Scientific paper

Dating of the Dome Fuji shallow ice core based on a record of volcanic eruptions from AD 1260 to AD 2001

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Abstract

We measured the concentration of non-sea-salt sulfate ($nssSO_4^{2-}$) in the Dome Fuji shallow ice core (Antarctica) from the surface to 40 m depth with the aim of dating the core with reference to the record of volcanic eruptions. Three huge spikes related to large-scale volcanic eruptions were detected at depths of 12.5, 29.9, and 38.8 m, correlated to the eruptions of Tambora (AD 1815), Kuwae (AD 1452) and an unknown event (AD 1259), respectively. We identified another nine $nssSO_4^{2-}$ spikes related to accurately dated eruption events. The shallow ice core was dated from AD 1260 to AD 2001 based on these 12 eruption events and the assumption of constant annual snow accumulation in the periods between eruption events. The results yield a maximum correction of ~20 years compared with the dating proposed in a previous study. The annual accumulation varied within ± ~15% of the average water equivalent value over the study period (25.5 mm).

Keywords: Ice core; Dating; Volcanic eruption record; Non-sea-salt sulfate; Antarctica

1. Introduction

The accurate and precise dating of polar ice cores is important for various studies, including investigations of past climate change and the recent history of the paleoatmosphere. Such dating may involve the counting of annual ice layers, the identification of remarkable events, mathematical modeling (e.g., the densification model of firn proposed by Herron and Langway, 1980), and curve fitting using profiles from other ice cores (Langway et al., 1995; Wilson and Hendy, 1981).

In terms of the precise dating of polar ice cores from inland Antarctica for the period over the past 1000 years, an effective method is to identify events in the ice cores for which reliable dates are available, thereby providing a time-stratigraphic layer. The counting of annual layers, based on seasonal variations in stable isotopes or chemical components, is unsuitable for most inland ice cores because some layers may be missing (i.e., a hiatus) and the accumulation rate of snow is typically low (Langway et al., 1995). Indeed, Kameda et al.'s (2008) measurements using 36 bamboo stakes (6 × 6 m grids spaced at 20-m intervals) from 1995 to 2006 at Dome Fuji station suggest that the annual mean surface mass balance is 27.3 mm water equivalent (weq) and that the probability of a hiatus is 9.4% under present-day conditions.

The presence of fallout from a large volcanic eruption provides a promising time-stratigraphic layer in ice cores, as such eruptions may inject large amounts of ash and gas into the upper troposphere, and often directly into the stratosphere (Legrand and Wagenbach, 1999). Sulfur dioxide (SO_2), the main component of volcanic gases, is oxidized to sulfuric acid (H_2SO_4) within aerosol particles in the atmosphere and on their surfaces (Carey and Sigurdsson, 1986; Jäger et al., 1995). The aerosol particles, rich in H_2SO_4, are transported globally via atmospheric circulation and reach the polar regions, where they are deposited and preserved in snow layers (Delmas et al., 1985). Hence, the fallout is marked by enhanced concentrations of SO_4^{2-} in polar ice cores, providing a chronological reference for ice-core dating. Such a time-stratigraphic layer is herein referred to as a “time-marker volcanic eruption event” or a “time marker”.

In 1993, a 112.9-m-deep ice core was drilled at Dome Fuji Station as a pilot hole for a deep-core drilling operation. Preliminary dating of the core for the past 1000 years has already been performed based on electrical conductivity measurements

(ECM) (Watanabe et al., 1997a). The ECM data reveal the same five volcanic eruptions as those recorded in an ice core at Byrd Camp, Antarctica (Hammer et al., 1994, 1997; Langway et al., 1994, 1995), with dates of AD 1464, AD 1259, AD 865, AD 639, and 346 BC. However, spike signals in such ECM data are not only produced by volcanic eruptions: other processes may result in high biogenicacidity and the variations in density (Karlöf et al., 2000). This makes it difficult to correlate ECM spikes with the known record of volcanic eruptions.

A more reliable approach is to identify signals of volcanic eruption by directly measuring the SO_4^{2-} concentration in ice cores, because large eruptions are considered the primary source of SO_2 (Delmas et al., 1985, 1992).

In this paper, we report on the dating of a shallow ice core drilled at Dome Fuji Station (77°19′01″S, 39°42′12″E, 3810 m above sea. level; Fig. 1) in November 2001. Based on measured concentrations of ions, we attempted to date the ice core from the surface to 96 m depth, based on the timing of large volcanic signals. We succeeded in dating the core to 40 m depth, in which interval we were able to correlate spikes in ion concentrations with reliably dated volcanic eruptions.

2. Sample preparation and chemical analysis

We prepared ice samples for continuous chemical analysis with a time resolution of about 1 year, which is necessary for the detection of volcanic eruptions. The ice cores (lengths of ~50 cm) were transported in a frozen state from Dome Fuji station to a freezer at the National Institute of Polar Research (NIPR) in Japan. Subsequent sample preparation was performed in a cold laboratory. After stratigraphic observations, measurements of bulk density and ECM were performed, and the ice cores from the snow surface to a depth of 39.35 m were divided into 4–5 cm lengths, of which a quarter of the core cross-section was analyzed. To avoid contamination, the surface layer (3-mm thick) was scraped off using a ceramic knife and the remaining sample was cleaned with extra-pure water on a clean bench, removing fine particles larger than 0.3 μm in diameter. The ice samples were kept in a clean, dust-free plastic bag until chemical analysis. The ice cores at depths from 1.84 to 7.69 m were crushed and could not be used for the present analysis. Ultimately, 719 samples were prepared.

Volcanic signals in the ice core were identified from concentrations of SO_4^{2-} and Na^+. We measured the concentrations of these and several other ions in each melted sample, using an ion chromatograph (Dionex DX-500). The isocratic and gradient methods were utilized for cations and anions, respectively. The eluant concentration in the anion measurements was increased step-wise with appropriate time intervals. The accuracy of such measurements is typically estimated to be ~10% . For details of the ion chromatography analysis, see Igarashi et al. (1998).

