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ISOTOPIC COMPOSITION OF ICE AND TRAPPED GASES INDICATE RAPID TEMPERATURE ЬAND GLACIATION-DEGLACIATION CHANGES AS REVEALED FROM ICE CORES Part 2

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У статті порівнюються методологія та результати досліджень глибинних частин льодовиків, проведених різними дослідницькими командами, з метою визначення ізотопного складу елементів захоплених у полярній кризі газів та кисню самої криги. Результати з різних свердловин, які відповідають періодам часу, що перекриваються, привели до порівняння альтернативних даних. Результати досліджень ізотопного складу зіставлено з відповідними кліматичними подіями минулого, так що їхній зв'язок із зміною клімату стає очевидним.

В статье сравниваются методология и результаты исследований глубинных частей ледников, проведенных различными исследовательскими командами, с целью определения изотопного состава элементов захваченных в полярных ледниках газов и кислорода самого льда. Результаты из разных скважин, отвечающие перекрывающимся периодам времени, привели к сопоставлению альтернативных данных. Результаты исследований изотопного состава сопоставлены с соответствующими климатическими событиями прошлого, так что их связь со сменой климата становится очевидной.

INTRODUCTION

In this paper, the author makes an attempt to investigate methods and results of ice core-based research on determination of trapped gas and oxygen of ice isotopic composition in the polar ice cores over up to 420 kyr before the present. The author tried to find alternative studies from different ice core drills so that the time periods covered would overlap at least partialy. This allowed comparison of data from alternative sources.

This paper also describes types and applications of data, obtained for particular isotope-research data. The paper is structured in the way, the data for a particular time period is interpreted in close concern with the time period in the Past itself. This allows the reader to trace and confront isotopic effects to certain climatic events at a particular time in the past.

ISOTOPIC COMPOSITION OF ICE-TRAPPED GASES, IN PARTICULAR, NITROGEN AND ARGON, ALSO OXYGEN OF WATER, AS AN INDICATOR OF RAPID TEMPERATURE AND GLACIATION-DEGLACIATEION CHANGES

Perhaps, the most well-known isotopic difference effect, on the basis of which useful data about past climate variations can be obtained is the $^{16}O/^{18}O$ one. Because ^{16}O is lighter than ^{18}O, $H_2{}^{16}O$ evaporates more readily (due to lower vapor pressure) than $H_2{}^{18}O$. For the same reason, heavier $H_2{}^{18}O$ condenses and deposits more readily than water with lighter oxygen isotope. This effect causes World Ocean's water to get depleted in the lighter oxygen isotope as water is evaporated and deposited in ice, which leads to $^{16}O/^{18}O$ ratio in the ice cores to be different depending on depth (and thus, the time period in the past) reflecting the current (at that time) amount of ice in glaciers and the changes in the hydrological cycle [1]. The $^{16}O/^{18}O$ ratio is also affected by water vapor traveling to the poles and thus, lighter water content in the vapor over poles is even further increased. Water from polar snow will thus be found to be most depleted in $H_2{}^{18}O$. The temperature, at which snow for that or another layer (that later became bubbled ice) is formed, is thus "recorded" along the depth of an ice core [2]. Hydrogen in the water formulae above can be either ^1H or ^2H (Tritium is not a concern here due to its very low concentration). The ratio of isotopes in condensed (or deposited) water is in dependence on the temperature at which condensation (deposition) occurs. Such fractionation leads to greater depletion of deposited water with Deuterium with the decrease in temperature at which deposition occurs. This effect causes polar ice cores to have varying $^1H/^2H$ ratio depending on temperature [1].

Petit and colleagues [1] also conducted δD and $\delta^{18}O_{atm}$ determination in the framework of their Vostok ice core research. The most important results for glacial terminations I to IV and the subsequent interglacial periods (Holocene, stage 5.5, stage 7.5 and stage 9.3) are depicted in figure 1. As it is seen in the figure, the last interglacial period (Holocene) is the most stable in terms of δD and $\delta^{18}O_{atm}$ and thus, temperature, which is represented by much smoother δD and $\delta^{18}O_{atm}$ lines. Based on literature data, researchers concluded that $\delta^{18}O_{atm}$ tracks $\delta^{18}O_{sw}$ (SW stands for 'surface water') with a lag of approximately 2 kyr. Authors suppose that this interrelationship can be used to follow deglaciation-associated large ice amount variations. In the obtained

measurements, $\delta^{18}O_{atm}$ changes in amplitude are parallel to those of $\delta^{18}O_{sw}$ for all terminations I to IV. In the course of each termination, as seen in figure 1, $\delta^{18}O_{atm}$ decreases quickly, which should be caused by strong deglaciation.

