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Volcanic synchronization of Dome Fuji and Dome C Antarctic deep ice cores over the past 216 kyr

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Abstract

Two deep ice cores, Dome Fuji (DF) and EPICA Dome C (EDC), drilled at remote dome summits in Antarctica, were synchronized to better understand their chronology. A total of 1401 volcanic tie points were identified covering the past 216 kyr. DFO2006, the chronology for the DF core characterized by strong constraining by the O_2/N_2 age markers, was compared with AICC2012, the chronology for 5 cores including the EDC core, and characterized by glaciological approaches combining ice flow modelling with various age markers. The age gaps between the two chronologies are within 2 kyr, except at Marine Isotope Stage (MIS) 5. DFO2006 gives ages older than AICC2012, with peak values of the gap of 4.5 and 3.1 kyr at MIS 5d and MIS 5b, respectively. Accordingly, ratios of duration DFO2006/AICC2012 are 85 % at a period from the late stage of MIS 6 to MIS 5d and 114 % at a period from MIS 5d to 5b. We then compared the DFO2006 with another chronology of the DF core, DFGT2006, characterized by glaciological approaches with weaker constraining by age markers. Features of the DFO2006/DFGT2006 age gaps are very similar to those of the DFO2006/AICC2012 age gaps. This fact lead us to hypothesize that a cause of the systematic DFO2006/AICC2012 age gaps at MIS 5 are associated with differences in the dating approaches. Besides, ages of speleothem records from China agreed well with DFO2006 at MIS 5c and 5d but not at MIS 5b. Thus, we hypothesize at least at MIS 5c and 5d, major sources of the gaps are systematic errors in surface mass balance estimation in the glaciological approach. Compatibility of the age markers should be carefully assessed in future.

1 Introduction

Ice-core records are rich archives of climate history over time scales of glacial–interglacial cycles up to ~800 kyr before present (BP) (e.g., EPICA Community Members, 2004; Kawamura et al., 2007; Petit et al., 1999). In ice core studies, dating is a central issue that must be studied in order to better constrain the timing, sequence and duration of past climatic events (e.g., Bazin et al., 2013; Kawamura et al., 2007; Parrenin et al., 2004, 2007a; Veres et al., 2013; Lemieux-Dudon et al., 2010). Recently, efforts to establish common age scales of several Antarctic ice cores (Vostok, EPICA Dome C (EDC), EPICA Dronning Maud Land (EDML) and Talos Dome (TALDICE)) have been made (Bazin et al., 2013; Lemieux-Dudon et al., 2010; Veres et al., 2013). This common age scale is called the Antarctic Ice Core Chronology 2012, abbreviated as AICC2012. For the past 60 kyr, the dating scale was constrained by layer counting of Greenland's ice cores (Veres et al., 2013). For ice older than 60 kyr, dating of Antarctic cores is based on various approaches combining ice flow modelling with orbital tuning age markers and other age markers. Typical orbital tuning markers include the isotopic composition of oxygen (hereinafter, $\delta^{18}O_{atm}$) from air bubbles, total air content (hereinafter TAC), and the O_2/N_2 ratios of occluded air. Typical maximum age uncertainties of these markers are claimed to be ~ 6, ~ 4 (Bazin et al., 2013) and ~ 2 kyr (Kawamura et al., 2007; Parrenin et al., 2007b; Hutterli et al., 2009), respectively, although some studies suggest that larger errors can occur in some O_2/N_2 ratio age markers (e.g., Hutterli et al., 2009; Landais et al., 2012). As a result, dating uncertainties depend on the availability and choice of these kinds of age markers for each of the deep ice cores such as EDC (Parrenin et al., 2007a), Vostok (Parrenin et al., 2004; Suwa and Bender, 2008) and DF ice cores (Kawamura et al., 2007; Parrenin et al., 2007a). To better constrain common dating scales, synchronization of deep ice cores using common events such as volcanic markers is a very important task.

Usually in ice core studies, electrical conductivity measurements are performed first because such methods are useful in quickly locating positions of volcanic events in the ice cores. These methods include electrical conductivity measurement (ECM) (e.g., Hammer, 1980; Wolff, 2000), dielectric profile (DEP) (e.g., Moore and Paren, 1987; Wilhelms et al., 1998) and ACECM (e.g., Fujita et al., 2002c). In addition, fast ion chromatography (FIC) yields continuous profiles of ions including sulfate ions (Traversi et al., 2002) useful in locating volcanic events. Fallout of sulfuric acid is known to occur for one or more years following eruptions (e.g., Gao et al., 2006; Hammer et al., 1980). These signals of volcanic events are very useful in synchronizing ice cores. For example, the EDC core has been volcanically synchronized with other major ice cores: with the Vostok ice core by 102 tie points covering 142 ka (Parrenin et al., 2012), with the EDML ice core by ~ 320 tie points covering 150 ka (Ruth et al., 2007; Severi et al., 2007), and with the TALDICE core by ~ 130 tie points covering 42 ka (Severi et al., 2012). These tie points are used to make a common chronology among them (Bazin et al., 2013; Veres et al., 2013).

The DF core was drilled at the dome summit in the Dronning Maud Land in East Antarctica, located at 77°19′ S, 39°42′ E (Fig. 1) (Watanabe et al., 1999). The elevation of WGS84 is 3800 m, and the ice thickness is 3028 (±15) m (Fujita et al., 1999). The EDC core was drilled at one of the dome summits located at 75°06′ S, 123°21′ E, ~ 2000 km away from DF. (Fig. 1) (EPICA Community Members, 2004). The elevation of EDC is ~ 570 m lower than DF at 3233 m at WGS84, and the ice thickness is 3273 (±5) m (Parrenin et al., 2007b). In the published original age scale of the DF core called DFO2006 (Kawamura et al., 2007), there are 23 O_2/N_2 age markers at an age span of between 80 ka BP and 340 kyr BP. Therefore, synchronization between the DF core and the EDC core means that the O_2/N_2 age markers of the DF core can be examined in terms of the latest chronology used commonly for cores such as EDC, Vostok, EDML and TALDICE, namely, AICC2012 (Bazin et al., 2013; Veres et al., 2013). In the AICC2012 chronology, for the period over the past 216 kyr studied in this paper, ice age markers of TAC and the O_2/N_2 ratio were used from the EDC core and the Vostok core, respectively. In addition, gas age markers of $\delta^{18}O_{atm}$ have been used from the EDC, Vostok and TALDICE cores. These gas age markers were linked to the age of ice through assumptions of firn thickness and the lock-in depths of air. Based on the DF-EDC synchronization in this paper, two time scales can be compared in detail, which is a major step toward improving our understanding of the chronology of Antarctic ice cores.

2 Methods

2.1 Datasets

At each of the two sites described above, two deep ice cores have been drilled. At DF, the first core (hereinafter referred as the DF1 core) was recovered during the period 1992–1998 to a depth of 2503 m (Watanabe et al., 2003). The second 3035 m long core (hereinafter referred as DF2 core), reaching nearly to the ice sheet bed, was drilled in the period 2004–2007 at a site ∼ 43 m away from the DF1 borehole (Motoyama, 2007). At EDC, the first core (hereinafter referred as the EDC96 core) was started in the 1996/97 season to a depth down to 790 m. The second 3270 m long core (hereinafter referred as the EDC99 core), reaching nearly to the ice sheet bed, was started during the 1999/2000 season at a site 10 m away from the EDC96 core (EPICA Community Members, 2004). Ice core signals from these four cores were used in the synchronization work in this study. From these ice cores, we used data profiles indicative of strong acids originated from large volcanic eruptions (see Table 1). Resolutions are from 1 to 4 cm. For all these cores, depth determinations were based on the widely used method of logging of ice cores.