3. Candidate signals of volcanic eruptions

Although SO_4^{2-} is derived from sea salt and marine biogenic emissions, via atmospheric disturbances, volcanic eruptions are the major source of SO_4^{2-} during active eruptions. To identify volcanic signals in the Dome Fuji shallow ice core, we therefore examined a profile of non-sea-salt SO_4^{2-} (nssSO_4^{2-}) concentrations (Castellano et al., 2005; Cole-dai et al., 1997). Because SO_4^{2-} originating from sea salt is always accompanied by Na^+ ions, and because this pathway is the dominant source of Na^+, we calculated the $nssSO_4^{2-}$ concentration as

$$[nssSO_4^{2-}] = [SO_4^{2-}] - 3.02 \cdot 10^{-2} \cdot [Na^+] \qquad (1)$$

where $[SO_4^{2-}]$ and $[Na^+]$ denote the total SO_4^{2-} and Na^+ equivalent concentrations ($\mu eq. \cdot L^{-1}$) in the ice core, respectively, and $3.02 \cdot 10^{-2}$ is their ratio in seawater.

Figure 2a and 2b shows depth profiles of Na^+ and SO_4^{2-}, respectively. From these profiles, we obtained the $nssSO_4^{2-}$ profile in Fig. 2c, via eq. (1). On average, the $nssSO_4^{2-}$ concentration is ~90% of the total SO_4^{2-} concentration. Many spikes, as seen in the total SO_4^{2-} profile (Fig. 2b), remain after subtracting the estimated sea-salt concentration.

The procedure employed to identify candidate signals of volcanic eruptions in the $nssSO_4^{2-}$ profile involved the following steps (Fig. 2c).

1) The mean value M and the standard deviation σ were calculated using $nssSO_4^{2-}$ values from all the measured data points, yielding M = 2.19 $\mu eq \cdot L^{-1}$ and σ = 2.12 $\mu eq \cdot$

L^{-1}.

2) We selected spikes with values greater than $M+2\sigma = 6.43\ \mu eq \cdot L^{-1}$.

3) The mean value M' and the standard deviation σ' were recalculated after excluding the spikes selected in step (2), yielding $M' = 1.93\ \mu eq \cdot L^{-1}$ and $\sigma' = 0.83\ \mu eq \cdot L^{-1}$.

4) We selected spikes from all $nssSO_4^{2-}$ concentration data with values greater than $M'+2\sigma' = 3.59\ \mu eq \cdot L^{-1}$.

Previous studies have identified at least 10 eruption events from AD 1260 to the drilling year in ice cores from Antarctica (Cole-Dai et al., 1997, 2000; Delmas et al., 1992; Hammer et al., 1997; Karlöf et al., 2000; Kurbatov et al., 2006; Langway et al., 1994, 1995; Moore et al., 1991; Traufetter et al., 2004; Zhou et al., 2006). Therefore, $M+2\sigma$ is probably an overestimation in terms of a threshold value for identifying volcanic eruptions, in the case that the $nssSO_4^{2-}$ data contain several giant spikes that presumably correspond to very large volcanic eruptions. This gives rise to the possibility that we overlooked spikes associated with medium-sized eruptions at sites close to Antarctica, or large eruptions located far from Antarctica. Because Dome Fuji station is located at an inland site in Antarctica, the contribution to $nssSO_4^{2-}$ of large

SO_4^{2-} spikes derived from marine biogenic emissions is considered to be negligibly small. In fact, we did not find any relation between large spikes in SO_4^{2-} and enhanced levels of methanesulfonic acid (MSA) produced by the oxidation of dimethyl sulfide (DMS) released by marine phytoplankton. Moreover, Suzuki et al. (2001) reported that the concentration in surface snow of Cl^- and Na^+ derived from sea salt shows an exponential decrease with increasing distance from the coast up to 200 km inland, on the route to Dome Fuji station. Similarly, we consider that the concentration of SO_4^{2-} from marine biogenic emissions shows a marked decrease with coastal distances. Accordingly, we believe that steps (1)–(4) outlined above are appropriate in terms of identifying spikes related to volcanic eruptions.

The application of steps (1)–(4) to the $nssSO_4^{2-}$ profile resulting in the identification of 22 spikes that are candidate volcanic signals (Fig. 2c). In contrast, the application of steps (1) and (2) yielded only seven spikes.

4. Estimation of the rate of snow accumulation

To estimate the rate of snow accumulation, the length of the ice core should be converted to a water equivalent value using the depth-dependent density. The density of the ice core from Dome Fuji station shows an increase with depth, from 273.1 kg・m^{-3} at the top of the core to 604.1 kg・m^{-3} at a depth of 40 m (Fig. 3). A quintic polynomial expression, as an approximation of the depth-dependent density using a least squares method, was obtained previously from measurements between the surface and 2500 m depth (Watanabe et al., 1997b). However, this quintic polynomial expression (solid line in Fig. 3) lies above most of the measurements, including those of the present study, from the surface to ~20 m depth. Therefore, we separately fitted the density measurements of the present study by a linear function over this depth region. As a result, the depth-dependent density is approximated by

$$y = 7.9923x + 339.29 \quad \text{for} \quad x \leq 22.34 \text{ m} \quad (2)$$

$$y = 1\text{E-}10x^5 + 5\text{E-}06x^4 - 0.0011x^3 + 0.0658x^2 + 3.4841x + 418.23 \quad \text{for} \quad x > 22.34 \text{ m}, \quad (3)$$

where x is depth (m) and y is the ice density (kg・m^{-3}).

By multiplying the density given by eq. (2) or (3) by the length of each sample, we obtained the water equivalent amount. Then, the total water equivalent from the surface to 40 m depth was calculated by summing the water equivalent values for all samples.