Based on the differences in thermal diffusion of different Argon and Nitrogen isotopes through the open-pore snow/firn/open-bubble ice system depending on the actual snow surface temperature, the study of $^{15}N/^{14}N$ and $^{40}Ar/^{36}Ar$ provides record of rapid temperature changes. The gas isotopes separate in firn due to gravitational settling and temperature gradient-induced fractionation (heavier gases and, in particular, heavy isotope-enriched $^{15}N^{14}N$ and heavy isotope $^{15}N_2$ and ^{40}Ar, tend to move to colder regions). In their research, Severinghaus and colleagues [3] measured these isotopes in trapped air bubble in the framework of Greenland Ice Sheet Project 2 (GISP2). Laboratory calibration allowed determining dependences of Argon and Nitrogen isotope thermal diffusion-based fractionation and thus, permitted application of these data to determine temperature changes on the basis of these isotopes in the ice-trapped air. One more advantage is that atmospheric methane concentration changes are recorded parallel with nitrogen isotope changes because the diffusion intensity of both is close.

Additionally, temperature estimations based on Argon and Nitrogen isotopes can be more precise to determine snow surface temperature when other gases were trapped because other methods of temperature determination like oxygen-isotope had been found to may not always correspond to temperature changes but be caused by $^{16}O/^{18}O$ fluctuations, inferred by other factors (e.g. ice amount changes).

Figure 2 shows the profile, taken in summer when snow is significantly colder than the air above. Heavy isotopes are driven by this temperature gradient down the firn and mixed by diffusion with gases, already there. The $\delta^{15}N$- and $\delta^{40}Ar$/4-enriched air, represented by the peak around the depth of 6 m, is formed because of gravitational settling.

Sudden temperature increases create a temperature gradient in the firn, which is 'conserved' for hundreds of years (so-called "thermal equilibration time of the firn"). This triggers thermal fractionation. Because gas diffusion is tenfold faster than heat diffusion in polar firn, temperature increase-related isotopic ratio changes reach the firn bottom about 10 years before thermal equilibration is set. There, at the firn bottom, where air bubbles are finally enclosed, they trap smoothed by diffusion abrupt increases in $\delta^{15}N$. These increases are followed by a steady decrease in $\delta^{15}N$

