GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 22, PAGES 4243-4246, NOVEMBER 15, 2001

# A tentative chronology for the EPICA Dome Concordia ice core

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**Abstract.** A tentative age scale (EDC1) for the last 45 kyr is established for the new 788-m EPICA Dome C ice core using a simple ice flow model. The age of volcanic eruptions, the end of the Younger Dryas event, and the estimated depth and age of elevated $^{10}$Be, about 41 kyr ago were used to calibrate the model parameters. The uncertainty of EDC1 is estimated to ± 10 yr for 0 to 700 yr BP, up to ± 200 yr back to 10 kyr BP, and up to ± 2 kyr back to 41 kyr BP. The age of the air in the bubbles is calculated with a firn densification model. In the Holocene the air is about 2000 yr younger than the ice and about 5500 yr during the last glacial maximum.

## Introduction

In the framework of the European Project for Ice Coring in Antarctica (EPICA) an ice core of 788 m length has been retrieved at Dome Concordia (75°06'06" S; 123°23'42" E; 3233 m a.s.l. [*Tabacco et al.*, 1998]) in 3 drilling seasons from 1996/7 to 1998/9 (hereafter EPICA DC). The drill site is on a local dome and is located about 55 km south of the 'old Dome C' drill site where a 906 m core was recovered in 1977/8. An accurate age scale of any ice core is the basis for the interpretation of the information obtained by analyzing samples of the core. There exist numerous methods for dating ice cores [*Hammer et al.*, 1978], like counting annual layers, identifying historically known or previously dated time markers (for example volcanic deposits), modeling the ice flow, and synchronization with the variations of the earth's orbital parameters. At a low accumulation site like Dome C counting of annual layers is not feasible because seasonally varying tracers are generally smoothed by diffusion during firnification, and annual precipitation layers are disturbed by wind scouring and the snow of individual years may even be entirely removed [*Petit et al.*, 1982].

Synchronization with other Antarctic ice cores is possible by matching variations in the stable isotope records and by identifying corresponding signals of volcanic deposits [*Wolff et al.*, 1999]. Generally a direct synchronization with Greenlandic cores based on climatic signals is not possible because of phase lags between the Northern and Southern hemisphere [*Blunier et al.*, 1998]. Only large equatorial volcanic eruptions produce global signals, but due to the local eruptions from Iceland and coastal Antarctic regions, the identification of global signals is a challenging task and has so far only been possible for a few events. Another important tool for global synchronization are cosmogenic radioisotope variations. However, there are only a few clear age markers, like for example the $^{10}$Be peak about 40 kyr ago [*Yiou et al.*, 1997].

Variations in atmospheric trace gases, especially those of methane ($CH_4$), allow an indirect 'global' synchronisation [*Blunier et al.*, 1998]. This method takes into account the age difference between ice and air in a sample (hereafter $\Delta$age), which depends predominantly on accumulation rate and temperature and can be modeled for past climatic conditions [*Schwander et al.*, 1997].

It is the scope of this paper to present a tentative age scale for the EPICA DC ice core (age of the ice and age of the trapped air to the present drilling depth), denoted as EDC1. On the long term it is desirable to have only one common time scale for all paleo-records and on the short term we should work with as few age scales as possible. From this point of view it would be better to synchronize EDC1 with an existing one. The Vostok ice core is the only candidate to which it could be linked with high confidence [*Wolff et al.*, 1999]. But since the current Vostok age scale [*Petit et al.*, 1999] is probably a little too young in the glacial period, we preferred to create a new age scale for EPICA DC, which we compare with other Antarctic and Greenlandic ice core chronologies.

## New Dome C Chronology

### Flow Model

The horizontal ice flow at Dome C is nearly zero. Therefore no upstream corrections are necessary and the vertical strain can be described with a simple one-dimensional model under the assumption of a fixed ice sheet thickness and uniform vertical deformation in the vicinity of the Dome C location. This is indeed not obvious since an anomaly in vertical strain rate is expected in the vicinity of an ice divide with the result that layers should arch up over the divide [*Vaughan et al.*, 1999]. However radar profiles from the Dome C area, showing many internal reflection layers, do not reveal any sign of anomaly in vertical strain [*Tabacco et al.*, 1998].

