Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Earth and Planetary Science Letters 217 (2003) 163–170
EPSL
www.elsevier.com/locate/epsl

Reassessing Lake Vostok's behaviour from existing and new ice core data

R. Souchez [a,*], J.-R. Petit [b], J. Jouzel [c], M. de Angelis [b], J.-L. Tison [a]

[a] Département des Sciences de la Terre et de l'Environnement, Faculté des Sciences, CP 160/03, Université Libre de Bruxelles, 50 av. F.D. Roosevelt, B-1050 Brussels, Belgium
[b] Laboratoire de Glaciologie et de Géophysique de l'Environnement, rue Molière 54, Domaine Universitaire, B.P. 96, F-38402 Saint-Martin-d'Hères, France
[c] Laboratoire des Sciences du Climat et de l'Environnement, Bâtiment 709, Orme des Mérisiers, CE Saclay, F-91191 Gif-sur-Yvette, France

Received 17 June 2003; received in revised form 13 October 2003; accepted 14 October 2003

Abstract

Interpretation of new ice core data and reappraisal of existing data, both from the basal part of the Vostok ice core, give strong support to a kind of thermohaline circulation in Lake Vostok. Although the salinity of the lake is considered as weak (less than 1 ‰), the prominent influence of salinity at high pressure and low temperature on water density makes such a circulation possible. As a consequence, subglacial melting along the northern shores of the lake is balanced, further south, by frazil ice production in the upper water column, its accretion and consolidation at the ice–water interface followed by accreted ice export out of the system together with the southeasterly glacier flow. The dynamics of the system is documented by a stable water isotope budget estimate, by inferences concerning accreted ice formation and by an investigation of ice properties at the transition between meteoric ice and accreted ice. This complex behaviour is the controlling factor on water, biota and sediment fluxes in the lake environment.

Keywords: ice composition; stable isotopes; Lake Vostok; Antarctica

1. Introduction

Lake Vostok is a huge subglacial lake, one of the 70 lakes identified beneath the Antarctic Ice Sheet [1]. It is about 240 km long and 50 km wide and lies under 3750 m of ice in its southern part and under 4150 m of ice in its northern part. The ice ceiling is tilted, being at 750 m below sea level in the north and at 250 m below sea level in the south. The water depth near Vostok station in the southern part of the lake is about 680 m.

Interpretation of radio-echo-soundings [1,2] has promoted a lake system with melting occurring in the northern part of the lake while ice accretion characterises the area around Vostok station in the southern part of the lake. Later radio-echo-sounding studies [3] have indicated that accreted

---

* Corresponding author. Tel.: +32-2-650-22-16; Fax: +32-2-650-22-26.
E-mail addresses: glaciol@ulb.ac.be (R. Souchez), petit@lgge.obs.ujf-grenoble.fr (J.-R. Petit), jouzel@lsce.saclay.cea.fr (J. Jouzel).

0012-821X/03/$ – see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/S0012-821X(03)00588-0

ice is exported out of the lake system along with glacier flow at the south-eastern margin of the lake. Ice flowing above the subglacial lake is coming from the Ridge B area (Fig. 1) and from Dome B in the northern part of the lake where subglacial melting is taking place.

The completion of ice drilling at the Russian Vostok station down to 3623 m, about 130 m above subglacial Lake Vostok, has allowed the extension of the record of atmospheric composition and climate to the past four glacial–interglacial cycles. The Vostok core has thus given one of the most interesting palaeoenvironmental record at interglacial–glacial timescales [4]. Below 3310 m depth, however, the climatic record cannot be directly deciphered because of complex ice deformation [5,6]. Below 3539 m depth, the ice is no more of meteoric origin (ice formed at the surface by snowfall) but is accreted ice produced by freezing of subglacial Lake Vostok waters [7,8].

The aim of this paper is mainly to reassess the isotopic properties of this accreted ice and to develop the consequences for Lake Vostok's behaviour.