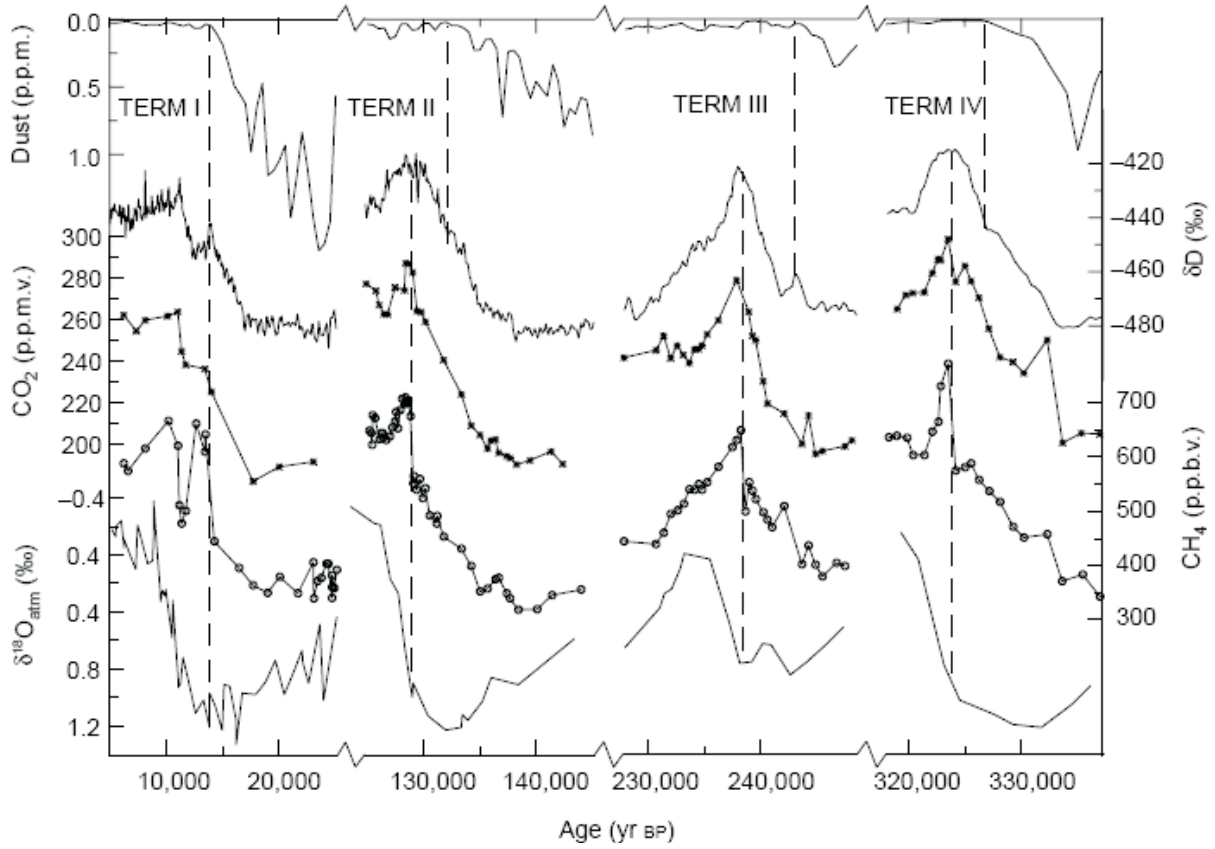

Fig. 1. (*adapted from* [1]). "Vostok time series during glacial terminations. Variations with respect to time of: **a**, dust; **b**, δD of ice (temperature proxy); **c**, CO_2; **d**, CH_4; and e, $\delta^{18}O_{atm}$ for glacial terminations I to IV and the subsequent interglacial periods (Holocene, stage 5.5, stage 7.5 and stage 9.3)"

