More Than 200 Meters of Lake Ice Above Subglacial Lake Vostok, Antarctica

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Isotope studies show that the Vostok ice core consists of ice refrozen from Lake Vostok water, from 3539 meters below the surface of the Antarctic ice sheet to its bottom at about 3750 meters. Additional evidence comes from the total gas content, crystal size, and electrical conductivity of the ice. The Vostok site is a likely place for water freezing at the lake-ice interface, because this interface occurs at a higher level here than anywhere else above the lake. Isotopic data suggest that subglacial Lake Vostok is an open system with an efficient circulation of water that was formed during periods that were slightly warmer than those of the past 420,000 years. Lake ice recovered by deep drilling is of interest for preliminary investigations of lake chemistry and bedrock properties and for the search for indigenous lake microorganisms. This latter aspect is of potential importance for the exploration of icy planets and moons.

The Vostok ice core in central Antarctica has provided the longest record of past changes in climate and atmospheric composition, showing four glacial-interglacial cycles down to a depth of 3310 m (zone C) (Fig. 1). The ice at that depth is ~420 ky (thousand years) old (*1*). Between 3310 and 3350 m (zone I), suggestions of complex ice deformation in the Vostok series are difficult to interpret (*1*). Below zone I, the climatic record is no longer reliable, as shown from the deuterium record, a proxy of local atmospheric temperature change (*1*). The decrease in magnitude (by a factor of 3 or more) (Fig. 1) of this isotopic signal in zone D (between 3350 and 3538.3 m) cannot be of climatic origin, but rather must result from ice flow disturbances.

The lower part of the ice core, however, provides interesting and unique information. The mean crystal size, the electrical conductivity measurements (ECM), and the total gas content of the ice as well as the number of solid inclusions (shown from 3525 to 3611 m in Fig. 1) reveal two very distinct types of ice that are separated by a sharp transition (zone T between 3538.3 and 3538.7 m), which represents the base of a shear zone that is interpreted as the sole of the moving ice sheet (*2*). Even if stratigraphically disturbed, zone D is clearly of glacier origin with a total gas content typical for such ice (*3*). In contrast, the properties of the ice below 3538.7 m (zone L) suggest that it was formed by freezing of the Vostok lake water (*4*). Both the low total gas content and the large mean crystal size (>20 cm to 1 m) are indicative of ice formed slowly from liquid water. One plausible explanation for low ECM values is the formation of recrystallized ice with associated changes in electrical properties, which gives additional support for a lake ice origin hypothesis. But the strongest evidence for formation from liquid water comes from the isotopic properties of this ice, specifically from the combined use of deuterium (δD) and oxygen-18 ($\delta^{18}O$) (*5*) isotope compositions. Here we present the interpretation and implications of the isotopic characteristics of this "lake ice" that is found below 3538.7 m.

As a result of fractionation processes during the atmospheric water cycle, there is a link between the isotopic composition of precipitated water (δD or $\delta^{18}O$) and meteorological parameters that allow local temperature change over the past 420 ky to be reconstructed (*1*). The deuterium excess profile ($\delta D - 8 \times \delta^{18}O$) provides access to changes in the source region for Antarctic precipitation (*6*). Major shifts in deuterium and deuterium excess are observed at the 3538 m transition. Within less than 50 cm (Fig. 1), deuterium values increase by about 10 per mil (‰) and deuterium excess values shift from around 14‰, a value typical for glacier ice in this area (*6*), to 7 or 8‰. In a $\delta D/\delta^{18}O$ diagram (Fig. 2), data points from zones I and D lie on the Vostok precipitation line with a slope of 7.93 calculated over the past 420 ky (*7*). In contrast, data from zone L cluster to the right side of this precipitation line. These isotopic characteristics are a clear fingerprint of the isotopic modifications resulting from a freezing process (*8, 9*).