We used the empirical model developed by Herron and Langway (1980; herein, H–L), based on Antarctic and Greenland ice cores, to confirm our depth-dependent density fitting. In applying the model, we used a mean annual temperature of 215 K (Watanabe et al., 2003), an accumulation rate of 0.027 m weq·year^{-1}, an initial snow density of 273.1 kg·m^{-3} at the surface and 589.9 kg·m^{-3} at a depth of 38.795 m, and with the largest $nssSO_4^{2-}$ spike (spike 22, see Fig. 3) in the Dome Fuji shallow ice core between the surface and 40 m depth. The model gave a date of AD 1257±10 for this spike (38.795 m depth). If spike 22 correlates with the unknown eruption at AD 1259 (Cole-Dai et al., 2000; Delmas et al., 1992; Hammer et al., 1997; Karlöf et al., 2000; Kurbatov et al., 2006; Langway et al., 1994, 1995; Moore et al., 1991; Traufetter et al., 2004; Zhou et al., 2006), the time difference between the result of the H–L model and the quintic polynomial expression is just 2 years.

5. Dating of spikes in the $nssSO_4^{2-}$ profile

We attempted to correlate the 22 spikes in the $nssSO_4^{2-}$ profile (see Table 1) with known volcanic eruptions. We started with spikes 5 (12.455 m depth), 16 (29.92 m depth), and 22 (38.795 m depth), which are by far the largest of the 22 spikes. Spike 5 can be reliably correlated with the AD 1815 Tambora eruption, which usually shows a prominent double spike due to its temporal proximity to an unknown eruption that occurred in AD 1809 (Cole-Dai et al., 1997, 2000; Delmas et al., 1992; Hammer et al., 1997; Karlöf et al., 2000; Langway et al., 1994, 1995; Moore et al., 1991; Traufetter et al., 2004; Zhou et al., 2006). In the present core, a significant sulfate spike was found at 12.785 m depth (spike 6 in Table 1 and Fig. 2c), slightly below spike 5. Furthermore, if spike 5 corresponds to the Tambora eruption, the weq depth calculated using eq. (2) is 4.86 m weq and the annual rate of snow accumulation between 1816 and 2001is 26.3 mm weq, which is similar to an estimate based on snow stake measurements for the period from AD 1995 to AD 2006 (27.3 mm weq; Kameda et al., 2008). Therefore, we equate spike 5 with the Tambora eruption (the correlated volcanic events are listed in the second column of Table 1).

The largest spike (spike 22), at 38.795 m depth (19.15 m weq depth), corresponds to a large ECM spike found at a similar depth (37.8 m) in another Dome Fuji ice core drilled in 1993 at a site located 43 m south of the present borehole (Motoyama , 2007; Watanabe et al., 1997a). Based on the present-day annual mean accumulation at Dome Fuji (27.3 mm weq) and the surface snow density (~300 kg·m^{-3}; see Fig. 3), the height difference between the tops of the two ice cores is ~0.7 m. In addition, the firn stratification detected from ground-penetrating radar and VHF radio waves around Dome Fuji station from the surface to 700 m depth is imaged as a flat, continuous reflection horizon (Fujita et al., 2002). Consequently, we consider that spike 22 corresponds to the large ECM spike found at 37.8 m depth in the other core. This interpretation is supported by the results obtained using the H–L model (Section 4). Spike 22 is therefore correlated with the large signals detected in most other ice cores drilled in Antarctica (Cole-Dai et al., 2000; Delmas et al., 1992; Hammer et al., 1997; Karlöf et al., 2000; Kurbatov et al., 2006; Langway et al., 1994, 1995; Moore et al., 1991; Traufetter et al., 2004; Zhou et al., 2006). Previous studies have assigned an age of AD 1259–1260 to this spike, although the volcanic event remains unknown. Therefore, we correlate spike 22 with the unknown eruption that occurred in AD 1259.

Spike 16, at a depth of 29.92 m (14.03 m weq depth), may correspond to another large ECM spike reported by Watanabe et al. (1997a), at a similar depth of 29.1 m in their sample. This depth difference between the two studies is minor considering the different locations and surface elevations of the two ice cores. Watanabe et al. (1997a) assigned an age of AD 1464 to this event, referring to an analysis of the Byrd ice core (Langway et al., 1995). In a later study, a large eruption of Kuwae in AD 1452 was identified by analyzing the widths of annual tree rings (Briffa et al., 1998). We therefore correlate this spike 16 with the AD 1452 Kuwae event. Considering the time taken to transport volcanic ejecta through the atmosphere, we assigned spikes 5, 16, and 22 ages of AD 1816, AD 1454, and AD 1260, respectively, as given in the seventh column in Table 1.

Turning to the remaining 19 spikes, we roughly estimated their ages by assuming a constant rate of annual snow accumulation for the sections of core between the three time-marking spikes determined above (for details of the method employed to estimate ages, see Section 6). Relevant historical volcanic eruptions were selected from a list sorted by the value of the Volcanic Explosivity Index (VEI; Newhall and Self, 1982; Simkin and Siebert, 1994), using the following criteria:

1) VEI value ≥ 5.

2) Latitude of the volcano < +20° (20°N).

These first two criteria are employed because volcanic signals in the Antarctic ice sheet are likely to reflect very large volcanic eruptions (VEI ≥ 5) in the region south of 20°N (Kohno et al., 1999).

3) Degree of uncertainty in the eruption date is < 1 year.

4) The recorded eruption date should agree, within ±10% years B.P., with one of the 19 spikes when referring to their roughly estimated years (e.g., if the recorded eruption date is 100 years B.P., the allowable margin is ±10 years). This margin (±10% years B.P.) is based on the findings of Kameda et al. (2008), who reported that 10 years of observations of a single snow stake yield an estimate of the annual surface mass balance with an uncertainty of ±10%.

5) Within the range of uncertainty, there should exist no other great eruption with a large uncertainty in its eruption date.

