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International Effort Helps Decipher Mysteries of Paleoclimate from Antarctic Ice Cores

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Vostok Project Members

Ice cores drilled at Vostok Station, Antarctica, and studied over the past 10 years by Russia, France, and the United States (Figure 1) are providing a wealth of information about past climate and environmental changes over more than a full glacial-interglacial cycle. The ice cores show that East Antarctica was colder and drier during glacial periods than during the Holocene and that large-scale atmospheric circulation was more vigorous during glacial times. They also support evidence from deep-sea sediment studies favoring orbital forcing of Pleistocene climate, reveal direct correlations of carbon dioxide and methane concentrations with temperature, and indicate how the accumulation of trace compounds have changed through time.

Vostok has operated as a year-round station for more than 37 years. In the 1970s, the Soviets drilled a set of holes 500–952 m deep in the ice, which allowed the studies of borehole geodesic properties and preliminary studies of the oxygen isotope composition of the ice. Then three more holes were drilled. In 1984, Hole 3G reached a final depth of 2202 m following a 2-year hiatus. A final depth of 2546 m was reached at Hole 4G in 1990, and drilling at Hole 5G ended in September 1993 once a depth of 2755 m was struck. During the 1993–1994 field season, activity focused on maintaining the borehole conditions over the winter to allow drilling to resume after the reopening of the station. The station was temporarily closed in January 1994 due to fuel resupply problems, but it reopened last November. The drilling continued during the winter of 1995.

Ice cores give access—on a continuous and largely quantifiable basis—to key properties of paleoclimate including local temperature and precipitation rate, moisture source conditions, and wind strength. They also provide records of changes in atmospheric composition including trace gas concentrations, chemical impurities of terres-

trial and marine origin, other trace compounds or isotopes, cosmogenic isotopes, extraterrestrial material, and aerosols of volcanic and anthropogenic origin. Vostok ice cores were the first to cover a full glacial-interglacial cycle and—despite recent drillings in Central Greenland—they still carry the distinction of being the only ice cores undoubtedly undisturbed for the last interglacial and the penultimate glacial periods [e.g., Jouzel, 1994].

Interpreting Paleoclimate From Ice Cores

Due to fractionation processes, there is a progressive depletion of the deuterium and oxygen 18 content of the precipitation formed in a given airmass. In polar regions, this fractionation results in a linear relationship between the average isotopic content of

