A detailed 2840 year record of explosive volcanism in a shallow ice core from Dome A, East Antarctica

Su JIANG,[1] Jihong COLE-DAI,[2] Yuansheng LI,[1] Dave G. FERRIS,[2] Hongmei MA,[1]
Chunlei AN,[1] Guitao SHI,[1] Bo SUN[1]

[1]*Key Laboratory for Polar Science of State Oceanic Administration, Polar Research Institute of China, Shanghai, China*
[2]*Department of Chemistry and Biochemistry, South Dakota State University, Brookings, SD, USA*
E-mail: jihong.cole-dai@sdstate.edu

ABSTRACT. A detailed history of volcanism covering the last 2840 years is reconstructed from the top 100.42 m of a 109.91 m ice core from Dome A (DA2005 ice core), East Antarctica. Using two known volcanic stratigraphic markers, the mean accumulation rate during the period AD 1260–1964 is found to be 23.2 mm w.e. a^{-1}, consistent with the previously reported accumulation rate at Dome A. This mean accumulation rate is used to date the entire core. Volcanic eruptions in the period 840 BC–AD 1998 are detected as outstanding sulphate events. Seventy-eight eruptions are identified, with a mean of 2.7 eruptions per century. Comparisons with previous Antarctic ice-core volcanic records are made to assess the quality of this new DA2005 record. In terms of dates for volcanic events, the DA2005 record is in good agreement with previous records in the second millennium AD (AD 1000–1998). A series of volcanic signatures found in both the DA2005 record and several other Antarctic ice-core records in the first millennium AD (AD 1–1000) appear to validate the DA2005 record during this time period. For the older periods, direct comparisons are difficult between the DA2005 record and other Antarctic ice-core records due to the lack of well-dated stratigraphic horizons.

INTRODUCTION

Explosive volcanic eruptions, one of the natural forcings causing short-term climatic variations, inject large amounts of ash particles and gases into the atmosphere (Hofmann, 1987; McCormick and others, 1995). The ash particles can block sunlight and darken the skies visibly, resulting in reduced solar heating (Cole-Dai, 2010). However, such effects are typically short-lived and geographically limited since the ash is rapidly removed from the local atmosphere (Robock, 1981, 2000). Of the abundant gaseous emissions, sulphur compounds (mainly SO_2) are the most climatologically important component. The SO_2 is subsequently converted into the chemically stable $H_2SO_4{\cdot}H_2O$ or sulphuric acid aerosols. The net effect of aerosols is the reduction of energy receipt near the surface; therefore the most significant climatic impact of volcanic eruptions is the cooling at the surface and in the lower troposphere (Cole-Dai, 2010). One of the best-known historical examples of the climatic impact of volcanic eruptions is 'the year without a summer' (1816) following the great AD 1815 Tambora eruption on an Indonesian island (Cole-Dai and others, 2009).

Ice cores from the polar regions provide perhaps the best means to evaluate the impact of past volcanism on global climate (Robock, 2000). With the detection and measurement of volcanic acids (Karlöf and others, 2000; Udisti and others, 2000) or sulphur compounds (Delmas and others, 1992; Cole-Dai and others, 1997) in polar ice cores, the history of volcanic eruptions can be recovered. Many ice cores from Greenland (Hammer, 1980; Zielinski and others, 1994, 1996, 1997; Clausen and others, 1997) and Antarctica (Moore and others, 1991; Delmas and others, 1992; Cole-Dai and others, 2000; Palmer and others, 2001; Traversi and others, 2002; Traufetter and others, 2004; Castellano and others, 2005; Kurbatov and others, 2006; Zhou and others, 2006; Ren and others, 2010) have been used to reconstruct the history of volcanic eruptions. These records improve the overall quality of the chronological record of global volcanism (Kurbatov and others, 2006), which in turn assists with assessing the role of volcanism in radiative forcing and climate change. Furthermore, the volcanic records provide an effective way to evaluate and improve the climate models (Gao and others, 2008; Schneider and others, 2009), which are the primary tools to predict future climate change. However, the timing and magnitude of a particular volcanic signal is quite variable from site to site where the ice core is drilled (Dai and others, 1991; Gao and others, 2006), due to variations in the atmospheric transport of volcanic substances, and their deposition and preservation on large ice sheets. Therefore, the current ice-core volcanic records of various length and quality need to be augmented with records of ice cores from additional polar locations to improve our understanding of the volcanism–climate system.

Dome Argus (Dome A), located along the main glaciological dividing line of the East Antarctic plateau, has the highest altitude in East Antarctica (Fig. 1). Preliminary investigation has shown that the annual mean temperature (measured at 10 m below the surface) at Dome A is –58.5°C, the lowest annual mean temperature ever recorded on the surface of the Earth (Hou and others, 2007). The average snow accumulation rate during the past several decades (AD 1966–2004) at Dome A is 23 mm w.e. a^{-1}, which is similar to that at other Antarctic inland sites (Hou and others, 2007). In addition, the detailed radar survey and Antarctic climate history indicated that the subglacial Gamburtsev mountains at Dome A are probably older than 34×10^6 years and were the main centre for ice-sheet growth (Sun and others, 2009). The glaciology research suggests that the Dome A region holds high potential for 'oldest ice' cores (Xiao and others, 2008), and it has attracted attention from ice-core researchers. During the 21st Chinese Antarctic Research Expedition (CHINARE 21) in the 2004/05 austral summer, a 109.91 m shallow ice core (DA2005 ice core) was