2.2 Method of synchronization

Firstly, by using depth-profile graphs of the data sets above and comparisons among them, major tie points were extracted manually. Typically, we attempted to extract a tie point within at least each 5 m depth, although this was not always possible. In glacial periods, there is often a lack of convincing tie points – presumably because of the frequent loss/disturbance of signals of volcanic eruptions due to the smaller accumulation rate and possible accumulation hiatus. At this initial stage, ∼ 650 tie points were extracted down to a depth of ∼ 2250 m for both cores. At deeper depths, there are still more tie point candidates, but they were excluded from this study because we plan to perform detailed analysis of synchronization for deeper depths only in future.

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Secondly, a semiautomatic computer-aided synchronization interface was constructed (see Fig. 2). Based on the initial ∼ 650 major tie points, as many plausible minor tie point peaks as possible were extracted using an interface that automatically extracted further tie point candidates. A final determination was made by an operator who evaluated the shape, size and synchronicity of the candidate peaks. We note that there are no uncertainties associated with the use of different proxy records (ECM, DEP, ACECM and FIC) for the identification of volcanic events: these signals of different proxy records are commonly useful for locating volcanic events. Using a PC interface (see Fig. 2), 1401 tie points were extracted. We note that even for cores at the same site (such as EDC96 and EDC99, DF1 and DF2), there are variable relative depth offsets caused by borehole inclinations, cumulative small errors of ice core logging, fractures, and post-coring relaxations of the core. The offsets were also extracted (data not shown) to avoid any complexity caused by the variable relative depth offsets between cores at the same dome sites. For the EDC core, we converted all depths into depths equivalent to the DEP data of the EDC99 core because these data cover the longest continuous depth span at EDC. Similarly, we converted all the DF2 depths into equivalent depths of the DF1 core. We did not use the height of the peak signals because they were highly variable due to spatially and temporally heterogeneous depositional conditions by winds on the surface of the ice sheet (Barnes et al., 2006; Kameda et al., 2008; Wolff et al., 2005). When the patterns of data fluctuations agreed between one or more sets of data at DF and EDC, they were extracted as tie points with confidence. Difficulty in tie point extraction was met in some cold stages of glacial periods, which are shown below. When we synchronized volcanically between the EDC core and the DF core, the ECM data of the Vostok ice core (Parrenin et al., 2012) were synchronized together. See the graph of Vostok ECM data in the interface in Fig. 2. Between DF and Vostok, and between EDC and Vostok, we identified more than 800 tie points covering the past 140 kyr. The simultaneous nature of the synchronization work for the three deep ice cores provided an opportunity for crosschecks, and we were able to identify tie points confidently. Assessment of the confidence associated with the

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1401 tie points is given in the Supplement of this paper. In this paper, the Vostok data are not developed in order to focus our discussions on the relations between the two dome sites at DF and EDC.

3 Results

3.1 Features of the tie points

The EDC-DF volcanic matching consists of 1401 depth tie points. Data are distributed heterogeneously in time on a time-series graph (Fig. 3). There was the difficulty in finding confident tie points in some cold periods, this is explicable if we assume a frequent occurrence of periods of very low surface accumulation or a hiatus in cold periods. In Fig. 3, depths of the tie points in each ice core are plotted vs. time using a single common dating scale. In the present case, we tentatively use the DFO2006 scale (Kawamura et al., 2007), which is characterized by ice flow modelling strongly constrained by 23 age markers of the O_2/N_2 ratio in an age span between ~ 80 and ~ 340 kyr BP. In Fig. 3, the variations in the gradient on the profiles are due to variable surface mass balance (SMB) multiplied by thinning effects after deposition. For the periods of MIS 3 and 5, large number of tie points were found, typically 10–20 points over every 1 kyr (Fig. 3 bottom). The variations in the number of tie points are due to variable number of major volcanic eruptions, variable atmospheric circulation on the earth, variable depositional environment such as SMB and possible signal diffusion effects in ice after deposition.

3.2 Difference in age between DFO2006 and AICC2012 age scales

From these 1401 tie points, we can calculate the difference in dating scales of the DF core and the EDC core, respectively. For comparison, here we use the DFO2006 and AICC2012 chronologies. The differences in age scales are given in Fig. 4a and b. We find that for the periods of MIS 1–4, 6 and 7a, the difference ranges between 0 and

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−2.0 kyr. Here, positive/negative values mean that the DFO2006 chronology tends to have older/younger ages with reference to the AICC2012 chronology. In the period of MIS 5, the difference ranges between 0 and +4.5 kyr. A remarkable feature is that the age difference has peak values of +4.5 and +3.1 kyr at timings of MIS 5d and MIS 5b, respectively. Before the MIS 5d and after the MIS 5b, there are tails of the profile covering almost the entire MIS 5. Over the period of a very large scale of ∼ 200 kyr, there are very large periodical changes: there is a negative difference for ∼ 70 kyr in MIS 7a and MIS 6, a positive difference for ∼ 60 kyr in MIS 5, and again a negative difference for ∼ 70 kyr in MIS 4, 3 and 2.

3.3 Difference in event durations between DFO2006 and AICC2012 age scales

We also investigated the difference in durations of climatic events between DFO2006 and AICC2012. In Fig. 4a and b, the variable gradient of the red profiles is associated with the ratio of duration of the same climatic event on DFO2006 and AICC2012. Positive and negative gradients mean shorter and longer durations on DFO2006 compared to those on AICC2012, respectively. The duration between the O_2/N_2 age markers of the DF core on the two different time scales and their differences are listed in Table 3. We use these markers because they are the most reliable ice age markers that can be placed directly on ice depths of the DF and EDC cores at ages greater than ∼ 80 kyr BP. We find that differences in duration often range 10–20 %. In some cases, the duration difference is even larger. Because of the maximum DFO2006/AICC2012 age gap at MIS 5d, the differences in durations are large before and after MIS 5d. For example, at a time span between age markers ID 3 and 6 (Tables 2 and Fig. 4a), duration on DFO2006 is 114 % of the duration on AICC2012. This time span contains MIS 5b, 5c and 5d. The difference in duration is 4.4 kyr, which is much larger than the 2σ confidence interval of 2.7 kyr. Similarly, at a time span between age markers ID 6 and 9, DFO2006 gives a duration of 85 % of the duration on AICC2012. This time span contains the late stages of MIS 6 and MIS 5e. The difference in duration is 6.1 kyr, which is again much larger than the 2σ confidence interval of 2.7 kyr. Over

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a period of a very large scale of ∼ 200 kyr, AICC2012 and DFO2006 tend to give longer and shorter durations, respectively, in periods from the middle of the glacial periods toward interglacials (e.g., from MIS 3 to MIS 2, and from MIS 6 to MIS 5e). In contrast, AICC2012 and DFO2006 tend to give shorter and longer durations, respectively, in the middle of glacial periods (e.g., from MIS 5d to MIS 5a).

4 Discussions

The dating scale for the DF core, DFO2006, is a glaciological interpolation of the O_2/N_2 age markers. It is therefore strongly constrained by them (Kawamura et al., 2007). In contrast, the dating scale AICC2012 is the best compromise between a background chronology (based on modelling of the SMB, and snow densification into ice and ice flow) and observations (absolute ages or certain reference horizons, and stratigraphic links among several cores and orbital ages) (Bazin et al., 2013). Because of the weaker constraining by the age markers as compared to the case of DFO2006, a character of the AICC2012 is "the glaciological chronology" which has more weight on estimation of glacial flow as compared to the O_2/N_2-markers-based chronology. Therefore, the age gaps between the two chronologies are caused by both dating approaches and the complex effects from elements used in the dating approaches. To understand the age gaps, we should see, on one hand, age marker errors, SMB errors and errors in estimation of ice thinning, and possible propagation of the errors through stratigraphic links. On the other hand, we should examine how the age gaps are associated with differences in the dating approaches.