We compared the roughly estimated years for the 19 spikes with the volcanic eruption dates selected using the above criteria, yielding six additional reliable correlations that satisfy all five of the above criteria (spikes 1, 2, 3, 4, 11, and 13). Spikes 8, 9, and 14 fulfilled criteria (1)–(4), but not criterion (5). The ages of these additional reliable time markers and the corresponding volcanoes are listed in Table 1.

Spikes 19–22 have been reported in most other studies of Antarctic ice cores, with similar ages assigned to the spikes in all cases (Cole-Dai et al., 2000; Delmas et al., 1992; Karlöf et al., 2000; Kurbatov et al., 2006; Langway et al., 1995; Watanabe et al., 1997a; Zhou et al., 2006). Following these studies, the years of spikes 19–21 are determined to be AD 1287, AD 1278, and AD 1270 (Table 1). These spikes are used as time markers, in addition to the nine events identified above.

6. Correspondence between year estimates and ice-core depth

Following the procedure described in Section 5, we dated the present ice core at 12 discrete depth points. In order to interpolate the age data between successive time-marker events, it is necessary to know the rate of snow accumulation during the interval. In Section 4, we described a method for estimating the rate of snow accumulation by fitting the depth-dependent density using eq. (2) or (3). The water equivalent of each sample was obtained from the density and the length of each sample. Then, the total water equivalent between successive time-marker eruption events was calculated by summing the water equivalent values for the intervening samples. The relation between the year and ice-core depth was then determined by assuming a constant rate of annual accumulation (weq) between the successive time-marker events. The resulting $nssSO_4^{2-}$ profile is shown in Fig. 4.

Figure 5 shows the years of volcanic eruption used in the present study and the corresponding years obtained by Watanabe et al. (1997a), as well as the difference between them. In contrast to the 12 time-marker eruptions identified in the present study, Watanabe et al. (1997a) identified just 3 eruptions. In particular, the present analysis, using the $nssSO_4^{2-}$ profile, identified four new volcanic signals in the 19th century. In addition, eq. (2) was used as an improved approximation of the depth–density relation from the surface to 22 m depth. Consequently, we have successfully improved the dating of shallow ice cores at Dome Fuji, with a maximum correction, compared with the dating reported by Watanabe et al. (1997a), of ~20 years. The present results allow us to estimate the average rate of annual accumulation during the periods between the 12 time-markers (see Table 2 and Fig. 6). The rates vary from 21.8 to 29.5 mm weq, representing a range that is ± ~15% of the value of 25.5 mm weq averaged from AD 1260 to AD 2001. The minimum and maximum values appeared in the periods from AD 1837 to AD 1885 and from AD 1994 to AD 2001, respectively.

The average annual accumulation for the most recent period (29.5 mm weq) is comparable to the value of 29 mm weq reported by Iizuka et al. (2004) for the period from AD 1963 to AD 1999. In contrast, Kameda et al. (2008) reported an average annual accumulation of 26.5 mm weq for the period from AD 1995 to AD 2001 (see table 1 in their paper), based on snow stake measurements between AD 1995 and AD 2006. Although these discrepancies among the studies may reflect short-term fluctuations, their exact cause remains unclear at present.

7. Conclusion

An analysis of $nssSO_4^{2-}$ concentrations in a shallow ice core from Dome Fuji (surface to 40 m depth) revealed 12 spikes that correspond to historically recorded volcanic eruptions. The shallow part from surface to 40m depth of the ice core was dated from AD 1260 to AD 2001, based on the interpreted ages of the 12 spikes and the assumption of a constant annual rate of snow accumulation in the intervals between spikes. The present results are considered to improve the accuracy of previous dating (Watanabe et al., 1997a) by up to ~20 years. The annual accumulation varied by ± ~15% around the average value for the study period (25.5 mm weq). The present results are expected to contribute to studies of past climate change.

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Captions for Figures and Tables

Fig. 1. Map of Antarctica, showing the location of Dome Fuji on the East Antarctic ice sheet. Also shown are the locations of Byrd Station, South Pole, Siple Station, Dyer Plateau, Plateau Remote, Siple Dome, EPICA DML, DT263 and G15.

Fig. 2. Vertical distributions of (a) Na^+, (b) total SO_4^{2-}, and (c) nssSO_4^{2-} concentrations in the Dome Fuji shallow ice core. The dashed line in the nssSO_4^{2-} profile represents the threshold employed for the detection of volcanic events (3.59 μ eq.・L^{-1}). Spikes that exceed the threshold are labeled from 1 to 22. The ice cores at depths from 1.84 to 7.69 m were crushed and could not be used for the present analysis.

Fig. 3. Density–depth section for the Dome Fuji shallow ice core. The solid regression line was calculated from a quintic polynomial approximation obtained from the measured density between the surface and 2500 m depth (Watanabe et al., 1997b). The dashed line was calculated from raw data from the surface to 22.3 m depth.

Fig. 4. As for Fig. 2c, but as a function of the ages determined in the present work.