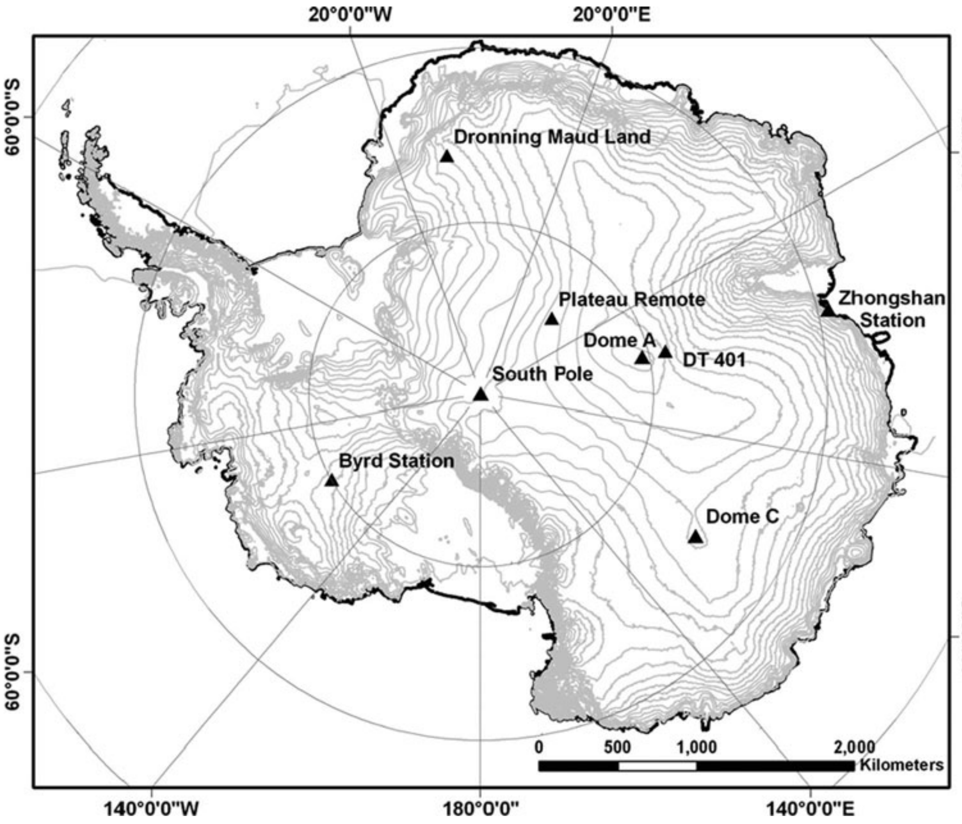

Fig. 1. Location of ice-core sites in Antarctica referred to in the text.

recovered at a site ~300 m from the summit of Dome A (80°22′ S, 77°22′ E; 4092.5 m a.s.l. (Zhang and others, 2007)) (Fig. 1). This is the first ice core retrieved from the Dome A summit region.

We present a new regionally representative record of volcanic eruptions over the last 2840 years from the DA2005 ice core using a methodology similar to that used in previous studies (Cole-Dai and others, 2000; Budner and Cole-Dai, 2003). This DA2005 record is constructed using sulphate measurement of nearly 8000 samples from the top 100.42 m of the DA2005 core. Comparisons with several previously published Antarctic ice-core volcanic records are made to assess the quality of this new record. The mean accumulation rates at the Dome A region in the last three millennia are also reported.

ICE-CORE SAMPLING AND ANALYSIS

The DA2005 ice core, drilled with an electromechanical drill, started at ~0.4 m from the 2005 snow surface and reached 109.91 m depth. The bulk density of each of the 80 cm long snow/ice cylinders was measured in the field. The cylinders were then wrapped in clean plastic sheets and shipped frozen to the Polar Research Institute of China in Shanghai.

One-half (cross section) of the DA2005 core was transported to the Ice Core and Environmental Chemistry Laboratory at South Dakota State University, USA. The top 100.42 m was analyzed for major chemical impurities, and the bottom 9.49 m of the core is reserved for other analysis. The traditional discrete sampling method with stringent contamination control procedures (Cole-Dai and others, 1995) was used to sample the porous top 1.76 m of the DA2005 ice core, with an average depth resolution of 55 mm per sample. The samples were analyzed by ion chromatography for the concentrations of major chemical impurities (Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, SO_4^{2-}). The technique of continuous flow analysis coupled with ion chromatography (CFA-IC) was used to analyze the core from 1.76 to 100.42 m. The CFA-IC system, as described by Cole-Dai and others (2006), consists of an ice-core melter, eight ion chromatographs (ICs; four for cation measurement and four for anion measurement) and an interface that distributes meltwater to the ICs.

The CFA-IC system was set up to perform one analysis per minute of all the ions in the continuous meltwater stream from the melter. In order to achieve high temporal resolution while supplying the ICs with sufficient meltwater, the ice samples were melted at relatively slow melt rates (10–22 mm min^{-1}). Altogether, 7927 samples were analyzed to 100.42 m depth with both discrete sampling and the CFA-IC system, and the average depth resolution was 13 mm per sample. With the bulk density data of each snow/ice cylinder, a third-order polynomial was fitted to the density–depth profile for the DA2005 ice core and was used to calculate the density of each sample. Then the snow/ice depth was converted to the water equivalent depth using the calculated density.

RESULTS

Ice-core dating and error estimates

Hou and others (2007), using field density measurement and the β-activity horizon in snow from the 1960s atmospheric nuclear tests, estimated the mean accumulation rate at Dome A during the period 1966–2004 to be ~23 mm w.e. a^{-1}.

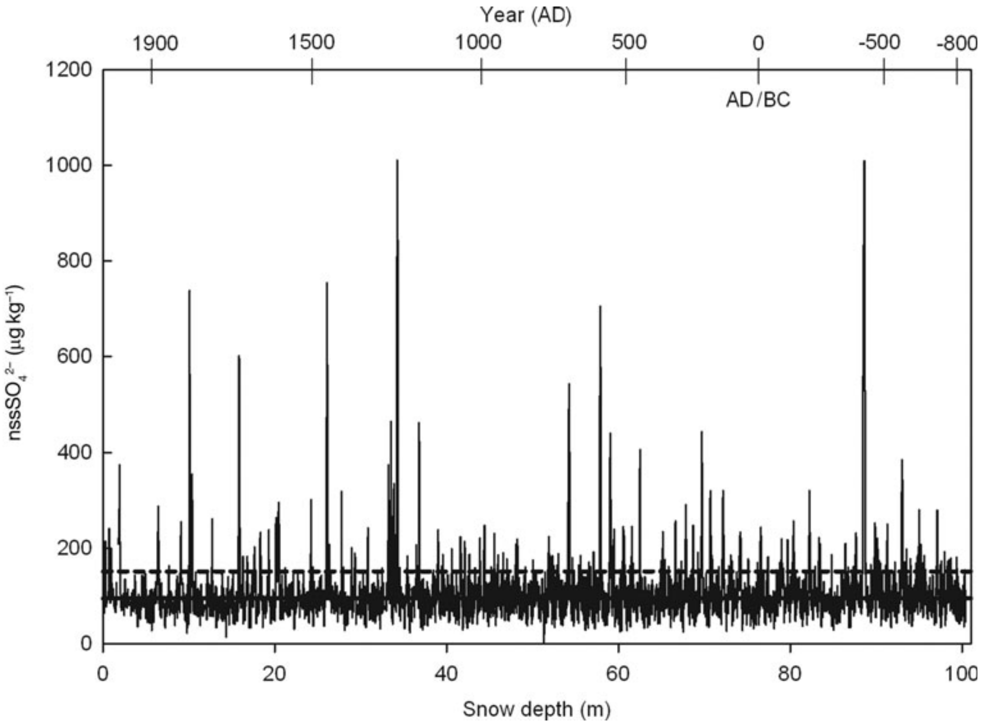

Fig. 2. Continuous profile of non-sea-salt sulphate concentrations in the DA2005 ice core as a function of snow depth. The solid horizontal line indicates the nonvolcanic background, and the dashed line represents the detection threshold (background + 2σ).