The model is based on a constant horizontal strain rate $\dot{\varepsilon}_x = \dot{\varepsilon}_{x0}$ of the upper part of the ice sheet, a shear layer of thickness $h$ below with horizontal strain rate $\dot{\varepsilon}_x$ decreasing linearly, and the bottom of the ice sheet sliding with the

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Paper number 2000GL011981.
0094-8276/01/2000GL011981$05.00

velocity $q \cdot v_{x0}$ [*Johnsen and Dansgaard*, 1992], where $v_{x0}$ is the horizontal flow velocity at the surface. The vertical strain $\varepsilon_z$ is readily derived by observing continuity ($x$ and $z$ are horizontal and vertical coordinates, where $z$ is zero at the bed rock and positive $z$ point upwards).

$$\varepsilon_z = \begin{cases} 1 - k(H - z) & h \le z \le H \\ kz(q + \frac{1-q}{2h}z) & 0 < z < h \end{cases} \quad (1)$$

where $k = \frac{2}{2H - h(1-q)}$, and $H$ is ice sheet thickness (ice equivalent). $h$ is of the order of $H/3$ to $H/2$ [*Paterson*, 1994]. Reported values for $q$ are of the order of 0.15 [*Johnsen and Dansgaard*, 1992]. The bedrock elevation at EPICA DC is close to sea level. The total ice sheet thickness is estimated to 3250 m. Since we use ice equivalent coordinates we must subtract the air filled space in the firn and ice. The total correction is 34.2 m, yielding $H = 3215.8$ m. We put $h =$ 1200 m and $q = 0.15$. Note that, to the present depth, the choice of $h$ and $q$ affects the resulting age scale much less than uncertainties in the age reference points. $h$ and $q$ will be more important and better determined once the core extends over one or more glacial cycles. Then we may also need to use a more sophisticated flow profile and to account for past variations of the ice sheet thickness.

## Past Accumulation Rates

¿From the flow model we can derive an age scale if we know past accumulation rates $a(z)$.

$$age(z) = \int_z^H \frac{dz'}{\varepsilon_{z'} \cdot a(z')} \quad (2)$$

Past accumulation rates are supposed to be proportional to the derivative of the mean saturation vapor pressure at the inversion layer with respect to temperature [*Jouzel et al.*, 1987]. The mean surface temperature $T_s$ is estimated from the stable isotope ratio in the ice: $T_s = T_{s0} + \beta^{-1}(\delta\mathrm{D} - \delta\mathrm{D}_0)$. $\delta$D is the measured per mille deviation of the isotopic ratio $^2\mathrm{H}/^1\mathrm{H}$ in the ice core [*Jouzel et al.*, in press] relative to mean ocean surface water corrected for past changes in isotopic ratio [*Sowers et al.*, 1993] and temperature. The modern deuterium ratio (last five centuries), $\delta\mathrm{D}_0$, is -396.5 per mille. $\delta$D has been measured to a depth of 585.2 m. For the remaining part of the core $\delta$D is estimated by matching the isotopic records of the old and the EPICA DC cores. The average modern firn temperature $T_{s0}$ is about -54°C. We set the inversion layer temperature as: $T_{inv} = T_{inv0} + \gamma(T_s - T_{s0})$. The present mean inversion temperature is about -40°C [*Jouzel and Merlivat*, 1984]. The value of $\beta^{-1}\gamma$ as well as the base-accumulation rate $a(T_{s0})$ result from calibrating the model with age reference points.

## Reference Ages

In principle two reference time points are required to determine $a(T_{s0})$ and $\beta^{-1}\gamma$. In case of more than two reference ages we adjust the model parameters by a least square fit of the data.

Our fixed age points (Table 1) are volcanic events, the end of Younger Dryas and the $^{10}$Be peak at about 40 kyr BP (before 1950 AD). It turned out that when applying the flow model with only one set of parameters for the entire depth range, we get modeled ages that lie partly beyond the estimated uncertainty of the reference ages. Therefore we decided to run the model with optimized parameter sets for the following three depth ranges.

