrain the possible driving mechanisms for circulation. Convection can be driven by the weak geothermal heat fluxes, which are estimated at 0.04 to 0.05 W m^{-2} based upon temperature gradients in the glacial ice [*Salamatin et al.*, 1998] and by using satellite magnetic data to estimate the heat flux [*Fox-Maule et al.*, 2005]. The four previous studies of circulation within lake Vostok conflict with regard to predictions of whether the lake (1) is stratified or well mixed, (2) has a circulation that is clockwise or anti-clockwise, and (3) has an intensified eastern boundary current due to a topographic beta-plane effect created by the sloping roof [*Wuest and Carmack*, 2000; *Williams*, 2001; *Walsh*, 2002; *Mayer et al.*, 2003; *Thoma et al.*, 2007].

[4] Understanding the basic features of the possible circulation is essential for the interpretation of any water samples recovered from future drill cores. To resolve the conflicting predictions of previous studies, we have conducted analogue experiments in a rotating cavity that can be heated and cooled at the top and bottom boundaries. We can estimate the circulation pattern based upon the relative strength of buoyancy to Coriolis forcing. Three dimensionless quantities, the Rayleigh (Ra) and Taylor (Ta) and Rossby (Ro) numbers, determine the convective flow regime within Lake Vostok:

$$Ra = \frac{Bh^4}{\kappa\nu}, \quad Ta = \frac{f^2h^4}{\nu^2}, \quad Ro = \sqrt{\frac{B}{f^3h^2}}, \qquad (1)$$

where B is the buoyancy flux, ν and κ are the kinematic viscosity and thermal diffusivity of water, and f is the Coriolis parameter. Ra measures the strength of heat transfer in the fluid, Ta the relative influence of Earth's rotation to viscous forces in the fluid, and Ro the relative influence of buoyancy forcing to Earth's rotation. Estimates in the literature [*Wuest and Carmack*, 2000] are that the buoyancy flux is $B = 1.5 - 2.6 \times 10^{-12}\ \text{m}^2\ \text{s}^{-3}$, the average lake depth [*Studinger et al.*, 2004] is $h = 850$ m and the Coriolis parameter is $f = 1.4 \times 10^{-4}\ \text{s}^{-1}$. Hence we estimate that $Ra = 10^{21}$, $Ta = 10^{16}$, and $Ro = 10^{-4}$, and thus Coriolis forces dominate the flow except in thin viscous boundary