Such a low accumulation rate, one of the lowest in Antarctica, along with the sampling resolution (13 mm or ~8 mm w.e. per sample) for the chemical measurement, indicated that the DA2005 core could not be dated by counting annual layers.

Another common method to date an ice core is to use a constant or average annual accumulation rate to calculate the age of each snow layer or depth in the core, after all depths are converted to water equivalent. Because of the possible variation in accumulation rate, a mean accumulation rate for a period longer than the 40 years was needed to date the DA2005 core using this method. This was accomplished by identifying prominent volcanic signals in the DA2005 non-sea-salt sulphate (nssSO_4^{2-}) profile (Fig. 2). Using the 23 mm w.e. a^{-1} accumulation rate by Hou and others (2007) as a guide, we found a very large nssSO_4^{2-} signal at a depth of 17.111 m w.e. which is likely the fallout from a massive eruption by an unknown volcano in 1259 (Delmas and others, 1992; Cole-Dai and others, 2000). To calculate a mean annual accumulation rate, and because the DA2005 core did not begin at the 2005 snow surface, another time-stratigraphic marker was needed. Another large nssSO_4^{2-} signal was found at 0.756 m w.e. and was identified as the fallout in 1964 of the 1963 Agung (Indonesia) eruption (Delmas and others, 1992; Cole-Dai and others, 2000). The computed annual accumulation rate from the depths of these two time-stratigraphic markers, 23.2 mm w.e. a^{-1}, is similar to that determined by Hou and others (2007) for 1966–2004 and indicates that, at Dome A, annual accumulation rate averaged over a period of at least 40 years is relatively constant. This mean annual accumulation rate was used to estimate that snow at the top of the DA2005 core (~0.4 m from the 2005 surface) was deposited in 1998.

We found the prominent nssSO_4^{2-} signals of several other well-known volcanic eruptions. The depth, year of eruption and year of expected appearance (year of eruption plus 1) of each signal, and the age of the snow layer calculated by the constant accumulation rate method are given in Table 1. The good agreement between the year of expected appearance and the calculated age suggests that the computed mean annual accumulation (23.2 mm w.e.) is temporally representative and that the variability in annual snow accumulation rate, averaged over a relatively long time period, is likely quite small at Dome A. Therefore, the 23.2 mm w.e. a^{-1} accumulation rate is used to date the entire DA2005 core (top axis in Fig. 2). According to this timescale, the 109.91 m core covers the last 3186 years before present (BP; present = end of AD 1998), and the analyzed 100.42 m part corresponds to the last 2840 years, from 840 BC to AD 1998.

The data in Table 1 also provide a measure of the uncertainty of the dating. Because dating is achieved with an averaged accumulation rate, the error in the calculated age of a snow layer results when the actual accumulation rate deviates from the average rate. The differences between the expected date and the calculated date shown in the last column in Table 1 are used to represent the dating uncertainty of the DA2005 core. The largest deviation, at 11 years for the 1453 Kuwae (Vanuatu) eruption (Gao and others, 2006), appears to suggest that the dating uncertainty for DA2005 is significantly smaller than those reported for ice cores from other Antarctic locations where the snow accumulation rates are low (e.g. Plateau Remote (Cole-Dai and others, 2000), DT401 (Ren and others, 2010)). We offer no explanation or suggestion for this apparent difference, except to note that the estimated annual accumulation rate (23.2 mm w.e. a^{-1}) is the lowest among these locations.

There are no known volcanic markers beyond that of Taupo, New Zealand (below a depth of 42.155 m w.e.). Assuming similar accumulation rate and similarly small variability of the rate for the deeper part of the core, dating errors are not expected to be significantly larger than those indicated in the last column of Table 1. The annual layers

Table 1. Well-documented volcanic eruptions in the last two millennia and their calculated dates in the DA2005 record. All dates are calendar years. Calculated dates refer to the event years computed using the mean accumulation rate (23.2 mm w.e. a^{-1}), and the AD 1259 Unknown event is used as the time reference for calculation. The Difference column represents the difference between the expected appearance date and the calculated date of a volcanic event in the core. Pluses denote the calculated date is later than the expected date; minus denotes the opposite

Volcano, year (AD) of eruption	Depth in core m	Depth m w.e.	Year (AD) of expected appearance in core	Calculated date (AD)	Difference years
Ice top	0.000	0.000		1998	
Agung, 1963*	1.97	0.756	1964		
Krakatau, 1883	6.49	2.614	1884	1885	+1
Cosiguina, 1835	9.10	3.753	1836	1836	0
Tambora, 1815	10.14	4.220	1816	1816	0
Unknown, 1809	10.42	4.349	1810	1810	0
Unknown, 1693	15.94	6.971	1694	1697	+3
Huaynaputina, 1600	20.27	9.174	1601	1602	+1
Kuwae, 1453	26.15	12.350	1454	1465	+11
Unknown, 1259*	34.34	17.111	1260		
Taupo, 186 ± 10	70.83	42.155	186	181	–5

*These two volcanic events are used as time-stratigraphic markers for dating. Their dates in the core are determined by comparison with previously published records.

thin at depth as a result of ice flow. Therefore, the 23.2 mm layer thickness is expected to decrease with depth. However, the thinning is estimated to be ~0.4 mm a^{-1}, or ~ 1% of the average layer thickness, at the bottom of the shallow core (110 m), relative to the ice-sheet thickness (~3000 m) at the summit of Dome A (Cui and others, 2010). The error of age determination due to thinning (~10 years at the bottom of the core) is therefore smaller than the uncertainty caused by variations in the average accumulation rate. Therefore, no correction due to thinning is made to the timescale.

Criteria for the detection of volcanic signals

Explosive volcanic eruptions are not the only source of sulphate in Antarctic snow. The presence of SO_4^{2-} in Antarctic snow is also linked to marine (sea-salt) inputs and dimethylsulphide (DMS) from marine biogenic emissions (Prospero and others, 1991; Legrand and Mayewski, 1997). Sea-salt sulphate and the oxidation products of DMS constitute the nonvolcanic or background sulphate. The background sulphate concentration varies temporally in an ice core, and the sulphate from volcanic eruptions is superimposed on this variable background. To detect volcanic signals in an ice core, a threshold must be established to distinguish volcanic sulphate from the background. In this work, the volcanic threshold is estimated using a method similar to that described by Cole-Dai and others (1997). However, two details are slightly different from the earlier method. First, instead of the sulphate concentrations, the $nssSO_4^{2-}$ concentrations, as calculated from the measured total SO_4^{2-} and Na^+ concentrations (Kärkäs and others, 2005), were used. Second, a minimum duration of 1 year (Delmas and others, 1992) was required for elevated $nssSO_4^{2-}$ concentration to qualify for a volcanic event in this work.