**Table 1.** Age reference points (additional data at http://www.pangaea.de/Projects/EPICA)

| Depth (m) | Age | Event |
|---|---|---|
| 0.64 - 41.52 | 1992 - 1177 AD | 14 historically documented and other well dated volcanic signals |
| 58 - 233 | 1200 - 7100 yr BP | 27 volcanic signals matched with Vostok GT4 age scale |
| 363.5 | 11.53 kyr BP | End of Younger Dryas |
| 742.2 | 41 kyr BP | $^{10}$Be peak |

The first range (0 to 41.5 m) contains historical and other well dated volcanic events and covers roughly the last 820 years [*Udisti et al.*, 2000]. The second range (41.5 to 233 m) extends back to 7100 yrs BP. Here we fit the model to the Vostok GT4 scale [*Petit et al.*, 1999], which is connected to the dendrochronology to within 100 years by matching cosmogenic production rates of $^{10}$Be and $^{14}$C [*Raisbeck et al.*, 1998]. The depth to depth relation between EPICA DC and Vostok is based on the volcanic match and is highly accurate for this interval. In the third range (233 to 788m) the model fits the end of the Younger Dryas (YD) and the $^{10}$Be peak. The depth at EPICA DC corresponding to the end of YD has been estimated by isotope match (EPICA DC/Byrd [*Hammer et al.*, 1994]) and $CH_4$ match (Byrd/GRIP [*Blunier et al.*, 1998]). The end of the Younger Dryas cold period in the GRIP core is dated to 11530 ± 50 yr BP [*Spurk et al.*, 1998]. The main uncertainty of this reference point comes from the $\Delta$age estimate on the GRIP and Byrd cores (± 100 yr), the GRIP/Byrd $CH_4$ match (± 100 yr), and from the stable isotope match between EPICA DC and Byrd (± 200 yr), yielding an overall uncertainty of ± 250 yr. This sets the EPICA DC depth corresponding to the end of YD to 363.5 ± 10 m. Direct $CH_4$ match between EPICA DC and GRIP is possible but is less accurate due to the larger uncertainty of $\Delta$age in the EPICA DC core than in the Byrd core. A reference age near the end of the core drilled to date is the elevated $^{10}$Be concentration found in several other ice cores [*Yiou et al.*, 1997]. As EPICA DC is not yet analyzed for $^{10}$Be the expected position must be estimated by comparison with the nearby old Dome C core. Matching the isotope record of the two cores reveals a linear relationship between corresponding ice equivalent depths: depth (EPICA DC) = 0.891*depth (old DC). Accordingly the expected depth for the $^{10}$Be peak in the EPICA core is at 742 m (708 m ice equivalent). The age estimates for this event range from 35 kyr to 42.5 kyr [*Yiou et al.*, 1997]. By $\delta^{18}$O-matching of Northern Atlantic sediment cores with the GISP and GRIP ice cores, *Wagner et al.* [2000] have shown that the $^{10}$Be and $^{36}$Cl peaks around 40 kyr BP coincide exactly with the Laschamp geomagnetic excursion. We adopt an age of 41 ± 2 kyr BP for the Laschamp event as obtained from U/Th dating [*Schramm et al.*, 2000].

The resulting model chronology is shown in Fig 1. We estimate the uncertainty of EDC1 to ± 10 yr for 0 to 700 yr BP, up to ± 200 yr back to 10 kyr BP, and up to ± 2 kyr back to 41 kyr BP. An independent check of the age scale near the end of the glaciation is a fluoride event found in the Byrd Station ice core [*Hammer et al.*, 1997]. Preliminary analysis of the EPICA DC core showed an elevated fluoride