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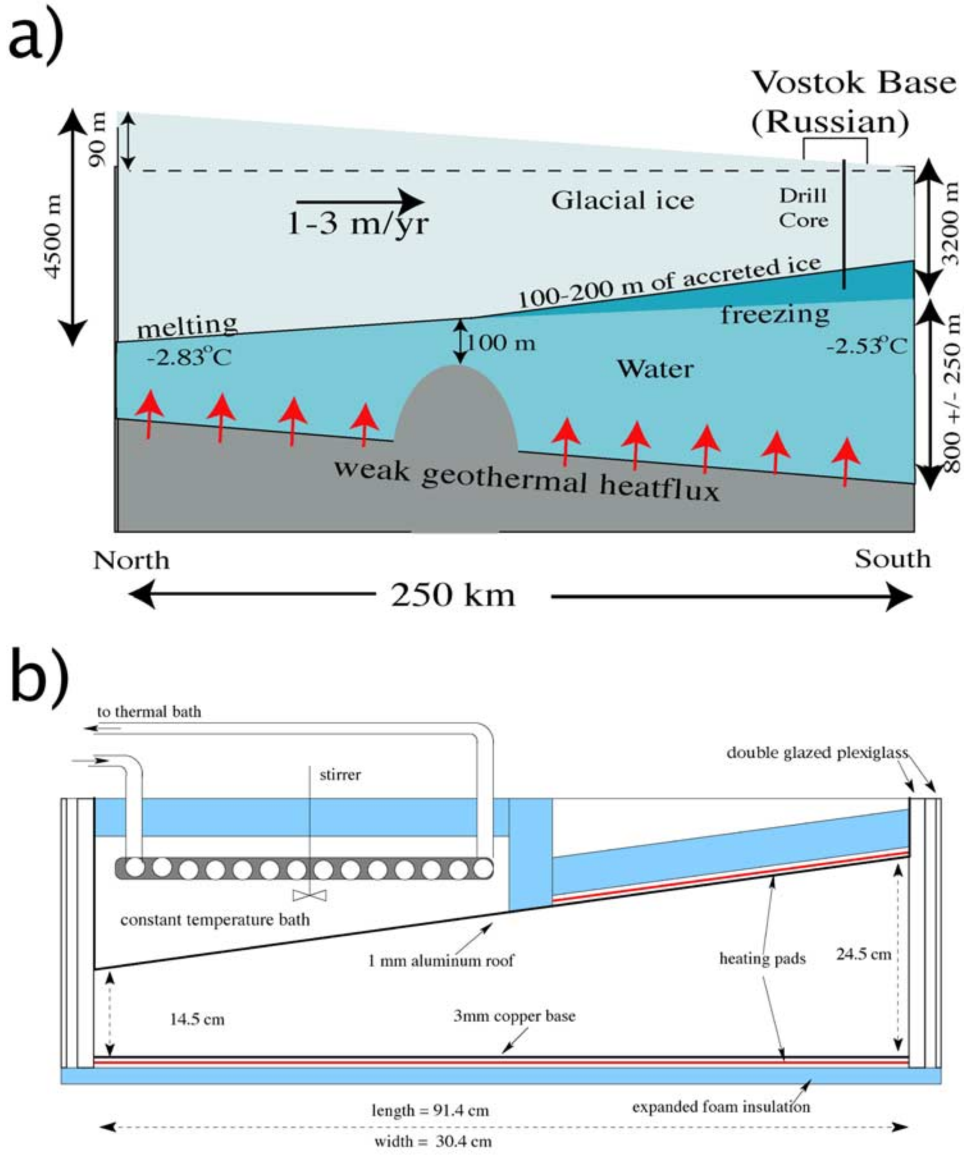

Figure 1. (a) A schematic diagram of Lake Vostok. The glacial roof of Lake Vostok slopes [*Bell et al.*, 2002] and the waters have a maximum depth of 800 ± 250 m and a shallow sill between the northern and southern end [*Studinger et al.*, 2004]. The sloping glacial roof is responsible for a small change in the pressure-dependent freezing point of water from $-2.83°$C at the north end to $-2.53°$C at southern end, so that in an isothermal lake, glacial ice would melt at the north end and refreeze at the southern end [*Wuest and Carmack*, 2000]. Such melting has been inferred from radar observations of the glaciers internal structure [*Bell et al.*, 2002]. (b) A diagram of the experimental cell showing the location of resistive heating pads and cooling on the sloping roof (see section 2).

layers. Previous experimental work [*Fernando and Smith*, 2001] delineates this regime as one where the convection will take the form of columnar vortices that can interact with one another creating irregular geostrophic turbulence. This is a form of convection seen in no other lake on Earth.

[5] The heat flux through Lake Vostok is equal to the geothermal heat flux [*Salamatin et al.*, 1998], F_{geo} = 0.05 Wm^{-2}, and is in steady state so that all the heat entering from below leaves the lake water at the ice ceiling. The accreted ice is enriched by a helium source [*Jean-Baptiste et al.*, 2001] with a radiogenic isotope signature typical of an old continental province, thus ruling out any significant strong hydrothermal energy input into the lake and showing that this heat flux is expected to be uniformly distributed, rather than from a few localized sources. However there may still be some weak geothermal activity in the shallow embayment of the lake that could provide a potential supplemental microbial food web based on chemolithotrophic primary production [*Bulat et al.*, 2004]. There are four buoyancy flux terms that must be considered to understand the water circulation; the basal heat flux F_{geo}, the (negative) heat flux F_{melt} released by ice melting in the northern end of the lake due to the latent heat of fusion of ice, the positive heat flux released by freezing and accretion of ice to the glacial roof at the southern end of the lake F_{freeze}, and the heat flux that is conducted vertically through the ice