Vostok lake water is believed to originate from the melting of ice formed from snow that precipitated on the Central Antarctic Plateau and then was transferred at depth in the ice sheet (*4*). Based on a steady-state theory, the mean age of the lake water is roughly estimated to be 1000 ky (*2*). No fractionation occurs upon melting because of the low isotopic diffusion coefficients in ice (*10*). The mean isotopic composition of the water that fed the lake through time (hereafter the "lake water") is therefore a weighted average over time and space of the isotopic content of precipitation in the Vostok Lake catchment area, and thus lies on the Vostok precipitation line. In contrast, when part of a water reservoir is allowed to freeze, the ice is enriched in deuterium and ^{18}O in comparison to the water (*8, 9*). Except for very high freezing rates (see below), isotopic equilibrium is reached at the ice-water interface; that is, $(1 + \delta_{ice}) = \alpha \times (1 + \delta_{water})$, where δ stands for either δD or $\delta^{18}O$ and α stands for the equilibrium fractionation coefficients ($\alpha_D = 1.0208$ and $\alpha_{18O} = 1.0030$). The slope S of the line that connects the water and ice data points in the $\delta D/\delta^{18}O$ diagram is called the freezing slope: $S = [(1 - 1/\alpha_D)/(1 - 1/\alpha_{18O})] \times (1 + \delta D_{ice})/(1 + \delta^{18}O_{ice})$; that is, $S = 6.81 \times (1 + \delta D_{ice})/(1 + \delta^{18}O_{ice})$.

Thus S is lower if the δ values of the initial water at the onset of freezing are more negative (*8, 9*). For zone L ice, S equals 3.98, which is about half the precipitation slope. The lake water isotopic composition corresponds to the intersection of the freezing line passing through the average zone L point and of the precipitation line as follows: $\delta D = -449.3‰$, $\delta^{18}O = -57.9‰$ (*11*). The straightforward explanation for the zone L data being on the right side of the precipitation line is that this ice was formed by freezing of water from the subglacial lake. The deuterium and ^{18}O enrichment of the lake ice (Fig. 2) in comparison to lake water (6.6‰ in δD and 1.65‰ in $\delta^{18}O$), however, is only ~60% of the corresponding isotopic equilibrium (11.4‰ and 2.8‰, respectively). There are several possibilities to explain this behavior, none of which affects the value of the freezing slope and thus the above estimate of the lake water isotopic composition.

The first possibility is a freezing rate effect with high freezing rates producing weaker isotopic enrichments. To be detectable, however, freezing rates would have to be on the order of millimeters per hour (*12*), but a maximum value of 4 mm/year is estimated, assuming that the upward heat flux through the ice sheet results only from the energy released by freezing (*13*).

Second, in a closed water reservoir, the

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isotopic enrichment of the ice formed leads to an impoverishment of the residual water (*8, 9, 14*). However (Fig. 1), the isotopic composition of the lake ice increases slightly from the transition downward, whereas such a reservoir effect would be expected to cause a decrease (*8, 9*). At the scale of Lake Vostok, there must be a dynamic equilibrium, with some melting occurring in certain areas at the separation line although freezing is prevalent elsewhere. The isotopic profile recorded in the lake ice suggests that the subglacial lake is an open system with an efficient circulation of water (equilibrium is almost reached in an open system and the renewal rate is larger than the freezing rate).

Even if the freezing itself occurs at equilibrium, a third possibility is that part of the liquid water may be trapped during ice accretion. Such water pockets would freeze completely afterward, and their bulk isotopic composition would not be modified. Therefore, the observed fractionation must be less than the true value, depending on how much water is included in water pockets in the ice during the course of freezing. (This "mixing" process also leaves the $\delta D/\delta^{18}O$ representative point on the freezing line.) The Vostok lake ice contains solid inclusions, which suggests that this ice was formed at or close to the separation line where the ice sheet leaves the substratum and begins to float on the lake. The solid inclusions are millimetric in size and consist of a mineral particle to which dirt is attached. The fact that they are incorporated in the ice supports the idea that water pockets can also be included during freezing. This water trapping provides the best explanation for the limited lake ice isotopic enrichment.

Solid inclusions are more numerous in the upper part of the lake ice profile and seem to be absent below 3609 m (Fig. 1). Available information (*4*) suggests that the ice-lake interface is at a higher level at the Vostok site than anywhere else above the lake, which makes this area colder because the glacial ice above is thinner. In fact, freezing can occur as soon as glacial ice loses contact with bedrock and ice accretion close to the grounding line traps dirt particles into the ice (Fig. 3). Once the lake becomes deeper, inclusion of particles is no longer possible, which explains the absence of inclusions in the bottom part of the lake ice. Instead, lake ice isotopic characteristics are exactly the same above and below the 3609 m depth (Fig. 1). This supports the idea that the processes of formation of the lake ice were unchanged throughout all the depth intervals we have analyzed (3538.7 to 3611 m).