2. Stable isotopes in accreted ice: previous interpretation

Major shifts in deuterium and deuterium excess are observed at the 3539 m transition. Within less than 50 cm, deuterium values increase by about 10 per mil (‰) and deuterium excess d ($d = \delta D - 8\delta^{18}O$) values shift from around 14‰, a value typical for meteoric ice in the Vostok area, to 7 or 8‰ [6,7]. In a δD–δ^{18}O diagram, data points above 3539 m lie on the Vostok precipitation line with a slope of 7.93 calculated over the past 420 000 years. In contrast, data from the zone below 3539 m depth cluster to the right

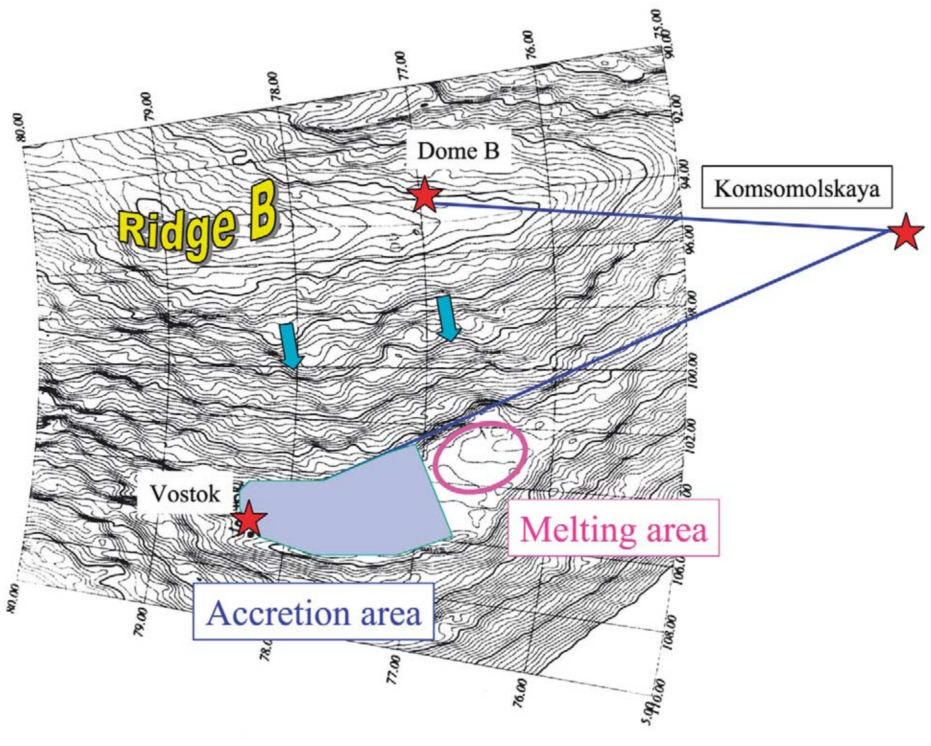

Fig. 1. The Lake Vostok environment with melting area and accreted ice formation area. Accretion area is derived from radio-echo-soundings [3]. Ice flow from Ridge B or Dome B is indicated by arrows. Traverse routes are shown by heavy straight lines and the stars are drilling sites. Surface contour lines are 5 m apart. The heavy isoline near Vostok station is 3500 m asl.

side of this precipitation line (figure 2 in [7]). Other ice properties also drastically change at this 3539 m transition (Fig. 2). These isotopic characteristics have been interpreted as a clear fingerprint of the isotopic modifications resulting from a freezing process [7,8] in accordance with fractionation effects occurring during this phase change [9,10]. In such a view, the explanation for the clustering point data being on the right side of the precipitation line is that accreted ice was formed by freezing of water from the subglacial lake. The lake water isotopic composition corresponds to the intersection of the freezing slope passing through the average point of the cluster and of the precipitation line. The theoretical freezing slope equals 3.98, which is about half the precipitation slope. Consequently, lower deuterium excesses are displayed in this ice.