$F_{diffusion}$. The buoyancy fluxes associated with melting (or freezing) are determined by $F_{melt} = \rho_s \mathcal{L} \partial H/\partial t$, where $\mathcal{L} \approx 3.34 \times 10^5$ J kg^{-1} is the latent heat of fusion, H is the thickness of the ice above the lake and ρ_s the density of the ice. The conductive heat flux is given by $k_s \nabla T$ where k_s is the thermal conductivity of ice and ∇T is the temperature gradient. The thermal conductivity of ice under 4700 m of ice is approximately $k_s = 2.17$ W m^{-1} K^{-1}. With a temperature gradient of $\nabla T = 0.02$ K m^{-1} the conductive heat flux through the ice of 0.0435 Wm^{-2}, comparable to the typical geothermal heat fluxes of $F_{geo} = 0.04$ to 0.05 Wm^{-2} from old lithospheric material [*Salamatin et al.*, 1998]. F_{geo} leads to a buoyancy flux [*Wuest and Carmack*, 2000] of $B = \frac{g\alpha}{\rho c_\rho} F_{geo} = 2 \times 10^{-12}$ m^2 s^{-3} where $\rho c_\rho \sim 4.2 \times 10^{-6}$ J K^{-1} m^{-3} is the heat capacity of freshwater, and the pressure-dependent thermal expansion $\alpha(\rho)$ has an average value of 18×10^{-6} K^{-1}. In the southern end of the lake where ice is thought to grow, the latent heat of fusion is conducted vertically through the ice above and it may not necessarily influence the buoyancy forcing in the lake. We can estimate the heat fluxes associated with the melting and freezing from $F_{melt/Freeze}$ above using estimates [*Salamatin et al.*, 1998; *Bell et al.*, 2002] of $\partial H/\partial t$ of 3 – 20 mm/yr giving fluxes of $F_{Freeze} = 0.03–0.21$ Wm^{-2} i.e. from 0.6 to 4.2 times that of F_{geo}. However the heat flux associated with freezing had very little influence on the circulation in our laboratory experiments. In a steady state these fluxes must add to zero, and there are a number of ways that a balance can be achieved. The most likely is that the heat flux from the base dominates, and a steady state is reached by conduction through the ice roof. Another possibility is that the pressure dependent melting and freezing at the glacial roof dominate the buoyancy flux terms and the flow is driven by this "ice pump". However by itself the ice pump is a relatively inefficient mechanism for mixing waters in lake Vostok, because the small temperature gradients that occur along the sloping roof would be expected to only operate within a thin boundary layer, similar to the type of overturning circulation that would be present in the ocean if there were no turbulent mixing to maintain a deep thermocline [*Wunsch and Ferrari*, 2004]. By contrast the available potential energy released by geothermal heating at the base can be readily converted to kinetic energy to drive a circulation. The basal geothermal heating also provides an unstable buoyancy flux, that is expected to prevent any significant vertical salinity stratification within the lake.

[6] It is worth comparing the buoyant forcing in Lake Vostok to a typical winter heat flux in the Great Lakes, the latter being of order 100 Wm^{-2}, and hence $B = 10^{-8}$ m^2 s^{-3}. In a 100 m deep lake $Ro = 10^4$, so that convection is disordered and not controlled by the Earths rotation, rather, the circulation is driven by variations in topography which leads to differential heating, and more familiar forms of overturning circulation [*Wells and Sherman*, 2001].