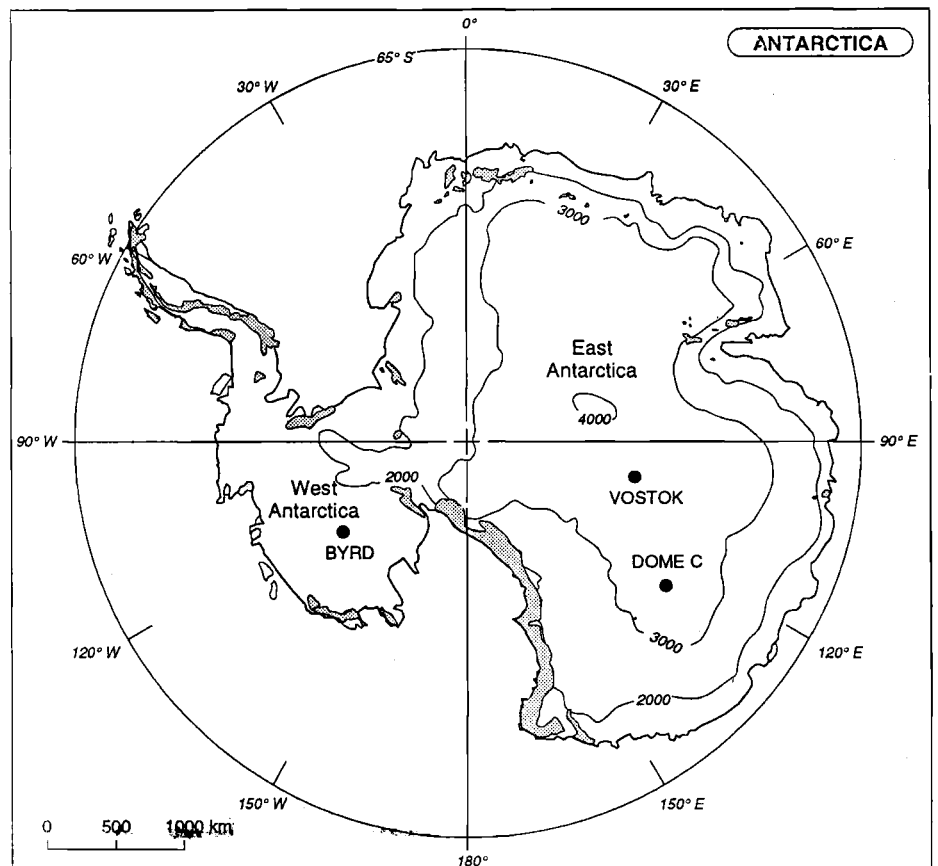


Fig. 1. Map of Antarctica. The deep drilling sites are indicated by black dots.

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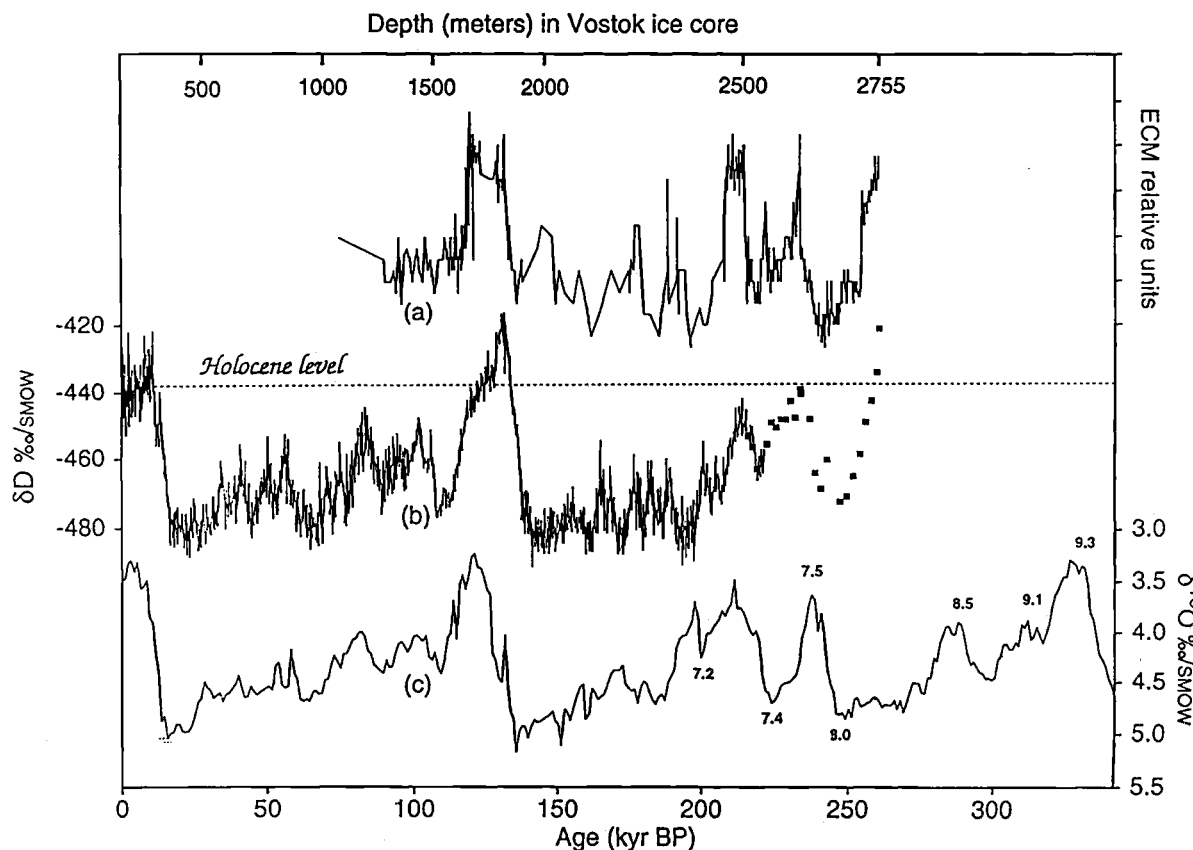