As the first step of analysis, here we perform a crosscheck of age markers. That is, we examine compatibility between ice age markers of DFO2006 and AICC2012 age. Also, we examine compatibility between ice age markers of AICC2012 and DFO2006 age. This analysis became possible because of the synchronization in this study. Then, we present preliminary discussions about possible errors in the glacial flow estimations. Possible errors in estimation of ice thinning will be excluded from possible causes of the large and systematic DFO2006/AICC2012 age gaps. The possibility of the propagation of errors through stratigraphic links will be also discussed based on close resemblance between AICC2012 age scale and a previous age scale of EDC core known as EDC3 (Bazin et al., 2013). We are interested in the difference in dating approaches and possible errors in SMB, as discussed below.

4.1 Crosscheck of age markers

For this purpose, we calculate [DFO2006 marker ages – AICC2012 age] and [DFO2006 age – AICC2012 marker ages]. The calculated results are shown as marker symbols in Fig. 4a and b, respectively, and also given in Tables 2 and 4, respectively. Here, we examine only ice ages of the markers (such as TAC markers, O_2/N_2 age markers and some other ice age markers) and ice ages of the chronology, and not gas age markers ($\delta^{18}O_{atm}$) or gas age chronology. This is because to assess compatibility between the gas age markers and ice age chronology, we must examine firnification models as well, which makes analyses very complex. In Fig. 4a, the data points are on the red line of the DFO2006/AICC2012 age gap, because DFO2006 is an age-markers-based time scale. In Fig. 4a, the number at each data point is the ID of each age marker in Table 2. Error bars are 2σ confidence intervals of the age markers (Kawamura et al., 2007). We find here that the DFO2006/AICC2012 age gaps clearly violate the 2σ-confidence intervals at points with IDs from 4 to 7, systematically. In addition, at a point with ID 8, the DFO2006/AICC2012 age gaps are still well above the 1σ-confidence interval. In Fig. 4b, the data points are not on the red line of the DFO2006/AICC2012 age gap because AICC2012 is a glaciological time scale. In Fig. 4b, the number at each data point is the ID of each age marker in Table 4. Blue symbols and green symbols are for age markers from the EDC core and the Vostok core, respectively (Bazin et al., 2013). The O_2/N_2 age markers with IDs 9 and 10 are from the Vostok core, originally published by Suwa and Bender (2008). Bazin et al. (2013) attributed 4 kyr as the 2σ-confidence intervals of these O_2/N_2 age markers instead of the 2 kyr intervals originally assessed by Suwa and Bender (2008). Bazin et al. (2013) used conservative values

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of the uncertainty because of their questions about the phasing of the local insolation curve and O_2/N_2 curve. Note that we did not use ice age markers from the Vostok core older than 140 ka for our analysis because they are not volcanically synchronized with the EDC core or the DF core (Parrenin et al., 2012). We find here that the DFO2006/AICC2012 age gaps violate the 2σ-confidence intervals at very limited points such as ID 6. Around this single age marker, the DFO2006/AICC2012 age gap is as large as 3 kyr in MIS 5b, which can be partly explained as the effect of this ID 6 TAC age marker. However, in MIS 5b–5e, the DFO2006/AICC2012 age gap is not well explained by the effects of age markers with IDs 7–11. A remarkable feature in Fig. 4b is that in periods of MIS 5b–5e, the DFO2006/AICC2012 age gaps (red line) are systematically larger than values of [DFO2006 age – AICC2012 marker age] by 1–3 kyr. Thus, the 1–3 kyr gaps are apparently not driven by the age incompatibility between the ice age markers used for establishing the two chronologies. Remaining possibilities include (i) errors in the SMB, (ii) errors in thinning calculations or (iii) complex effects of other ice core orbital markers and numerous stratigraphic links with the influence of background scenarios. We mentioned above differences in dating approaches between the O_2/N_2 age-markers-based dating and the glaciological dating. In principle, errors due to differences in dating approaches include both (i) errors in the SMB and (ii) errors in thinning calculations. The possible errors (iii) includes errors in gas age markers influencing the age of ice through models of firnification.

4.2 Possible causes of the DFO2006/AICC2012 age gaps

One of the possibilities above is errors in the estimation of vertical thinning. However, we find no glaciological explanation that at the two coring sites of DF and EDC, synchronized ice covering the entire MIS 5 deforms spatially heterogeneously, causing the observed gaps in ages and differences in durations. In addition, according to the concept of conservation of mass, a thinner layer at one location can only be explained if there is a thicker layer in a neighboring location. However, no irregularity is seen in

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the isochronal layers observed by radio echo sounding (e.g., Fujita et al., 1999, 2012; Tabacco et al., 1998). We therefore conclude that this possibility can be excluded.

As for the possibility of complex effects of the other ice core orbital markers and numerous stratigraphic links with the influence of background scenarios, an assessment must be made based on simulations of synchronized and optimized age scale. Bazin et al. (2013) used numerous gas age markers of $\delta^{18}O_{atm}$ from the Vostok core and the TALDICE core for periods covering MIS 5. These numerous gas age makers are linked with the ice age of the AICC2012 through assumptions of firn thicknesses at each site and lock-in depths. However, there is circumstantial evidence that raises a question as to this possibility. The previous age scale of the EDC core is known as EDC3 (Parrenin et al., 2007a). EDC3 is the glaciological chronology based on the use of a set of independent age markers, and the SMB and mechanical flow modelling. Bazin et al. (2013) show that the timing and duration of MIS 5 in AICC2012 is basically unchanged compared to EDC3. We performed analysis of the DFO2006/EDC3 age gap, just like the analysis of the DFO2006/AICC2012 age gap. We found that the basic profile of the DFO2006/EDC3 age gap is similar to the DFO2006/AICC2012 age gap (purple dotted line in Fig. 4b). Again, we find peak values of +3.6 kyr and +3.6 kyr at timings of MIS 5d and MIS 5b, respectively. Because the EDC3 age scale is independent of any stratigraphic links to other ice cores, this means that “the stratigraphic links to other cores” introduced to the AICC2012 gave no major effects to the observed major features of the age gaps. In addition, according to Bazin et al. (2013), the ice age difference between the O_2/N_2 chronology and the $\delta^{18}O_{atm}$ chronology on the Vostok ice have no anomalous bias that occur particularly at periods around MIS 5 (see Fig. 4 in Bazin, et al. 2013). We therefore conclude that this possibility can be excluded as well.

We are interested in the remaining possibility, errors in estimating SMB during MIS 5 associated with difference in the dating approaches. To examine this possibility, we introduce a comparison between DFO2006 chronology with the glaciological chronology of the same DF core, DFGT2006 (Parrenin et al., 2007a) in Fig. 5. In building DFGT2006 chronology, as compared to DFO2006, Parrenin et al. (2007a) used smaller number of the age markers with larger uncertainty setting to less constrain the age by the age markers in purpose, to observe features of the glaciological chronology. In Fig. 5, we find that the DFO2006/DFGT2006 age gap have variations with peak gaps at MIS 5b and 5d, very similar to variation of the DFO2006/AICC2012 age gap or variation of the DFO2006/EDC3 age gap (see Fig. 4). The similarity lead us to hypothesize that the DFO2006/AICC2012 age gap is associated with difference between the O_2/N_2 age-markers-based dating and the glaciological dating, in particular, SMB errors.