[7] Scaling estimates for the vertical (horizontal) velocity u_V (u_H) and the horizontal radius $\mathcal{R}$ within rotational dominated convective cell can be derived [*Fernando and Smith*, 2001; *Maxworthy and Narimousa*, 1994] as

$$u_V \sim 2.4\sqrt{B/f}, \quad u_H \sim 4\sqrt{B/f}, \quad \mathcal{R} \sim 15\sqrt{B/f^3}. \qquad (2)$$

Using the Lake Vostok values the horizontal scale of the eddies will be $10 < \mathcal{R} < 30$ m. The rising and sinking convective plumes have $u_V = 2.4\sqrt{B/f} \sim 0.3$ mm s^{-1}, and therefore a thermal plume to travel the depth of the lake ($h = 500 - 800$ m) in a time of approximately $h/u_V =$ 20–30 days.

2. Analogue Experiments

[8] Our laboratory analogue of Lake Vostok is sketched in Figure 1b. We control the ratio of the roof to base heat fluxes, $\mathcal{F}$, as well as Ra, Ta and Ro. The length of the experimental tank shown in Figure 1b is 91.4 cm, the width is 30.4 cm and the depth varies between 14.5 and 24.5 cm. To simulate the effects of the boundary heat fluxes due to ice melting/freezing and the geothermal heat fluxes, cooling is provided to the shallowest half of the cell roof using a recirculating bath at a constant temperature of 18°C connected to a Thermo-Haake thermal bath, heating is applied to the deepest part of the roof and beneath the copper base using resistive elements that can provide up to 2000 W of heating, corresponding to a maximum buoyancy flux of $B = 5 \times 10^{-6}$ m^2 s^{-3}. In steady state all the heat flux into the tank is removed through the shallow cooled region, and the average temperature is constant. The cell side-walls are insulated with transparent double-glazed plexiglass, allowing photography. The entire cell is mounted on a precision controlled rotating platform where the Coriolis parameter is varied between $f = 0 - 1$ rad/s. We simulate ice melting/freezing and the geothermal heat fluxes by setting the temperature over the shallowest half of the cell roof, and $\mathcal{F}$ over the remainder of the roof and base. We fixed the basal buoyancy flux at $B = 3 \times 10^{-7}$ m^2 s^{-3}, the mean depth is $h = 20$ cm and the Coriolis parameter is varied as $f = 0.1$, 0.2 0.5 and 1 rad/s. Thus we have $Ra \approx 10^6$, $10^7 \leq Ta \leq 10^9$, and $0.0015 \leq Ro \leq 0.05$. We extrapolate the previous experimental work [*Fernando and Smith*, 2001] using the corresponding in-situ dimensionless numbers and find that the vortices are in the domain dominated by "irregular geostrophic turbulence" and "rotationally modified turbulence". Therefore, in both our experiment and in Lake Vostok rotation plays a dominant role in controlling the nature of the convective motions.

[9] The circulation patterns in our non-rotating experiments are shown in Figure 2a, where streak-lines display an overturning circulation. When $\mathcal{F} > 1$, a small stratified domain forms under the roof, while the deeper region has an overturning circulation. When $\mathcal{F} < 1$ a similar overturning circulation arises, with sinking beneath the cold region, rising in deep region, but no stratified domain forms at the roof.

[10] The influence of rotation is clearly shown in Figures 2b and 2c where the circulation is dominated by columnar eddies that transport the heat directly from the base to the top. Hence there is a distinct lack of an overturning circulation, as was clearly seen in Figure 2a. The horizontal movement of the dye occurs predominantly in thin top and bottom boundary layers, as seen in numerical simulations [*Lee et al.*, 2004]. This mode of dispersion will have strong implications for interpreting any future water samples in Lake Vostok from below the Russian base. If the weak nutrient supply to the lake is mainly provided at the lateral