The lake water isotopic composition differs significantly from that of the overlying glacier ice (zone D) (*15*), and the point representative of the last four climatic cycles is isotopically even lighter than zone D (bottom right of Fig. 2). Zone D is expected to be older than 420 ky and younger than the lake water itself. The decreasing isotopic sequence (lake water, disturbed ice, and glacier ice) may result from a warmer average Antarctic climate before 420 thousand years ago (ka). This Antarctic surface cooling (~2°C using the present-day isotope/temperature gradient) could simply reflect the general deterioration of the global climate during the Quaternary, which would suggest that lake water is older than 1 million years (*16*). Alternatively, the higher lake isotopic value could be caused by a difference in geographical origin between the ice recovered at the Vostok site and the lake water itself. However, the ice accumulated at Vostok during the past 420 ky already comes from a large area (between Ridge B and Vostok), which makes this alternative less likely than a slow cooling trend of central Antarctica during the Quaternary.

There is no reason to believe that the deeper ice down to the water interface (about 3750 m depth) would not also be refrozen lake water. Therefore, a total thickness of about 210 m of lake ice can reasonably be

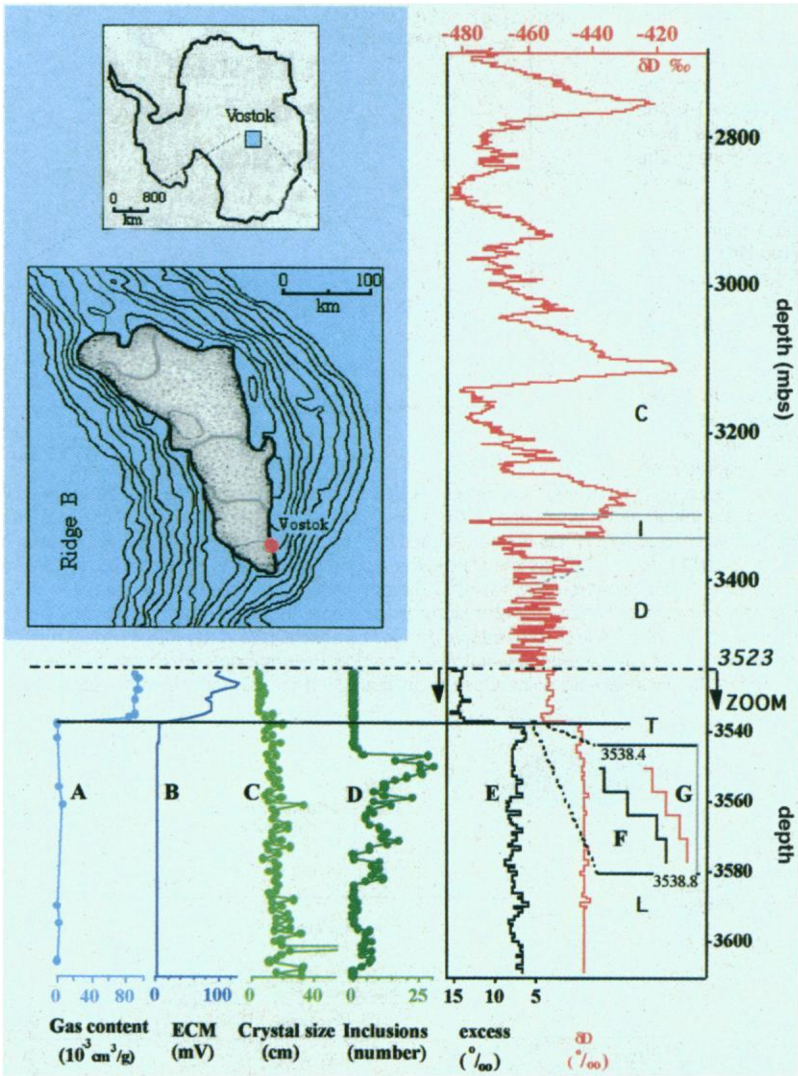

Fig. 1. (Bottom) Total gas content (**A**), ECM (**B**), crystal size (**C**), number of visible inclusions per meter (**D**), and deuterium excess (**E**) in the Vostok ice core from 3525 to 3611 m. Deuterium excess values were computed from δD and $\delta^{18}O$ measurements were expressed in per mil with respect to Vienna standard mean ocean water. Mean crystal sizes were determined by counting the number of crystals per meter of the ice core on a longitudinal thin section 4.5 cm wide. The ECM signal (1 mV is equivalent to a conductivity of 0.22 μS) represents the mean values on 1 m of core. The total gas content measurements (given in 10^{-3} cm^3/g at standard temperature and pressure) were made in Grenoble by the barometric method (*22*). The deuterium profile is given on the right from 2700 to 3611 m to show the full range of variation of this parameter. The zones mentioned in the text are indicated along this profile. An enlarged diagram of the δD (**F**) and deuterium excess (**G**) inside the ice and the transition between the glacier and the lake ice (zone T, from which 10-cm samples were analyzed) (middle left) are shown. The map of the Vostok lake area (upper left) is adapted from A. Kapitsa *et al.* (*4*).