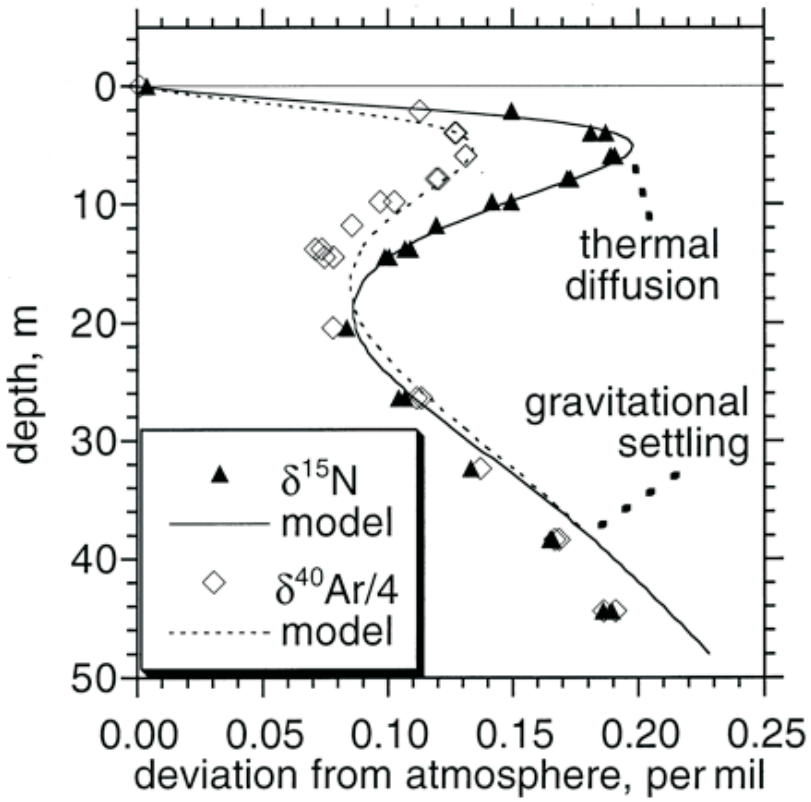

Fig. 2. (*adapted from* [3]*).* "Depth profile of nitrogen and argon isotope ratios in air withdrawn from the snow pack at Siple Dome, Antarctica, on 14 January 1998, $\delta^{15}N$ is defined as $[(^{15}N/^{14}N_{sample})/(^{15}N/^{14}N_{atmosphere}) - 1] \times 10^3$ and is expressed in units of per mil (parts per thousand). $\delta^{40}Ar$ is the corresponding quantity for the $^{40}Ar/^{36}Ar$ ratio and is divided by 4 to facilitate comparison with $\delta^{15}N$

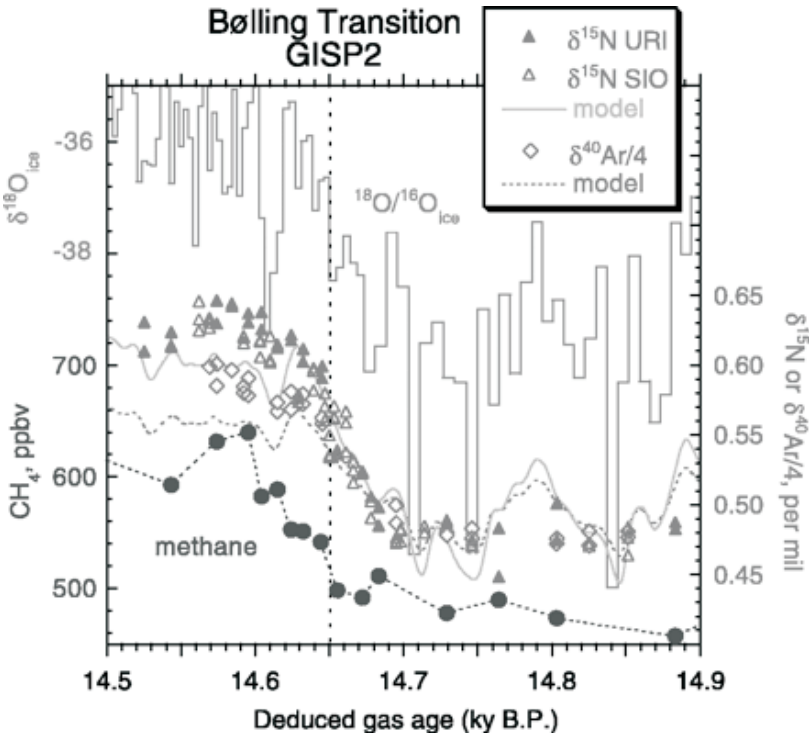

Fig. 3. *(adapted from* [3]*).* "The 400-year window encompassing the Bølling Transition (rapid warming around 14,5 kyr), showing high-resolution measurements of oxygen isotopes of ice and nitrogen, argon, and methane measurements made on trapped air bubbles. The gas age is deduced by assuming that the abrupt change in nitrogen isotopes marked by the dashed vertical line corresponds to the shift in oxygen isotopes at 14.65 kyr"

over several hundred years, during which temperature throughout firn stabilizes again [3].

An example of practical Nitrogen/Argon isotope ice core data recovery is shown in figure 3, representing the period of so-called Bølling Transition when rapid warming occurred 14.67 kyr before the present. The start of this event marks the end of the last glacial period, also called 'Interstadial 1'. The cold period before the Bølling Transition is the Oldest Dryas.

Researchers [3] found $\delta^{15}N$ increase from +0.48 per mil to peak values of +0.63 per mil during this time period. Researchers examined the model estimates of the gas age-ice age difference as a part of their study. They found a mismatch between model and observed gas isotopes (as seen in figure 3 from 14.55 to 14.62 kyr). This is especially noticeable for $\delta^{15}N$ in figure 3. Authors attributed this to "gravitational enrichment from transient firn thickening brought about by the increase in snow accumulation, which was not included in the model" [3]. This factor, thus, should be considered during interpretation.

