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“EDML1”: a chronology for the EPICA deep ice core from Dronning Maud Land, Antarctica, over the last 150 000 years

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Abstract

A chronology called *EDML1* has been developed for the EPICA ice core from Dronning Maud Land (EDML). *EDML1* is closely interlinked with *EDC3*, the new chronology for the EPICA ice core from Dome-C (EDC) through a stratigraphic match between EDML and EDC that consists of 322 volcanic match points over the last 128 ka. The *EDC3* chronology comprises a glaciological model at EDC, which is constrained and later selectively tuned using primary dating information from EDC as well as from EDML, the latter being transferred using the tight stratigraphic link between the two cores. Finally, *EDML1* was built by exporting *EDC3* to EDML. For ages younger than 41 ka BP *EDML1/EDC3* is based on dated volcanic events and on a match to the Greenlandic *GICC05* time scale via ^{10}Be and methane. The internal consistency between *EDML1* and *EDC3* is estimated to be typically ~ 6 years and always less than 450 years over the last 128 ka (always less than 130 years over the last 60 ka), which reflects an unprecedented synchrony of time scales. *EDML1* ends at 150 ka BP (2417 m depth) because the match between EDML and EDC becomes ambiguous further down. This hints to a complex ice flow history for the deepest 350 m of the EDML ice core, which amongst other reasons may be caused by spatial variations of the geothermal heat flux.

1 Introduction

The chronology of an environmental archive is among the most fundamental aspects in paleo-climatology because it is an important basis for most data interpretation, particularly with respect to cyclicity, and to phasing between events at different sites. Techniques for the development of an ice-core chronology (or time scale) comprise (i) counting of annual layers if they are preserved in the core and the analytical resolution is sufficient, (ii) age-adoption of independently dated and unambiguously identified reference horizons such as selected volcanic eruptions, magnetic anomalies, as well

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as transitions or anomalies of temperature, aerosol tracers, gas composition, or other parameters, (iii) glaciological ice-flow modelling at various complexity and (iv) tuning of climatic and “non-climatic” parameters to orbital insolation changes, e.g. Hammer et al. (1978); Parrenin et al. (2007¹); Schwander et al. (2001). While the chronologies should be as “correct” as possible in an absolute sense, a lot more can be learned from climatic records if they are compared to others on the basis of a synchronised time scale. Even if such a time scale would be uncertain in an absolute sense, important questions regarding leads, lags and synchronicity of climatic events in two or more archives can be investigated only if their time scales are sufficiently synchronised. Therefore, for the two ice cores within the European Project for Ice Coring in Antarctica (EPICA), for the far-reaching core (EDC) from Dome C (EPICA-community-members, 2004) and for the higher-resolution core (EDML) from Dronning Maud Land (EPICA-community-members, 2006), a new synchronised time scale called *EDML1/EDC3* was constructed, which considered dating inputs from both cores. This was possible due to a tight stratigraphic link between the two cores. The scope of this paper is to summarize the EDML-aspects of this dating procedure. For further details on strategy and methods of the *EDML1/EDC3* time scale see Parrenin et al. (2007¹) and other papers in this special issue.

The EDML ice core was drilled at Kohnen station (75°00′ S, 0°04′ E, 2892 m [WGS84]) in the interior of Dronning Maud Land (DML), East Antarctica. The current snow accumulation rate is 64 kg/m² per year (Oerter et al., 2004), which makes it a potential site for layer counting during the Holocene. Although stochastic counting errors may be limited to a tolerable amount, an unconstrained counting leads to the danger of accumulating systematic counting errors. For the Holocene section it

¹Parrenin, F., Barnola, J.-M., Beer, J., Blunier, T., Castellano, E., Chappellaz, J., Dreyfus, G., Fischer, H., Fujita, S., Jouzel, J., Kawamura, K., Lemieux, B., Loulergue, L., Masson-Delmotte, V., Narcisi, B., Petit, J.-R., Raisbeck, G., Raynaud, D., Ruth, U., Schwander, J., Severi, M., Spahni, R., Steffensen, J. P., Svensson, A., Udisti, R., Waelbroeck, C., and Wolff, E.: The EDC3 agescale for the EPICA Dome C ice core, *Clim. Past Discuss.*, submitted, 2007.

therefore was preferable to transfer the well-established, counted Greenlandic ice core chronologies by matching profiles of Antarctic ^{10}Be production rates to the one from GRIP and to adopt the new unified Greenlandic Ice Core Chronology *GICC05* (Rasmussen et al., 2006). However, layer counting should still be attempted at EDML to interpolate between adopted control points.

The EDML drill site is located on a very gentle slope, 30 km west of the point where the main ice divide in DML coming from the east branches off into two ice divides running approximately to the northwest and southwest. The horizontal flow velocity at the drill site is 0.76 m/a (Wesche et al., 2007²). Thus, buried layers of ice originated at a surface position upstream of the drill site at higher elevation. Therefore, unlike for dome-positions such as EDC or GRIP, a 1-D glaciological ice flow model cannot be employed to find a realistic chronology. Instead, a 3-D glaciological model is necessary to consider the full ice flow dynamics and to take into account upstream variations of the snow accumulation rate. For example, the ice in the EDML ice core with an age of 150 ka originated 160 km upstream, where at present the surface elevation is 240 m higher and based on model calculations the accumulation is expected to be reduced by 35% compared to the drill site. Furthermore, accumulation does not only show a decreasing trend with increasing surface elevation (Oerter et al., 2000) but also shows considerable accumulation anomalies in excess of 20% on the scale of several 10 km (Eisen et al., 2005; Rotschky et al., 2004). If caused by underlying bedrock topography such variations would not be random but stationary in space and must be prescribed in the model because in the ice core they would appear as variations over time. The resulting complexity of the 3-D glaciological model is such that an inverse parameterization method, used to make the modeled time scale fit prescribed control windows (Parrenin et al., 2007¹), becomes impractical. Therefore, for dating the EDML ice core, the results of the 1-D ice flow modeling for EDC were adopted for EDML.

