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Dive into the timescales of deep ice cores

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We review some of the possible methods for building optimized and coherent timescales of deep polar ice cores. We focus on drilling sites characterized by a low temporal resolution due to minimal accumulation of snow at the ice-sheet surface.

Deep polar ice cores are unique archives of past climate. Their investigation is valuable to study mechanisms governing the Earth's climate variations during the glacial–interglacial cycles of the late Quaternary. Precise ice-core chronologies are essential to determine the sequences and durations of climatic events, as well as questioning phase relationships between the external forcings and the climatic responses. One example of climate forcings are the orbital parameters governing the amount of solar energy received at the Earth's surface.

Three challenges are associated with the dating of deep ice cores:

i. A coat of unpacked snow (50–120 m), the firn, covers the ice sheet. The atmospheric air circulates freely within the firn. At the firn-ice transition, the air is enclosed in bubbles and no longer diffuses. Hence, the construction of two separate chronologies is required: one for the ice and one for the younger air.

ii. Most of the paleoclimatic information is recorded within the deepest part of the ice core, due to the thinning of ice layers from their deposition at the surface to the bottom of the ice sheet. Improving the timescales of deep ice cores is therefore of great concern for the ice-core community, along with extending them further back in time.

iii. Ice cores drilled at sites characterized by high accumulation rates of snow at the surface (10–30 cm/year) are dated by counting annual layers via identification of a seasonal cycle in some records (Sigl et al. 2016). Conversely, some East Antarctic sites show comparatively low accumulation rates (1–5 cm/year), which prevent annual layers from being identified and counted. Chronologies of deep ice cores therefore involve other strategies, summarized below.

Glaciological modeling

Glaciological models simulate the flow and thinning of annual layers over time, from surface deposition down to the bedrock, thus providing the ice age–depth relationship (Parrenin et al. 2004). The model inputs are past scenarios of snow accumulation and temperature at the surface, estimated from water–isotope measurements, together with a calculated temperature–depth profile in the ice sheet. This strategy is highly dependent on poorly known boundary conditions and physical constants. Glaciological modeling is thus combined with dating constraints, which are depths with a known ice or gas age.

Dating constraints

Absolute dating constraints in ice cores can be determined using radioactive isotope records. The ^{10}Be production rate in the atmosphere relates to the geomagnetic field and solar activities. The Laschamp Excursion, a rapid drop in the Earth's geomagnetic field intensity, is visible as a peak in the ice-core ^{10}Be records, and is independently dated with different series at 41 kyr BP (thousand years before 1950; Raisbeck et al. 2017). Ice-core ^{40}Ar records reflect past atmospheric concentration modulated by the radioactive decay of ^{40}K in the Earth's crust (Yan et al. 2019). Recently, ^{81}Kr measurements on ice samples of a few kilograms provided age estimates between 1300 and 300 kyr BP (Buizert et al. 2014).

Another approach, called "orbital dating", consists in synchronizing ice-core proxies to the Earth orbital parameters (or targets), whose variations are precisely modeled in time. The alignment of the proxy with its target gives ice- or gas-age constraints (Fig. 1). Three orbital proxies are used: $\delta^{18}O_{atm}$, $\delta O_2/N_2$, and total air content. The oxygen in air bubbles ($\delta^{18}O_{atm}$) is sensitive to ocean