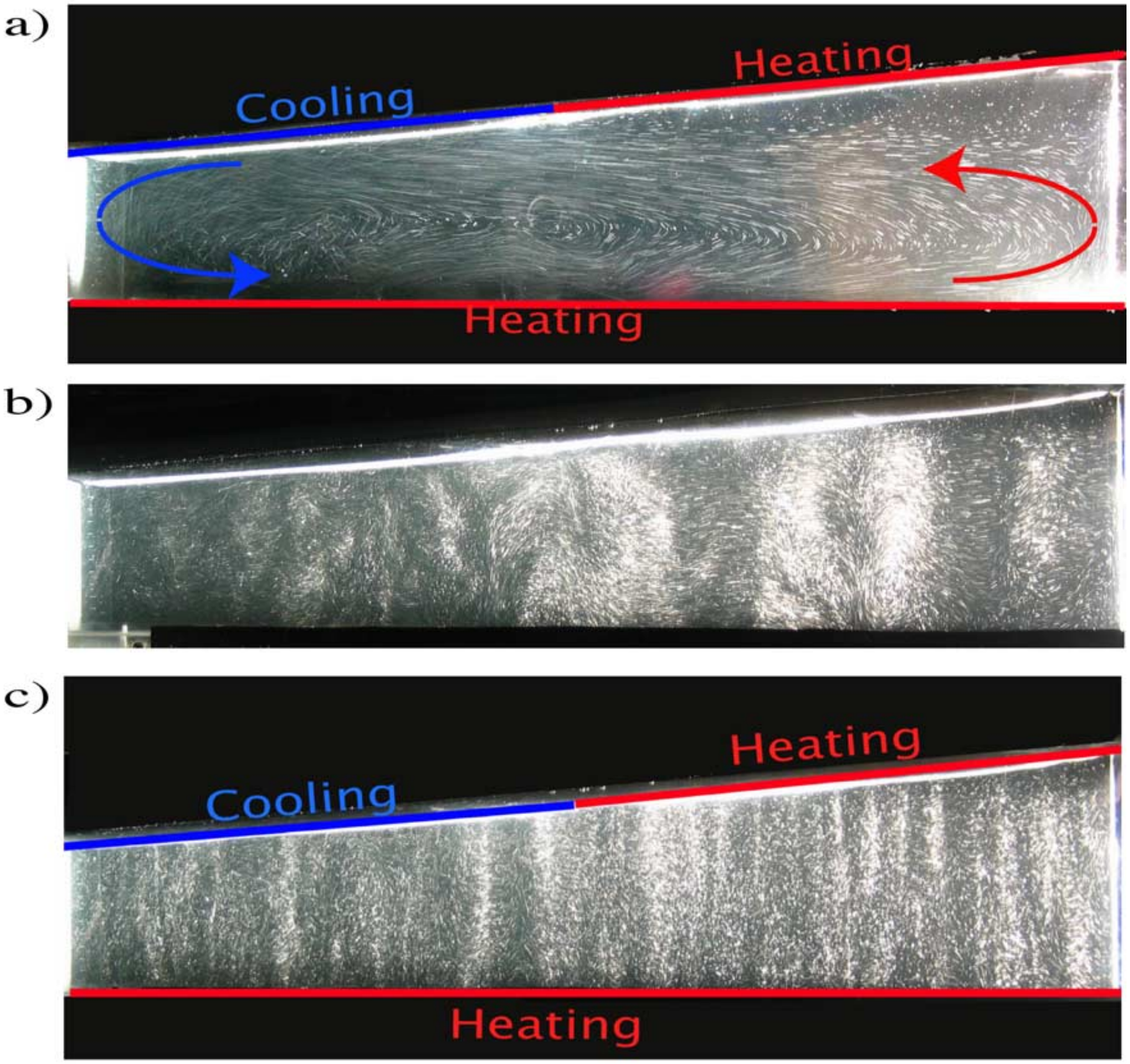

Figure 2. In all these images the heat flux is the same, but the rotation rate is increased from (a) $f = 0$ rad/s to (b) $f = 0.2$ rad/s and (c) $f = 1.0$ rad/s. The circulation clearly changes from an overturning circulation to one dominated by sinking (in the cold region) and rising (in the remainder of the tank) columnar vortices, although the sense of the vertical motion is not discernible from these streak images. The streaks in the image give an indication of the velocities of the fluid, and result from 5 second exposure of 100 μm particles illuminated in a sheet of light. As the rotation rate increases, the vortices reduce in size and the upwelling/downwelling velocities decrease, consistent with scaling of equation (2).

boundaries, through either melting of glacial ice at the roof [*Christner et al.*, 2006] or from chemicals released from weak geothermal action at a few locations on the base [*Bulat et al.*, 2004], then we speculate that the distribution of biota within Lake Vostok would mimic the distribution of upwelling versus downwelling convective cells. For instance, the low nutrient supply to the lake waters from the roof [*Christner et al.*, 2006] would be consumed by any active bacteria in the 20–30 days it takes a downwelling cell to travel from the roof to lake floor.

[11] A sill may exist between the north and south basins, which may limit inter-basin water exchange [*Studinger et al.*, 2004]. When we place a sill in our non-rotating experiments, the temperature gradient across the sill drives an effective exchange flow between the two basins so that there is rapid mixing of a dye tracer, as observed in previous analogue models of estuarine overturning [*Finnigan and Ivey*, 1999]. The action of strong rotation changes the flow dynamics dramatically so that within each basin the columnar vortices rapidly stir passive tracers, but there is only weak exchange between the basins due to the rotational suppression of hydraulic exchange there [*Pratt and Lundberg*, 1991]. Hence the chemistry and biology within the basins in Lake Vostok may in fact be different, supporting the existence of two distinct but related ecosystems [*Studinger et al.*, 2004]. Figures S1 and S2 are available in the auxiliary material.[1]