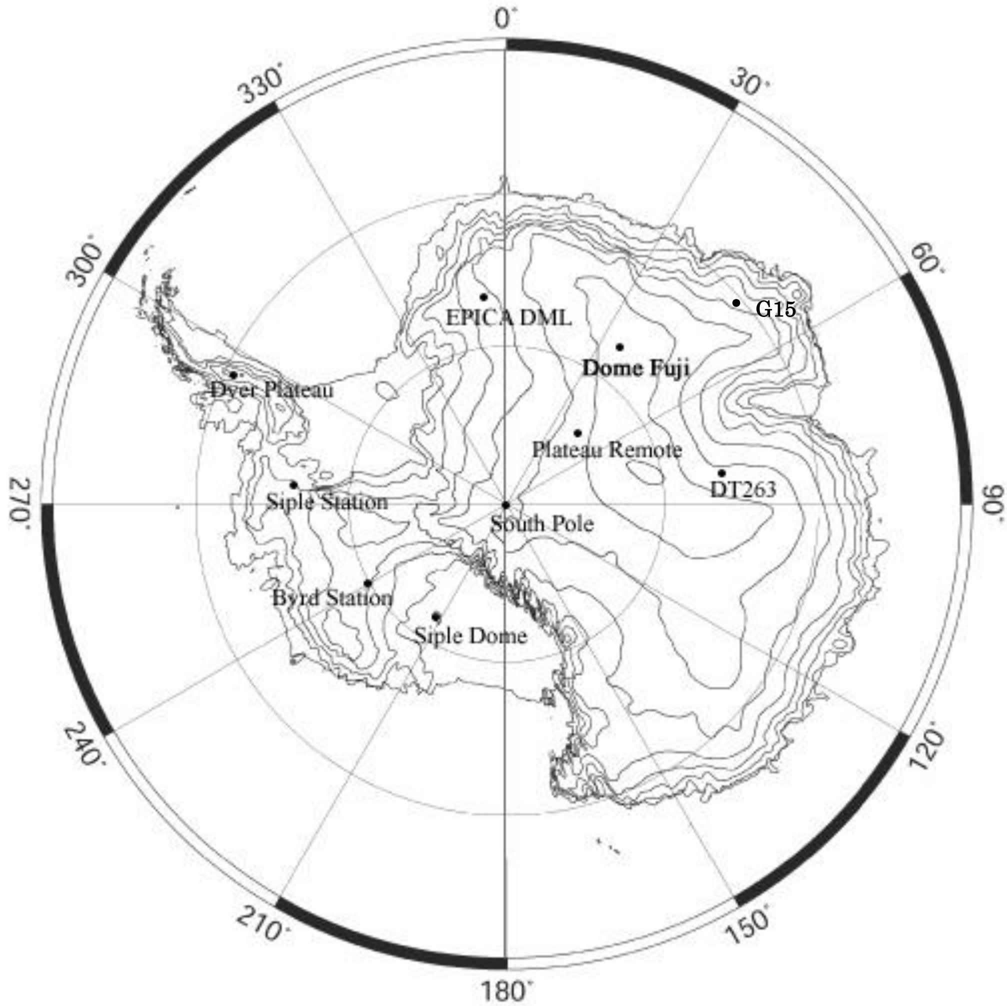
Fig. 5. (a) Relation between depth in the Dome Fuji shallow ice core and the age determined in this work and by Watanabe et al. (1997a). Symbols represent spikes in the core correlated with dated volcanic eruptions, as identified in this work (+) and by Watanabe et al. (◆). (b) Depth distribution of the difference in the age of the ice core estimated in this work and by Watanabe et al. (1997a). ΔT = (this work) – (Watanabe et al.).

Fig. 6. Average annual rate of snow accumulation at Dome Fuji between AD 1260 and AD 2001. Black diamonds (♦) indicate the time markers utilized in the present study.

Table 1. Volcanic events of the last 740 years identified in ice cores from Antarctic locations. VEI = volcanic explosivity index.

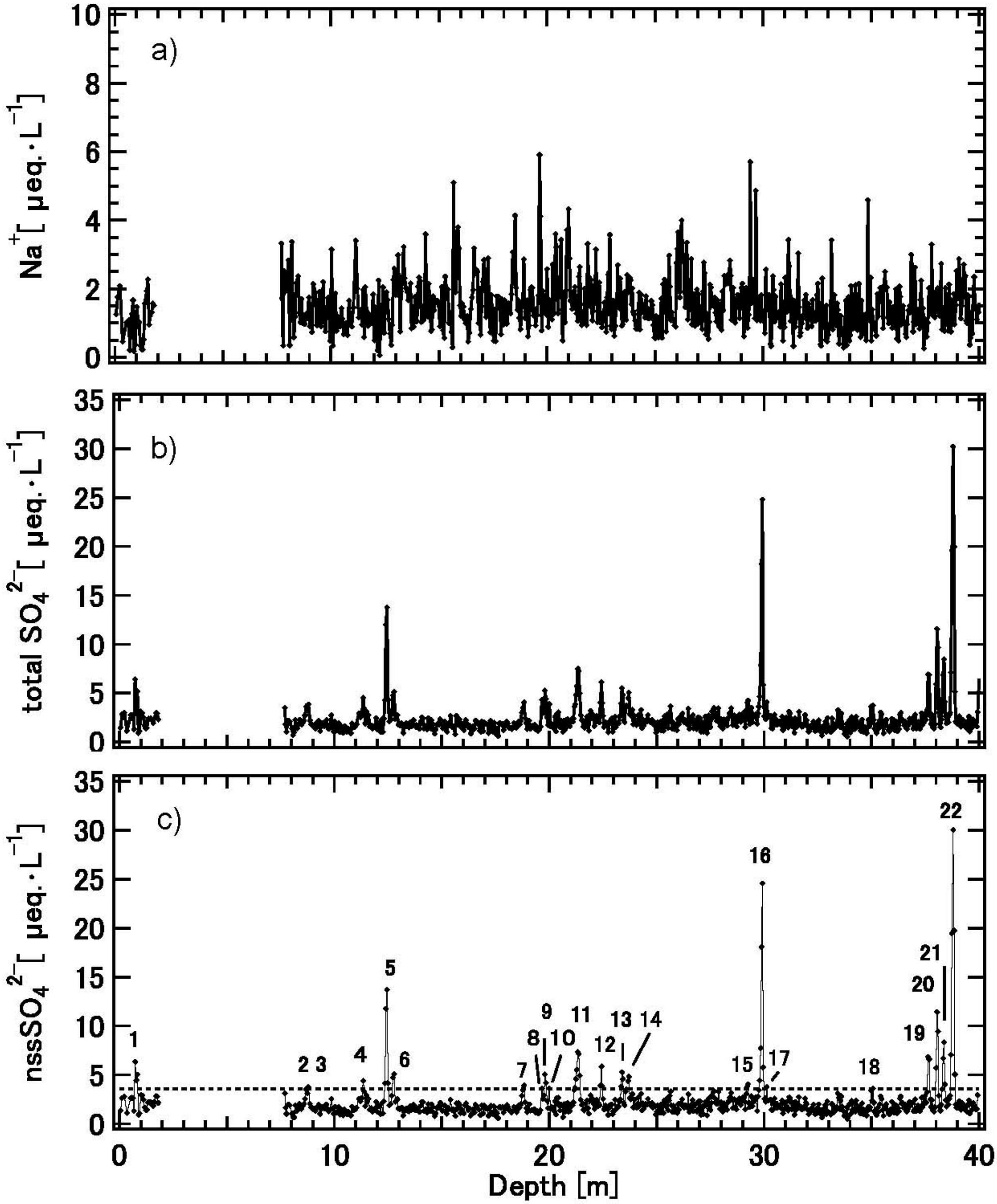
Table 2. Accumulation rates for periods between dated layers