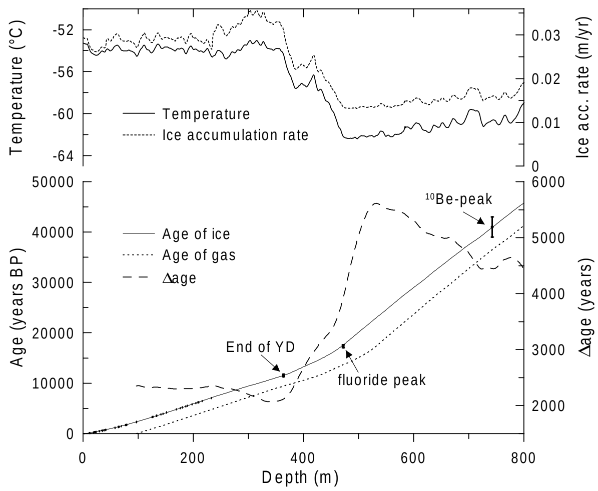


**Figure 1.** Tentative age scale for the EPICA DC core and age difference between ice and air (bottom) with past temperatures and accumulation rates (top). Reference points and fluoride peak are indicated with error bars. (Numerical data at http://www.pangaea.de/Projects/EPICA).

concentration (but less pronounced than in the Byrd core, pointing to a local Antarctic source) in a depth interval from 471.3 to 472.8 m. The comparison of the electrical conductivity signal of the EPICA DC and Byrd cores around the fluoride peak provides evidence that it is in fact the same event (Fig 2). Stratigraphic layer counting on the Byrd core yields an age of 17320 ± 300 yr BP [*Hammer et al.,* 1997, tuned by $CH_4$ matching at YD]. EDC1 age is 17620 yr BP, i.e. equal within the uncertainties.

The sensitivity $\beta^{-1}\gamma$ amounts to 0.1304 ± 0.0142 °C/per mille. The standard deviation results from the uncertainties of the fixed age points. At the Dome C area the present value of $\beta$ is about 7.5 per mille/°C [*Delmotte*, 1997]. The inferred value of $\gamma$ is 0.98 ± 0.11, which is significantly higher than 0.67 obtained from the modern spatial relation [*Jouzel and Merlivat*, 1984]. There are several possible reasons for the discrepancy. First, the temporal value of $\beta$ and/or $\gamma$ is in fact different from the modern spatial value. Second, we could have underestimated the uncertainty in our age reference points, especially of the $^{10}$Be peak. Third, there exist variations in accumulation rate not explained by the saturation vapor pressure estimated from the stable isotope ratio. Such non-thermal variations in accumulation rate seem to exist for example in the Holocene. The age model implies a decreasing trend through the Holocene (Fig. 1). The estimated change in $T_{inv}$ would account for only about one fourth of this change, suggesting additional causes, like changes in the atmospheric circulation or in the evaporation/precipitation ratio. An accurate estimate of the past accumulation rates is indeed the basis for an accurate age scale (equation 2) and new independent proxies are needed to improve ice core chronologies at low accumulation sites.

## The Gas Age Scale

Using estimated past surface temperatures and accumulation rates, we calculated Δage with a combined firn-densification/heat-transfer model [*Schwander et al.*, 1997]. The gas age vs. depth relation is shown in Fig. 1 together with the input data, $T_s(z)$ and $a(z)$. $T_s(z)$ is based on $\beta =$ 7.5 per mille/°C and $a(z)$ is inferred by the ice chronology. From the deviation between the direct link with the GRIP scale and the indirect link via the Byrd core (see next section and Fig 3) we estimate that the modeled EDC1 Δage record has an uncertainty of about 10%.

## Comparison with other Ice Chronologies

Because of the very similar stable isotope records and the unambiguous correspondence of volcanic signals we can compare EDC1 straightforwardly with the Vostok chronology. Several age scales were created for Vostok during the last decades. Here we restrict to the latest GT4 scale [*Petit et al.*, 1999]. The difference between GT4 and EDC1 is mainly due to difference in age assigned to the $^{10}$Be event (Fig. 3).