Figure 3 presents a good combination of data to carry out $\delta^{15}N$ and $\delta^{40}Ar$ comparison with methane concentration changes (the reason for authors' choice of methane is described above) and also with $\delta^{18}O$. In the period from 14.65 to 14.60 kyr, methane concentration grows. At the same time, $\delta^{15}N$ first grows noticeably out of the interval of Oldest Dryas variability at 14.672 ky (1821.16 m depth). This is the start of the warming and, as seen in the figure, it is accompanied by 1.7 per mil growth of $\delta^{18}O_{ice}$. Authors also cite that evidence to the abrupt doubling of snow accumulation at this time exists. At the same time, during this period, CH_4 concentration does not go out of Oldest Dryas variability range of 470 to 510 p.p.b.v. in 14.672 kyr ice sample and in the next sample at 14.655 kyr. Methane concentration goes out of this only later (around 27 years after the corresponding change in $\delta^{15}N$) at 14.645 kyr (1820.17 m). It was concluded that methane concentration started rising only after the start of the Greenland warming.

On the basis of $\delta^{15}N$ and $\delta^{40}Ar/4$ values in the Bølling interval, researchers [3] determined that air temperatures warmed by 9 ± 3°C by 14.60 kyr. They also assumed their $\delta^{18}O_{ice}$ data ($\delta^{18}O_{ice}$ increased by 3.4 per mil during the Bølling transition), from which they were able to determine oxygen isotope temperature sensitivity across the transition could serve to verify the borehole calibration.

CONCLUSIONS

1. The most extensive coverage of the past climate change and in particular, atmospheric gas composition and temperature change was fulfilled in the framework of extended drilling project at Vostok station, East Antarctica. It allowed investigation of atmospheric composition and climate ice record encompassing the past four glacial–interglacial cycles. Researchers [1] found repetitiveness of changes throughout all four climate cycles. Moreover, change pattern during interglacial terminations was similar, gas concentrations and temperature changed roughly within particular limits between stable limits.
2. Ice core research discovered that interglacials' development and length were somewhat different from cycle to cycle.
3. Present interglacial period, Holocene, appeared to be the most stable in terms of sharpness of atmospheric composition and temperature changes when compared to other interglacial periods over the past 420 kyr.
4. Petit and colleagues described that during the last four glacial terminations initially, temperature increased accompanied by carbon dioxide and methane concentration increase. Then, there was a rapid increase in methane concentration that concurred with the beginning of the $\delta^{18}O_{atm}$ decrease that the authors attributed to rapid melting of the Northern Hemisphere ice sheets including warming in Greenland.
5. $\delta^{18}O_{atm}$ tracks $\delta^{18}O_{sw}$ (SW stands for 'surface water') with a lag of approximately 2 kyr. It is supposed that this interrelationship can be used to follow deglaciation-associated large ice amount variations.
6. In the obtained measurements, $\delta^{18}O_{atm}$ changes in amplitude are parallel to those of $\delta^{18}O_{sw}$ for all terminations. In the course of each termination, $\delta^{18}O_{atm}$ decreases quickly, which should be caused by strong deglaciation.
7. Temperature estimations based on Argon and Nitrogen isotopes can be more precise to determine snow surface temperature when other gases were trapped because other methods of temperature determination like oxygen-isotope had been found not always corresponding to temperature changes but be caused by $^{16}O/^{18}O$ fluctuations, inferred by other factors (e.g. ice amount changes).
8. Researchers [3] also determined on the basis of $\delta^{15}N$ and $\delta^{40}Ar/4$ values in the Bølling interval that air temperatures warmed by 9 ± 3°C by 14.60 kyr. They also assumed their $\delta^{18}O_{ice}$ data, from which they were able to determine oxygen isotope temperature sensitivity across the transition, could serve to verify the borehole calibration.

LITERATURE CITED

1. Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davisk, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pépin, L., Ritz, C., Saltzmank, E., Stievenard, M. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, *Nature* (1999), **399**, 429–436.
2. Óskarsson, B.V. Ice core evidence for past climates and glaciation. Science Institute, Náttúrufræðahúsið, University of Iceland, 101 Reykjavík. http://www.hi.is/~oi/Nemendaritgerdir/Ice%20core%20evidence%20for%20past%20climates%20and%20glaciation.pdf Document created 20thof March 2004.
3. Severinghaus, J.P., Brook, E.J. Abrupt Climate Change at the End of the Last Glacial Period Inferred from Trapped Air in Polar Ice. *Science* (1999), **286**, Issue 5441, 930–934.