In order to further examine possible causes of the DFO2006/AICC2012 age gaps during MIS 5, DFO2006 and AICC2012 ages are compared with the ages of the absolutely dated speleothem record from China (hereinafter speleo age) (Cheng et al., 2009) based on synchronization between the EDC core record and the Chinese speleothem records (Barker et al., 2011) and on the DF-EDC volcanic synchronization. The speleothem synchronization made the assumption that rapid changes in speleothem $\delta^{18}O$ are synchronous with rapid changes in Greenland temperature, which were in turn deduced as the inflection points in the Antarctic deuterium record. Details of the comparison are given in Fig. 6. At MIS 1–5a, 5e and 6, three chronologies (DFO2006, AICC2012 and the speleo age) are within 2 kyr. At MIS 5b, the speleo age and the AICC2012 ages agree well whereas only the DFO2006 age is deviated by up to 3 kyr. At MIS 5c and 5d, the speleo age and the DFO2006 ages agree well whereas only the AICC2012 age is deviated by up to 4 kyr. At MIS 7a, the DFO2006 and the AICC2012 ages agree well whereas only the speleo age is deviated by up to 4 kyr. However, the features used to match the speleothems with the EPICA Dome C deuterium at this depth are ambiguous; so it is possible that the matching process at this depth was in error. In summary, based on the comparison with the ages of the absolutely dated speleothem record, our suggestions are as follows.

i. At MIS 5c and 5d, reliability of the O_2/N_2 age markers dating (DFO2006) are supported by the absolutely dated speleothem records from China. Thus,

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plausible cause of the DFO2006/AICC2012 age gaps during these periods is errors in the AICC2012 age.

ii. At MIS 5b, two absolutely dated markers, that is, the O_2/N_2 age markers and the speleothem ages do not reconcile with each other within their confidence intervals. Thus, we should identify which is correct in future.

iii. At the same time, as we find at MIS 7a that only the absolute speleothem age is deviated. Thus we should be in mind any of absolutely dated records potentially contain yet unidentified errors.

The large gap of age at MIS 5, at least at MIS 5c and 5d as examined above, are explained by an overestimation of the SMB as compared to true SMB values at each site in a period from the late stage of MIS 6 until MIS 5b in all of the glaciological chronologies such as AICC2012, EDC3 and DFGT2006. If this overestimation occurs, ice around the interglacial periods such as MIS 5 will have a systematic bias of errors to be younger. Consequently, durations will have a systematic bias of errors to be longer. Besides, there should be a period for compensation for this "strain" of dating accumulated in the chronology. The shorter duration in MIS 5a–5c in the glaciological chronologies can be explained as the appearance of a period for such compensation. In addition, as we describe in the results section, the DFO2006/glaciological-chronology age gaps appears to have a large scale periodicity of the glacial/interglacial period (Figs. 4 and 5). It is possible that such a large-scale periodicity is present because errors in estimation of SMB is associated with variations of the relations between water isotope ratios and SMB over the glacial/interglacial periods. In the past ~ 60 kyr, the DFO2006/glaciological-chronology age gaps are small because of the wealth of reliable constraints (e.g., Veres et al., 2013). But in time periods of older ice with limited constraints for dating, the DFO2006/glaciological-chronology age gaps with a large scale periodicity of glacial/interglacial period can be present because methods for establishing a chronology are consistent. These topics of possible SMB errors are further developed in our companion paper (Parrenin et al., 2015).

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5 Concluding remarks

In summary, based on the DF-EDC synchronization, several time scales, DFO2006, AICC2012, EDC3, DFGT2006 and ages of the speleothem record from China, were compared in detail. The DF-EDC volcanic matching consists of 1401 depth tie points, that are distributed heterogeneously in time on a time-series. From the 1401 tie points, we calculated the difference in dating scales between the DFO2006 chronology and the AICC2012 chronology. For the periods of MIS 1–4, 6 and 7a, the difference ranges between 0 and −2.0 kyr. For the period of MIS 5, the difference ranges between 0 and +4.5 kyr, with peak values of +4.5 and +3.1 kyr at timings of MIS 5d and MIS 5b, respectively; positive values mean the DFO2006 chronology has older ages than the AICC2012 chronology. Accordingly, differences in event durations often range from 10–20 %, and even larger in some cases. At MIS 5, the DFO2006/AICC2012 age gaps are large and systematic, and they are driven apparently not mainly by incompatibility of the ice age markers used for establishing each of the two chronologies. If we base analyses on the confidence intervals of the O_2/N_2 age markers from the DF core, we hypothesize that the systematic age gaps are mainly driven by the errors associated with the glaciological approaches of dating, plausibly in errors in estimation of the SMB. At least at MIS 5c and 5d, both the O_2/N_2 age markers for DFO2006 chronology and the absolutely dated speleothem records from China agree with each other within narrow range of a few hundred years, suggesting that errors should be mainly in the AICC2012 age at these periods. In addition, we find that a DFO2006/glaciological-chronology age gaps with a large scale periodicity of a glacial/interglacial period can be present. Overall, a crosscheck of age markers and various chronologies brought us new insights into the chronologies of deep ice cores. Our hypothesis of plausible SMB errors is explored by analyses of SMB based on this DF-EDC volcanic synchronization in our companion paper (Parrenin et al., 2015).

The reliability of the orbital age markers such as O_2/N_2 age markers and ages of the speleothem records is a key factor that influences the entire discussion and

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conclusions. The TAC age markers are another important set of ice age markers that are free from assumptions of firn thickness and the lock-in depths of air (e.g., Fig. 4b). The reliability of the O_2/N_2 age markers and the TAC age markers is currently under investigation by many researchers (e.g., Bender, 2002; Fujita et al., 2009, 2014; Hutterli et al., 2009; Kawamura et al., 2004, 2007; Landais et al., 2012; Lipenkov et al., 2011; Raynaud et al., 2007; Suwa and Bender, 2008; Hörhold et al., 2012; Courville et al., 2007). It is beyond the scope of this paper to delve into this. But it now seems clear that we need to study how the O_2/N_2 age markers and the TAC age markers can attain compatibility through a better understanding of the related physical mechanisms in firn. In addition, considering the two examples of major age gap between the age of the O_2/N_2 age markers and ages of the speleothem records at MIS 5b and MIS 7a, we must identify causes of these age gaps. Finally, we note that the two deep ice cores are well synchronized in the studied age span, which will strengthen climate change research using ice core signals from these two ice cores. In particular, the timing and duration of the glacial and interglacial periods can be studied with better understanding. This new stratigraphic constraint will be incorporated into the next synchronized and optimized age scale. In particular, possible errors in the SMB must be tested.

Appendix A: Confidence level of the tie points

We examine occurrence probability for choosing wrong tie points in the DF-EDC volcanic synchronization. The sequence of the 1401 tie points are distributed on a smooth profile in Fig. A1. The 1401 DF-EDC tie points were within time span of the past 216 kyr. Thus, the average time span from one tie point to another is ~ 154 years although the tie points are distributed irregularly along time. In depth scale, as we discuss below, candidates of tie points are found in most cases within 0.1 m in depth of the synchronicity. For volcanic events as rare as every ~ 154 years (in average), probability for accidental appearance of confusing volcanic signals within depths of ~ 0.1 m between the two cores should be very small.

Conditions for choosing the wrong tie points by an operator of the PC interface are schematically shown in Fig. A2.

i. The volcanic signal 1 in DF core and the volcanic signal 2 in EDC core must be significantly observable.

ii. At the same time, the volcanic signal 1 in EDC core and the volcanic signal 2 in DF core must be faint or absent, to induce misjudgement of an observer.

iii. These two peaks should be within depths of ~ 0.1 m or so of the location expected assuming the layer thickness ratio between the adjacent volcanic match pairs remains constant. Otherwise, it is highly probable that the observer does not think that a pair of peak signals is a candidate of tie points.

