# On the occurrence of annual layers in Dome Fuji ice core early Holocene ice

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**ABSTRACT**

Whereas ice cores from high accumulation sites in coastal Antarctica clearly demonstrate annual layering, it is debated whether a seasonal signal is also preserved in ice cores from lower accumulation sites further inland and particularly on the East Antarctic Plateau. In this study, we examine five metres of early Holocene ice from the Dome Fuji (DF) ice core in high temporal resolution by continuous flow analysis. The ice was continuously analyzed for concentrations of dust, sodium, ammonium, liquid conductivity, and water isotopic composition. Furthermore, a dielectric profiling was performed on the solid ice. In most of the analyzed ice, the multi-parameter impurity dataset appears to resolve the seasonal variability although the identification of annual layers is not always unambiguous. The study thus provides information on the snow accumulation process in central East Antarctica. A layer counting based on the same principles as those previously applied to the Greenland NGRIP and the Antarctic EPICA Dronning Maud Land (EDML) ice cores leads to a mean annual layer thickness for the DF ice of 3.0 ± 0.3 cm that compares well to existing estimates. The measured DF section is linked to the EDML ice core through a characteristic pattern of three significant acidity peaks that are present in both cores. The corresponding section of the EDML ice core has recently been dated by annual layer counting and the number of years identified independently in the two cores agree within error estimates. We therefore conclude that, to first order, the annual signal is preserved in this section of the DF core. This case study demonstrates the feasibility of determining annually deposited strata on the central Eastern Antarctic Plateau. It also opens the possibility of resolving annual layers in the Eemian section of Antarctic ice cores where the accumulation is estimated to have been greater than in the Holocene.

## 1. INTRODUCTION

Detection of annual layers has long been the method of preference for obtaining high-precision ice-core chronologies (Alley et al., 1997; Hammer et al., 1978). Annual layer detection in ice cores was originally based mostly on the water isotopic composition of the ice but has evolved to also include the seasonal variation of ice core impurities, such as dust and ionic species (Rasmussen et al., 2006; Sommer et al., 2000). Ice core dating based on annual layer counting is limited by the temporal resolution of the ice but it is feasible for annual layers thicknesses down to about one centimeter by application of Continuous Flow

Analysis (Vallelonga et al., 2012). Other high-resolution techniques are available that can resolve thin annual layers, such a discrete millimetre-scale sampling (Thomas et al., 2008) and laser ablation mass spectrometry (LA-ICP-MS) for in-situ and mostly non-destructive analysis of ice (Della Lunga et al., 2014; Reinhardt et al., 2001; Sneed et al., 2015). In Greenland, ice cores have been dated continuously by annual layer counting back to 60 kyr (Svensson et al., 2008) and in Antarctica the younger section of ice cores at high-accumulation sites have been dated by layer counting (Fudge et al., 2013; Plummer et al., 2012; Sommer et al., 2000).

Large volcanic eruptions can spread sulphate and ash across large parts of the globe, thus producing acid and tephra strata that can be used to synchronize ice cores globally (Gao et al., 2008; Sigl et al., 2012). Historical volcanic eruptions furthermore provide important constraints on the accuracy of layer counting techniques for the past two millennia. Through bipolar synchronization of ice cores the Greenland ice core chronologies have been transferred to Antarctic ice cores back to 60 kyr, but beyond that limit the accuracy and the precision of ice core chronologies generally decreases (Bazin et al., 2013; Veres et al., 2013). Annual layer counting in older parts of both Greenland and Antarctic ice cores could potentially improve this situation.

Until now, the identification of annual layers in ice cores from the East Antarctic Plateau (EAP) has been very limited. At the EAP the present day annual accumulation is typically a few centimeters of ice equivalent and therefore dating by annual layer counting is generally challenging and during colder climatic periods of low accumulation annual layer identification is probably impossible. On the other hand, only ice cores from the EAP appear to continuously cover the last interglacial period in Antarctica, so if this period should be dated by layer counting it will have to be in a core from that region.

Dome Fuji is the summit of the EAP Dronning Maud Land located at 77°19'S, 39°42'E (Figure 1) (Watanabe et al., 1999). The Dome Fuji elevation is 3800 m, and the ice thickness is 3028 (±15) m (Fujita et al., 1999). The glaciological conditions at Dome Fuji, such as the surface mass balance and subglacial conditions have been investigated (Fujita and Abe, 2006; Fujita et al., 2011; Fujita et al., 2012). The Dome Fuji deep ice cores 1 (DF1) and 2 (DF2) were retrieved by the Japanese Antarctic Research Expeditions (JARE) in 1992-98 and 2004-07, respectively (Motoyama, 2007; Watanabe et al., 1999). DF1 covers the upper 2503 m of the ice sheet, whereas the DF2 core is 3035 m long and reaches almost to bedrock. At Dome Fuji the present day (1995 - 2006) annual accumulation is 2.73±0.15 cm water equivalent (Kameda et al., 2008). The DF cores have mainly been dated by orbital tuning using $O_2/N_2$ age markers (Kawamura et al., 2007) and by glaciological modelling based on a set of age markers (Parrenin et al., 2007). A recent study is concerned with transfer of the EDML ice core time scale to the DF cores for the last two millennia (Motizuki et al., 2014). In addition, the Dome Fuji deep ice cores have recently been synchronized to the EPICA Dome C (EDC) ice core (EPICA community members, 2004) using a total of 1401 volcanic tie points over the past 216 kyr (Fujita et al., 2015). Using the established EDC/EDML volcanic synchronization (Ruth et al., 2007), the DF ice cores are thus indirectly synchronized with the EDML ice core.