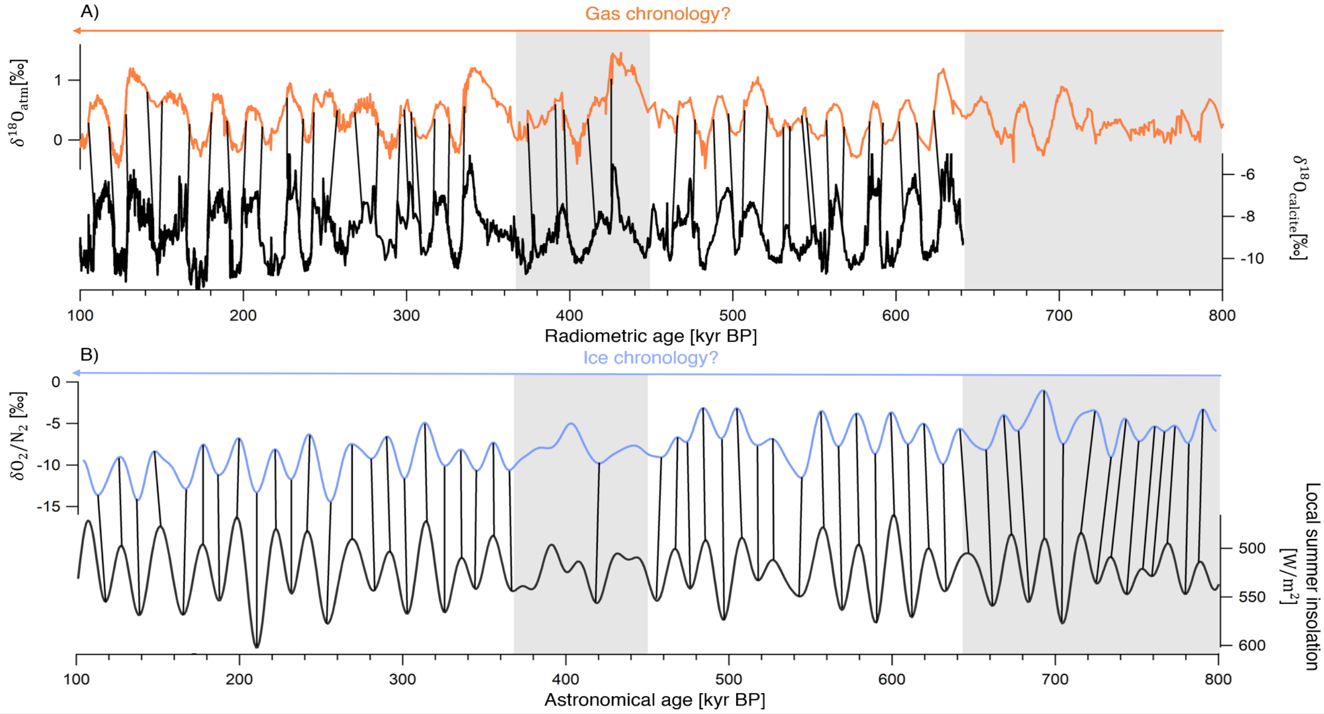

Figure 1: Synchronization of ice-core records with well dated series. Alignment of EPICA Dome C records of (A) $\delta^{18}O_{atm}$ and (B) $\delta O_2/N_2$ (Extier et al. 2018) to $\delta^{18}O_{calcite}$ from East Asian speleothems and local summer insolation, respectively. $\delta O_2/N_2$ is filtered in the insolation frequency band. Gray areas indicate time intervals of large dating uncertainty.

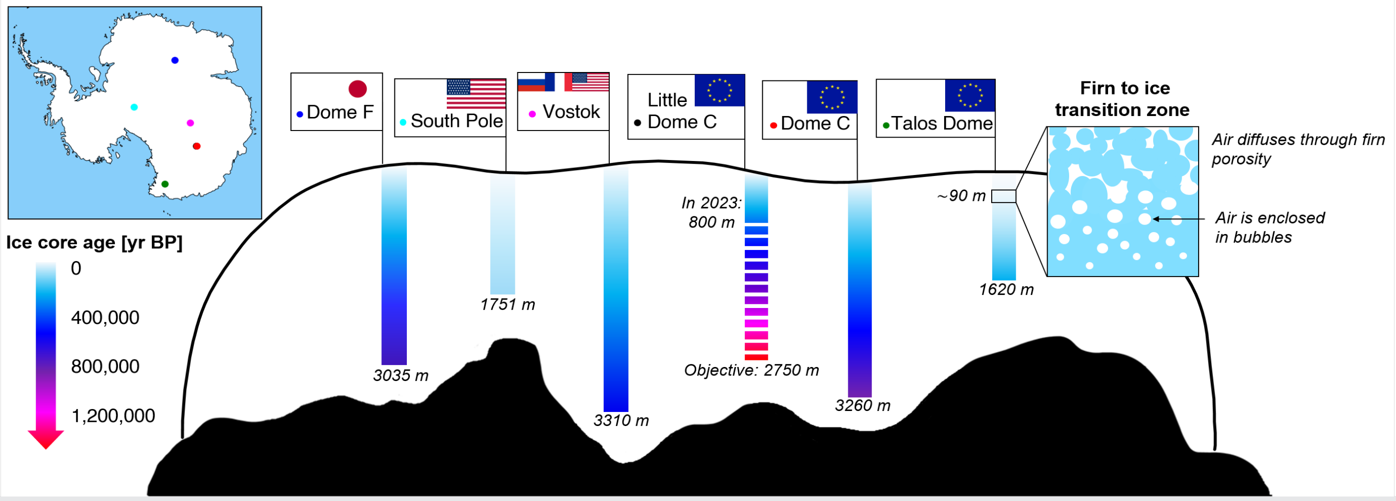

Figure 2: Deep East Antarctic ice cores and age scale. The numbers at the bottom of each ice core indicates the maximum depth drilled. Dome F (720 kyr BP), South Pole (54 kyr BP), Vostok (420 kyr BP), Dome C (800 kyr BP) and Talos Dome (340 kyr BP). The Little Dome C drilling aims to reach 2750 m, and 1.5 Myr BP.