assumed. The discovery of a great thickness of lake ice at the bottom of the Vostok ice core enables the search for indigenous microorganisms that have been isolated from the rest of the biosphere for a long time (*17, 18*). This opens the way for exciting microbiological perspectives and technological developments (*19*) that are also of interest for the exploration of icy planets and moons (*20*). For example, satellites of Jupiter (Europa and Callisto) recently revealed evidence of previously unknown bodies of water that might be home to unique life forms (*20*). Lake chemistry can also be investigated through lake ice analyses, and the presence of large solid inclusions offers a unique opportunity to study bedrock properties below this central part of the Antarctic ice sheet.

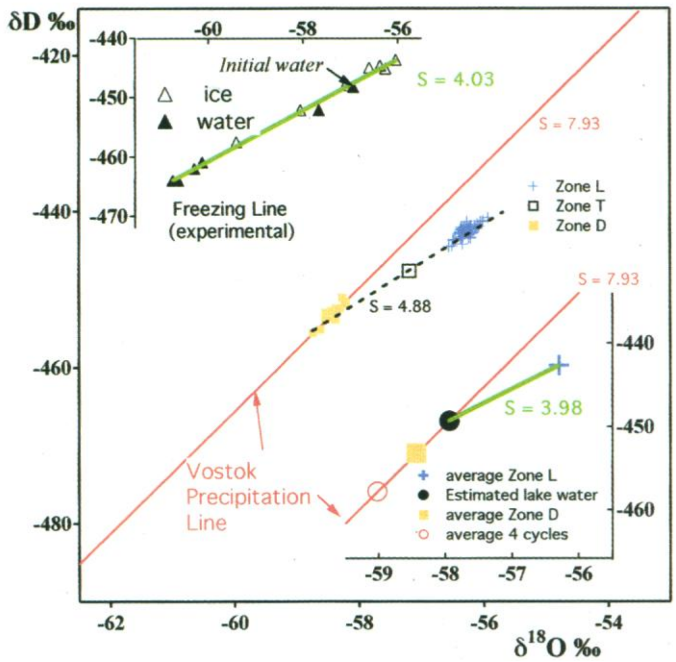

Fig. 2. (**Center**) δD/δ^{18}O diagram featuring the precipitation line that corresponds to the ice samples from the past four climatic cycles (*6, 7*) and samples from 3520 to 3611 m. Yellow squares, samples from the bottom part of the disturbed zone D; open square, sample from the transition (zone T); blue crosses, samples from the lake ice (zone L). The straight line passing through these ice samples has a slope of 4.88 (*15*). (Top left) δD/δ^{18}O diagram of ice (open triangles) and water (black triangles) samples from a progressive freezing experiment of a limited water reservoir where initial water had δD = −408.8‰ and δ^{18}O = −51.7‰ [adapted from Souchez and Jouzel (*8, 9*)]. The results have been scaled to account for the difference between the isotopic contents of the initial water and those of the Vostok lake water [see equation in the main text; each experimental value from (*8, 9*) has been multiplied by (1 − 0.4493)/(1 − 0.4088) for δD and by (1 − 0.0579)/(1 − 0.0517) for δ^{18}O]. After the scaling, the experimental slope is equal to 4.03 and is close to the theoretical value (3.98). (Bottom right) δD/δ^{18}O diagram showing the positions of the mean value for ice from the past four climatic cycles, from the disturbed sequence in the ice deformation zone (zone D), and from the lake ice samples (zone L). The isotopic composition of the lake water (black circles) corresponds to the intersection of the precipitation line and the theoretical freezing slope, which has a slope of 3.98 and passes through the mean lake ice point. Open circle, average of the last four climatic cycles.