Several studies have considered the occurrence of annual layers in the Dome Fuji ice cores. A case study of high-resolution discrete chemistry records discuss the preservation of annual layering in ice from Marine Isotope Stage (MIS) 2 (Iizuka et al., 2004). Based on counting of seasonal cycles in sodium and non-sea-salt (nss) sulphate the authors conclude that high-resolution stratigraphic dating at Dome Fuji may be feasible. During the last glacial period, the annual layers are, however, likely to be of the order of 1 cm thick

(Kawamura et al., 2007) and the layer identification is very challenging and uncertain. The volcanic synchronization between the Dome Fuji and the EDC ice cores revealed periods where no reliable tie points could be identified in MIS 2, 4, 5b, and 6 (Fujita et al., 2015). In those cold periods, there are frequent losses or disturbances of volcanic signals due to the low accumulation rate and possible accumulation hiatus. Thus, the preservation of annual layers in these cold periods should be very carefully assessed. A study of the ice core visual stratigraphy investigated the preservation of annual layers in various sections of the ice core (Takata et al., 2004). Although the conclusion concerning the existence of annual layers in the ice core stratigraphy is positive the investigated sections were restricted to the deeper part of the ice core in MIS 2, 5c, and 6, where annual layers are very thin.

A detailed stake measurement survey of the surface mass balance was carried out at the Dome Fuji site for the period 1995-2006 (Kameda et al., 2008). Accumulation at 36 stakes was measured at least annually and whereas the average accumulation agrees with the average DF ice core accumulation of the last millennium, a negative or zero accumulation was measured for 8.6 % of the annual stake measurements. This result suggests that post-depositional processes influence the local mass balance, and that today not all annual layers are preserved at the DF site.

Recently, Hoshina et al. (2014) measured the major ion concentrations of a 4 m pit at the Dome Fuji site that covers the past 50 years. By counting seasonal cycles in profiles of chemistry and crust layers the authors find that the frequency distribution of the annual accumulation rates agree well with the stake study mentioned above (Kameda et al., 2008). The agreement of the two independent accumulation estimates suggest that annual layers can be counted with some probabilistic limitations in the present Holocene layering.

In this work, we present high resolution chemistry and dust data from a 5.0 m section of early Holocene ice from the Dome Fuji 1 ice core. Based on this dataset we attempt to date the DF ice by annual layer counting and we discuss issues related to layer counting at low accumulation sites. We apply prominent acidity spikes to synchronize the measured section of DF ice to the EDML ice core (Barbante et al., 2006) from the Atlantic Antarctic sector (Figure 1). The EDML ice core has thicker annual layers in the early Holocene due to its more coastal location and higher accumulation. The EDML ice core has, in turn, been synchronized to the Greenland NGRIP by bipolar volcanic matching. The synchronization of the three cores allows for a comparison of their respective time scales over the time interval of synchronization allowing for an evaluation of the DF layer counting.

## 2. ANALYSES AND RESULTS

For this study, 5.0 m of high quality ice from the Dome Fuji 1 (DF1) ice core were selected. The samples cover the interval 301.90-306.90 m depth and are in sticks of 0.5 m length with a cross-section of 3.4 x 3.4 $cm^2$. The ice is Holocene and has an age close to 9.8 ka BP. The samples were analysed in January 2012 at the Niels Bohr Institute in Copenhagen using a Continuous Flow Analysis (CFA) system optimized to provide the highest possible depth resolution (Bigler et al., 2011). The samples are melted continuously and the melt water is separated into an inner part (sample) and an outer part (waste) to avoid contamination. The continuous sample water flow is distributed into several detection systems measuring concentrations of ammonium ($NH_4$), sodium (Na) and mineral dust particles, the electrolytic conductivity of the melt water, and the water isotopic composition, respectively. A low ice melt rate of approximately 1.5 cm per minute allows for obtaining records of very high depth resolution that can resolve annual layers and other features of less than a centimetre thickness (Bigler et al., 2011; Vallelonga et al., 2012). In addition, a Dielectric Profile (DEP) of the solid ice has been obtained at the National Institute of Polar Research (NIPR), Tokyo, using a parallel set of samples.

Dual water isotopic measurements ($\delta^{18}O$ and $\delta D$, Figure S6) were performed online using a cavity ring down spectrometer (Picarro 1102-i) and a continuous vaporization system (Gkinis et al., 2011). Measurements are set on the VSMOW scale using a 2-point calibration with local standard waters. In order to account for diffusion imposed by the CFA system a Wiener deconvolution filter was applied. The precision of the analysis is in the order of 0.06 ‰ ($\delta^{18}O$) and 0.5 ‰ ($\delta D$).

An overview of the Dome Fuji profiles obtained for this study is presented in Figure 2. The CFA profiles cover the full 5 m interval continuously except for short core breaks every 0.5 m and a less than 10 cm data gap at around 305.45 m depth. The average $\delta^{18}O$ values and the impurity levels over the entire interval are in good accordance with the long-term Dome Fuji profiles of the early Holocene (Watanabe et al., 2003).

The DEP and electrolytic conductivity records show three major acidity spikes at around 303.51, 304.70, and 306.44 m depth that are denoted P1, P2, and P3, respectively (Figure 2). Events P1 and P2 are associated with the most prominent dust peaks observed in the 5 m profiles. Those peaks are discussed in section 3.3.

Just above P3, in the depth interval 306.25-306.40 m, the four CFA profiles and the DEP profile express a characteristic smooth shape that is not observed anywhere else in the dataset. There were no irregularities in the melting system or measurement equipment which could lead to such anomalous results, hence we interpret this event to result from anomalous snow deposition and/or remobilization. The event is discussed in detail in section 3.4.