The deuterium and oxygen 18 enrichment of the accreted ice in comparison to lake water is however only about 60% of the corresponding isotopic equilibrium. After considering different possibilities to explain such a situation, Souchez et al. [6,8] developed arguments for a lake ice origin by accretion of frazil ice crystals at the bottom of the ice cover followed by slow freezing of the host water present between the frazil ice crystals.

This overall process, based on the freezing slope concept, is still valid in a general way but, as shown below, recent developments on Lake Vostok's dynamics call for a reassessment of this isotopic interpretation. Firstly, subglacial melting at the ice–lake interface is limited to the northern part of the lake where glacier ice can be aligned on another meteoric water line in a δD–δ^{18}O diagram than that of Vostok station. This will affect the lake's isotopic composition. Secondly, the in-

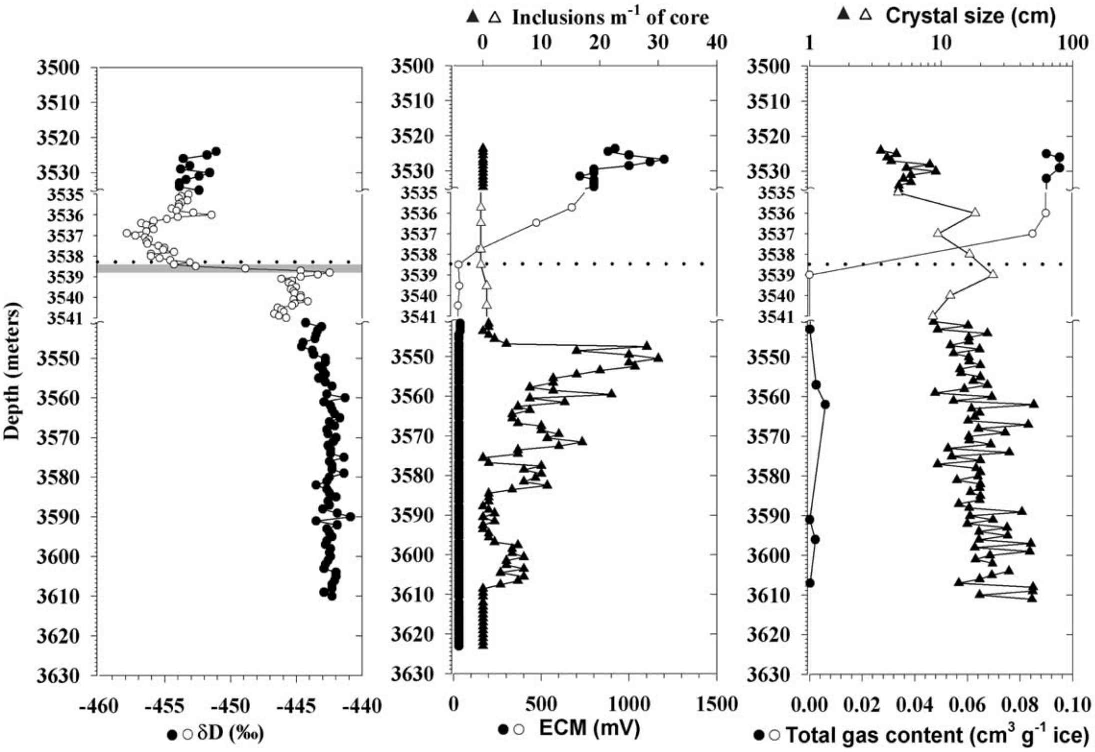

Fig. 2. The isotopic composition, ECM values and mineral particle aggregate (inclusion) number profile, crystal size and total gas content in the basal part of the Vostok ice core. Open symbols are used for the depth range 3535–3541 m where the resolution for isotopic measurements is 0.1 m. Samples in the shaded area of the isotopic profile have been used for the δD–δ^{18}O diagram shown in Fig. 5. The dotted line is considered as the contact between meteoric ice and accreted ice. Note that the ECM and inclusion number profiles are now prolonged to 3623 m depth.

clined ice–lake interface must be considered as the result of a dynamic equilibrium. Melting in the north of the lake and freezing in the south are conducive in the long run to an horizontal interface but, in the mean time, accreted ice is exported out of the lake by glacier movement, maintaining the inclination of the interface. Thirdly, the lake is geologically old – most probably several millions years old – and there is evidence from the chemistry of the accreted ice that an ancient evaporitic-type reservoir contributed to its chemistry [11]. The lake must therefore be considered as having been several times renewed. These considerations are taken into account in the new isotopic model developed hereunder.