The strategy chosen was to construct first a tight stratigraphic link between the EDML

²Wesche, C., Eisen, O., Oerter, H. Schulte,, D., and Steinhage, D.: Surface topography and ice flow in the vicinity of EDML deep-drilling site, *J. Glaciol.*, submitted, 2007.

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and EDC ice cores mainly based on a volcanic synchronization (see also Severi et al., 2007³). Then selected dating constraints from EDML were transferred to EDC and were considered in the construction of the new modeled time scale for EDC, called *EDC3* (Parrenin et al., 2007¹). Finally, the dependent timescale called *EDML1* was established by transferring *EDC3* from EDC to EDML using the same stratigraphic EDML-EDC link. All *EDML1/EDC3* dates are given as years before present (a BP) with reference to AD 1950.

2 EDML-EDC stratigraphic link

The stratigraphic link between the EDML and EDC ice cores was established by matching volcanic events in the cores down to 2366.1 m in EDML, which corresponds to 1683.93 m in EDC99 or an *EDML1/EDC3*-age of 128.3 ka BP. Beyond 2366.1 m the stratigraphic link of EDML to EDC was established using profiles of dust concentration and stable water isotopes (see below). A complete list of all stratigraphic match points used is given in Table S1 (see the electronic supplement <http://www.clim-past-discuss.net/3/549/2007/cpd-3-549-2007-supplement.zip>)

It should be noted that there are two EPICA cores at Dome C: the ~788 m deep core (~45 ka BP) called *EDC96* (drilling commenced in 1996) with its time scale originally being *EDC1* (Schwander et al., 2001) and the core to bedrock called EDC99 with its timescale originally being *EDC1* back to 45 ka BP and *EDC2* beyond (EPICA-community-members, 2004). The last volcanic match of EDML to core *EDC96* is (EDML depth 1435.08 m/EDC depth 778.36 m); the first match to core *EDC99* is (1439.06 m/780.59 m). At the transition from *EDC96* to *EDC99* there is a small depth off-set of 73 cm (Wolff et al., 2005).

³Severi, M., Castellano, E., Morganti, A., Udisti, R., Ruth, U., Fischer, H., Huybrechts, P., Wolff, E., Parrenin, F., Kaufmann, P., Lambert, F., and Steffensen, J. P.: EDML-EDC ice-core synchronisation for the last 52 kyr by volcanic signatures matching, *Clim. Past Discuss.*, in preparation, 2007.

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Further, it should be noted that there are also two cores at Kohlen station: the ~150 m deep core B32, which was drilled 1.7 km west (downstream) from the EDML drill site during the pre-site survey in the 1997/98 season and has a counted chronology (Traufetter et al., 2004), and the main core called EDML. For the top 113 m of EDML the counted chronology was transferred from B32 to the EDML deep core (matching based on DEP peaks in the 3-inch access drilling of the EDML core and SO₄ peaks in B32). There is a considerable depth off-set between EDML and B32 of >5 m at 150 m depth. The volcanic horizons used to translate between EDML, B32 and EDC are listed in Table S2 (see the electronic supplement <http://www.clim-past-discuss.net/3/549/2007/cpd-3-549-2007-supplement.zip>).

2.1 Volcanic match points

Explosive volcanic eruptions inject large quantities of sulphuric acid (H₂SO₄) and its gaseous precursor SO₂ into the atmosphere, where H₂SO₄/water droplets form. This leads to increased concentrations of H⁺ and SO₄²⁻ in deposited snow. H⁺-anomalies can be identified in frozen ice by means of Dielectric Profiling (DEP) (Wolff et al., 1999) and the Electric Conductivity Method (ECM) Clausen et al., 1997 or in melted samples by measuring the electrolytical conductivity (Cond) (Röthlisberger et al., 2000); SO₄²⁻-concentrations can be measured using Ion-Chromatography (IC) or Fast-Ion-Chromatography (FIC) Traversi et al., 2002. The deposits of large volcanic eruptions occur as singular events with durations of weeks to years and can be used as isochrones in ice cores. If found in two ice cores, a series of events resembling a pattern with characteristic intervals between the peaks or characteristic peak heights can be used to match the cores with high confidence. Slow but persistent diffusive broadening of H⁺ and SO₄²⁻-peaks in the ice (Barnes et al., 2003) eventually limits the matching at greater depth.

During the volcanic synchronization between EDML and EDC, three groups of investigators first worked independently to generate a list of suggested matches, each group using different combinations of parameters (in the following denoted as [EDML/EDC]-

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pairs): (i) [DEP/DEP], (ii) [$\text{SO}_4^{2-}/\text{SO}_4^{2-}$], and (iii) [electrolytical conductivity/ SO_4^{2-}]; the latter was double checked by [electrolytical conductivity/electrolytical conductivity], which however did not produce any different results for these cores from interior East Antarctic sites. Table 1 gives an overview of the parameters involved for respective depth ranges. The profiles of insoluble dust concentrations were used for a first rough alignment of the two cores. This procedure is based on the assumption that the East Antarctic sites receive dust from a common Patagonian dust source during glacial times, and that changes in source strength, or in processes near the source, are the main control on the significant changes seen in both ice cores (Delmonte et al., 2006; Mulvaney et al., 2000). Each volcanic match was assigned a confidence value ranging from 1 meaning “certain” to 4 meaning “tentative”. If a match consisted of a series of peaks with an unambiguous pattern clearly recognizable in both cores it was labelled “certain”; a match with no or only a weak pattern was labelled “tentative”. The so-called “tentative” matches should be treated with more caution than the others but also these provide likely stratigraphic links. Although the choice of the confidence value is admittedly very subjective it still provides some indication of the reliability of each match.