## 3. DISCUSSION

### 3.1 Layer counting

The entire CFA chemistry dataset presented in Figure 2 is shown in high depth resolution in Figures 3 and 4 and in supplementary Figures S1-S5. In high depth resolution, the chemistry and dust records show clear evidence of a periodic signal that we interpret as seasonal variability in impurity fluxes to the ice. Using this dataset we count the annual layers of the measured section following the same principles as applied for the glacial section of the Greenland NGRIP ice core (Rasmussen et al., 2006) and for deeper sections of the Antarctic EDML ice core (Svensson et al., 2013). In the DF1 dataset the annual layers are found to be of more than two centimetres thickness on average, which are reliably resolved by the CFA system used (Bigler et al., 2011). The annual signal in DF1 is generally quite pronounced in the sodium, ammonium, and dust records. When data are missing over a short interval the layer marks are interpolated based on adjacent intervals. In case of an ambiguity, layers are indicated as ‘uncertain’. The ‘uncertain’ layers are counted as (½±½) year (that is, either the year is present, ½+½, or the year is not present, ½-½) and the uncertainties are added up to provide a cumulative uncertainty of the layer counting.

For the entire 5 m section we obtain 165±17 years corresponding to a mean annual layer thickness of approximately 3.0±0.3 cm ice. The counting uncertainty of around 10% is greater than that of other deep ice cores with similar layer thicknesses (Svensson et al., 2008) in part due to the occurrence of the event discussed in section 3.4. The mean annual layer thickness for this early Holocene period is slightly greater than the modelled layer thickness of 2.6 cm ice based on surface mass balance estimated from water isotopes, in agreement with what was inferred at EPICA Dome C (Parrenin et al., 2007). The determined mean annual layer thickness is comparable to the present day accumulation of 2.98±0.16 cm ice (Kameda et al., 2008) and greater than the 2.7 cm ice mean accumulation of the last eight millennia (Fujita et al., 2011). The result is thus in accordance with the existence of a widespread Antarctic early Holocene optimum occurring between 11.5 and 9 ka BP (Masson et al., 2000).

**3.2 Synchronizing DF to EDML and NGRIP**

The three characteristic acidity peaks P1, P2, and P3 are also recognized in the EDML ice core in the corresponding age interval (Figure 5). Based on those and other significant acidity peaks in adjacent ice the two ice cores are synchronized over the investigated interval within a few years of uncertainty (Fujita et al., 2015; Ruth et al., 2007). The EDML Holocene ice has thicker annual layers than DF and the early Holocene part of EDML has been dated by both layer counting (Vinther et al., 2012) and modelling (Ruth et al., 2007; Veres et al., 2013). The EDML-DF matching allows for a comparison of the dating of the two cores between the acidity spikes (Tables 1 and 2). The comparison shows an agreement of the layer-counted interval durations within the error estimates generated by the assignment of 'uncertain' annual layer counts. The depth matching of the volcanic synchronization between the EDML and DF ice cores adds a few years of uncertainty to the interval duration comparison.

In the Holocene the EDML ice core is matched to the Greenland NGRIP ice core (Andersen et al., 2004) by identification of bipolar volcanic markers (Veres et al., 2013). The DF and EDML acidity spikes have Greenland counterparts that allows for a time scale comparison to the layer counted Greenland ice core chronology GICC05 (Vinther et al., 2006) between the spikes (Tables 1 and 2). Within uncertainties, the DF layer counting is in agreement with the Greenland time scale, but in this case, the bipolar matching may add more importantly to the uncertainty of the interval durations.

**3.3 Dust peaks**

The DF1 dust profile obtained in this study was measured with an Abakus instrument that also provide approximate dust size distributions in the 1-15 micrometre range (Ruth et al., 2003). In Figure 6 the background dust volume distribution of the present study is compared to those related to the three prominent acidity spikes P1, P2, and P3 (Figure 2). The background dust size distribution is centred around 3 micrometre and is similar to that determined for other sections of the Dome Fuji core. The dust peaks associated with P1 and P2 - in particular - are seen to hold significant fractions of large particles, whereas the dust size distribution associated with the P3 acidity peak is very comparable to that of the background dust. A recent study of dust particles from the WAIS (West Antarctic Ice Sheet) Divide ice core suggests that dust peaks associated with acidity peaks may be of volcanic origin although the argument is based solely on dust size distributions and not on geochemical analyses (Koffman et al., 2013). Based on Figure 3 we suggest that the large fraction particles related to P1 and P2 are tephra particles, whereas no tephra appears to be related to P3. Future geochemical analyses of the dust peaks, as it was done for 26 visible Dome Fuji tephra layers by Kohno et al. (2004), will allow a definitive evaluation of the presence of tephra in the dust peaks.

### 3.4 A peculiar event

In the DF depth interval 306.25-306.40 m, at the tail of the major acidity spike P3, the impurity records show an unusual behavior (Figure 4). In contrast to the rest of the analyzed depth interval, where all impurities show clear evidence of an annual cycle, the chemical and dust profiles all show an unusually smooth pattern in a 15 cm long interval corresponding to the accumulation of 5-6 years in adjacent ice. We refer to this depth interval as 'the peculiar event'. The event occurs immediately after the largest volcanic signal in the analyzed section.

The peculiar event cannot be attributed to the melting or measurement process. The ice-core melt speed was typical and constant and the analytical systems were operating normally. Furthermore, the DEP profile that is obtained on the solid ice shows a very comparable pattern across the event. The ice was melted down-core (i.e., from 306.10 m to 306.40 m depth) and the section of interest occurs toward the end of an ice core section terminating at 306.40 m depth. The large P3 acidity spike peaking at around 306.44 m depth was analyzed in the following ice core section and was physically separate from the event during measurement.

The event is unique for the analyzed section of DF ice and nothing comparable is seen in the proximity of the other major acidity spikes in the analyzed DF ice. A similar event is not appearing in the corresponding section of the EDML ice core (Figure 5). To our knowledge, similar smooth profiles have not been observed following other large acidity spikes in Antarctic and Greenland ice cores.