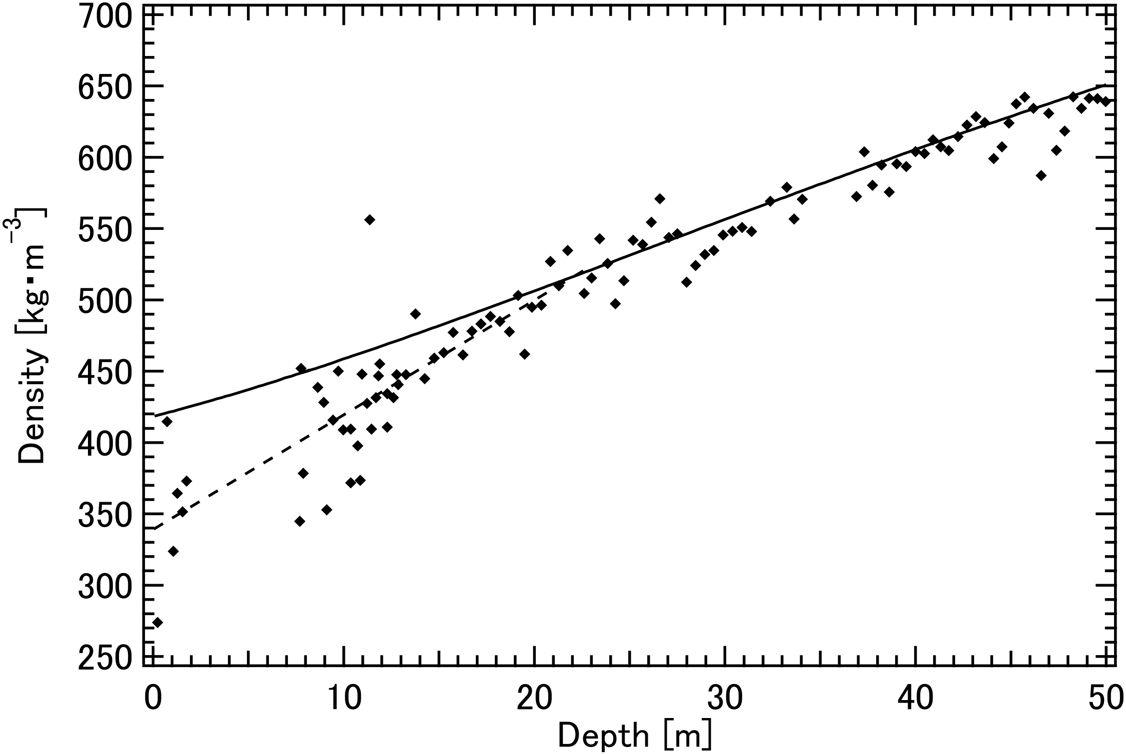
Figure1



0°
30°
60°
90°
120°
150°
180°
210°
240°
270°
300°
330°
EPICA DML
G15
Dome Fuji
Dyer Plateau
Plateau Remote
DT263
Siple Station
South Pole
Byrd Station
Siple Dome

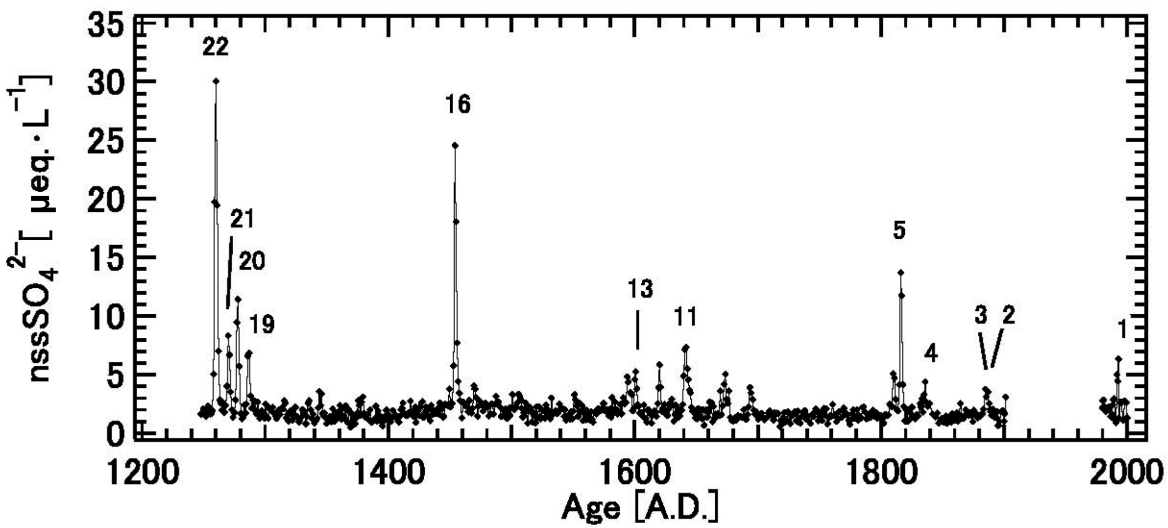
Figure2


a)
b)
c)
Na$^+$[μeq.·L^{-1}]
total SO$_4^{2-}$[μeq.·L^{-1}]
nssSO$_4^{2-}$[μeq.·L^{-1}]
Depth [m]
0
10
20
30
40
0
2
4
6
8
10
5
15
25
35
1
2 3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22