After completion of the independent work of the three groups, the suggested matches were synoptically reviewed. There was a great mutual support of the matches, and among the three groups only five matches proved incompatible with others and needed to be withdrawn. From the other matches a “synthesis list” was generated to avoid double assignments and disturbances resulting from small off-sets of the depth scales associated with the different parameters used. This resulted in a list of 322 volcanic EDML-EDC matches (including 51 “tentative” matches). One of these matches was independently confirmed by geochemical fingerprinting of associated tephra shards in both cores [Kohno, pers. communication].

The volcanic matching was based on SO_4^{2-} concentration data where available, as this is a specific volcanogenic tracer for interior East-Antarctic sites (Udisti et al., 2004). For details and implications of the volcano-stratigraphic link see (Severi et al., 2007³).

For ages older than 52 ka BP there is no SO_4^{2-} data available yet and the matching was based on slightly less specific conductivity data, which however also provide good indication for volcanic events. Figure 1 illustrates examples of volcanic matches based on electrolytical conductivity from ~2100 m EDML-depth (~92 ka BP).

The volcanic matching becomes increasingly difficult below 1900 m (75 ka BP) being limited by considerable peak diffusion at EDML. Only the largest volcanic events can be identified, which is reflected by increasing intervals between adjacent match points. The last “certain” match is at 2273 m (115 ka BP). Beyond 2366 m (128 ka BP) there are no appreciable acidic spikes left in EDML because the volcanic acid deposits are too diffused to be clearly recognised.

2.2 Non-volcanic match points

A volcanic match is not feasible below 2366 m (128 ka BP) because of peak diffusion in the EDML core. It offered no solution to let the glaciological flow-model run freely beyond the last volcanic match as this produced too young ages for the termination of MIS6. This indicates that the annual layers at this depth are thinned more than expected. Below 2366 m EDML and EDC were thus linked via three match points based on insoluble dust concentrations and isotopes (EDML-depth / EDC99-depth/*EDC3*-age): (2382 m/1745 m/133 ka), (2410 m/1831 m/148 ka), and (2452 m/1901 m/162 ka). Given the extremely high covariance of $\delta^{18}\text{O}$ and dust at EDC and EDML in the top part, it appears justified to assume a continuing synchronicity of these parameters also for deeper ice in the EDML and EDC ice core. The match at 2382 m is placed at mid-transition of termination 2 and has an estimated error of several centuries; the match at 2410 m is placed on an increase of dust concentrations and the match at 2452 m on a feature in dust and isotopes. The last two matches are increasingly uncertain, possibly by several thousand years (see supplemental Fig. S1 <http://www.clim-past-discuss.net/3/549/2007/cpd-3-549-2007-supplement.zip>). The *EDML1* chronology is restricted to 150 ka BP (2417 m depth) because the match becomes ambiguous beyond.

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2.3 Interpolation between the stratigraphic match points

Between the match points a piecewise cubic Hermite interpolation (similar to cubic spline interpolation except that it produces no over-shoots) (MathWorks, 2002) was chosen to interpolate between EDML-depth and EDC-depth. Thus every EDML-depth d_{EDML} between the match points was assigned a corresponding EDC-depth d_{EDC} . Then the *EDC3*-age was determined for d_{EDC} . That way the EDC-accumulation history (inferred from EDC isotopes during construction of *EDC3*) is used implicitly for interpolation between the match-points at EDML.

3 Constructing the chronology

The *EDML1* time scale is based on *EDC3*, which is a modelled glaciological time scale at EDC, modified in places by tuning. *EDC3* is consistent with paleo-snow-accumulation rates and ice thinning at EDC. Paleo-accumulation rates were reconstructed from isotopic temperatures at EDC, and model parameters were optimized such that the resulting time scale is consistent with the prescribed dating constraints.

The resultant modelled scale was then tuned to force it through a set of particularly well-controlled points. Most dating constraints for the Holocene and late glacial period were “imported” from EDML, while others derive from direct comparisons from EDC to other palaeoclimatic records. In the following we summarize the dating constraints relevant for *EDML1*. For a detailed description see (Parrenin et al., 2007¹).

3.1 Dating constraints for *EDML1/EDC3*

The primary dating constraints from EDML are dated volcanic eruptions during the last ~1000 years, a synchronization to the Greenlandic *GICC05* chronology via ¹⁰Be (during Holocene) and methane (Termination 1).

The top part of the *EDML1/EDC3* chronology is based on the counted time scale of B32. The counting was performed on high-resolution data of continuous flow analyses

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(CFA) and discrete ion chromatography (IC) of major ion composition (Sommer et al., 2000; Traufetter et al., 2004). Seven volcanic events, the oldest one of which dated to 779 ± 5 BP, were selected to transfer the B32-dating to *EDML1/EDC3* (see Table 2).