We do not know the cause of this event, but, possibly, it may be related to sastrugi formation at the surface. Sastrugi are local snow dunes caused by post-depositional redistribution of surface snow. We note that the subsequent annual layers are thinner than the average (Figure 4), which would be expected from deposition on top of an elevated surface. It is surprising, however, that the event is unique in the 165 year long timeseries presented here. The recent snow stake study at DF (Kameda et al., 2008), where 8% of the observed stake sites experienced zero or negative accumulation, does support the possibility of local snow remobilization at DF, although on a much smaller scale than suggested by the peculiar event.

Another possible explanation for the event is related to unusual meteorological conditions. It is possible that the sulphate flux from a large volcanic eruption could have contributed to unusual meteorological conditions and hence unusually high accumulation at the DF site. Such a scenario is highly unlikely because we do not see a similar event in the matched record from the EDML ice core. Nonetheless, high snow precipitation events have been recorded for East Antarctica, often due to rare meteorological situations such as atmospheric rivers (Gorodetskaya et al., 2014) and blocking anticyclonic systems (Hirasawa et al., 2000; Schlosser et al., 2010). Enomoto et al. (1998) observed such a blocking high in June 1994, when temperatures at DF increased by 40°C in two days. Of particular interest is that heat was transported to DF from the Northeast, the opposite direction to EDML.

## 4. CONCLUSIONS

The high-resolution impurity profiles obtained from the early Holocene section of the Dome Fuji ice core demonstrate the feasibility of determining annually deposited strata on the central Eastern Antarctic plateau during warm climates. For the most part of the analyzed section annual layer counting was feasible and the average annual layer thickness is found to be 3.0±0.3 cm. The preservation of annual layers at this low accumulation site may have implications for the understanding of the air enclosure process and for the determination of gas age-ice age differences (Landais et al., 2006).

Synchronization of the analyzed Dome Fuji section to corresponding sections of the EDML and NGRIP ice cores allows for a comparison of the independent layer counted time intervals. Within the error estimates of the layer counting and taking into account the uncertainty related to the matching of the cores, the dating of the DF core agrees with the EDML and NGRIP chronologies.

Our results show that annual layers can be resolved in the interior of Antarctica in the early Holocene. Over longer time intervals, a low percentage of individual annual layers may be missing, due to remobilisation of surface snow. Additionally, we observe one 'peculiar event' in the 165-year record in which 5-6 years' accumulation appears to have been deposited in one year. The event occurs immediately after a large volcanic eruption, and may have resulted from surface sastrugi or anomalously high accumulation following a blocking high. Despite these disturbances, our study suggests that the original deposition at Dome Fuji is often preserved and that a counted time scale can be established from high-resolution ice-core impurity profiles.

During the Eemian period (MIS 5e) the accumulation is known to have been higher than in the Holocene. The present study suggests that annual layer counting in the Antarctic Eemian period may help to constrain the chronology of that section, if annual layers are preserved. In Greenland, Eemian annual layers are preserved at least in some sections of the NGRIP ice core (Svensson et al., 2011). The Antarctic cores of interest for layer counting in the Eemian are Vostok, where the Eemian covers a 300 m depth interval (1600-1900m), EPICA Dome C, where the Eemian covers a 250 m depth interval (1510-1760m), and Dome Fuji, where the Eemian covers a 200 m depth interval (1610-1810m).

## ACKNOWLEDGEMENT

We thank the Dome Fuji and EPICA Dronning Maud Land drilling teams and all the field participants for their efforts.

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| Depth intervals | | | |
|---|---|---|---|
| Interval | Dome Fuji (m) | EDML (m) | NGRIP (m) |
| P1 → P2 | 303.51 → 304.70 | 593.30 → 595.34 | 1368.35 → 1371.54 |
| P2 → P3 | 304.70 → 306.44 | 595.34 → 598.32 | 1371.54 → 1376.59 |
| P1 → P3 | 303.51 → 306.44 | 593.30 → 598.32 | 1368.35 → 1376.59 |
| Full interval | 301.90 → 306.90 | | |

Table 1. The depth intervals defined by the characteristic acidity spikes P1, P2, and P3 in the ice cores (see Figures 2 and 5).

| **Ice Core** | **Time scale** | **Number of years** | | | | **P3 age** | **Reference** |
|---|---|---|---|---|---|---|---|
| | | P1 → P2 | P2 → P3 | P1 → P3 | Full interval | (yr BP) | |
| Dome Fuji | Layer count | 43±3 | 59±9 | 102±12 | 165±17 | | This work |
| EDML | AICC2012 | 46 | 67 | 113 | | 9,852 | Veres et al., 2013 |
| EDML | Layer count | 45±3 | 61±5 | 106±8 | | | Vinther et al., 2012 |
| NGRIP | GICC05 | 39±1 | 64±1 | 103±2 | | 9,849 | Vinther et al., 2006 |

Table 2. The number of years between the characteristic acidity spikes P1, P2, and P3 (see Table 1).