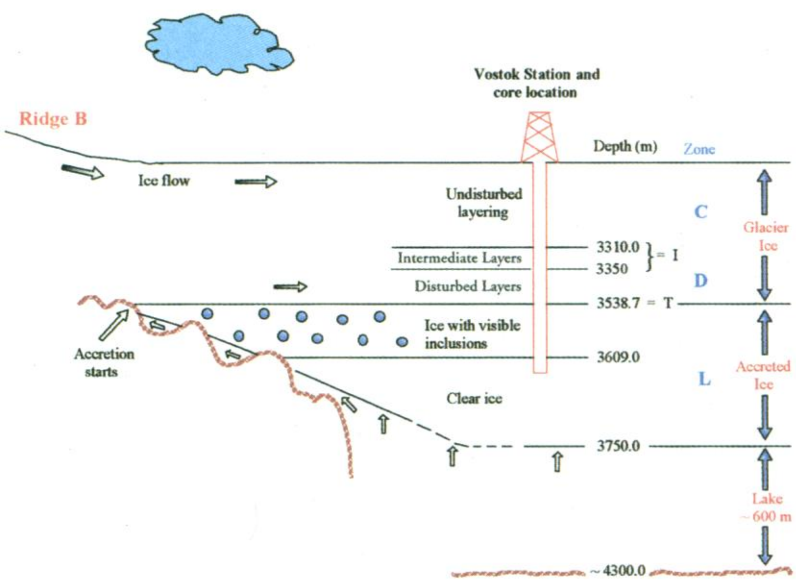

Fig. 3. Sketch of the ice sheet along the stream line that passes by the Vostok core site. Ice accretion is thought to begin at the point where the ice sheet overrides the lake and continue throughout. Trapping of particles likely occurs in the shallow depths of the lake.

References and Notes

1. J. R. Petit *et al.*, *Nature* **399**, 429 (1999). Ice coring was stopped at 3623 m, the depth reached in January 1998, which is about 120 m above the interface with subglacial Lake Vostok (*4*), to avoid any contamination by the drilling fluid.
2. V. Lipenkov and N. Barkov, *Proceedings of the International Workshop on Lake Vostok. Lake Vostok Study: Scientific Objectives and Technical Requirements* (Arctic and Antarctic Research Institute, St. Petersburg, Russia, 1998), p. 31.
3. P. Martinerie *et al.*, *J. Geophys. Res.* **99**, 10565 (1994).
4. Lake Vostok is 230 km long and 50 km wide and has an area of about 14,000 km^2. The Vostok drilling site (Fig. 1) is at the southern end of the lake and has a thickness of 3750 m of ice with 600 m of water below the ice. At its northern end, 200 km away, the ice is 4300 m thick and the water below is shallower. For more information see A. Kapitsa *et al.*, *Nature* **381**, 684 (1996); M. Siegert and J. Ridley, *J. Geophys. Res.* **103**, 10195 (1998).
5. The δ^{18}O notation is $\delta^{18}O = [(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{std} - 1] \times 1000$, where std is the standard mean ocean water reference (the same applies for δD).
6. F. Vimeux, V. Masson, J. Jouzel, M. Stievenard, J. R. Petit, *Nature* **398**, 410 (1999).
7. This slope is similar to that of 7.86 obtained for the past 150 ky (*6*) and is close to that of the worldwide Meteoric Water Line (slope of 8) [H. Craig, *Science* **133**, 1702 (1961)]. Both δD and δ^{18}O have now been measured down to 3611 m. In a δD/δ^{18}O diagram, data points from zones I and D are undistinguishable from those of the past 420 ky (zone C), as illustrated by the individual data points from the bottom part of zone D (Fig. 2).
8. J. Jouzel and R. Souchez, *J. Glaciol.* **28**, 35 (1982).
9. R. Souchez and J. Jouzel, *J. Glaciol.* **30**, 369 (1984).
10. Diffusion coefficients of HDO and $H_2{}^{18}O$ molecules in ice are very low, on the order of 10^{-11} cm^2 s^{-1}. The same coefficients in liquid water are on the order of 10^{-5} cm^2 s^{-1}.
11. There is no reason to expect a significant change of the δD/δ^{18}O relation for periods before 420 ka, because the central part of the Antarctic ice sheet and its surrounding oceans probably have not been subject to changes larger than those during the past 420 ky.
12. A numerical simulation with the use of a simple diffusion model and the assumption that pure diffusion is limited to the boundary layer at the ice-water interface is described [R. Souchez *et al.*, *Geophys. Res. Lett.* **14**, 599 (1987)]. This shows that a higher freezing rate will produce a weaker isotopic enrichment in the ice than that produced at equilibrium.
13. A. Salamatin, R. N. Vostretsov, J. R. Petit, V. Y. Lipenkov, N. I. Barkov, *Data Glaciol. Stud.* **85**, 233 (1998).
14. This second process is illustrated by an experiment of progressive freezing (top left of Fig. 2) adapted from R. Souchez and J. Jouzel (*9*). Although freezing is sufficiently slow for isotopic equilibrium to be achieved at the liquid-water interface, both the newly formed ice and the remaining liquid become more depleted in heavy isotopes during the course of this experiment. In a closed system (Rayleigh model), the isotopic content of the liquid is equal to $[(1 + \delta_1)] \times f^{(\alpha-1)}) - 1$, where δ_1 is the isotopic content of the initial liquid reservoir and f is the fraction of liquid remaining. The apparent 60% enrichment of the ice in comparison to the initial liquid is obtained when ~30% of the reservoir has frozen. As expected from the Rayleigh model, the data both for ice and liquid samples align on the freezing slope, and such laboratory experiments were used to support the melting-refreezing theory that two of us have developed (*8, 9*). This experimental freezing slope is close to the theoretical value (Fig. 2).