700
650
600
550
500
450
400
350
300
250
Density [kg·m⁻³]
0
10
20
30
40
50
Depth [m]

Figure4



35
30
25
20
15
10
5
0
1200
1400
1600
1800
2000
Age [A.D.]
nssSO4 2− [μeq.·L−1]
22
21
20
19
16
13
11
5
4
3
2
1

Figure5

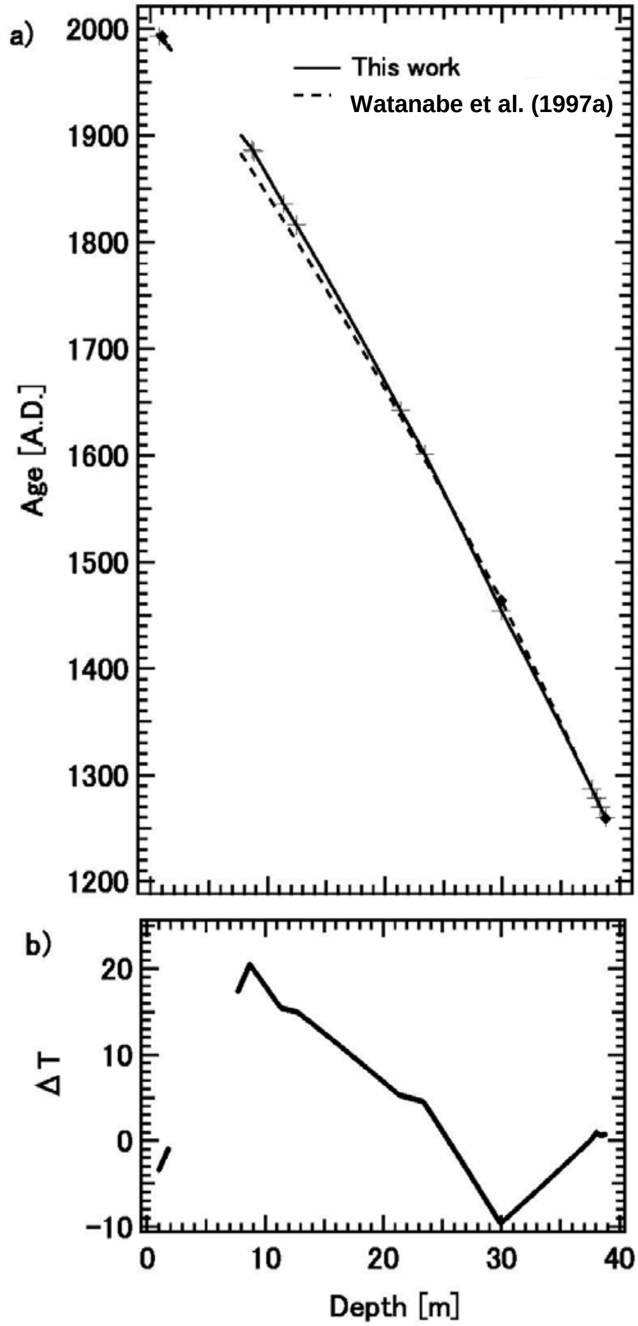

a)
This work
Watanabe et al. (1997a)
Age [A.D.]
2000
1900
1800
1700
1600
1500
1400
1300
1200
b)
ΔT
20
10
0
−10
0
10
20
30
40
Depth [m]