**FIGURES**

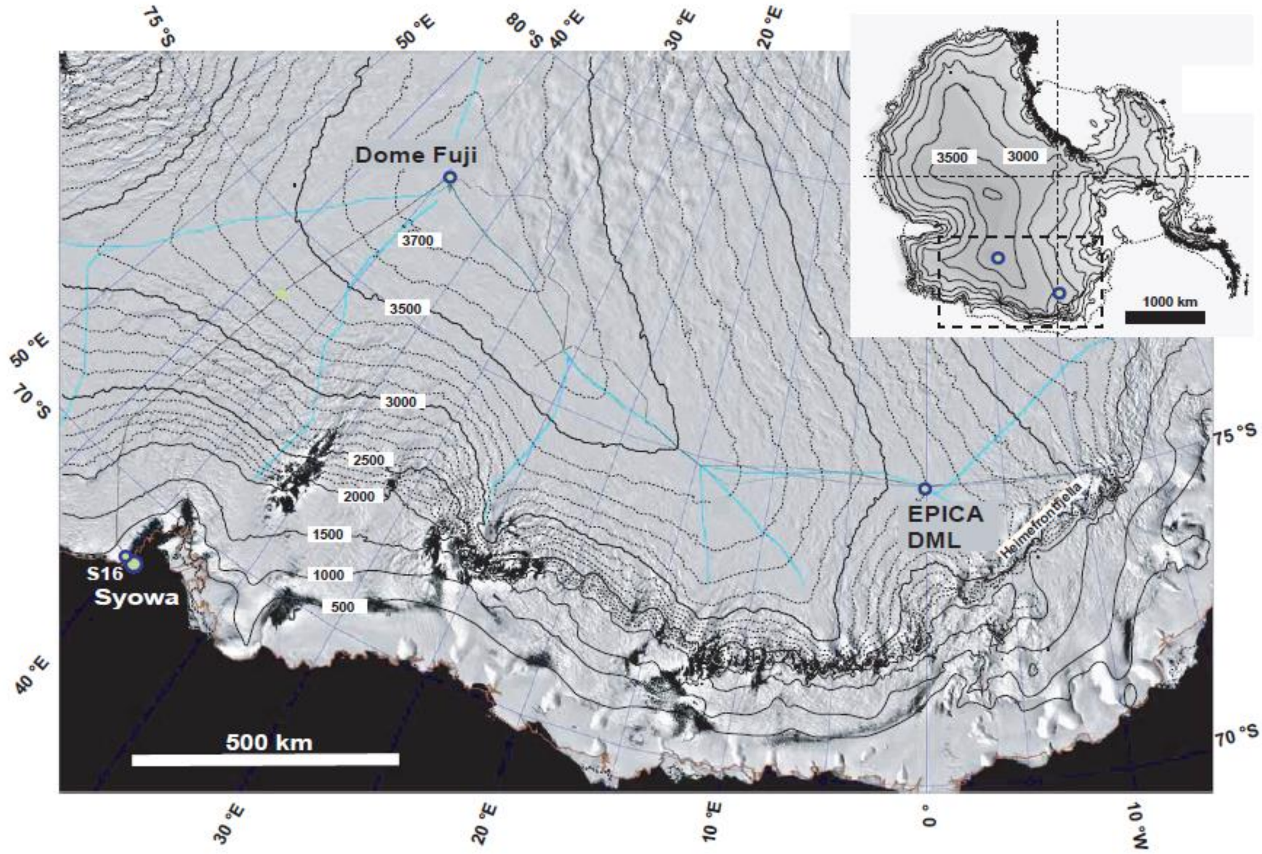


Figure 1:

The Atlantic sector of the East Antarctic Ice Sheet with the positions of Dome Fuji (DF) and the EPICA Dronning Maud Land (EDML) drilling sites. Black lines are elevation curves in metres, blue curves indicate major ice flow lines, and the grey lines are traverse tracks. Satellite image from MODIS (Haran et al., 2005, updated 2006).