3. A new isotopic model

Accreted ice sampled in the Vostok ice core was formed in the postglacial period. Because of ice flow (3 m per year) older accreted ice, if present, was exported out of the lake system. Within this timescale with no significant climatic change, the lake can be considered as having a constant volume ($dV=0$). This assumption is perhaps questionable at glacial–interglacial timescale where climate and ice sheet configuration have changed. Even at this timescale, it still represents a reasonable first approximation for an isotopic model in view of the huge dimensions of the lake and of its tectonic setting regulating subglacial water collection.

With $dV=0$, the water discharge brought into the lake as a result of ice melting (Q_{in}) is equal to the water discharge (Q_{out}) exported out of the lake system in the form of accreted ice. If C is the concentration of an isotopic species in the lake water with the index 'in' for meltwater and index 'out' for accreted ice, the isotopic mass balance of the system can be written as:

$$V\,dC = Q_{in}C_{in}\,dt - Q_{out}C_{out}\,dt = Q_{in}\tau\,dC \tag{1}$$

where τ is the residence time of lake water.

Since there is fractionation on water freezing, $C_{out}=\alpha C$ with α being the fractionation coefficient for deuterium or oxygen 18 between ice and water, and:

$$\frac{dt}{\tau} = \frac{dC}{C_{in} - \alpha C} \tag{2}$$

Integrating Eq. 2 gives:

$$C = \frac{C_{in}}{\alpha} + \left(C_0 - \frac{C_{in}}{\alpha}\right)e^{(-\alpha t/\tau)} \tag{3}$$

where C_0 is the initial C value at $t=0$.

It can easily be shown that, for $t \geq 3\tau$, $C = C_{in}/\alpha$ and $C_{in} = C_{out} = \alpha C$. The isotopic composition of the accreted ice is the same as the isotopic composition of the meltwater produced. For deuterium as an example, the evolution in time follows the equation:

$$1 + \delta D_{lake\ water} = (1 + \delta D_{meltwater})/\alpha +$$

$$(\delta D_0 - \delta D_{meltwater}/\alpha)e^{(-\alpha t/\tau)}\ \text{(Fig. 3)} \tag{4}$$

If δD is expressed in ‰, then 1 has to be replaced by 1000 in Eq. 4.

The time required for ice to cross the lake and reach Vostok station is about 16000 years so that the uppermost accreted ice cannot be older than this, while the ice at the bottom of the accreted layer is probably very recent. Within this timescale, the isotopic composition of the accreted ice is nearly constant, reflecting the steady-state situation reached by the lake system (Fig. 2). The isotopic composition of the meltwater produced gives the mean isotopic composition of the glacier ice subjected to melting since there is no fractionation in water isotopes on ice melting. This model considers the evolution in isotopic

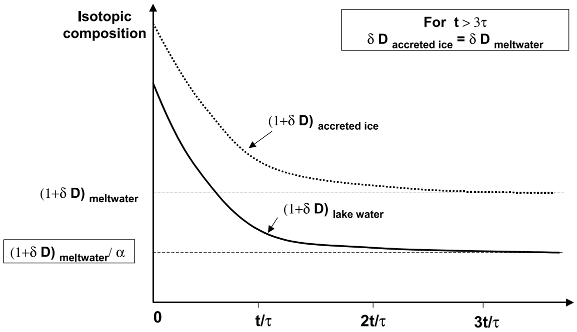

Fig. 3. Schematic diagram showing the evolution of the deuterium composition of lake ice and water in the course of time.