The calculated DA2005 background $nssSO_4^{2-}$ concentration is 95.0 μg kg^{-1} (solid line in Fig. 2), with a standard deviation of 28.3 μg kg^{-1}. The threshold of 151.6 μg kg^{-1} (the background plus two standard deviations) is indicated by the dashed line in Figure 2. Altogether, 78 volcanic events are found with this threshold and the 1 year duration criterion. A complete list of the events is shown in Table 2. Usually, the appearance of an eruption in Antarctic snow lags the date of a low-latitude eruption by 1 or 2 years (Cole-Dai and Mosley-Thompson, 1999; Legrand and Wagenbach, 1999). Therefore, the actual eruption years may be 1 or 2 years earlier than the dates in Table 2. The events and their associated dates and duration are designated as the DA2005 volcanic record and numbered in chronological order. In the following discussion, the volcanic events are referred to by their numbers.

Volcanic fluxes

Volcanic sulphate mass flux, *f*, of a sample is calculated by first subtracting background $nssSO_4^{2-}$ from the sample $nssSO_4^{2-}$ concentration and then multiplying by the sample length in water equivalent (Cole-Dai and Mosley-Thompson, 1999). The total flux for a volcanic event is the sum of the volcanic flux of all samples associated with that event. All the volcanic fluxes are shown in Table 2.

The rate of deposition, i.e. flux, depends on several local factors at the ice-core site, such as surface irregularity, elevation, temperature, wind redistribution and relative contribution of wet–dry deposition, so the volcanic flux of a particular eruption is quite variable from site to site (Clausen and Hammer, 1988; Gao and others, 2006). In this work, the normalized flux (volcanic flux normalized against that of the AD 1815 Tambora eruption, as described by Cole-Dai and others (1997)) which may minimize the location-specific effects, is used to compare the magnitude of a volcanic event found in different ice cores. The volcanic events are categorized into three groups according to their f/f_T values (Table 2), where f_T is the volcanic sulphate mass flux of the AD 1815 Tambora eruption. Large eruptions (L) are those with $f/f_T \geq 1$, moderate eruptions (M) are those with $0.5 \leq f/f_T < 1$, and small eruptions (S) are those with $f/f_T < 0.5$. As seen in Table 2, a total of 12 large events, possibly explosive eruptions with global climatic implications, are recorded in the DA2005 ice core. It is worth

Table 2. Volcanic events found in the DA2005 ice core. The date for a volcanic event is assigned to the year of appearance of the sulphate peak. Negative event dates represent years BC

Volcanic eruption	Event No.	Year(AD)	Duration	Depth in core	Depth	Peak nss-sulphate	Volcanic flux, *f*	f/f_T	Signal strength*
			years	m	m w.e.	$\mu g\,kg^{-1}$	$kg\,km^{-2}$		
	DA1	1985	1.8	0.74	0.280	241.1	5.18	0.29	S
	DA2	1982	1.7	0.94	0.357	200.0	3.17	0.18	S
Agung†	DA3	1964	3.8	1.97	0.756	374.5	14.97	0.84	M
Krakatau and Tarawera	DA4	1885	3.7	6.49	2.614	287.6	9.03	0.51	M
Cosiguina	DA5	1836	2.4	9.10	3.753	255.2	6.57	0.37	S
Tambora	DA6	1816	2.8	10.14	4.220	738.1	17.84	1.00	L
Unknown, 1809	DA7	1810	2.8	10.42	4.349	355.4	12.04	0.67	M
	DA8	1764	1.5	12.72	5.417	261.5	4.42	0.25	S
Unknown, 1693	DA9	1697	4.3	15.94	6.971	601.5	27.17	1.52	L
	DA10	1678	1.9	16.82	7.409	183.2	3.34	0.19	S
	DA11	1658	4.6	17.75	7.877	203.2	7.85	0.44	S
	DA12	1644	2.2	18.36	8.191	233.3	5.67	0.32	S
	DA13	1623	2.1	19.32	8.682	238.4	3.97	0.22	S
Huaynaputina	DA14	1602	4.2	20.27	9.174	264.1	11.60	0.65	M
	DA15	1597	4.5	20.48	9.286	296.0	12.71	0.71	M
	DA16	1511	1.2	24.23	11.289	301.4	3.89	0.22	S
Kuwae	DA17	1465	4.2	26.15	12.350	754.2	36.23	2.03	L
	DA18	1388	1.5	29.32	14.152	189.5	2.56	0.14	S
	DA19	1349	3.1	30.86	15.043	242.8	6.21	0.35	S
	DA20	1287	3.1	33.29	16.484	374.5	14.94	0.84	M
	DA21	1280	3.4	33.58	16.657	465.6	18.16	1.02	L
	DA22	1272	3.1	33.88	16.838	335.3	10.82	0.61	M
Unknown, 1259†	DA23	1260	5.9	34.34	17.111	1011.0	63.27	3.55	L
	DA24	1194	3.4	36.86	18.649	462.8	16.46	0.92	M
	DA25	1135	2.1	39.04	20.011	238.4	5.41	0.30	S
	DA26	1062	4.6	41.73	21.712	224.4	9.42	0.53	M
	DA27	1051	1.5	42.13	21.968	214.4	3.64	0.20	S
	DA28	1001	1.8	43.91	23.120	221.5	3.61	0.20	S
	DA29	986	3.7	44.44	23.470	247.9	9.28	0.52	M
	DA30	954	1.5	45.58	24.214	230.9	4.33	0.24	S
	DA31	925	1.0	46.58	24.880	190.7	1.95	0.11	S
	DA32	883	1.6	48.06	25.863	208.3	3.00	0.17	S
	DA33	877	3.1	48.26	25.995	219.2	7.59	0.43	S
	DA34	769	2.7	51.96	28.507	224.4	6.34	0.36	S
	DA35	766	1.3	52.04	28.561	170.3	2.03	0.11	S
	DA36	764	1.3	52.12	28.616	181.5	2.08	0.12	S
	DA37	737	1.2	53.02	29.239	188.7	2.30	0.13	S
	DA38	698	7.5	54.33	30.146	544.4	45.58	2.55	L
	DA39	614	1.0	57.11	32.097	192.4	1.90	0.11	S
	DA40	588	6.0	57.97	32.711	705.2	42.71	2.39	L
	DA41	551	7.0	59.16	33.559	440.7	29.72	1.67	L
	DA42	541	4.4	59.48	33.787	239.5	9.24	0.52	M
	DA43	506	4.3	60.62	34.606	245.2	9.98	0.56	M
	DA44	477	2.5	61.55	35.281	245.5	5.31	0.30	S
	DA45	446	4.0	62.54	36.001	406.2	15.56	0.87	M
	DA46	369	2.1	64.96	37.772	173.8	3.31	0.19	S
	DA47	363	2.1	65.16	37.921	234.2	5.01	0.28	S
	DA48	315	4.3	66.68	39.045	257.3	11.38	0.64	M
	DA49	276	4.9	67.88	39.940	291.5	13.46	0.75	M
	DA50	250	3.1	68.70	40.549	247.6	6.68	0.37	S
	DA51	215	6.7	69.77	41.354	443.7	26.64	1.49	L
Taupo	DA52	181	6.6	70.83	42.155	320.2	22.66	1.27	L
	DA53	133	5.2	72.27	43.247	320.6	14.37	0.81	M
	DA54	106	2.8	73.09	43.873	185.6	4.71	0.26	S
	DA55	76	1.2	74.02	44.586	183.8	2.30	0.13	S
	DA56	68	6.0	74.26	44.771	233.8	15.82	0.89	M
	DA57	38	3.0	75.15	45.451	177.3	4.89	0.27	S
	DA58	–10	5.4	76.61	46.584	243.7	14.59	0.82	M
	DA59	–37	3.1	77.40	47.196	182.2	4.89	0.27	S
	DA60	–82	1.3	78.76	48.256	170.0	2.16	0.12	S
	DA61	–93	5.2	79.07	48.498	219.4	8.80	0.49	S
	DA62	–114	2.6	79.69	48.983	217.8	5.29	0.30	S
	DA63	–138	3.5	80.41	49.551	257.5	9.69	0.54	M
	DA64	–201	4.6	82.27	51.017	320.8	16.43	0.92	M
	DA65	–239	3.5	83.37	51.887	222.2	8.38	0.47	S