A probability for occurrences of these three conditions together should be very small.

From a viewpoint of an operator of the PC interface, almost all tie points were determined without ambiguity, because the operator rarely found indication of confusing candidates of volcanic peaks that could be sources of errors. When we search for possible candidates of the tie points, we found each pair of candidates in most cases, within 0.1 m in expected depths. We note that the variances of ~ 0.1 m are acceptable and understandable considering the past roughness of the Antarctic surface (Barnes et al., 2006). If we find a volcanic signal in one core but not in expected depth in another core, we just ignore such single signal and nothing is recorded. Thus, lone peak is not any source of error. Figure A3 is given to show candidates of the tie points were found within narrow depth range in depth.

Along the sequence of the 1401 DF-EDC tie points, depth span between adjacent tie points (Δz) are calculated for depths of both DF and EDC cores. Δz ranged from 0.02 m (minimum) to ~ 29 m (maximum). In Fig. A3, 12 XY plots, Δz at DF vs. Δz at EDC, were made using logarithmic scale both in X and Y. Figures labelled from a to l are for age span of DFO2006 and at Marine Isotope Stage (MIS) indicated in each figure. With these figures, we can see how depth span between adjacent tie points were almost common along DF core and along EDC core, with only very small deviations of Δz of the order of 0.1 m.

Overall, as mentioned in the main text, determination by an operator was made confidently using the shape, size and synchronicity of the candidate peaks along the two ice cores. Among them, synchronicity was quite good. As a result, smooth continuity of the trace in Fig. A1 is also good. We therefore argue that they are almost unambiguous tie points, except possible very rare cases of conditions indicated in Fig. A2.

In addition, even if a few erroneous tie points are accidentally included within the 1401 tie points found in this work, error size in depth is of the order of ~ 0.1 m. Therefore, there will be virtually no impact in further analysis.

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Table 1. Summary of datasets of ice core signals used for synchronization.

Core	Name of measurement	Depth range used (m)	Measured properties	Measurement temperature (°C)	Depth resolution (cm)	Reference
DF1	ECM	2–2250	Direct current of solid ice	−20 ∼ −30	1	Fujita et al. (2002a–c)
	AC-ECM	112–2250	High-frequency conductance of solid ice at 1 MHz	−20 ∼ −30	1	Fujita et al. (2002a–c)
DF2	ECM	889–2250	Direct current of solid ice	−20	1	This study
	AC-ECM	889–2250	High-frequency conductance of solid ice at 1 MHz	−20	1	This study
EDC96	ECM	99–788	Direct current of solid ice	−20	1	EPICA Community Members (2004)
	Sulfate	7–788	Concentration of sulfate ions		4	Udisti et al. (2000)
	DEP	7–788	High-frequency conductivity of solid ice at 100 kHz	−20	2	Wolff et al. (2005)
EDC99	ECM	772–3188	Direct current of solid ice	−20	1	EPICA Community Members (2004)
	Sulfate	769–2094	Concentration of sulfate ions		2	Udisti et al. (2004)
	DEP	7–3165	High-frequency conductivity of solid ice at 100 kHz	−20	2	Wolff et al. (2005)

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Table 2. Depths and AICC2012 ages of EDC core at depth/age of age markers of DF core.

ID	Type	DF core			EDC core		Age difference
		Depth of DF1 core (m)	Age of age marker (A) (yr b2k)	2σ of age marker (years)	Synchronized depth on EDC99 core (m)	Age on AICC2012 chronology (B) (yr b2k)	A – B (years)
1	ACR-Holocene	371.00	12 390	200	371.46	12 296	94
2	Be10 peak	791.00	41 205	500	739.35	41 227	−22
3	O_2/N_2	1261.55	81 973	2230	1170.17	81 923	50
4	O_2/N_2	1375.69	94 240	1410	1278.73	91 132	3108
5	O_2/N_2	1518.87	106 263	1220	1417.10	103 518	2745
6	O_2/N_2	1605.26	116 891	1490	1498.03	112 443	4448
7	O_2/N_2	1699.14	126 469	1660	1614.13	122 718	3751
8	O_2/N_2	1824.78	137 359	2040	1769.25	135 839	1520
9	O_2/N_2	1900.68	150 368	2230	1849.02	152 058	−1690
10	O_2/N_2	1958.32	164 412	2550	1910.13	164 814	−402
11	O_2/N_2	2015.00	176 353	2880	1969.00	178 365	−2012
12	O_2/N_2	2052.25	186 470	2770	2008.59	186 471	−1
13	O_2/N_2	2103.11	197 394	1370	2066.08	198 399	−1005
14	O_2/N_2	2156.64	209 523	1980	2131.85	209 998	−475

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Table 3. Duration between O_2/N_2 time markers on two different time scales and their differences.

ID	Duration		Difference in duration	Fraction of duration difference on each of the time scales	
	on DF O_2/N_2 age marker (C) (years)	on AICC2012 age scale (D) (years)	D – C (years)	(D – C)/C (%)	(D – C)/D (%)
3–4	12 267	9209	−3058	−25	−33
4–5	12 023	12 387	363	3	3
5–6	10 628	8925	−1703	−16	−19
6–7	9578	10 275	697	7	7
7–8	10 890	13 121	2231	20	17
8–9	13 009	16 219	3210	25	20
9–10	14 044	12 756	−1288	−9	−10
10–11	11 941	13 551	1610	13	12
11–12	10 117	8106	−2011	−20	−25
12–13	10 924	11 928	1004	9	8
13–14	12 129	11 599	−530	−4	−5

Table 4. Depths and DFO2006 ages of DF core at depth/age of age markers of AICC2012 chronology.

ID	Type	Age markers used to constrain AICC2012 age scale				Age on DFO2006 chronology		Age difference
		Original core	Depth in original core (m)	Age of age marker (E) (yr b2k)	2σ of time marker (years)	Synchronized depth on DF1 core (m)	Age on DFO2006 chronology (F) (yr b2k)	F – E (years)
1	Be10	Vostok	178.00	7230	100	233.27	7372	142
2	TAC	EDC	501.65	22 000	2879	514.14	20 132	−1868
3	TAC	EDC	693.67	39 000	2211	738.20	36 732	−2268
4	Be10	Vostok	601.00	40 700	950	781.66	39 864	−836
5	Be10	EDC	740.08	40 700	950	791.81	40 642	−58
6	TAC	EDC	1255.93	87 000	3082	1352.73	91 495	4495
7	Mt. Berlin tephra	EDC	1265.10	93 250	4400	1361.74	92 580	−670
8	TAC	EDC	1377.67	101 000	4031	1473.94	102 438	1438
9	O_2/N_2	Vostok	1675.00	121 850	4000	1673.08	124 172	2322
10	O_2/N_2	Vostok	1853.70	132 350	4000	1777.84	132 221	−129
11	TAC	EDC	1790.29	143 000	6468	1843.81	140 540	−2460
12	TAC	EDC	2086.69	203 000	6403	2121.00	200 939	−2061