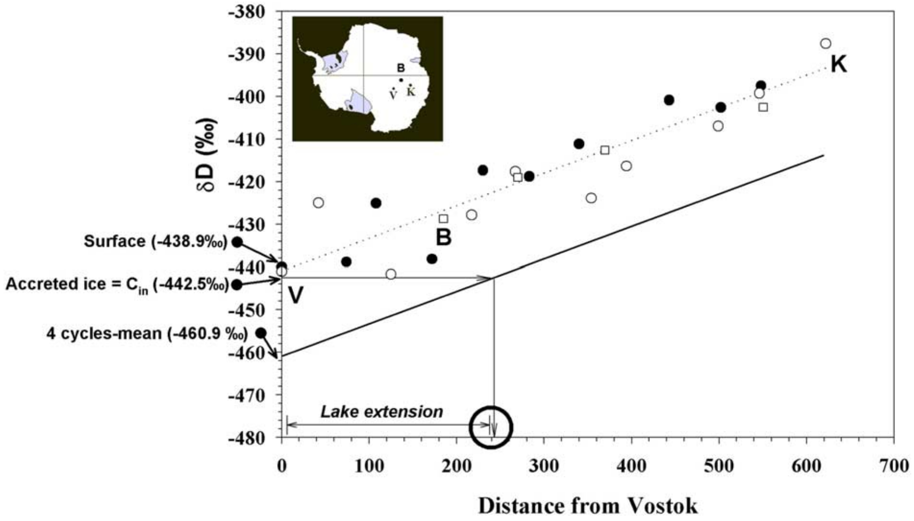

Fig. 4. Use of the δD surface distribution between Vostok (V), Dome B (B) and Komsomolskaya (K) to infer the melting source for the accreted ice. The solid line is drawn parallel to the regression line for surface points through the four cycles – mean value at Vostok (see text for details). Open squares: surface snow samples between B and K (Vaikmae, personal communication); open and black circles: surface snow samples between V and K for two different traverses.

concentration through time. No effort has been devoted yet to model the spatial distribution of stable isotopes in the lake system.

4. Reassessment

What are the consequences of this model on the interpretation of the isotopic data?

A first problem concerns the deuterium values. In Fig. 4, the deuterium concentration in surface snow samples is given along traverses Vostok–Komsomolskaya (a station north of the lake) and Dome B–Komsomolskaya as a function of the distance from Vostok station (upper straight line). Assuming that the mean deuterium concentration for meteoric ice of the four climatic cycles shows the same geographic variation than present-day snow, a parallel is drawn passing through the point representing the mean deuterium concentration for a complete interglacial–glacial climatic cycle at Vostok (or for the four climatic cycles). A δD value of −442.5‰, the mean value observed in the accreted ice, is reached at a distance about 200 km north from Vostok i.e. along the northern shores of the lake. Although the authors are fully aware that extrapolating the present surface isotope gradient over an entire interglacial–glacial cycle or over four climatic cycles is questionable, notably because of change in ice sheet configuration in such a long time period, at least the results indicate that it is possible for the subglacial meltwater in the north of the lake to have the isotopic composition of the accreted ice. Furthermore, similar variations in stable isotopes are observed in Dome B and Vostok from the Last Glacial Maximum (LGM) to the present-day while accumulation and surface configuration have probably varied.

A second problem concerns the deuterium excess. Deuterium excess varies between 12 and 18‰ along the four glacial–interglacial climatic cycles at Vostok station [12]. Accreted ice has a mean deuterium excess of 7.5‰. The implications of the model developed are that the latter value of deuterium excess will also be that of glacier ice melting in the northern part of the lake. This ice is coming from the Dome B area. But deuterium excess values of 7–7.5‰ are only present in some ice from the LGM in the Dome B core. It is thus unlikely that a mean deuterium excess value of 7.5‰ could be reached by melting of a substantial part of ice coming from the Dome

B area. There is however another possibility. The weak deuterium excess in accreted ice could result from the influence of hydrothermal waters. In hydrothermal areas, spring waters are known to be enriched in oxygen 18 with respect to precipitation supplying the system [13,14]. Oxygen shift with respect to the meteoric water line results from isotopic exchange with ^{18}O-rich rocks at high temperature. From helium studies in the accreted ice [15,16], a crustal hydrothermal contribution to Vostok lake water probably occurs in connection with a seismo-tectonic activity of the area [16,17]. A reasonable shift of $\Delta\delta^{18}O = 0.5$‰ due to this effect will permit the deuterium excess of the accreted ice to reach values as low as 7‰.