Table 2. continued

Volcanic eruption	Event No.	Year(AD)	Duration	Depth in core	Depth	Peak nss-sulphate	Volcanic flux, f	f/f_{T}	Signal strength*
			years	m	m w.e.	μg kg^{-1}	kg km^{-2}		
	DA66	–242	1.0	83.44	51.946	209.6	2.30	0.13	S
	DA67	–343	1.0	86.38	54.292	209.4	2.39	0.13	S
	DA68	–387	4.9	87.66	55.331	231.6	12.85	0.72	M
	DA69	–425	12.3	88.73	56.196	1009.8	156.74	8.79	L
	DA70	–463	1.6	89.82	57.076	252.5	4.52	0.25	S
	DA71	–475	4.2	90.16	57.353	220.9	9.58	0.54	M
	DA72	–486	2.6	90.49	57.618	169.0	4.12	0.23	S
	DA73	–514	1.8	91.27	58.258	250.7	4.64	0.26	S
	DA74	–578	5.9	93.09	59.747	385.3	25.02	1.40	L
	DA75	–646	4.4	95.00	61.324	280.7	10.16	0.57	M
	DA76	–666	1.4	95.58	61.801	184.9	2.68	0.15	S
	DA77	–722	5.2	97.15	63.100	279.3	12.64	0.71	M
	DA78	–769	1.3	98.45	64.188	176.1	2.30	0.13	S

*L denotes large, M denotes moderate and S denotes small.
†These two volcanic events are used as time-stratigraphic markers for dating.

noting that volcanic flux of an eruption in polar snow is related to the latitude location of the source volcano (Langway and others, 1988). A small or moderate eruption in the Antarctic and sub-Antarctic region may result in a large event in the DA2005 ice core. However, since only a few volcanoes are known to be active in the Antarctic and sub-Antarctic regions, few such events are expected and they may be differentiated by comparison with other Antarctic ice-core records (Cole-Dai and others, 2000).

DISCUSSION

Comparing volcanic events recorded in ice cores from different sites helps to improve ice-core dating and also to remove spurious sulphate signals arising from atmospheric and glaciological effects which may be locally important, but unrelated to volcanic aerosols (Cole-Dai and others, 2000). Depending on the availability of existing well-dated volcanic records for comparison, the following discussion of the DA2005 record is divided into three time periods: (1) the last 1000 years (AD 1000–1998), (2) the period AD 1–1000 and (3) the period 840–1 BC. Comparisons with several Antarctic ice-core volcanic records are made to corroborate the volcanic events in the last 1000 years of the DA2005 record. For the period AD 1–1000, in which the Taupo eruption at 181 is the only known stratigraphic horizon, the DA2005 record is compared with four Antarctic records covering this time period. Comparisons are also made with Greenland records to identify possible low-latitude eruptions. The lack of well-dated stratigraphic horizons during the period 840–1 BC makes it difficult to compare specific events between the DA2005 record and other Antarctic and Greenland ice-core records. Therefore, the discussion of this period focuses on the largest event (DA69).

The last 1000 years (AD 1000–1998)

Twenty-eight volcanic events are detected in the DA2005 ice core during the period AD 1000–1998. Table 3 lists all volcanic events in the last 1000 years recorded in the DA2005 ice core, and those in six other Antarctic ice cores covering this time period: the PR core from Plateau Remote (Cole-Dai and others, 2000), the EDC96 core from Dome C (Castellano and others, 2005), the DT401 core from the East Antarctica plateau (Ren and others, 2010), the SP2001 core from South Pole (Budner and Cole-Dai, 2003), the DML05 core from Dronning Maud Land (Traufetter and others, 2004) and the NBY89 core from Byrd Station (Langway and others, 1994). As seen in Table 3, most of the volcanic events found in the other Antarctic ice-core records are also detected in the DA2005 record. These include the well-known volcanic events in the last millennium: Agung (1963); Krakatau, Indonesia (1883); Cosiguina, Nicaragua (1835); Tambora (1815); an unknown eruption (1809); Unknown (1693); Mount Parker, Philippines (1641); Deception Island, Antarctica (1641); Huaynaputina, Peru (1600); Kuwae (1453); and Unknown (1259). A signal with its $\mathrm{nssSO_4^{2-}}$ concentration above the threshold was dated at 1994 which is around the expected appearance date of the 1991 Pinatubo (Philippines) eruption. However, this signal does not satisfy the 1 year duration criterion for the volcanic event and is not included in the list. The 1641 eruption of Mount Parker (VEI = 6) and a contemporaneous sub-Antarctic volcanic eruption on Deception Island are found as a single sulphate event (DA12), similar to event PR9 in the PR record. A doublet, identified as Krakatau (1883; VEI = 6) and Tarawera, New Zealand (1886; VEI = 5), was found in the DML05 record (Trauffetter and others, 2004), but only one signal is detected in the DA2005 record. As Cole-Dai and others (2000) stated, it is not unusual for two volcanic signals within a few years to appear as a continuous event in ice cores from low-accumulation sites.