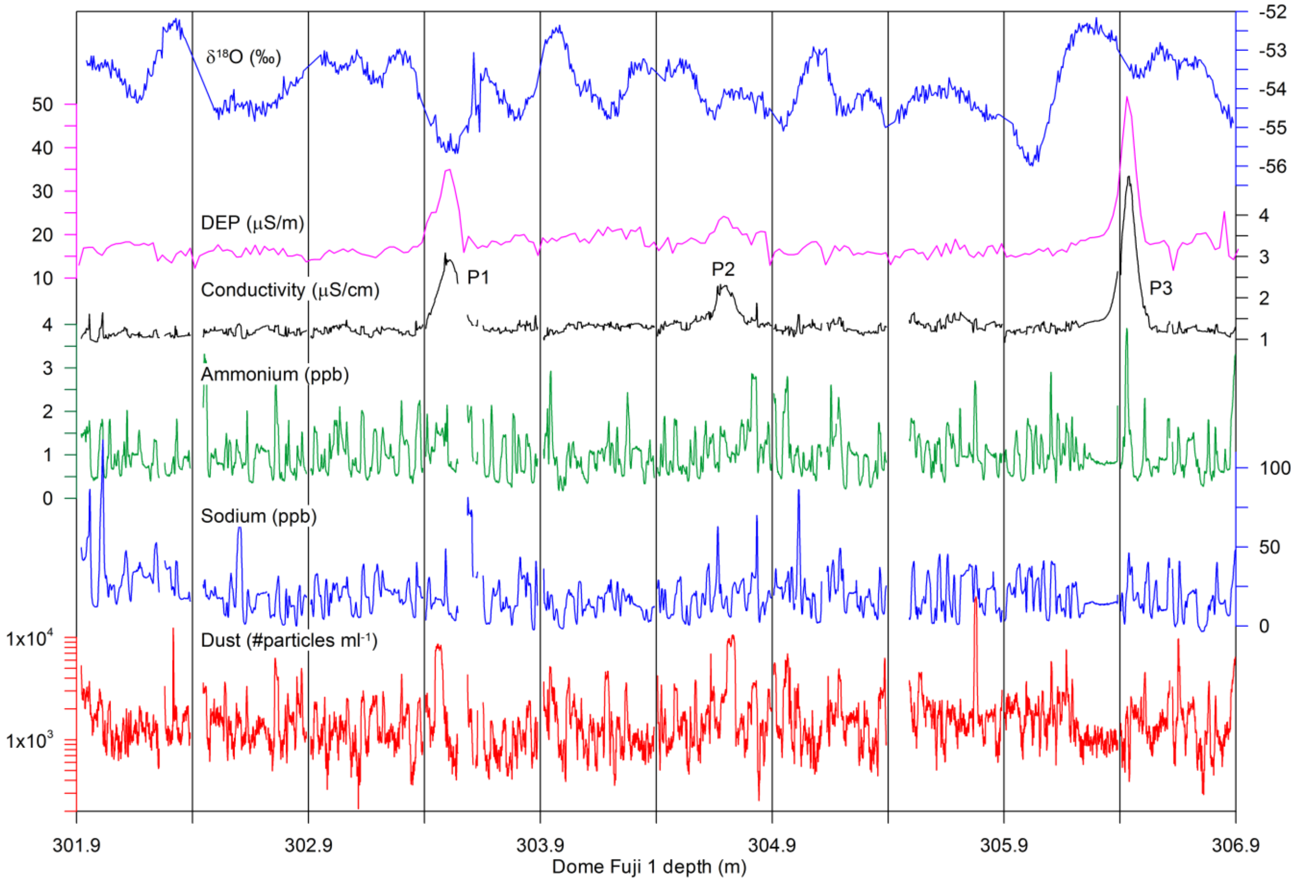


Figure 2:

Overview of the high-resolution records obtained from the five metres of early Holocene Dome Fuji ice. From top, the $\delta^{18}O$ is obtained continuously on a cavity ring down spectrometer and the Dielectric Profiling (DEP) is made on the solid ice. The electrolytic (liquid) conductivity, the Ammonium, the Sodium, and the dust concentrations were obtained on the Copenhagen CFA analytical system. Data gaps are due to core breaks or failure of the analytical systems. The three major acidity spikes P1, P2, and P3 centred at 303.51, 304.70, and 306.44 m depth, respectively, are indicated.

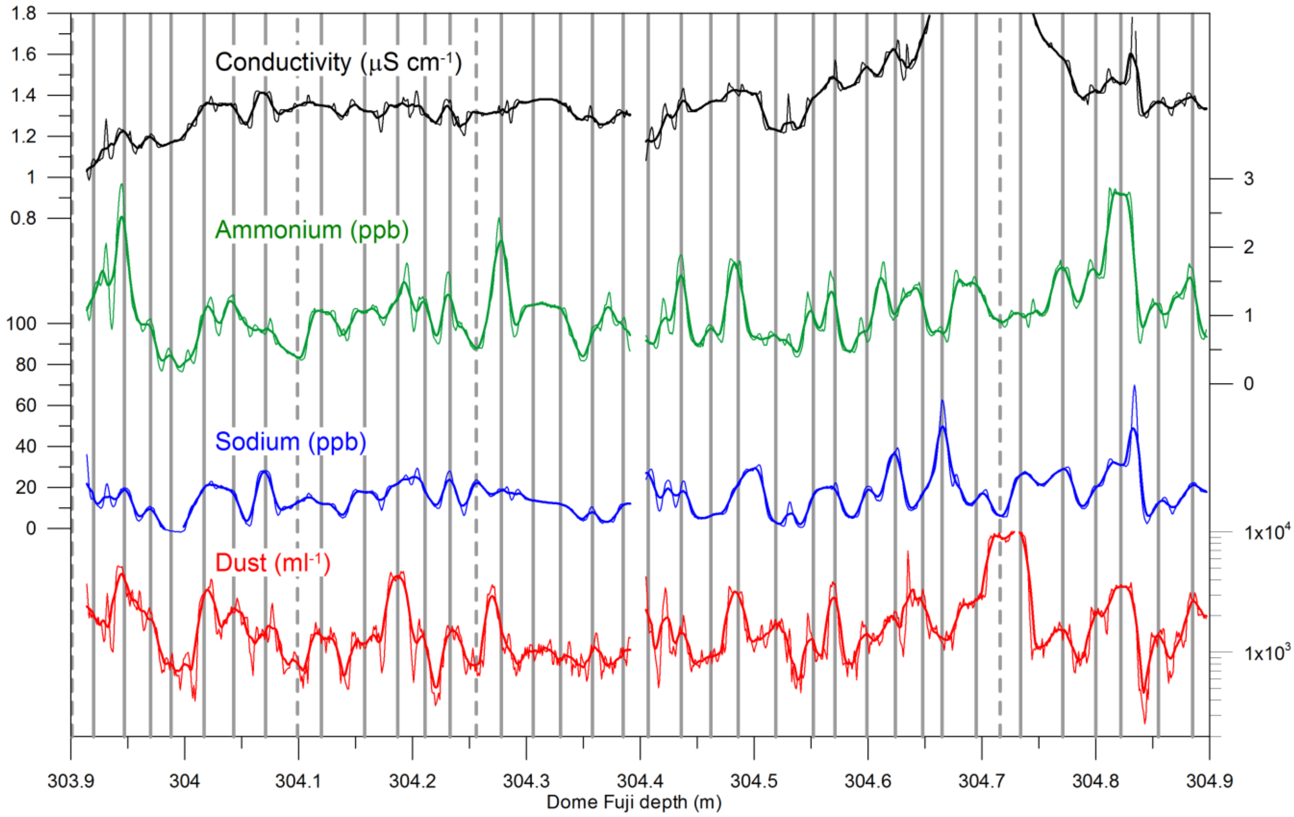


Figure 3.

Example of high-resolution profiles of electrolytic conductivity, Ammonium, Sodium, and dust concentrations. Thin curves show the records in 1 mm depth resolution and thicker curves are 1 cm averages. ‘Certain’ and ‘uncertain’ annual layer marks are indicated with full and dashed vertical lines, respectively. The entire dataset is shown in the supplementary material Figures S1-S5.