A third problem is related to the frazil ice hypothesis since effective freezing at a level of 60% equilibrium value cannot be considered anymore. But, as developed below, thermodynamic considerations can help to solve this problem.

A somewhat weak salinity (between 0.1 and 1‰) is suggested for Lake Vostok from chemical studies on the accreted ice in the Vostok ice core [8,18]. Even with such a weak salinity, because of the high pressure (about 337 bars), a thermohaline circulation can occur if lower density waters are produced by melting in an area where the ice ceiling is at lower altitude like in the northern part of the lake. Siegert et al. [2] showed the water circulation pattern if a weakly saline water is considered. The meltwater produced will progressively form a plume propagating in the upper water column along the inclined ice–water interface. Along this path, supercooling occurs and frazil ice crystals are generated [8]. A loose accreted frazil ice crystal layer is formed; the liquid water initially present decreases as a result of progressive freezing downwards of the host water.

Based on radio-echo-soundings, Bell et al. [3] suggest an ice accretion rate in subglacial Lake Vostok of 0.7 cm per year for Vostok station. Now, there is a thermal gradient in the bottom of the drilling hole of 0.02°C/m, which corresponds to 45 mW/m^2. If this is the amount of heat that is released by freezing of ice at the ice–water interface, only 0.45 cm of ice is produced in one year. In perspective of a process where ice originates as frazil crystals within the upper water column, the following reasonable assumption can be proposed. While the latent heat produced by the formation of the frazil ice crystals themselves is released into the lake water, the heat conducted upwards through the solid ice corresponds to freezing of the host water present between the accreted frazil crystals leading to the consolidation of the loose bottom ice layer. Then, the percentage of ice resulting from host water freezing would represent 64% of the accreted ice layer. Another way to approach the problem is to consider that the accreted ice layer, although having a nearly constant isotopic composition [7], is in fact composed of two different layers (Fig. 2). The upper layer consists of ice loaded with solid mineral particles usually aggregated (inclusions); it is about 69 m thick and is most probably formed in the shallow western embayement of the lake discovered by Bell et al. [3]. The lower layer devoid of solid mineral particles (inclusions) has now been sampled to 3623 m depth and is supposed to be about 141 m thick (if it extends to the ice–water interface); it is formed in an area where the lake is deeper. If the transit time for ice from the bedrock ridge separating the shallow embayement from the deep lake to Vostok is taken as 15 000 years (annual ice velocity: 3 m per year), freezing of host water would represent 48% of the accreted ice layer at Vostok station. Let us use a value of 50% as a rule of thumb. Such a value is comparable to those obtained in experimental and field studies of frazil ice formation [8].

Given reasonable apparent fractionation coefficients for frazil ice crystals and frozen host water [8], the lake's deuterium composition could be calculated but, due to the relative importance of mixing processes in the lake, such a value is not well constrained. It is however, in a δD–$\delta^{18}O$ diagram, on the freezing slope for the accreted ice but not necessarily at the intersection with the meteoric water line defined for Vostok station as previously suggested.