The DA2005 record also contains a number (four) of large and moderately large eruptions in the 13th century, with the 1259 event ($f/f_{\mathrm{T}} = 3.55$) being the most outstanding (Table 2). An event that appears around 1230 in several other records (DML05-27, EDC96-17, PR18, SP2001-24, DT401-16 and NBY89-23) as a relatively large event is not present in the DA2005 record. Cole-Dai and others (2000) found by bipolar comparison that the 1230, 1259 (DA23) and 1287 (DA20) events are likely from large low-latitude eruptions. The 1230 event may not be detectable at Dome A or other locations due to local features, such as surface snow redistribution, accumulation rates, and frequency of snowfalls.

Table 3. Volcanic events during the last 1000 years found in the DA2005, DML05, EDC96, PR, SP2001, DT401 and NBY89 ice cores. Dates are eruption years (AD) given in each core. Events in each core are numbered sequentially

Volcanic eruption	DA2005, East Antarctica (this work)	DML05, East Antarctica (Traufetter and others, 2004)	EDC96, East Antarctica (Castellano and others, 2005)	PR, East Antarctica (Cole-Dai and others, 2000)	SP2001, East Antarctica (Budner and Cole-Dai, 2003)	DT401, East Antarctica (Ren and others, 2010)	NBY89, West Antarctica (Langway and others, 1994)
Pinatubo		1992(DML05-1)	1992(EDC96-A)				
	1985(DA1)						
	1982(DA2)	1982(DML05-2)					
		1969(DML05-3)					
Agung	1964(DA3)	1964(DML05-4)	1964(EDC96-B)	1968(PR1)		1964(DT401-1)	1965(NBY89-1)
		1932(DML05-5)					
							1893(NBY89-2)
		1889(DML05-6)					1889(NBY89-3)
Tarawera	1885(DA4)	1886(DML05-7)		1884(PR2)			
Krakatau	1885(DA4)	1884(DML05-8)	1887(EDC96-1)	1884(PR2)		1900(DT401-2)	1884(NBY89-4)
			1881(EDC96-2)				
			1861(EDC96-3)				
Cosiguina	1836(DA5)	1835(DML05-9)		1836(PR3)	1842(SP2001-1)	1852(DT401-3)	1835(NBY89-5)
					1837(SP2001-2)		1832(NBY89-6)
Tambora	1816(DA6)	1816(DML05-10)	1816(EDC96-4)	1816(PR4)	1816(SP2001-3)	1816(DT401-4)	1816(NBY89-7)
Unknown	1810(DA7)	1809(DML05-11)	1807(EDC96-5)	1810(PR5)	1809(SP2001-4)	1795(DT401-5)	1811(NBY89-8)
					1800(SP2001-5)		
	1764(DA8)	1762(DML05-12)	1758(EDC96-6)		1759(SP2001-6)		1768(NBY89-9)
Unknown	1697(DA9)	1695(DML05-13)	1696(EDC96-7)	1694(PR6)	1694(SP2001-7)	1685(DT401-6)	
		1691(DML05-14)			1691(SP2001-8)		
	1678(DA10)	1676(DML05-15)	1675(EDC96-8)	1671(PR7)	1668(SP2001-9)	1662(DT401-7)	
	1658(DA11)			1653(PR8)			
Parker and Deception	1644(DA12)	1640(DML05-16)		1639(PR9)	1636(SP2001-10)		1648(NBY89-10)
	1623(DA13)		1624(EDC96–9)		1618(SP2001-11)	1610(DT401-8)	1628(NBY89-11)
Huaynaputina	1602(DA14)	1601(DML05-17)	1601(EDC96-10)	1600(PR10)	1600(SP2001-12)		1609(NBY89-12)
							1607(NBY89-13)
	1597(DA15)	1596(DML05-18)		1595(PR11)	1596(SP2001-13)		1605(NBY89-14)
		1542(DML05-19)					1539(NBY89-15)
	1511(DA16)				1508(SP2001-14)		
			1480(EDC96-11)			1477(DT401-9)	
Kuwae	1465(DA17)	1453(DML05-20)	1460(EDC96-12)	1454(PR12)	1458(SP2001-15)	1454(DT401-10)	1464(NBY89-16)
					1422(SP2001-16)		
					1396(SP2001-17)		
	1388(DA18)	1376(DML05-21)			1383(SP2001-18)	1386(DT401-11)	1384(NBY89-17)
	1349(DA19)	1343(DML05-22)	1347(EDC96-13)	1343(PR13)	1347(SP2001-19)	1345(DT401-12)	1348(NBY89-18)
	1287(DA20)	1285(DML05-23)	1288(EDC96-14)	1285(PR14)	1287(SP2001-20)	1287(DT401-13)	1287(NBY89-19)
	1280(DA21)	1278(DML05-24)		1277(PR15)	1276(SP2001-21)	1283(DT401-14)	1278(NBY89-20)
	1272(DA22)	1269(DML05-25)	1271(EDC96-15)	1269(PR16)	1270(SP2001-22)		1270(NBY89-21)
Unknown	1260(DA23)	1258(DML05-26)	1259(EDC96-16)	1260(PR17)	1260(SP2001-23)	1260(DT401-15)	1259(NBY89-22)
		1228(DML05-27)	1230(EDC96-17)	1234(PR18)	1236(SP2001-24)	1222(DT401-16)	1227(NBY89-23)
	1194(DA24)	1188(DML05-28)	1190(EDC96-18)	1197(PR19)	1195(SP2001-25)		
		1172(DML05-29)	1170(EDC96-19)		1174(SP2001-26)		1168(NBY89-24)
						1143(DT401-17)	
	1135(DA25)					1130(DT401-18)	
		1111(DML05-30)			1113(SP2001-27)		
		1108(DML05-31)					
					1094(SP2001-28)		
					1083(SP2001-29)		
	1062(DA26)						
	1051(DA27)						
		1040(DML05-32)				1043(DT401-19)	
	1001(DA28)						

In addition to the above well-dated volcanic events, six other events (DA8, DA10, DA13, DA18, DA19 and DA24) are also in agreement with the other Antarctic ice-core records. The small event DA10, dated around 1678 in the DA2005 record, was assigned to the 1673 Gamkonora (Indonesia) eruption with VEI = 5 (Traufetter and others, 2004; Castellano and others, 2005). Event DA19 is detected in all the above records and assigned to the 1325 ± 75 Cerro Bravo (Colombia) eruption by Traufetter and others (2004). The moderate event DA24 (1194) and the small event DA8 (1764) may be signals of eruptions in the mid- to high latitudes of the Southern Hemisphere, since corresponding events were not