^{10}Be is a cosmogenic radionuclide like ^{14}C ; their production rates are modulated by solar activity and by the strength of the Earth's magnetic field and therefore include a variability that can be recognised globally. Changes in the production rate of ^{10}Be and ^{14}C provide a global signal which can be used to synchronize ice cores between the hemispheres or with the INTCAL tree ring chronology. Two control points have been used to constrain the *EDML1/EDC3* chronology at 2.75 ka BP and 5.3 ka BP. These two points result from ^{10}Be -based dating exercises of the EDML core (this work) and of the Vostok BH1 core (G. M. Raisbeck, personal communication, 1998), with Vostok matched to EDC by a similar volcanic matching procedure (Udisti et al., 2004); these have been matched to *GICC05* via GRIP ^{10}Be and to INTCAL. At these two control points both cores agreed to within a few decades, after checking consistency via volcanic stratigraphic markers (Severi et al., 2007⁸; Udisti et al., 2004; Wolff et al., 1999). Both control points are chosen during times of considerable variations of the ^{10}Be production rate, thus adding further confidence on the matching approach (see supplemental Fig. S2 <http://www.clim-past-discuss.net/3/549/2007/cpd-3-549-2007-supplement.zip>). *GICC05*-dates were applied for the two control points chosen, but within the error bar of 50 years used at this depth when building *EDC3* (Parrenin et al., 2007¹) there is no difference between the Greenlandic *GICC05* ice core chronology and the INTCAL tree ring chronology.

Synchronisation of Antarctic and Greenlandic ice core records is also possible via methane concentrations, which have a common global signature and show rapid jumps that follow closely rapid jumps in Greenland temperature. However, the low accumulation rate at EDC leads to a large uncertainty for the calculation of delta-depth (the depth difference between ice and enclosed air of the same age) and delta-age (the age difference between ice and enclosed air at the same depth). For EDML this uncertainty is strongly reduced due to a higher accumulation rate and a higher annual mean

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temperature (e.g. for the Younger Dryas-Preboreal transition $\Delta\text{age}_{EDC} \approx 3200 \pm 770$ yrs while $\Delta\text{age}_{EDML} \approx 1000 \pm 200$ yrs). For the rapid warmings at the onset of the Bölling and the demise of the Younger Dryas the EDML methane data were matched to the Greenlandic NGRIP stable isotope record (NGRIP-project-members, 2004). The corresponding NGRIP-*GICC05* dates were transferred first from the EDML gas depth-scale to the EDML ice depth-scale by subtracting the calculated delta-depth and then further on from EDML to EDC via the volcanic match between the two cores (Severi et al., 2007³).

Apart from these constraints from EDML, the *EDC3* chronology was further constrained based on dating information from EDC at the ¹⁰Be-peak of the Laschamp event and during Termination 2. For Laschamp, the ¹⁰Be double-peak centered at 740.08 m in EDC96 (Raisbeck et al., 2002) was placed at 41.2 ka BP following the layer-counted Greenlandic *GICC05* date (Andersen et al., 2006; Svensson et al., 2006). After completion of the *EDML1* time scale Laschamp was also measured and identified in EDML and confirmed the volcanic synchronization. During Termination 2 a rapid methane event is used to place 1698.91 m EDC99 (ice), which corresponds to 2370.5 m in EDML, at 129.2 ka BP on the basis of U/Th speleothem dates. For more details on the construction of *EDC3* and a list of all control points used for *EDC3*, including those beyond the range of the synchronisation with EDML, see (Parrenin et al., 2007¹).

3.2 Time scale results and dating uncertainties

The resulting depth-age relation for EDML is shown in Fig. 2 and provided numerically in Table S3 (see online supplement <http://www.clim-past-discuss.net/3/549/2007/cpd-3-549-2007-supplement.zip>). The associated annual layer thickness λ is also shown: during the densification process λ rapidly decreases rapidly from >150 mm/a at the surface to ~70 mm at 100 m depth (~1 ka BP); λ is >45 mm for the entire Holocene. During MIS2 – MIS4 λ is around 20 mm at EDML. λ is always larger at EDML than at EDC for the last ~80 ka; also, variations of λ are more distinct at EDML, which may possibly be related to climatic variations of accumulation rates; between 80 ka and 93 ka λ

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is about the same for EDML and EDC (~10 mm); and for ages older than ~93 ka BP λ is larger at EDC than at EDML.

Thus, the time-resolution of the data will be better at EDML for the last 80 ka, if not longer considering that surface reworking or wind erosion may be more destructive at Dome C due to the lower accumulation rate.

The dating uncertainty for *EDML1* is the sum of three possible contributions: (i) the uncertainty of the EDC3 time scale, (ii) possible errors in the stratigraphic match between EDML and EDC, and (iii) the uncertainty of the stratigraphic interpolation in between these match points.

The absolute dating uncertainty for *EDC3* is estimated by (Parrenin et al., 2007¹) to be ~100 a for most of the Holocene, and increases to ~1.5 ka at 40 ka BP and to ~6 ka at 130 ka BP. A possible error is difficult to quantify, but probably minimal. Although theoretically still possible, the chance for volcanic match-point errors has been minimized: Several teams have worked independently, and dust records have been used to avoid severe apparent mismatches between the cores. Further, the differentiated depth-depth relationship has been checked to avoid severe anomalies of the depth-age relationship. The uncertainty of the stratigraphic interpolation between the match points is estimated in the next subsection; this estimate also takes into account possible errors of the so-called “tentative” matches (see below).

As stated earlier, the match-point error may be considerable for the non-volcanic match-points used below 2366 m (128 ka BP). Here, the synchronisation uncertainty amounts to several 100 years during termination 2 and quickly increases to several 1000 years at 150 ka BP. The stratigraphic synchronisation error will in any case be less than the absolute time scale uncertainty of *EDC3*.

3.3 Uncertainty of the stratigraphic interpolation

The median time span between two consecutive volcanic matches is 230 years and the maximum is 3800 years (at 125 ka BP). For the period younger than 75 ka BP the median time span is 190 years and the maximum is 1500 years (at 66 ka BP). Figure 3b

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shows a time series of these values and also differentiates between all matches and all “non-tentative” matches.