5. The transition zone

A study of ice properties in the transition zone between meteoric ice and accreted ice in the Vostok core supplies additional information in the context of this paper. Fig. 2 gives the electrical conductivity measurements (ECM), mineral particle aggregates (inclusions) number, gas content and crystal size at a 1 m sampling length across the meteoric ice–accreted ice contact. Also shown is the δD profile with a 0.1 m sampling length between 3535 and 3541 m depth. A striking feature of this figure is that the transition in ECM values from 800 mV, a value typical for meteoric ice, to the detection limit (30 mV) in accreted ice lies above the isotopic transition. Furthermore, the gas content is nil at the level of and below the isotopic transition. Gases and impurities are indeed expelled in ice resulting from water freezing. This is the main reason for the total absence of gases in the accreted ice. The isotopic transition is developed along an ice core thickness of about 0.7 m. If this is considered as the length over which diffusion is noticeable, then solid state diffusion is excluded as the main mechanism to explain the situation. It can indeed be computed that, with a solid state isotopic diffusion coefficient in ice of 10^{-15} m^2/s, diffusion will only be discernible at a distance of 0.1 m in 16 000 years, the maximum age for the accreted ice as seen above. Therefore, diffusion within the host water surrounding the accreted frazil ice crystals must be considered.

The progression of the freezing front in this host water consolidating the accreted ice is to be viewed as the result of a continuous exchange liquid water ↔ solid ice, a consequence of thermal agitation and heat transfer. The isotopic composition in the transition zone represents a combined signal of the initial isotopic composition in the accreted ice and that of the influence of diffusion in liquid water during consolidation of the accreted frazil and recrystallisation. A similar process was invoked to explain the transition between glacier ice and marine ice present in a former crevasse of an ice shelf [19]. In a δD–δ^{18}O diagram (Fig. 5), the points representing the samples of the isotopic transition zone are well aligned on a slope joining a point representing the lowest meteoric ice sample in the core to a point representing the upper unmodified accreted ice sample. This can be considered as a mixing line although mechanical mixing of the two end members is not considered.

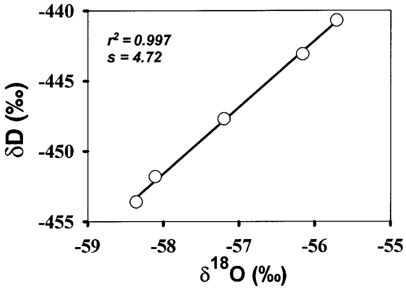

Fig. 5. δD–δ^{18}O diagram for the isotopic transition zone to the accreted ice. *S* is the slope of the regression line.

6. Conclusion

The physical environment of Lake Vostok is primarily the consequence of the kind of thermohaline circulation implying ice formation in the upper water column of the lake. Strong arguments for such a dynamics are developed thanks to a detailed investigation of isotopic properties in the accreted ice present in the basal part of the Vostok ice core. In a lake system having been renewed several times, owing to meltwater input and accreted ice export, the isotopic concentration of the accreted ice is shown to be the same as that of the glacier ice subjected to melting. The dual origin of the accreted ice layer – frazil ice crystals and frozen host water – is supported by thermodynamic considerations. A detailed survey of the transition zone between meteoric ice and accreted ice adds further weight to the suggested processes.

Acknowledgements

R.S. and J.-L.T. are grateful for the support of the Belgian Antarctic programme (Science Policy Office). Dr R. Koerner is gratefully acknowledged for the very careful review which led to a significant improvement of the manuscript. ***[BARD]***

References

[1] M.J. Siegert, Antarctic subglacial lakes, Earth Sci. Rev. 50 (2000) 29–50.

[2] M.J. Siegert, J. Ellis-Evans, M. Tranter, C. Mayer, J.R. Petit, A. Salamatin, J. Priscu, Physical, chemical and biological processes in Lake Vostok and other Antarctic subglacial lakes, Nature 414 (2001) 603–609.

[3] R.E. Bell, M. Studinger, A. Tikku, G. Clarke, M. Gutner, C. Meertens, Origin and fate of Lake Vostok water frozen to the base of the East Antarctic ice sheet, Nature 416 (2002) 307–310.

[4] J.R. Petit, J. Jouzel, D. Raynaud, N. Barkov, J.M. Barnola, I. Basile, M. Bender, J. Chappellaz, M. Davis, G. Delaygue, M. Delmotte, V. Kotlyakov, M. Legrand, V. Lipenkov, C. Lorius, L. Pépin, C. Ritz, E. Saltzman, M. Stiévenard, Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, Nature 399 (1999) 429–436.