The comparison with the Byrd Station chronology [*Hammer et al.*, 1994] is made by matching the stable isotope records, which is less accurate because of deviations in the characteristic patterns. However, the fluoride event as well as the larger oscillations in the stable isotope records can clearly be identified in the EPICA DC and Byrd Station cores so that a coarse comparison is still possible.

The link to the Greenlandic ice cores [*The Greenland Summit Ice Cores CD-ROM*, 1997] is then made from the Byrd core to the GRIP core (SS09 scale by flow modeling and stratigraphic scale by layer counting) through variations in the $CH_4$ mixing ratio [*Blunier et al.*, 1998], and GRIP and GISP2 (layer counting) are linked by matching their stable isotope records. The comparison by the less accurate direct match of the $CH_4$ records from EPICA DC [*Monnin*, 2001] and GRIP is also shown in Fig. 3 (GRIP SS09 direct). The difference between the direct and the indirect match (via Byrd) suggests that the densification model somewhat overestimates EPICA DC Δage at glacial conditions, in agreement with an unexpectedly shallow glacial firn layer at old DC indicated by $\delta^{15}$N measurements [*Sowers et al.*, 1992]. We emphasize here that the comparison shown in Fig. 3 holds no judgment on accuracy of the different chronologies. All of them are still roughly within the uncertainty of EDC1.

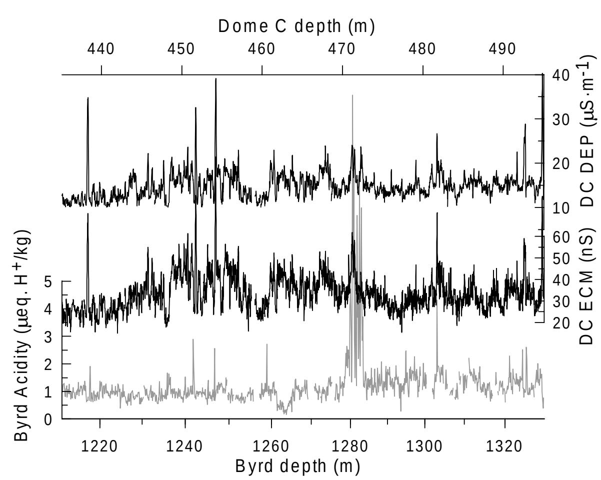


**Figure 2.** A fluoride peak has been found at 1281 m in the Byrd core and at 471 m in the EPICA DC core. The correspondence of volcanic signals in this interval provides evidence that the fluoride peaks in the two cores are from the same event. ECM and DEP are electric conductivity signals [*Wolff et al.*, 1999].

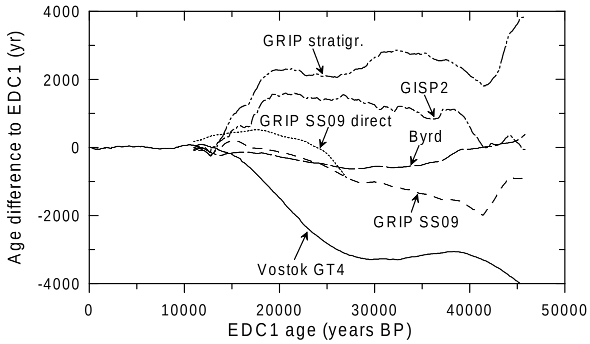


**Figure 3.** Deviations between other ice core chronologies and EDC1 (see text for details).

**Acknowledgments.** This work is a contribution to the "European Project for Ice Coring in Antarctica" (EPICA), a joint ESF (European Science Foundation)/EU scientific programme, funded by the European Commission under the Environment and Climate Programme (1994-1998) contract ENV4-CT95-0074 and by national contributions from Belgium, Denmark, France, Germany, Italy, the Netherlands, Norway, Sweden, Switzerland and the United Kingdom. This is EPICA publication no. 26. We thank A. Dällenbach, J. Beer, G. Wagner, H. Clausen, S. Johnsen, V. Masson, and B. Stauffer for constructive discussions, and our colleagues involved in drilling, science and logistics at Dome C.

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(Received July 5, 2000; revised December 15, 2000;
accepted March 14, 2001.)