15. The sample in the transition aligns on the straight line that is defined by the cluster of samples above (disturbed glacier ice) and below (lake ice) but has a slope (4.88) significantly higher than 3.98. We interpret this alignment as a result of a diffusion process at a sharp transition between the two types of ice, and not as a freezing effect.
16. D. Paillard, *Nature* **391**, 378 (1998); R. Tiedeman *et al., Paleoceanography* **9**, 619 (1994). Data suggest that there was a warmer global climate (lower continental ice volume) for the period between 2 million and 1 million years ago than for the past 1 million years.
17. J. Priscu *et al., Science* **286**, 2141 (1999); D. M. Karl *et al., Science* **286**, 2144 (1999).
18. J. M. Tiedje, in (*21*), p. 19; D. C. White, in (*21*), p. 22.
19. R. G. Kern, in (*21*), p. 24.
20. F. Carsey, in (*21*), p. 21.
21. *National Science Foundation Workshop–The Lake Vostok Study: A Curiosity or a Focus for Interdisciplinary Investigations*, Washington, DC, 7 to 8 September 1998. See www.ldeo.columbia.edu/vostok/.
22. V. Lipenkov *et al., J. Glaciol.* **41**, 423 (1995).
23. This work is part of the joint project between Russia, France, and the United States to study the Vostok ice core. We are indebted to the Russian drill engineers from the St. Petersburg Mining Institute who conducted the field operations, and we thank all participants for field work and ice sampling. We acknowledge the Russian Antarctic Expeditions (RAE), the Institut Français de Recherches et Technologies Polaires (IFRTP), and the Division of Polar Programs (NSF) for logistic support. The project is supported in Russia by the Russian Ministry of Sciences; in France by the PNEDC (Programme National d'Etudes de la Dynamique du Climat) and by the Commission of European Communities (Environment Programme, ENV4-CT95-0130); and in the United States by NSF. R.S. and V.V. are grateful for the support of the Belgian Antarctic programme (Science Policy Office). We thank J. M. Barnola, J. Chappellaz, M. Delmotte, P. Duval, F. Ferron, G. Hoffmann, J. L. Jaffrezo, P. Jean-Baptiste, D. Paillard, L. Pépin, A. Salamatin, and D. Weis for helpful discussions and comments on the manuscript and T. Sowers and an anonymous reviewer for constructive criticism.

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Geomicrobiology of Subglacial Ice Above Lake Vostok, Antarctica

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Data from ice 3590 meters below Vostok Station indicate that the ice was accreted from liquid water associated with Lake Vostok. Microbes were observed at concentrations ranging from 2.8×10^3 to 3.6×10^4 cells per milliliter; no biological incorporation of selected organic substrates or bicarbonate was detected. Bacterial 16*S* ribosomal DNA genes revealed low diversity in the gene population. The phylotypes were closely related to extant members of the *alpha-* and *beta-Proteobacteria* and the Actinomycetes. Extrapolation of the data from accretion ice to Lake Vostok implies that Lake Vostok may support a microbial population, despite more than 10^6 years of isolation from the atmosphere.