Figure6

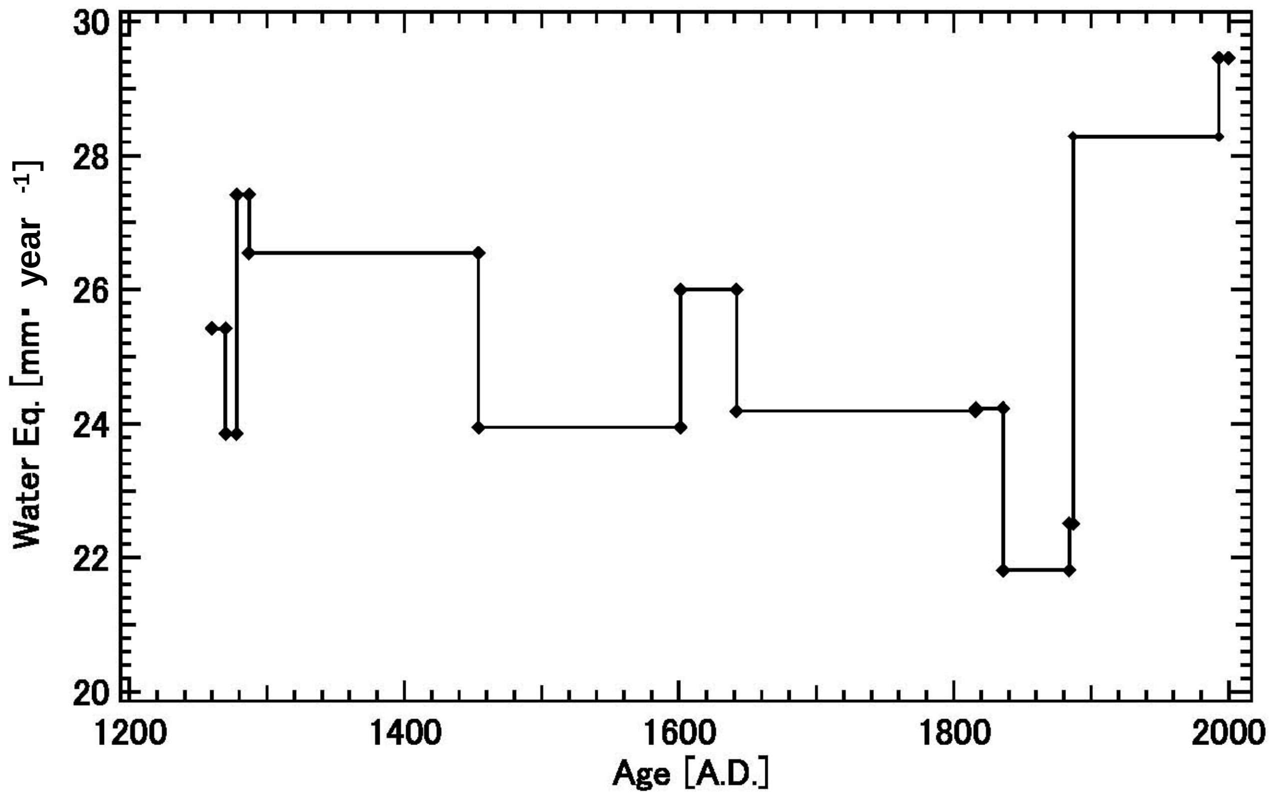

30
28
26
24
22
20
Water Eq. [mm· year -1]
1200
1400
1600
1800
2000
Age [A.D.]

Table1

Table 1. Volvanic Event During the Last 740 Years Found in Ice Cores from Several Antarctic Locations

Event	Volcanic eruption	Country	Date	VEI	Dome Fuji (This work) depth [m]	Dome Fuji (This work) year [A.D.]	Dome Fuji[*1] year [A.D.]	Byrd Station[*2] year [A.D.]	South Pole[*3] year [A.D.]	Siple Station[*4] year [A.D.]	Dyer Plateau[*4] year [A.D.]	Plateau Remote[*5] year [A.D.]	EPICA DML CV[*6] year [A.D.]	EPICA DML05[*7] year [A.D.]	Siple Dome[*8] year [A.D.]	DT263[*9] year [A.D.]	G15[*10] year [A.D.]
	Snow Surface				0	2001	1993										
1	Hudson	Chile	1991.8.12	5+	0.785	1993		--	--	--	--	--	1991	1992±1	--	1992	--
	Pinatubo	Philippines	1991.6.15	6				--	--	--	--	--			--	1992	--
2	Tarawera	New Zealand	1886.6.10	5+	8.685	1887			1886, 1887	1886	1887	1884		1886±1	1887	1886	1886
3	Krakatau	Indonesia	1883.8.27	6	8.79	1885		1884	1884	1884	1885		1883	1884±1	1883	1884	1883
4	Coseguina	Nicaragua	1835.1.20	5	11.34	1836		1835	1836	1836-37	1836-38	1836		1835±1		1836	1835
5	Tambora	Indonesia	1815.4.10	7	12.455	1816		1816	1816	1816-17	1816-17	1816	1815	1816±1		1816	1815
6	Unknown				12.785			1811	1809	1810-11	1810-11	1810	1809±2	1809±3	1809	1810	1808
7	Unknown				18.83					1695-96	1696-97	1694		1695±3			
8	(Tongkoko)	Indonesia	1680	5?	19.655												1680
9	(Gamkonora)	Indonesia	1673.5.20	5?	19.805					1673-74	1673-74	1671	1673	1676±3			
10	(Long Island)	New Guinea	1660±20		20.005												
11	Paker	Philippines	1641.1.4	5?	21.33	1642		1648	1641	1640-41	1640-41	1639	1641	1640±1			
	Deception	Antarctic	1641														
12	Unknown	Sub-Antarctica?			22.43				1621	1619	1619-20						
13	Huaynaputina	Peru	1600.2.9	6	23.39	1601			1601	1599-1602	1599-1601	1600	1600	1600±1	1601		1600
14	(Raung)	Indonesia	1593	5?	23.71				1596	1593-95	1593-95	1595		1596±3	1592		
15					29.25						--				1471		
16	Kuwae	Vanuatu	1452	6	29.92	1454	1464	1464	1450	1454-57		1454	1452±10	1453±5	1448	1454	1460
17					30.13					--							
18					35.06			1348	1340			1343	1348±9	1343±5	1346	1343	
19	Unknown				37.635	1287		1287				1285	1287±2	1285±5		1286	
20	Unknown				38.05	1278		1278	1279			1277	1278±2	1278±5	1278	1277	
21	Unknown				38.37	1270		1270	1269			1269	1269±2	1269±5	1271	1269	
22	Unknown				38.795	1260	1259	1259	1259			1260	1259±2	1258±5	1259	1260	1259

1 Watanabe et al. (1997a); 2 Langway et al. (1994, 1995), Hammer et al. (1997); 3 Delmas et al. (1992);
4 Cole-Dai et al. (1997); 5 Cole-Dai et al. (2000); 6 Karlof et al. (2000); 7 Traufetter et al. (2004); 8 Kurbatov et al. (2006);
9 Zhou et al. (2006); 10 Moore et al. (1991)

Table 2 Accumulation rates for periods between dated layers

Age [A.D.]	Depth Top [m]	Depth Bottom [m]	Water Eq. [mm･annual^{-1}]	Water Eq./average
1994–2001	0	0.735	29.5	1.16
1888–1993	0.735	8.685	28.3	1.11
1886–1887	8.685	8.79	22.5	0.88
1837–1885	8.79	11.34	21.8	0.86
1817–1836	11.34	12.455	24.2	0.95
1643–1816	12.455	21.33	24.2	0.95
1602–1642	21.33	23.39	26.0	1.02
1455–1601	23.39	29.92	23.9	0.94
1288–1454	29.92	37.635	26.5	1.04
1279–1287	37.635	38.05	27.4	1.08
1271–1278	38.05	38.37	23.9	0.94
1260–1270	38.37	38.795	25.4	1.00
Average			25.5	