An empirical relationship was derived to estimate the synchronization error between the volcanic match points. This was done by determining the age shift Δt at the EDML-depth d_j of every volcanic match point that resulted from repeating the interpolation after removing this point from the table of synchronization match-points. Subsequently, the adjacent match points were also removed and the interpolation repeated until the nearest remaining match point was more than 10 000 years away. The resulting age shifts for each d_j are interpreted as the potential synchronisation errors that would have resulted if the match points had not been chosen. Plotting each age shift Δt vs. the age gap t_{nearest} to the nearest (remaining) match point leads to an empirical estimate of the interpolation uncertainty depending on t_{nearest} . Figure 4 illustrates the distribution of the interpolation uncertainty. Apparently, the probable interpolation error increases linearly with the t_{nearest} .

From the data in Fig. 4 the most-probable interpolation error $\langle err \rangle$ and the expected-maximal interpolation error $\langle err_{\text{max}} \rangle$ can be evaluated. This was done by calculating first the ratio $b = \Delta t / t_{\text{nearest}}$ for each data point, then grouping all data points into 22 bins j of t_{nearest} , and subsequently calculating the mean $b_{\text{mean},j}$ and maximum $b_{\text{max},j}$ slope for each of the 22 bins. Averaging over all bins j yields $\langle err \rangle = \text{mean}(b_{\text{mean},j}) = (2.6 \pm 0.5 \text{ years}/100 \text{ years}) \cdot t_{\text{nearest}}$ and $\langle err_{\text{max}} \rangle = \text{mean}(b_{\text{max},j}) = (15 \pm 6 \text{ years}/100 \text{ years}) \cdot t_{\text{nearest}}$, i.e. if the nearest match point is 100 years away then the most-probable interpolation error is 2.6 years whereas the expected-maximal interpolation error is 15 years.

The same results are obtained, regardless whether all volcanic match points are considered or only the “non-tentative”, or only Holocene or only Pleistocene match points. Most-probable and expected-maximal interpolation errors are indicated in Fig. 4 as blue and red lines. The value determined for $\langle err_{\text{max}} \rangle$ is a conservative estimate, because 99.5% of all points deviate less than suggested by this estimate; this is not only true for large but also for small values of d_{nearest} (see inset in Fig. 4). It proved im-

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portant to use the interpolation method as described above, i.e. first transfer any given EDML-depth to its corresponding EDC-depth and secondly determine its age. As an alternative method it was tested to first determine the ages for all EDML match points and then directly interpolate depth to age (i.e. to not use implicitly EDC accumulation rates); this alternative method yielded interpolation uncertainties larger by ~50% and therefore was not used.

The empirical parameterization for $\langle err \rangle$ and $\langle err_{max} \rangle$ can be used to calculate the most-probable and expected-maximal interpolation errors along the EDML ice core. The same parameter values are used for the full core, i.e. it is assumed that the nature of interpolation errors is the same throughout. For calculation of $\langle err_{max} \rangle$ only the “non-tentative” match points were considered and for $\langle err \rangle$ “tentative” match points were considered with 50% weight only, i.e. $\langle err_{max} \rangle$ further increases around “tentative” match points and $\langle err \rangle$ is the average of considering all and only “non-tentative” match points. The resulting profiles are shown in Fig. 3c (data provided together with time scale in Tab. S3, see online supplement). For the past 128 ka, the average values for $\langle err \rangle$ and $\langle err_{max} \rangle$ are 6 and 42 years; the maximum values are 50 and 450 years, respectively. For the past ~60 ka $\langle err \rangle$ is always less than 20 years and $\langle err_{max} \rangle$ is always less than 130 years. Thus, the interpolation error is always small compared to the absolute dating uncertainty. This information will be important for discussing possible leads or lags between climatic signals in EDML and EDC.

4 Comparison to other time scales for Holocene

A comparison of the *EDML1/EDC3* time scale to other time scales for the Pleistocene is given by (Parrenin et al., 2007¹). Here we discuss the Holocene. Figure 5 shows the deviations of other ice core time scales from *EDML1/EDC3*. Given the close volcanic link between EDML and EDC it is straight-forward to evaluate deviations of the *EDC1* and *EDC2* chronologies. During the last 8000 years these timescales agree within 100 years – within even 20 years during the last 2000 years. During early Holocene and

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the last glacial termination the deviations increase to over 200 years reaching ~500 years (*EDC1*) and ~800 years (*EDC2*) during the Late Glacial at around 20 ka BP. We propose that the new *EDML1/EDC3* chronology is a significant improvement for this period, however, it should be noted that *EDC2* never was a recommended time scale for ages younger than 45 ka BP, because it was constructed using a single set of model parameters that were strongly influenced by constraints in the deeper part of the ice.

For the comparison of *EDML1/EDC3* to the Greenlandic *GICC05* time scale ^{10}Be production rates as inferred from EDML and GRIP have been matched. An automated algorithm has been used to shift and stretch the EDML ^{10}Be production rates until the correlation to the GRIP ^{10}Be production rates (on the *GICC05* chronology) is maximized. This resulted in a proposed *GICC05*-like chronology for EDML, from which two control points were selected to constrain *EDML1/EDC3* (open circles in Fig. 5) as mentioned earlier. Figure 5 shows the deviation of this *GICC05*-like chronology from *EDML1/EDC3* from 1300 to 6000 years BP, which is the period for which EDML- ^{10}Be data are available so far. The differences are typically less than 40 years, i.e. there is a considerable degree of interhemispheric consistency between the time scales *EDML1/EDC3* and *GICC05*. The largest deviation is between 3300 and 4500 years BP, when the deviations increase to up to 160 years. However, this is a time where the ^{10}Be production rate shows only weak variations and the matching approach may possibly not be fully robust; therefore the *EDML1/EDC3* chronology was not further constrained during this period.