Fig. 2. Variations of Electrical Conductivity (ECM, curve a) and deuterium content (curve b) along the Vostok ice cores. These Vostok data are given with respect to time and depth. ECM values are reported in arbitrary units with an inverted scale. Continuous deuterium data are from cores 3G (from 138 to 2083 m) and 4G (from the surface down to 138 m and from 1920 to 2546 m). Discontinuous measurements (from 2500 to 2755 m) are from 5G. Also plotted is the oxygen 18 record of benthic foraminifera along the V19-30 deep-sea core in the Pacific Ocean with indications of marine stages.

snow and the mean annual temperature. This empirical relationship—illustrated by atmospheric circulation models—allows us to reconstruct local records of temperatures from the isotopic content of ice: in Antarctica, a cooling of 1°C —the atmospheric temperature above the inversion layer where precipitation are formed—results in a decrease of 9 per mil deuterium.

An accurate chronology is essential for interpreting ice core paleoclimate data. At Vostok, accumulation is too low for recognizable annual signals to form, so we developed a chronology combining an ice flow model and an accumulation model that accounts for the fact that accumulation was lower during colder periods and vice-versa. Because the accumulation rate is governed by saturation water vapor pressure, past accumulation may be estimated from the temperature record. Accumulation rates inferred in this way are supported by measurements of ^{10}Be in Vostok ice. Deposition of this cosmogenic isotope is assumed to be constant. Lorius *et al.* [1985] established the chronology down to 2083 m (age of 164 kyr BP). This chronology was revised (revised age of 156 kyr BP at this depth) and extended down to the deepest part of the 4G core (2546 m) dated at 220 ± 20 kyr BP [Jouzel *et al.*, 1993].

The combined deuterium record from the 3G and 4G cores is shown in Figure 2. The record shows the last two glacial-interglacial transitions with atmospheric temperature changes of $\sim 6^{\circ}\text{C}$. The last ice age is charac-

terized by three minima separated by slightly warmer episodes, which are called interstadials. The penultimate glacial is characterized by a long cold period with smaller amplitude of variation than that of the last ice age. This record is marked by a strong obliquity component (period of ~ 41 kyr resulting from changes in the tilt of the Earth) and weaker but significant precession components (periods of 23 and 19 kyr associated with the wobble of the axis), further supporting the role of orbital forcing in the Pleistocene glacial-interglacial cycles demonstrated by deep-sea core records.

There is additional support for the above chronology of the Vostok ice core derived from a glaciological model. Southern Ocean temperature variations correlate with those at Vostok. Also, the variations in $\delta^{18}\text{O}$ of O_2 in air trapped in the Vostok ice [Sowers *et al.*, 1993] roughly coincide with variations in $\delta^{18}\text{O}$ of seawater reflected in the isotopic content of the forams in deep-sea sediments. This comparison is based on the fact that photosynthesis transmits seawater variations to atmospheric O_2 . There is also a good correlation between the Vostok dust concentration and the record of mass accumulation rate in the RC27-61 Indian Ocean core [Jouzel *et al.*, 1993].

Beyond their use as correlating and dating tools, each parameter conveys specific geochemical information. Variations in ^{10}Be concentrations are caused by factors other than accumulation changes. The existence

of ^{10}Be peaks around 35 and 60 kyr BP have been attributed to increases in production of this cosmogenic isotope [Raisbeck *et al.*, 1987]. The $\delta^{18}\text{O}$ of O_2 record also contains information about fractionation by biogeochemical and hydrologic processes. Similarities between Vostok and Southern Ocean temperatures indicate that the Vostok record is representative of a large geographical extent, while the general qualitative agreement with the $\delta^{18}\text{O}$ of deep-sea core suggests that the main broad features of this record are somewhat global in character.

The changes in terrestrial aerosols [Petit *et al.*, 1990] contain climate-related information. Greater dust concentration during full glacial periods than during interglacials probably indicates that glacial periods were characterized by more extensive deserts, more intense surface winds in the desert source regions, and/or more efficient meridional transport. This idea of stronger circulation during glacial periods is reinforced by the fact that glacial values of marine aerosols are much higher than interglacial levels.