water $\delta^{18}O$ (and, therefore, to the global ice volume), as well as to the biosphere productivity and the low latitude water cycle. Conversely, the oxygen in precipitation ($\delta^{18}O_{ice}$) depends on local temperature changes, and, thus, not used for orbital dating. $\delta^{18}O_{atm}$ was synchronized to the Earth's axial precession, delayed by 5000 years, because such a delay was observed during the last deglaciation. However, the lag of $\delta^{18}O_{atm}$ behind precession fluctuates. Rapid climatic instabilities linked to breakdowns of the Northern Canadian Ice Sheet (Heinrich-like events) occur during deglaciations, which could be responsible for occasionally delaying the response of $\delta^{18}O_{atm}$ to orbital forcing via changes in the water cycle (Extier et al. 2018). The variability of this delay induces a lack of confidence in the $\delta^{18}O_{atm}$–precession synchronization, associated with an uncertainty of 6000 years, which corresponds to the quarter period of a precession cycle. Further, the ice core $\delta^{18}O_{atm}$ and Chinese speleothems $\delta^{18}O_{calcite}$ signals display identical features. The two series show orbital-scale (induced by the precession forcing) and millennial-scale oscillations, both types of variations being associated with changes in the low latitude water cycle imprinted in $\delta^{18}O_{atm}$ and $\delta^{18}O_{calcite}$ (Fig. 1a).

To improve the precision of the gas chronology, it is preferable to synchronize the $\delta^{18}O_{atm}$ variations with the $\delta^{18}O_{calcite}$ record from uranium-series-dated Asian speleothems (Cheng et al. 2016). In addition, Bender (2002) and Lipenkov et al. (2011) observed that the $\delta O_2/N_2$ and total air content records simultaneously oscillate with the local summer insolation (Fig. 1b). They formulated the subsequent hypothesis: insolation modulates near-surface snow properties (grain size and shape). This imprint is preserved as snow densifies in the firn and, later, affects the ratio $\delta O_2/N_2$ and the total air content in deep ice. The total air-content variations share more similarities with Earth's axial obliquity than $\delta O_2/N_2$, hence its insolation target is integrated over an extended summer interval. Wiggle-matching between $\delta O_2/N_2$ and total air content, and their insolation targets gives dating constraints with a relative uncertainty varying between 1000 and 7000 years (Bazin et al. 2013). The orbital dating accuracy is liable to:

1. The choice of the well-suited orbital target;
2. its synchronization with the orbital proxy, which can be ambiguous when Earth's orbit is nearly circular; and
3. the poor quality of measurements in the deepest sections of the cores (gray areas in Fig. 1).

Other tracers supplying relative dating constraints, or stratigraphic links, improve the consistency between timescales of different ice cores over the last glacial–interglacial cycle. The synchronization of globally well-mixed atmospheric-methane records from Greenland and Antarctic ice cores brings in stratigraphic links with an accuracy of 60 to 500 years (Epifanio et al. 2020). Climate independent constraints, such as large volcanic eruptions, leave singular sulfate patterns in ice cores from both hemispheres. The detection of these deposits results in highly precise (within 5 to 150 years) stratigraphic tie points between cores (Svensson et al. 2020).

Connecting ice and gas timescales

The lock-in depth, indicating the depth threshold where the air is trapped in enclosed bubbles and no longer diffuses (Fig. 2), determines the age difference between the ice and gas phases at each depth. Through the diffusion column (the interval between the surface and the lock-in depth), the preferential downward diffusion of heavy isotopes increases the $\delta^{15}N$ fraction of N_2. Measurements of $\delta^{15}N$ in air trapped in ice cores yields a first estimate of the diffusion column thickness, and, therefore, of the lock-in depth. This depth can also be calculated with firn densification modeling (Bréant et al. 2017).

Bayesian dating tools

To build consistent ice-core chronologies combining independent synchronization, absolute and relative dating constraints, as well as glaciological modeling, Bayesian dating tools have been developed. Now, they have gained improved mathematical, numerical, and programming capacities (Parrenin et al. 2021). Prior estimates of gas and ice timescales built by glaciological models are statistically adjusted by the Bayesian tools to comply with the dating constraints. These probabilistic tools use an inverse method, integrating all dating information and associated relative uncertainty, to produce a coherent timescale for distinct ice cores.

Perspectives

Deep ice-core chronologies strongly rely on gas measurements. To improve the chronological precision, it is crucial to collect highly resolved data from ice samples stored at cold temperatures (-50°C) to avoid gas diffusion and loss of signal for $\delta^{18}O_{atm}$ and $\delta O_2/N_2$. The dating accuracy is soon to be challenged by the upcoming Beyond EPICA ice core, expected to provide much more paleoclimatic information within a shallower depth range than present ice-core drillings (1.5 Myr BP zipped in ~2750 m, Fig. 2) (Fischer et al. 2013).

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