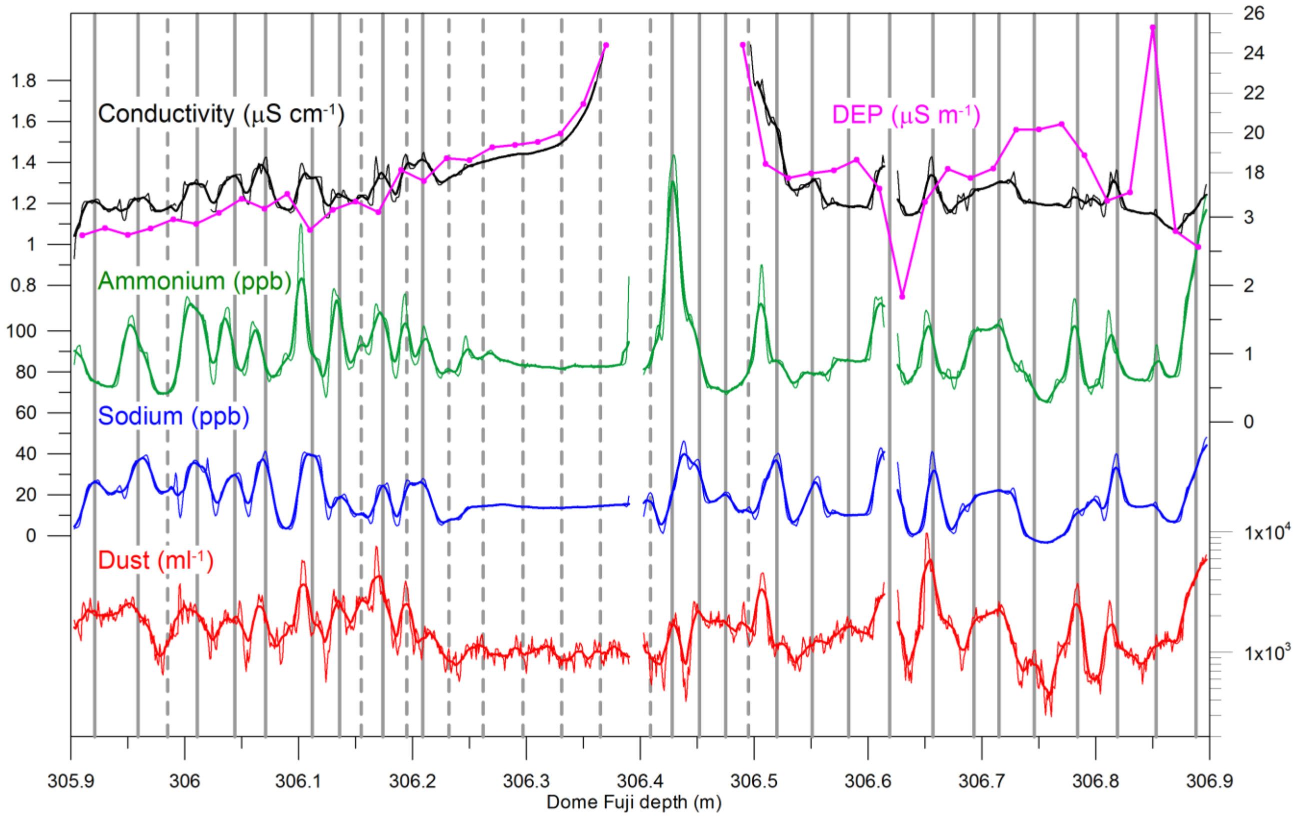


Figure 4.

Same records as shown in Figure 3 plus the DEP record for the section containing the major acidity peak P3 centred around 306.44 m depth and the 'peculiar event' with unusually smooth profiles 306.25-306.40 m depth. Thin curves show the records in 1 mm depth resolution and thicker curves are 1 cm averages. 'Certain' and 'uncertain' annual layer marks are indicated with full and dashed vertical lines, respectively. For the interval 306.25-306.40 the layer indication is tentative.