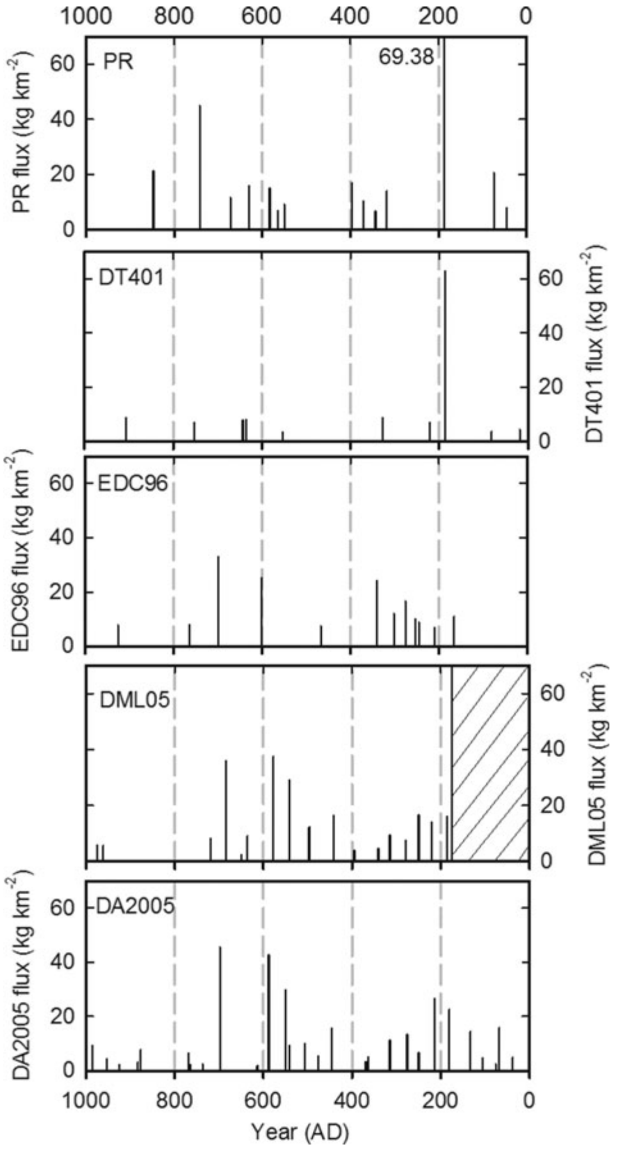

Fig. 3. Comparison of volcanic profiles (volcanic flux versus age) for the first millennium AD (AD 1–1000) from sulphate measurement in the PR, DT401, EDC96, DML05 and DA2005 ice cores. Shaded area indicates period not covered by ice core.

found in either the Dye 3 or the Greenland Icecore Project (GRIP) record (Clausen and others, 1997). Events DA13 (1623) and DA18 (1388) are small and likely from volcanoes in the mid- to high southern latitudes, as corresponding signals are not found in any Greenland cores (Zielinski and others, 1994; Clausen and others, 1997). Four other small events (DA2, DA11, DA16 and DA25) have a corresponding peak in only one of the other six Antarctic records. Event DA2 (1982) is contemporaneous with a similarly small event in the DML05 record (DML05-2), and they may be the result of the El Chichón (Mexico) eruption (Traufetter and others, 2004). Event DA11 (1658) confirms that the small signal PR8 (1653) in the PR record (Cole-Dai and others, 2000) is likely from a very minor volcanic eruption. And event DA16 (1511) may suggest that the small event SP2001-14 (1508) in the SP2001 record (Budner and Cole-Dai, 2003) is not a false positive detection but from a minor eruption.

Four events (DA1, DA26, DA27 and DA28) in the DA2005 record are not found in any of the six other Antarctic records. The small event DA1 is likely a spurious signal due to contamination from discrete sampling. As seen in Table 3, almost no contemporaneous events are found among the seven records during the period AD 1000–1100 when events DA26, DA27 and DA28 were recorded. This may be due to the dating errors of each core during this time period and may also indicate these Antarctic ice cores record different volcanic eruptions in the mid- to high southern latitudes. Also the possibility cannot be excluded that some of these signals are spurious.

Several events found in the DML05, EDC96, SP2001, DT401 and NBY89 records are not detected in the DA2005 record. Most of these events are detected in only one of the above records, with no corresponding signals in the other records. For example, no volcanic signal around 1969 is found in the EDC96, PR, SP2001, DT401 and NBY89 records to support event DML05-3 in the DML05 record. Some of these signals are so small that they may be spurious signals or easily missed in ice cores drilled at sites with quite low accumulation rates such as Dome A. Although no event around 1172 is recorded in DA2005, an event was detected in the DML05, EDC96, SP2001 and NBY89 records and was also recorded in another Antarctic ice core, the SP78 core (Langway and others, 1995). In the Greenland Ice Sheet Project 2 (GISP2; Zielinski and others, 1994), GRIP and Dye 3 (Clausen and others, 1997) records, an event was found at 1175, 1179 and 1180, respectively, and was attributed to an Icelandic eruption. Therefore, the event around 1172 may represent coincident eruptions in the mid- to high latitudes of both hemispheres.

AD 1–1000 (2000–1000 years BP)

The PR, DT401 and EDC96 records mentioned above also cover this time period, while the DML05 record (dated by counting annual layers) only presents the volcanic history as old as AD 186. Figure 3 compares the DA2005 record for the first millennium with those in the PR, DT401, EDC96 and DML05 records. Dates and event numbers of contemporaneous events found in the DA2005 record and at least two of the other four Antarctic records are listed in Table 4. We also found several events in the DA2005 record with potential counterparts in only one of the other four records. These events are not included in Table 4. Unlike the numerous well-dated volcanic eruptions in the last 1000 years, the only well-known event during this 1000 year period is the Taupo eruption at 181. Thus, a detailed discussion of all the contemporaneous volcanic events is not warranted for this 1000 year period and we summarize below the most prominent events.

As seen in Table 4, ten events in the DA2005 record (a total of 29 events) have corresponding signals in at least two of the other four records. The largest age difference of corresponding events is 30 years between EDC96-29 and DA51. However, all differences are well within the dating errors of these cores. Of the above ten events, five are large (DA38, DA40, DA41, DA51 and DA52) but none is of the 1259 Unknown event magnitude, and another four (DA45, DA48, DA49 and DA56) are moderate events. It is worth noting that there is good agreement among volcanic signatures in the period AD 180–700 at three different sites (Dome A, Dome C and DML) far away from each other (Fig. 1). Indeed, nine of fourteen events in the DML05 record and eight of nine in the EDC96 record are contemporaneous to the major events in the DA2005 record during the period AD 180–700.