5 Conclusions

A new ice core chronology has been developed jointly for the EPICA ice cores at Dronning Maud Land and Dome-C for the last 150 kyrs. Central to this new chronology is a detailed volcano-stratigraphic link between the two cores (Severi et al., 2007³). Using this link all primary dating constraints from the EDML core were first transferred to EDC, where ice flow configurations are less complex. Inverse 1-D ice flow modelling at

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Dome-C was then used to interpolate between all dating constraints from EDML and EDC (Parrenin et al., 2007¹). The resulting time scale for EDC was finally transferred to EDML using the same volcano-stratigraphic link. This strategy combines several advantages: first, primary dating information was used from two cores together in one time scale; second, the complex ice flow configuration at EDML with upstream variations of accumulation rate and temperature do not compromise the chronology; and last but not least, unprecedented internal consistency is obtained between the two cores from different parts of Antarctica with relative dating uncertainties being always much less than the absolute dating uncertainties for the last 128 ka. This high degree of internal synchronization will be the important basis to investigate regional phase shifts (leads or lags) in high-resolution data from the two EPICA ice cores.

Before 128 ka BP volcanic matching is impossible due to peak diffusion at EDML, and the match is based on dust and stable isotopes, which is still feasible back to 150 ka BP (2417 m depth), but gets increasingly uncertain. At EDML, layer thicknesses exhibit irregular thinnings below ~2300 m depth. Reasons for this complexity may include large upstream effects, unknown variations in ice fabric and ice hardness, and the fact that the ice at bedrock is very close to the pressure-melting point. Results from numerical experiments with a 3-D model of the Antarctic ice sheet show that the ice chronology in the bottom layers of the ice sheet is potentially influenced strongly by the unknown rate of basal melting, which is in turn controlled by the geothermal heat flux G , and that even slight variations of G can change the state from freezing to melting at and upstream of the EDML drill-site. Basal melting has almost no effect on the modelled chronology in the upper 90% of the EDML ice core. But an increase of G by only 5% results in a dramatic decrease of the age of the bottom ice. In addition to the overall uncertainty of G for Antarctica (Shapiro and Ritzwoller, 2004), local variations of G in DML seem probable (Fox-Maule et al., 2005), which further complicates the problem. Therefore, detailed modelling studies and further data analyses are necessary before building the chronology for the bottom 350 m of the EDML ice core.

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Table 1. Parameters used to stratigraphically link EDML and EDC for different EDML depth ranges. Parameters are given as [EDML/EDC]-pairs. DEP denotes “Dielectric Profiling” of the frozen ice. Cond. denotes the “electrolytical conductivity” after melting the ice. DEP, SO₄ (sulphate concentrations) and Cond. were used to identify corresponding spikes (i.e. singular events) caused by volcanic deposits. Insoluble dust concentrations and stable isotopes ($\delta^{18}\text{O}$, δD) were used to identify corresponding features in the profiles.

| EDML depth range (time interval) ↓ | Parameter ↓ EDML / EDC | DEP / DEP | SO ₄ / SO ₄ | Cond / SO ₄ Cond / Cond | Dust / Dust $\delta^{18}\text{O}$ / δD |
|---|---------------------------|-----------|-----------------------------------|---------------------------------------|---|
| 0 - 113 m (-0.05 – 1.2 ka BP) | | x | | | |
| 113 - 1050 m (1.2 – 24 ka BP) | | x | x | | |
| 1050 - 1556 m (2.4 – 52 kaBP) | | x | x | x | |
| 1556-1901 m (52 – 75 ka BP) | | x | | x | |
| 1901-2366 m (75 – 128 ka BP) | | | | x | |
| > 2366 m (> 128 ka BP) | | | | | x |

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Table 2. Volcanic horizons used for constraining the *EDML1/EDC3* time scale. EDML-depth is from the DEP data set of the 3-inch-access drilling. B32-depth and year are adopted from (Traufetter et al., 2004), with the exception of the date used for Kuwae, which is a weighted average of AD 1454±5 from B32 (Traufetter et al., 2004) and AD1459.5 from Law Dome (Palmer et al., 2001).

| Volcano | EDML-Depth (m) | B32-Depth (m) | Year (AD) |
|---------------------|----------------|---------------|-----------|
| Krakatau | 17.19 | 16.29 | 1884±0 |
| Tambora | 24.94 | 23.8 | 1816±0 |
| Huaynaputina | 46.10 | 44.35 | 1601±0 |
| Kuwae | 59.11 | 56.8 | 1458±2 |
| unknown/El Chichon? | 75.38 | 72.57 | 1259±5 |
| unidentified | 77.67 | 74.72 | 1228±6 |
| unknown | 82.32 | 79.23 | 1171±6 |