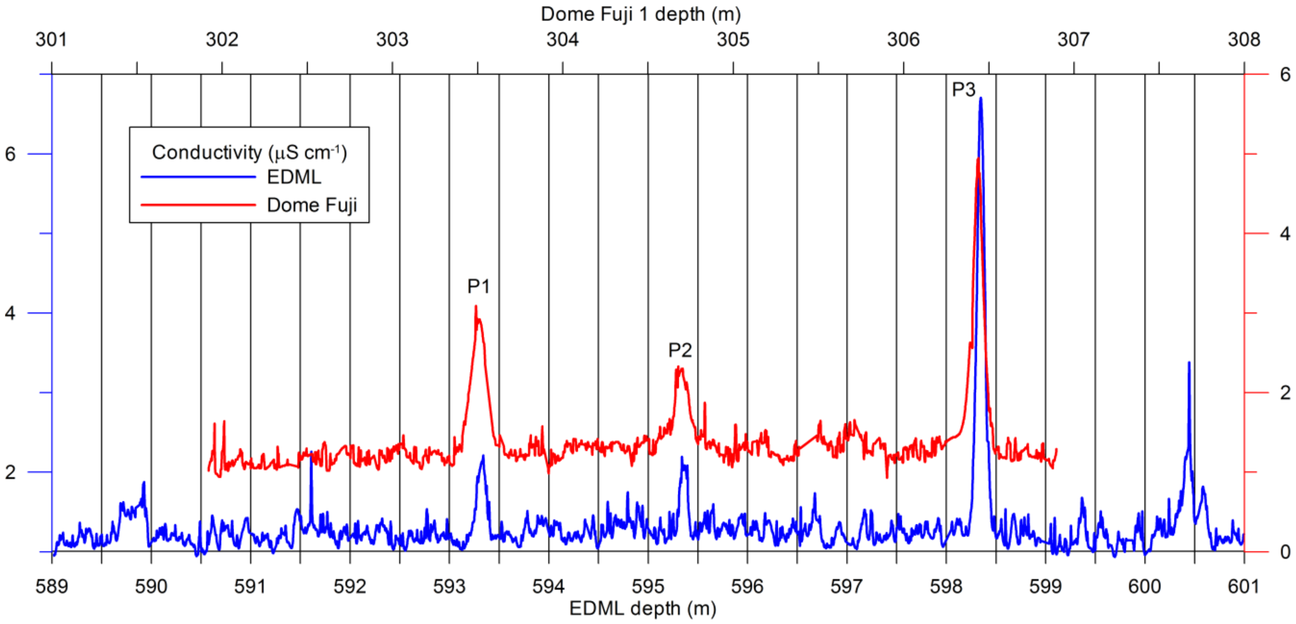


Figure 5.

Volcanic matching of the Dome Fuji and EPICA Dronning Maud Land (EDML) ice cores based on the three characteristic acidity peaks P1, P2, and P3 here shown in the electrolytic conductivity signal. Due to the different shapes of the acidity peaks the matching of the cores has an uncertainty of a few years.

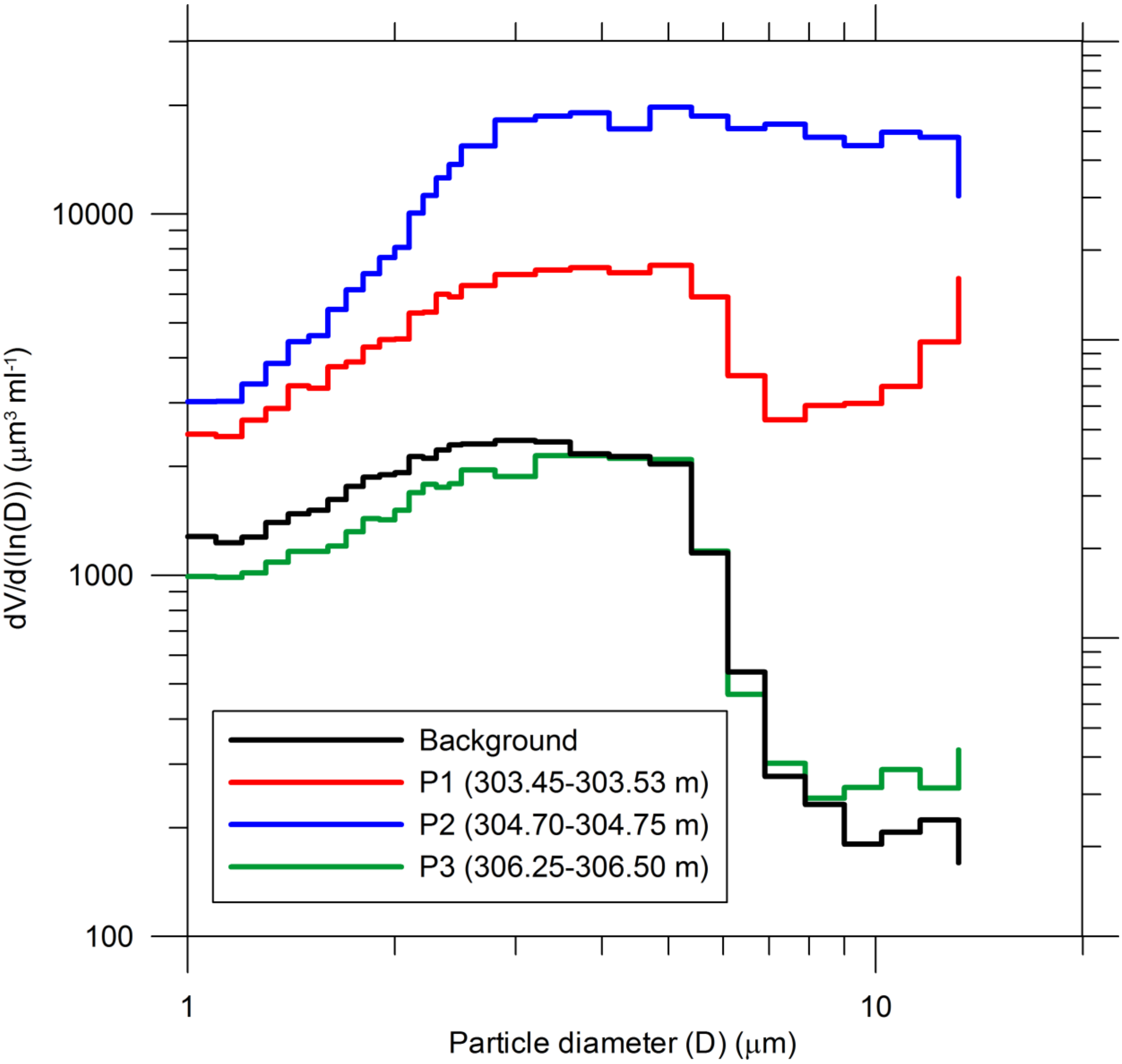


Figure 6.

Dust volume distributions of average background dust and across the three prominent volcanic peaks, P1, P2, and P3 (see Figure 2). The size distributions are obtained by an Abakus instrument that covers the particle size interval 1-15 μm (spherical equivalent diameter). The Abakus is known not to measure dust sizes as accurately as a Coulter counter instrument (Ruth et al., 2003) and the shape of the dust size distribution may be somewhat biased. The relative sample differences in dust sizes are, however, robust and significant.