Table 4. Contemporaneous events during the first millennium AD (AD 1–1000) found in DA2005 and at least two of the DML05, EDC96, PR and DT401 ice cores (all from East Antarctica)

DA2005 (this work)	DML05 (Traufetter and others, 2004)	EDC96 (Castellano and others, 2005)	PR (Cole-Dai and others, 2000)	DT401 (Ren and others, 2010)
698(DA38)	685(DML05-36)	699(EDC96-22)		
588(DA40)	578(DML05-39)	601(EDC96-23)	583(PR24)	
551(DA41)	542(DML05-40)		550(PR26)	553(DT401-24)
446(DA45)	442(DML05-42)	467(EDC96-24)		
315(DA48)	315(DML05-45)	340(EDC96-25)	317(PR30)	328(DT401-25)
276(DA49)	279(DML05-46)	302(EDC96-26)		
250(DA50)	250(DML05-47)	276(EDC96-27)		
215(DA51)	221(DML05-48)	245(EDC96-29)		222(DT401-26)
181(DA52)	186(DML05-49)	210(EDC96-30)	186(PR31)	187(DT401-27)
68(DA56)			74(PR32)	82(DT401-28)

The Taupo eruption at AD 186 ± 10 (Wilson and others, 1980) is regarded as one of the most significant eruptions (VEI = 6+) in the Southern Hemisphere in the first millennium (Cole-Dai and others, 2000). It has been detected in several Antarctic and Greenland ice cores (Zielinski and others, 1994; Cole-Dai and others, 2000; Traufetter and others, 2004; Ren and others, 2010). As seen in Figure 3, the Taupo event was a very large signal in both the PR and DT401 cores. However, in the DML05 core (Traufetter and others, 2004) and in an ice core from Siple Dome, West Antarctica (SDMA; Kurbatov and others, 2006), Taupo was either a moderate or small signal. The large signal dated at 181 (event DA52) in DA2005 may correspond to the Taupo eruption, with $f/f_T = 1.27$ compared to 3.10 in the PR record (Cole-Dai and others, 2000). According to Larsen and others (2008), three contemporaneous events (dated at 674/675, 567/568 and 533/534, respectively) in three Greenland ice-core (Dye 3, GRIP and NorthGRIP) records correspond to the DML deposits at 685 (DML05-36), 578 (DML05-39) and 542 (DML05-40), respectively. With the DML05 record as the reference, DA38 (698), DA40 (588) and DA41 (551) may be the corresponding events to the three events in the Greenland records. Hence, events DA38, DA40 and DA41 are most likely low-latitude eruptions. The moderate event DA56 dated at 68 appears to correspond to a large event (PR32 dated at 74) in the PR record (Cole-Dai and others, 2000) and a small event (DT401-28 dated at 82) in the DT401 record (Ren and others, 2010). In the GISP2 (Zielinski and others, 1994) and GRIP (Clausen and others, 1997) records, an event was also found at AD 77 and 79, respectively. However, the event in the above three Antarctic records and that in the two Greenland records are unlikely from the same eruption since the AD 77 event may have resulted from the AD 79 Mount Vesuvius (Italy) eruption in the Northern Hemisphere (Zielinski and others, 1994).

These comparisons with the other Antarctic volcanic records suggest that the DA2005 record during this 1000 year period is reliable. More ice-core-based volcanic records are needed to clarify the source and magnitude of the contemporaneous events found in DA2005 and previous Antarctic ice cores.

840–1 BC (2840–2000 years BP)

A total of 21 events are detected in the DA2005 ice core during the period 840–1 BC, compared to 8 in the PR core (Cole-Dai and others, 2000) and 5 in the EDC96 core (Castellano and others, 2005). Eruption frequency (2.8 per century) for the most recent 2000 years in DA2005 is also higher than those in the Antarctic ice cores from sites with low accumulation rates (e.g. the PR, EDC96 and DT401 cores). These differences may be due to a number of glaciological and atmospheric factors variable from site to site. Another influencing factor may be the temporal resolution of the sulphate measurement. Lower temporal resolution (larger sample length) could dilute the sulphate concentration of a volcanic event such that the event is below the detection threshold. Therefore, some small events may not be detected in ice cores with low-resolution analysis. For example, the DA2005 and DT401 cores are from locations only 120 km from each other in East Antarctica (Fig. 1), which may share similar glaciological and atmospheric features. The fewer volcanic signatures in DT401 may also be due to the lower temporal resolution of the analysis of the DT401 core (one measurement every 30 or 35 mm in DT401 compared to 13 mm in DA2005).

The largest volcanic event in the DA2005 record (DA69) is dated at 425 BC. The maximum sulphate concentration of DA69 (1009.8 μg kg^{-1}) is similar to that of the 1259 Unknown eruption (1011.0 μg kg^{-1}), but the volcanic flux (156.74 kg km^{-2}) of DA69 is more than twice that of the 1259 event (63.27 kg km^{-2}). The duration of DA69 (~12.3 years) is significantly longer than the typical duration of 1–3 years expected for volcanic events in Antarctic ice cores. The long duration may be attributed to the combined effect of a long atmospheric residence time of its volcanic aerosols and post-deposition modification (Cole-Dai and others, 2000). No such volcanic signals were found in the PR and DT401 records during this time period. However, in the EDC96 record, a large signal was detected at 384 BC (Castellano and others, 2005). Also in the SDMA record a very large event was found at 325 BC (Kurbatov and others, 2006). It is not possible, given that the differences in the ages are within the dating uncertainties of these cores, to determine whether these three signals are from the same eruption.

CONCLUSIONS

A total of 78 volcanic eruptions are identified in the top 100.42 m of the DA2005 ice core covering the period 840 BC–AD 1998. Of these, 12 are probable large events with fluxes larger than that of the AD 1815 Tambora eruption (VEI = 7). The largest event is dated at 425 BC, with its sulphate flux almost nine times that of the Tambora eruption. The mean eruption frequency for the entire 2840 years (2.7 events per century) in DA2005 is higher than those in previous Antarctic ice cores recovered from sites with low accumulation rates.

Comparisons with previous Antarctic ice-core volcanic records suggest that the DA2005 record is reliable in the most recent 2000 years. A series of volcanic events in the first millennium AD (AD 1–1000) in the DA2005 record are also found in several other Antarctic ice-core records. Three events, DA38, DA40 and DA41, during the period AD 1–1000 are likely from low-latitude eruptions since corresponding signals were found in several Greenland ice-core volcanic records. However, better-dated Antarctic ice-core volcanic records, ideally from sites with high accumulation rates, are needed to corroborate the DA2005 events in the older (840–1 BC) period.

The mean accumulation rate between the 1963 Agung and 1259 Unknown eruptions is 23.2 mm w.e. a^{-1}, which is quite similar to the value between 1966 and 2004 measured by Hou and others (2007). Dating results from the 700 year mean accumulation rate show that there is good agreement between the year of expected appearance and the calculated age of all the well-dated volcanic events in the last two millennia. This suggests that there is neither an indication of a change nor a trend in the accumulation rate apparent in the last 2000 years, which may indicate that no drastic change in deposition has occurred at Dome A within this time period.

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