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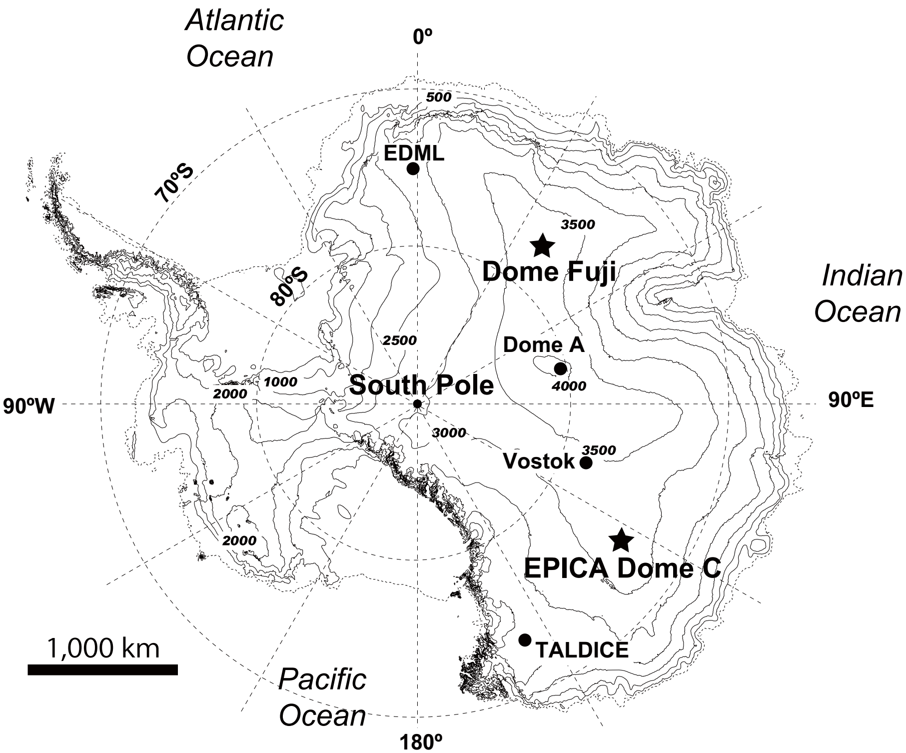

Figure 1. Map of the continent of Antarctica with elevation contours every 500 m. The two ice coring sites used in this study, Dome C and Dome Fuji, are marked with stars.

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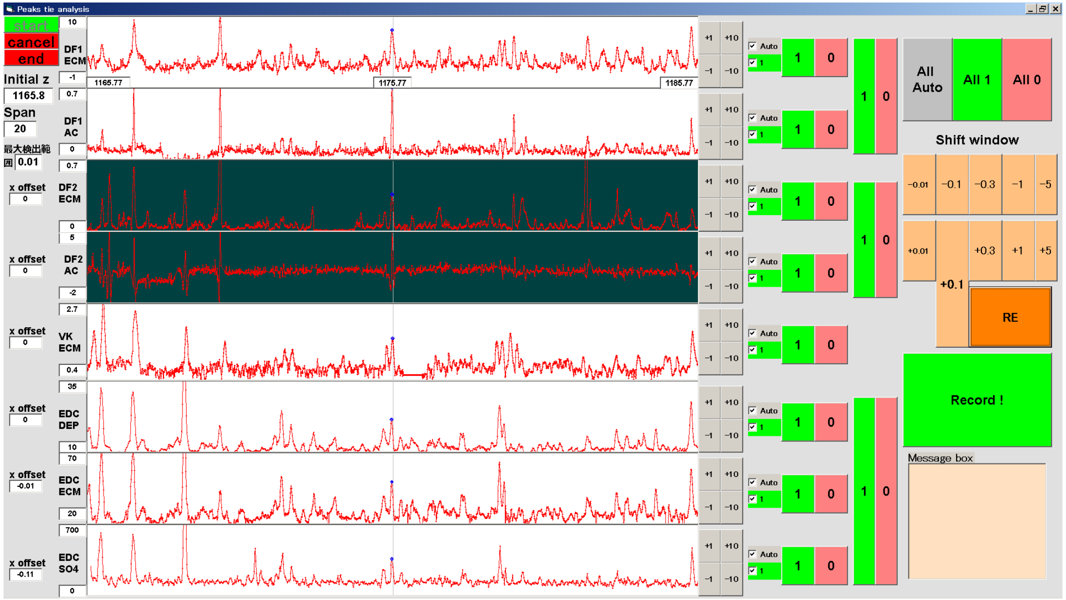

Figure 2. A PC interface window used to search for tie points semiautomatically. Based on preliminary tie points, a detailed search can be conducted easily. In the data profiles (red traces), the candidates for tie points were found by extracting local maxima (dots in the center of graphs). After choosing each datum or not (1/0 switches in the right side of the image), by clicking "Record" on the right, the data – depth of peak, peak height and background level – are recorded. This example is for a plausible Toba super eruption that occurred sometime at ∼ 74 ka studied by Svensson et al. (2012). Graphs from the top are: DF1 ECM, DF1 ACECM, DF2 ECM, DF2 ACECM, Vostok ECM, EDC DEP, EDC ECM and EDC sulfate (see Table 1).

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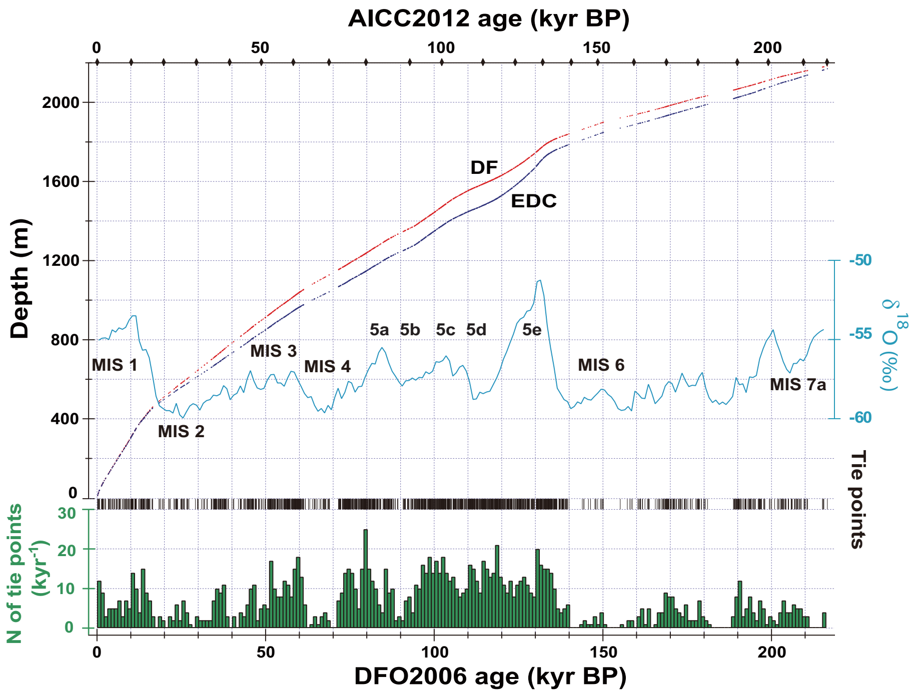

Figure 3. Result of volcanic synchronization: DF depth/EDC depth on a tentative common dating scale DFO2006 (bottom axis). AICC2012 scale is also given on the top axis as a reference. Blue trace with indications of the Marine Isotope Stages is $\delta^{18}O$ averaged over every 1 kyr for reference (Watanabe et al., 2003). Black vertical symbol markers are locations of the tie points on the age scale. Green histogram mean number of the tie points found over every 1 kyr.