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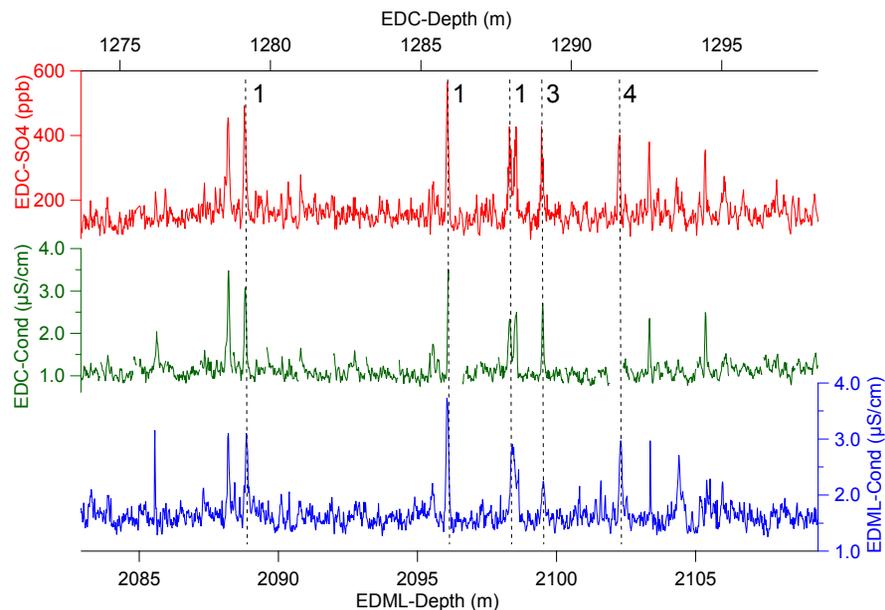


Fig. 1. Illustration of a volcanic match based on electrolytical conductivity (Cond) for EDML and SO₄ concentrations or Cond for EDC. The section shown is from a depth range where peak diffusion is already noticeable at EDML. The matches are indicated as vertical dashed lines. Numbers given at each match refer to the confidence value attributed to the matches ranging from “1” (“certain”) to “4” (“tentative”). The section shown covers the time from ~90.1 to ~92.6 ka BP.

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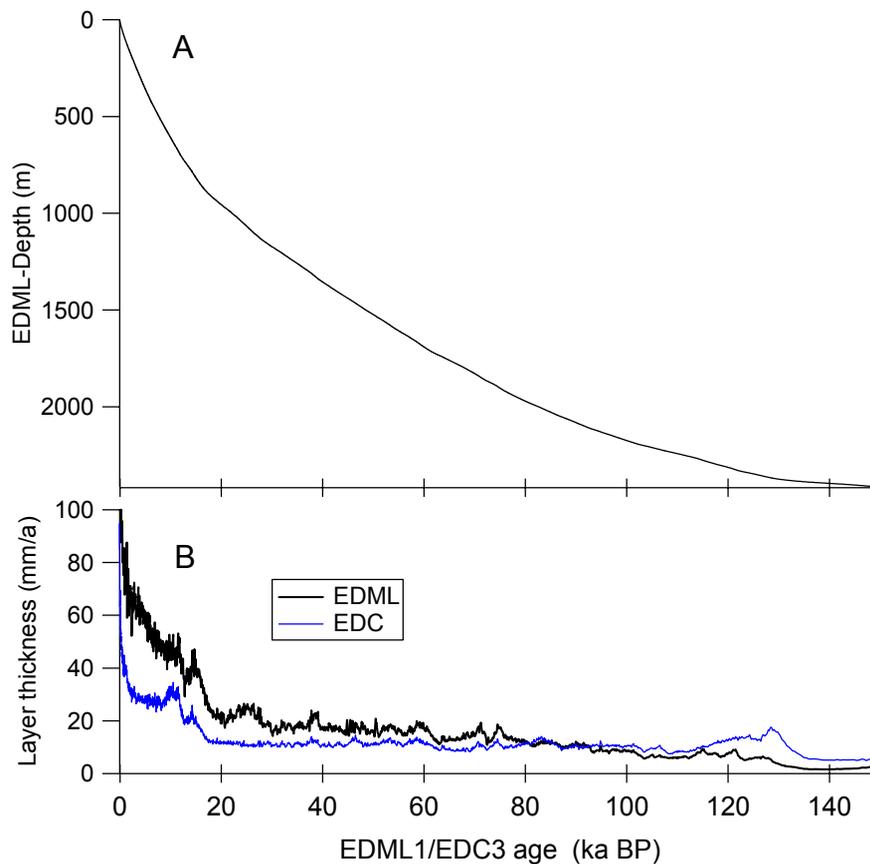


Fig. 2. Depth-age relationship for the EDML ice core (**A**), and corresponding thickness of annual layers (**B**) shown as uncorrected true depth for EDML (black, bold line) and for EDC (blue, fine line). Note, that variations in the EDML layer thickness may also include possible spatial upstream variations in snow accumulation in the past while upstream effects at the dome position of EDC do not exist.

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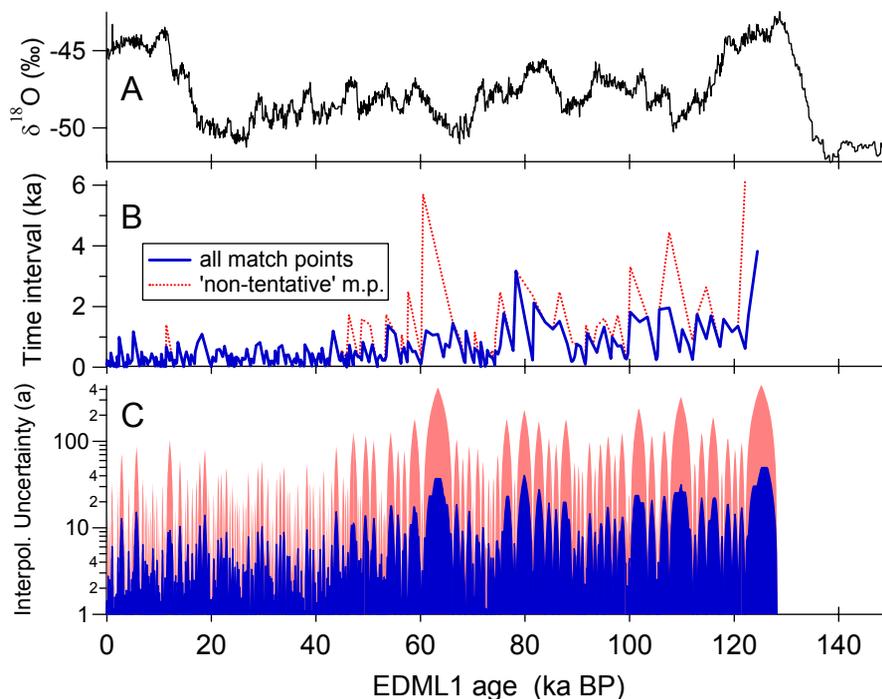