[5] R. Souchez, J.R. Petit, J. Jouzel, J. Simoes, M. de Angelis, N. Barkov, M. Stiévenard, F. Vimeux, S. Sleewaegen, R. Lorrain, Highly deformed basal ice in the Vostok core, Antarctica, Geophys. Res. Lett. 29 (2002) 40.1–40.4.

[6] R. Souchez, P. Jean-Baptiste, J.R. Petit, V. Lipenkov, J. Jouzel, What is the deepest part of the Vostok ice core telling us?, Earth Sci. Rev. 60 (2002) 131–146.

[7] J. Jouzel, J.R. Petit, R. Souchez, N. Barkov, V. Lipenkov, D. Raynaud, M. Stiévenard, N. Vassiliev, V. Verbeke, F. Vimeux, More than 200 meters of lake ice above subglacial lake Vostok, Antarctica, Science 286 (1999) 2138–2141.

[8] R. Souchez, J.R. Petit, J.L. Tison, J. Jouzel, V. Verbeke, Ice formation in subglacial Lake Vostok, Central Antarctica, Earth Planet. Sci. Lett. 181 (2000) 529–538.

[9] J. Jouzel, R. Souchez, Melting refreezing at the glacier sole and the isotopic composition of the ice, J. Glaciol. 28 (1982) 35–42.

[10] R. Souchez, J. Jouzel, On the isotopic composition in δD and δ^{18}O of water and ice during freezing, J. Glaciol. 30 (1984) 369–372.

[11] M. de Angelis, J.R. Petit, J. Savarino, R. Souchez, M. Thiemens, Contribution of an ancient evaporitic-type reservoir to lake Vostok chemistry, in prep.

[12] F. Vimeux, V. Masson, J. Jouzel, M. Stievenard, J.R. Petit, Glacial-interglacial changes in ocean surface conditions in the Southern Hemisphere, Nature 398 (1999) 410–413.

[13] R.N. Clayton, A. Steiner, Oxygen isotope studies of the geothermal system at Warakei, New Zealand, Geochem. Cosmochem. Acta 39 (1975) 1179–1186.

[14] H. Craig, The Isotopic Geochemistry of Water and Carbon in Geothermal Areas, Consiglio Nationale dell Ricerche, Laboratorio de Geologia Nucleare, Pisa, 1963, 53 p.

[15] P. Jean-Baptiste, J.R. Petit, V. Lipenkov, D. Raynaud, N. Barkov, Helium isotope in deep Vostok ice core (Antarctica) constraints on hydrothermal processes and water exchange in the subglacial lake, Nature 411 (2001) 460–462.

[16] P. Jean-Baptiste, J.R. Petit, D. Raynaud, J. Jouzel, S. Bulat, Helium signature and seismotectonic activity in Lake Vostok, Geophys. Res. Abstr. 5 (2003).

[17] M. Studinger, R. Bell, G. Karner, A. Tikku, J. Holt, D. Morse, T. Richter, S. Kemps, M. Peters, D. Blankenship, R. Sweeney, V. Rystrom, Ice cover, landscape setting, and geological framework of Lake Vostok, East Antarctica, Earth Planet. Sci. Lett. 205 (2003) 195–210.

[18] J. Priscu, E. Adams, W. Lyons, M. Voytek, D. Mogk, R. Brown, C. McKay, C. Takacs, K. Welch, C. Wolf, J. Kirshtein, R. Avci, Geomicrobiology of subglacial ice above Lake Vostok, Antarctica, Science 286 (1999) 2141–2144.

[19] R. Souchez, J.-L. Tison, R. Lorrain, C. Fléhoc, M. Stievenard, J. Jouzel, V. Maggi, Investigating processes of marine ice formation in a floating ice tongue by a high-resolution isotopic study, J. Geophys. Res. 100 (1995) 7019–7025.