3. Discussion

[12] Deep core material taken at 3590 m depth below the Russian Vostok base contains ice accreted onto the underside of the glacier and represents the only "direct" sample

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2007GL032162.

of water from Lake Vostok. This ice has been accreted from the lake over the last 8000 years and contains microbes [*Christner et al.*, 2006; *Priscu et al.*, 1999]. Although metabolic rates for microbial growth decrease with temperature and nutrient supply rate, many bacteria can reproduce at temperatures characteristic of Lake Vostok or colder. For example bacteria isolated from Siberian permafrost reproduce at −10°C with a 39 day doubling period [*Bakermans et al.*, 2003]. Therefore, while an extension of our laboratory results predicts that Lake Vostok may be thermally well mixed, if the nutrient supply is less than that required for reproduction of bacteria within the entire lake [*Christner et al.*, 2006], then there may only be relatively thin "biological boundary layers" at the roof of the lake, viz, the weak vertical flow will only be able to mix the biota several hundred meters from any nutrient rich source in the time it takes the bacteria to reproduce. In the northern end of the lake there may be a source of nutrients due to very slow dust/solute release from the ice in the melting zone [*Christner et al.*, 2006], however there is no melting of ice in the southern end of the lake, so the viability of bacteria will be limited by the nutrient supply released from either small localised geothermal sources at the base [*Bulat et al.*, 2004] or possibly by meltwater input from the bed beneath the glacier [*Wingham et al.*, 2006]. The possible lack of any reproducing biota in the surface waters in the southern portion of the lake below the Russian Vostok base will have an impact on future interpretations of water samples taken from near the upper roof. The Russian expedition is currently planning to directly sample waters from Lake Vostok [*Inman*, 2007] and there is also a proposal by the Sub Antarctic Lake Exploration group to sample the waters of the smaller sub-glacial Lake Ellsworth [*Siegert et al.*, 2007].

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