Lake Vostok is the largest (~14,000 km^2) and deepest (maximum depth ~ 670 m) lake identified beneath Antarctic glacial ice (*1, 2*). The residence time of the water in the lake has been estimated to be about 10,000 years, and the mean age of water, since deposition as surface ice, is about 1 million years (*2*). The ice above the lake has been cored to 3623 m, stopping ~120 m above the surface of the lake. The upper 3310 m is glacial ice that represents an environmental record covering four complete ice age climate cycles. Ice between 3310 and 3539 m is transitional between glacial and accretion ice; ice below 3539 m represents refrozen lake water accreted to the bottom of the glacial ice (*3, 4*). Here we describe the geomicrobiological environment within the accretion ice and use the information to predict conditions in Lake Vostok.

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We studied a core from a depth range of 3588.995 to 3589.435 m (core 3590) (*5*). Cross-polarized light observations of the optical section revealed two distinct ice crystals (Fig. 1). The crystal boundaries extended beyond the edge of the core, making it impossible to estimate the exact grain size of either crystal. The C axes of the two crystals made a three-dimensional angle of 24.3° with each other (*6*). The small and large crystals had declinations of 62° and 43° from the vertical direction, respectively. The horizontal and vertical crystal misalignment could have arisen from seed crystals that nucleated in the lake water or along the margins of the lake before attaching to the bottom of the overlying ice. Alternatively, sheer stresses may have reoriented or recrystallized the ice after accretion.

Unfiltered Cl^- and SO_4^{2-} concentrations in core meltwater fall between the Vostok modern and Vostok Last Glacial Maximum values, indicating that glacial and interglacial snow and ice have melted to produce Lake Vostok (Table 1). Elemental ratios for Al/Rb and Al/Ba in core 3590 were 714 and 192, which are similar to Earth crustal ratios of 704 and 116, respectively (*7*). NO_3^- in core 3590 was depleted relative to concentrations in ice from the Last Glacial Maximum and from the last interglacial period. It is not known whether the depletion of NO_3^- is related to its preferential retention in the lake or loss by biological incorporation or denitrification. Recent experiments (*8*) indicate little difference between liquid-solid water phase partitioning coefficients for Cl^- and NO_3^-, implying that NO_3^- was depleted biologically. Using liquid-solid chemical partitioning coefficients obtained from another Antarctic lake (*9*), we predict that the upper water column of Lake Vostok contains Na^+-SO_4^{2-} waters, similar to many lakes in North America (*10*).

The $\delta^{18}O$ (*11*) and δD values of core 3590 ice were −56.8‰ and −445‰, respectively, supporting the results of Jouzel *et al.* (*4*). If ice in this core was accreted from Lake Vostok water, as implied by our crystallography data, and the ice was in equilibrium with water at 0°C, the water in Lake Vostok should have isotopic values of −59‰ and −463‰ for $\delta^{18}O$ and δD, respectively (*12*). The δD value from core 3590 is within the range reported for Vostok glacier ice (−420 to −485‰) (*3, 4*), again suggesting that the lake water is derived from a mix of melted ice from glacial and interglacial periods.

Mineral analysis showed that biotite (73%), quartz (13%), potassium feldspar (9%), plagioclase (2%), muscovite (2%), and iron oxide (1%) were the primary minerals (*13*). The distribution of mineral phases in these sediments does not reflect the expected proportions of minerals observed in common crustal granitoid rock types (biotite: <20%; quartz: 20 to 55%; potassium feldspar + plagioclase: 40 to 80%; and muscovite and iron oxide: trace amounts) (*14*). Whether through transport by air, glacier, or subglacial streams, a mechanical sorting process likely operated to concentrate biotite to relatively high levels in core 3590.

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This article references the following linked citations:

References and Notes

[7] **Isotopic Variations in Meteoric Waters**
Harmon Craig
Science, New Series, Vol. 133, No. 3465. (May 26, 1961), pp. 1702-1703.
Stable URL:
http://links.jstor.org/sici?sici=0036-8075%2819610526%293%3A133%3A3465%3C1702%3AIVIMW%3E2.0.CO%3B2-J

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