Fig. 3. (A): The EDML-temperature proxy $\delta^{18}\text{O}$ (uncorrected for upstream effects) in 100-year averages (black) is shown for orientation (EPICA-community-members, 2006). **(B):** Illustration of time between consecutive volcanic EDML-EDC match points along the EDML core. The blue solid line results from considering all match points, the red dotted line results from considering only the so-called “non-tentative” match points. **(C):** Interpolation uncertainty for EDML, i.e. the empirically expected interpolation error between the volcanic EDML-EDC match points. The most-probable (blue) and the expected-maximal (light red) synchronisation error are shown. For details see text.

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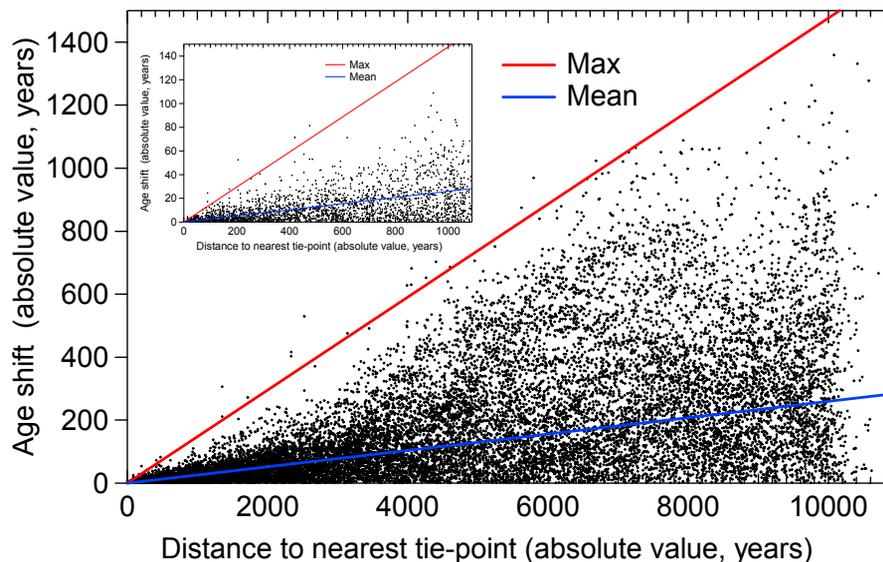


Fig. 4. Empirical estimate of the interpolation uncertainty between the match points. The age shift of every volcanic match point was calculated after it was not taken as a fixed match point any longer; the resulting age shift is interpreted as the potential synchronisation error that would have resulted without the match point. The blue line indicates the most-probable interpolation error for any given distance to the nearest match point (2.6 ± 0.5 years/100 years). The red line indicates the most expected-maximal interpolation error (15 ± 6 years/100 years). See text for details.

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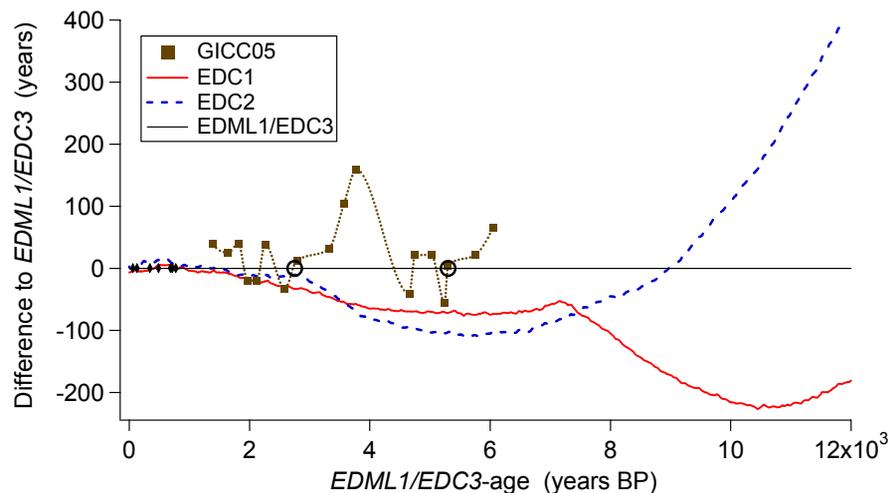


Fig. 5. Comparison of *EDML1/EDC3* time scale with *EDC1* (solid red line) and *EDC2* (dashed blue line) time scales (both via the volcanic match EDML-EDC) and with the Greenlandic *GICC05* (solid brown symbols and dotted line) time scale (via ^{10}Be -match EDML-GRIP). Positive numbers mean that the respective time scale gives an older date than *EDML1/EDC3*. Marked are also the volcanic control points (solid black symbols) and the two ^{10}Be -based control points (open black circles) used during construction of the *EDML1/EDC3* time scale.

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