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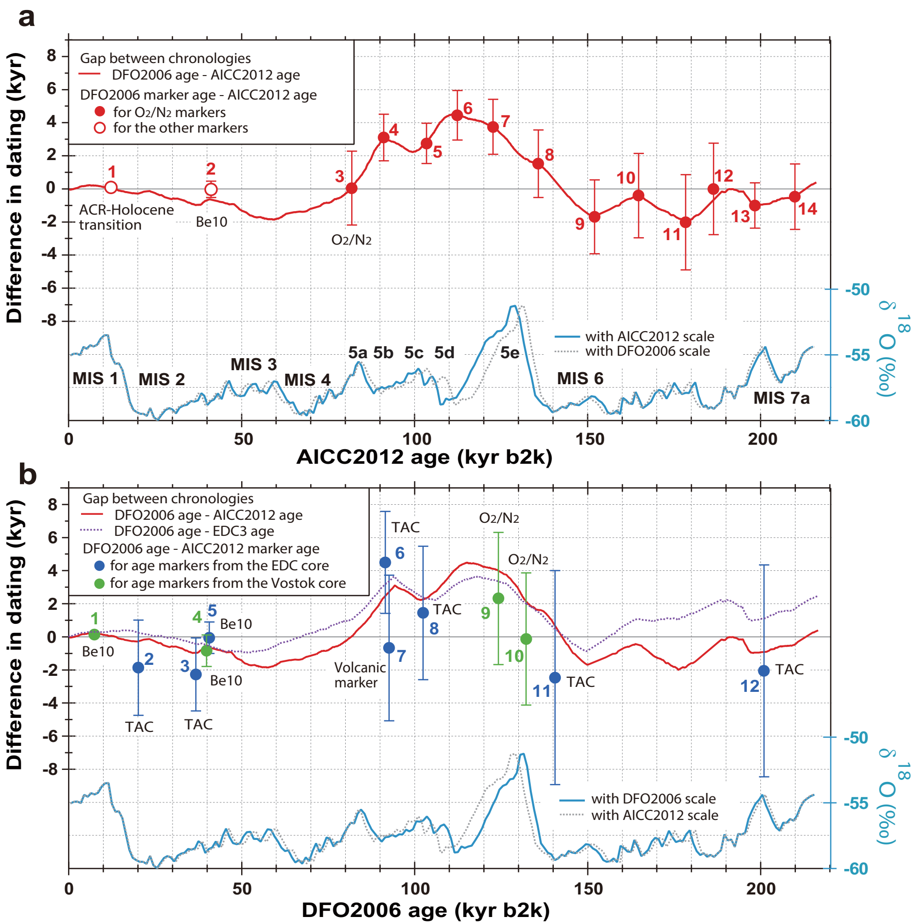

a
b
Gap between chronologies
DFO2006 age - AICC2012 age
DFO2006 marker age - AICC2012 age
for O2/N2 markers
for the other markers
Difference in dating (kyr)
ACR-Holocene transition
Be10
O2/N2
MIS 1
MIS 2
MIS 3
MIS 4
5a 5b 5c 5d
5e
MIS 6
MIS 7a
with AICC2012 scale
with DFO2006 scale
δ 18 O (‰)
AICC2012 age (kyr b2k)
DFO2006 age - EDC3 age
DFO2006 age - AICC2012 marker age
for age markers from the EDC core
for age markers from the Vostok core
TAC
Volcanic marker
with DFO2006 scale
with AICC2012 scale
DFO2006 age (kyr b2k)

Figure 4. Various gaps in dating clarified based on DF/EDC synchronization are shown with two chronologies, AICC2012 and DFO2006, in upper figure **(a)** and lower figure **(b)**, respectively. Red lines in both **(a)** and **(b)** are the age gaps between the two chronologies as [DFO2006 age – AICC2012 age]. The purple dotted line is [DFO2006 age – EDC3 age] discussed in Sect. 4.2. Blue traces with indications of the Marine Isotope Stages are δ^{18}O averaged over every 1 kyr for reference (Watanabe et al., 2003). In the top of **(a)**, age differences [DFO2006 marker age – AICC2012 age] (Table 2) are given. The number at each data point is the ID of each age marker in Table 2. Error bars are 2σ-confidence intervals of the age markers (Kawamura et al., 2007). Similarly, in the top of **(b)**, age differences [DFO2006 age – AICC2012 marker age] (Table 4) are given. Again, the number at each data point is the ID of each age marker in Table 4. The blue symbols and green symbols represent age markers from the EDC core and the Vostok core, respectively (Bazin et al., 2013). Vertical error bars are again the 2σ-confidence intervals of the age markers. In MIS 5b–5e, the DFO2006/AICC2012 age gaps (red line) are systematically larger than values of [DFO2006 age – AICC2012 marker age]. Details are discussed in the text.

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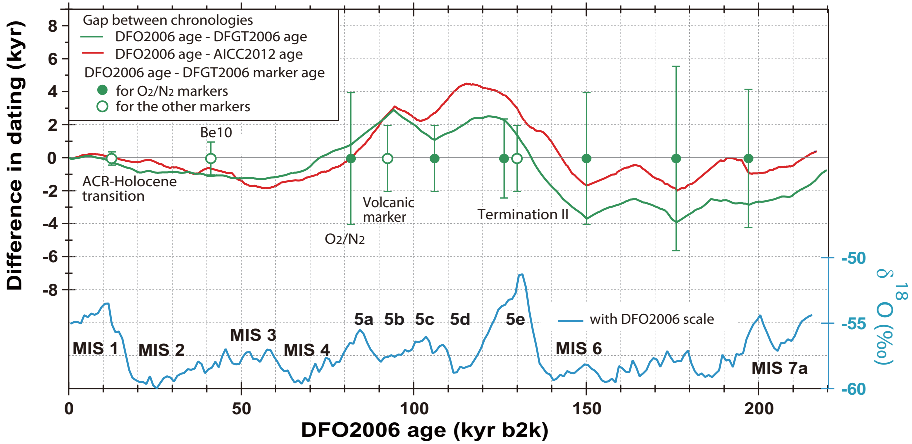

Figure 5. The O_2/N_2 chronology of the DF core, DFO2006, and the glaciological chronology of the same DF core, DFGT2006, are compared. Green line in the figure is the age gaps between the two chronologies as [DFO2006 age – DFGT2006 age]. Although age markers of the DFGT2006 age have no age gap with the age markers of the DFO2006, DFGT2006 use smaller numbers of the markers and with larger uncertainty setting (see circle symbol markers and the 2σ-confidence intervals) to less constrain the age by the age markers in purpose, to observe features of the glaciological chronology. Red line is the age gap [DFO2006 age – AICC2012 age], shown with a purpose of comparison. We observe that the green line and the red line have similar variations with peak gaps at MIS 5b and 5d. Blue traces with indications of the Marine Isotope Stages are $\delta^{18}O$ averaged over every 1 kyr for reference (Watanabe et al., 2003).