Another important aspect of change in the past atmosphere's aerosol load is a secondary aerosol composed of the nonseasalt sulphate and methanesulfonic acid (MSA), an oxidation product of dimethylsulfide (DMS) emitted by marine biogenic activity. Although studies based on MSA measurements show that the link between climate and biogenic marine activity could be more complex than initially thought, both non-

seasalt sulphate and MSA records indicate that the ocean-atmosphere sulphur cycle is extremely sensitive to climate change [Legrand *et al.*, 1991].

Air Sampling

Air initially enclosed in Vostok ice provides our only record of variations in the atmospheric concentrations of CO₂ and CH₄ over a complete glacial-interglacial cycle [e.g., Raynaud *et al.*, 1993]. For both greenhouse gases, concentrations are higher during interglacial periods than during full glacial periods. Since preindustrial times, levels of CO₂ and CH₄ have increased by about respectively 40% and a factor of 2. A close correlation between these gas concentrations and the Vostok isotopic temperature has been confirmed by extending the record over part of the previous cycle [Jouzel *et al.*, 1993]. However, at the end of the last interglacial, the CO₂ decrease significantly lags the Antarctic cooling, while CO₂ and Antarctic temperatures increase in concert during the warmings corresponding to the glacial-interglacial transitions. Interestingly, at least during certain deglaciation periods, the trace-gas increase precedes—by several thousands of years—the onset of most melting of the northern ice sheets.

From a climatic viewpoint, CO₂ and CH₄ have played an important role. Together with the growth and decay of the Northern Hemisphere ice sheets, these greenhouse gases have amplified the initial orbital forcing and they account for about half of the glacial-interglacial climate changes. As for climate sensitivity, these data suggest that positive feedbacks operate in the climatic system and support the idea that significant greenhouse warming will occur in the next century [Raynaud *et al.*, 1993].

Ice sheet modeling is used to date ice cores and study long-term interaction between climate and the dynamics of large ice sheets [Salamatin, 1992]. Information gained from studies of ice texture and fabric [Lipinkov *et al.*, 1989], ice rheology, and ice densification is central to this objective. Models predict that ice sheet over Vostok will thin during cold periods. In agreement with this, the long-term trends of total air content in the ice show that during colder periods air pressure was higher which well supports the idea that elevation of the ice sheet was lower. Other studies confirm that microorganisms—including species that have disappeared

elsewhere—could survive in the deep Antarctic ice for many thousands of years following anabiosis.

Sample Analysis—Exciting Results

In France and the United States, analysis of samples of the last 200 m of core 5G are nearly complete and exciting results have been forthcoming. Figure 2 shows a first set of deuterium data from the bottom part of this core, a discontinuous series of 27 samples every 10 m or so. The timescale has been extended down to 2755 m giving an age of 260 kyr BP ($\pm 10\%$).

Although the chronology is preliminary, we note that the correspondence with the $\delta^{18}\text{O}$ of oceanic record of ice volume, relatively easy to establish back to the penultimate glacial, is not straightforward for the earlier part of the record because the uncertainty in ages increases with time in the past.

Jouzel *et al.* [1993] suggest that the bottom of core 4G (2546 m) reached back to cold marine stage 7.4 (around 220 kyr BP). If we accept this age, then we would associate the subsequent isotopic temperature maximum at ~ 2620 m depth with stage 7.5. Stage 8 at Vostok would then be much shorter than the oceanic record indicates, and the isotopic temperature maximum at the very bottom of the core would correspond to stage 9. This chronology is problematic. It is more likely that the bottom of core 4G—2546 m deep—may correspond to stage 7.2, which suggests that the deepest 5G samples correspond to 7.5.

Figure 2 also shows electrical conductivity measurements (ECM) performed in the field to search volcanic events and study change in the background signal. We can assume that the change of the impurity content associated with climate changes modifies the ice acidity (SO₄, NO₃, Cl) and thus electrical conductivity. For the bottom part of the core below 2500 m, a link with isotope content is observed, which supports the use of ECM as an additional climatic indicator.

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