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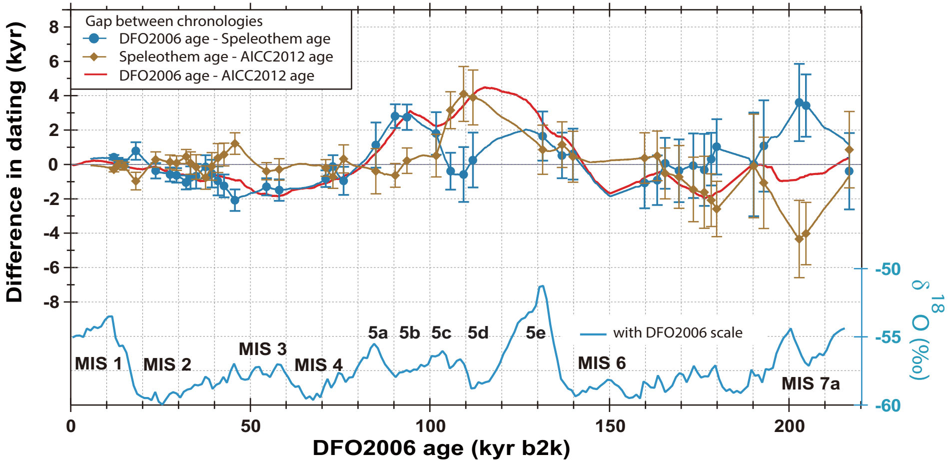

Figure 6. DFO2006 and AICC2012 ages are compared with the ages of the Chinese speleothem age (hereinafter speleo age) (Cheng et al., 2009) based on synchronization between the EDC core record and the Chinese speleothem records (Barker et al., 2011) and on the DF-EDC volcanic synchronization. Blue line in the upper figure is the age gaps [DFO2006 age – speleo age]. Blue solid circle symbol markers are from tie points between the EDC core record and the speleothem records (Table S1 in Barker et al., 2011). Indicated uncertainty is the combined uncertainty of the EDC-speleothem tuning errors and absolute errors of the speleo age. Profiles connecting the marker symbols are from an improved EDC age model given in Barker et al. (2011). Yellow line is the age gaps [speleo age – AICC2012 age]. Yellow diamond symbol markers are also from tie points between the EDC core record and the speleothem records. Indicated uncertainty is the same as above. Red line is the age gap [DFO2006 age – AICC2012 age]. Blue traces in the lower half with indications of the Marine Isotope Stages are δ^{18}O averaged over every 1 kyr for reference (Watanabe et al., 2003). Features of the data are discussed in the text.

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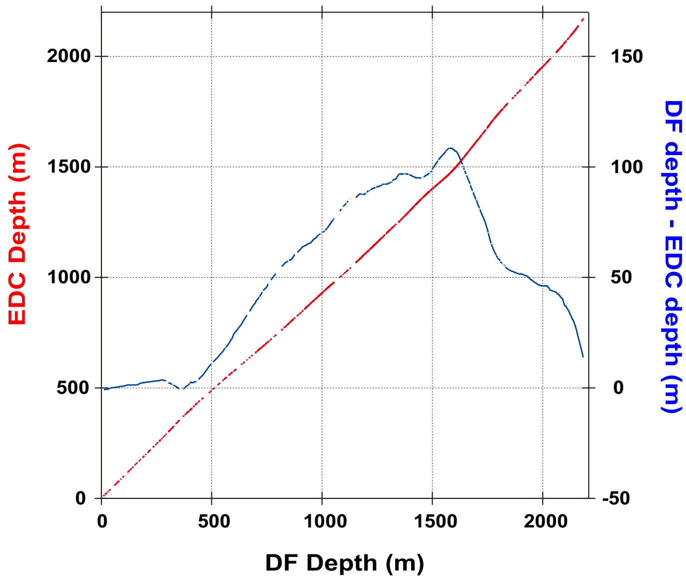

Figure A1. Result of the volcanic synchronization: DF depth/EDC depth diagram (red) and DF depth – EDC depth difference (blue).

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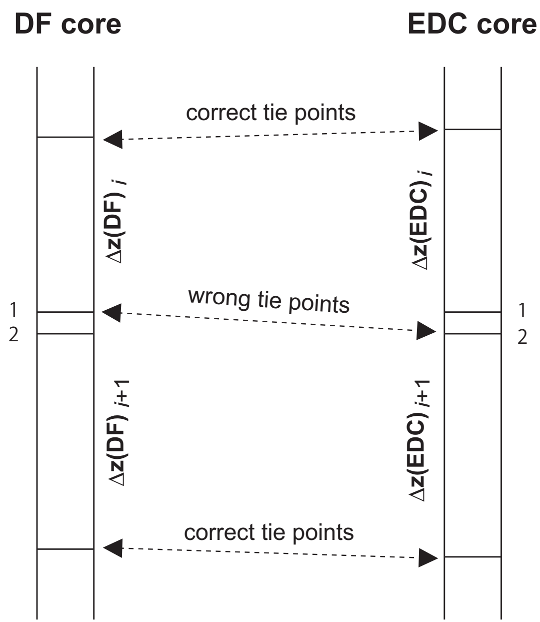

Figure A2. Schematic illustration of choosing the wrong tie points by an operator of the PC interface. The error can occur under conditions described below. (i) The volcanic signal 1 in DF core and the volcanic signal 2 in EDC core must be significantly observable. (ii) At the same time, the volcanic signal 1 in EDC core and the volcanic signal 2 in DF core must be faint or absent. (iii) These two peaks should be within depths of ∼ 0.1 m or so of the location expected assuming the layer thickness ratio between the adjacent volcanic match pairs remains constant. Otherwise, the observer will not think that two peak signals are candidates of true link.

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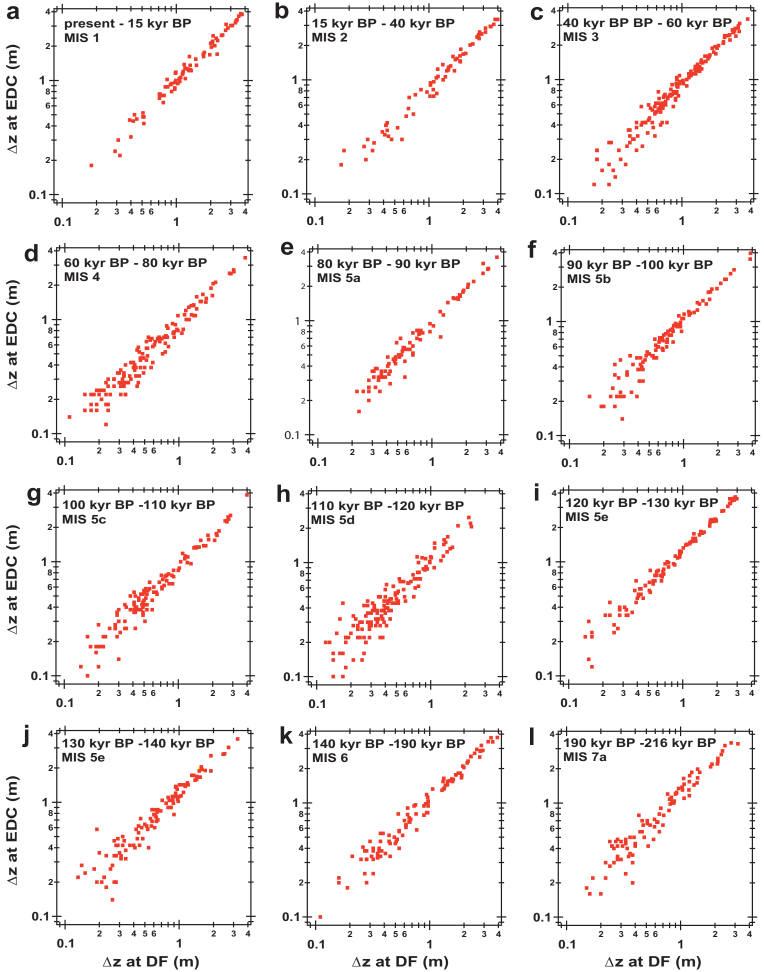

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Figure A3. Along the sequence of the 1401 DF-EDC tie points, depth span between adjacent tie points were calculated for depths of both DF and EDC cores. Here, $\Delta z_i = z_{i+1} - z_i$. i is is integer from 1 to 1400. Then, XY plots were made as Δz_i at DF vs. Δz_i at EDC. Figures from **(a)** to **(l)** are for age span on DFO2006 and at Marine Isotope Stage (MIS) indicated in each figure. With this figure, we can see how depth span between adjacent tie points were deviated between Δz_i at DF and Δz_i at EDC, with each other. We can observe that they are in most cases within ~ 0.1 m.

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