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A 4100-year record of explosive volcanism from an East Antarctica ice core

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Abstract. Extensive archives of volcanic history are available from ice cores recovered from the Antarctic and Greenland ice sheets that receive and preserve sulfuric acid fallout from explosive volcanic eruptions. The continuous, detailed (average 1.2 samples per year) sulfate measurements of a 200-m ice core from a remote East Antarctica site (Plateau Remote) provide a record of Southern Hemisphere volcanism over the last 4100 years. This extends the volcanic record beyond the last 1000 years covered by previous Antarctic ice cores. An average of 1.3 eruptions per century is recorded in East Antarctic snow during the last 4100 years. The record shows that on average eruptions have been more frequent and more explosive during the most recent 2000 years than in the previous 2100 years. Intervals up to 500 years are observed in which few explosive volcanic signals are detected. These periods include 2000-1500 B.C. (no eruptions), 500-1 B.C. (two eruptions), and 700-1200 A.D. (two eruptions). This new Plateau Remote volcanic record is compared with those from previous Antarctic ice cores covering the last 1000 years. In terms of dates for volcanic events, the new record is in excellent agreement with the earlier records. However, significant discrepancies are found between these records in relative signal magnitude (volcanic flux) of several well-known events. The discrepancies among the records may be explained by the differences in the glaciology at the ice core sites, analytical techniques used for sulfate and sulfuric acid measurement, and the selection of detection thresholds for volcanic signals. Comparison with Greenland ice core volcanic records indicates that during the last millennium, nine large, low-latitude eruptions contributed significant amounts of volcanic aerosols to the atmosphere of both hemispheres, potentially affecting global climate. In contrast, only one or possibly two such eruptions are found in the first millennium A.D.

1. Introduction

Snowfall contains traces of chemical species from the atmosphere. Continuous snow accumulation over the Antarctic and Greenland ice sheets preserves a history of atmospheric chemical composition. This history can be retrieved from ice cores drilled at carefully selected sites on the ice sheets. Among the most valuable ice core records is the history of explosive volcanism, based on ice core measurements of volcanic acids or sulfur compounds, which were first employed by Hammer and colleagues [*Hammer,* 1980; *Hammer et al.,* 1980]. The source of volcanic sulfuric acid or sulfate in snow is the emission of large quantities of sulfur compounds (mainly sulfur dioxide) into the atmosphere by explosive volcanic eruptions. These gaseous sulfur compounds are oxidized to sulfuric acid, which exists in the atmosphere mainly as particulate aerosols. During their residence in the atmosphere (from a few months to a few years), volcanic aerosols may be transported via atmospheric circulation to the polar regions, where they are deposited and preserved in the snow strata [e.g., *Delmas et al.,* 1985; *Legrand and Delmas,* 1987].

Volcanic sulfate aerosols in the atmosphere play an important role in climate variations. Ice core volcanic records are recognized as one of the most valuable and unique tools to study the climate-volcanism connection and its significance for climate change [e.g., *Robock,* 1991; *White et al.,* 1997; *Zielinski,* 2000]. However, ice core volcanic records may suffer from a number of weaknesses due to complexities in eruption dynamics, atmospheric aerosol transport, glaciological preservation, and signal retrieval. For example, the latitudinal location of a volcano and large-scale atmospheric circulation patterns determine if aerosols from a particular eruption are transported to the polar atmosphere and deposited on the Antarctic or Greenland ice sheet. In general, only aerosols from eruptions in the low latitudes (between 20°N and 20°S) of either hemisphere are capable of transport to both polar regions. Therefore volcanic signals found in an Antarctic ice core can be either from volcanoes located in the middle southern latitudes (e.g., South America and the South Pacific) and the high southern latitudes (the Antarctic continent and the subantarctic islands), or from volcanoes located in the low latitudes of either hemisphere. Additionally, a low-latitude eruption must be sufficiently explosive to inject volcanic materials directly into the stratosphere in order for its aerosols to be transported to the polar atmosphere and deposited in Antarctic or Greenland snow [*Hitchman et al.,* 1994]. Coincidentally, such large explosive eruptions are most likely to affect the global climate through radiative forcing by volcanic aerosols [*Robock,* 1991; *White et al.,* 1997; *Zielinski,* 2000]. Acidity or

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sulfate measurements on ice cores do not distinguish between middle- and high-latitude eruptions and large eruptions in the low latitudes, although chemical examination of tephra found in ice cores may help identify the source volcanoes [e.g., *Palais et al.*, 1992; *Zielinski et al.*, 1997]. Differentiating low-latitude eruptions from those in the middle and high latitudes is also possible when records of ice cores from several sites across Antarctica or Greenland are carefully compared [*Cole-Dai et al.*, 1997].

Northern Hemisphere volcanic records have been obtained from several early Greenland ice cores [e.g., *Hammer*, 1980; *Hammer et al.*, 1980; *Langway et al.*, 1988]. Recently, extended volcanic records have become available from the deep ice cores drilled in central Greenland [*Clausen et al.*, 1997; *Zielinski et al.*, 1994, 1996, 1997]. In comparison, Southern Hemisphere volcanic records from several previous Antarctic ice cores [*Cole-Dai et al.*, 1997; *Legrand and Delmas*, 1987; *Moore et al.*, 1991] are relatively short, with the longest published continuous records covering the last 1000 years [*Delmas et al.*, 1992; *Langway et al.*, 1995].

A 4100-year history of paleoclimate and atmospheric composition is available from two 200-m ice cores drilled in central East Antarctica (Plateau Remote). The climatic records from these cores have been presented previously [*Mosley-Thompson*, 1996]. In this study a volcanic record is constructed using sulfate measurements of nearly 5000 samples over the entire length of one of the cores. This new record extends the Southern Hemisphere volcanic history beyond the last 1000 years covered by previous Antarctic ice cores. The quality of the new Plateau Remote record is assessed by a detailed comparison with existing Antarctic ice core records covering the last 1000 years. Over the longer period (the last 4100 years) this new record can be compared with lengthy Greenland ice core records to identify the most explosive low-latitude eruptions that may have had a global climatic impact.

2. Ice Core Sampling and Analysis

The two 200-m cores were drilled during the 1986-1987 austral summer season at a remote site (Plateau Remote, 84°S, 43°E, elevation 3330 m above sea level) in central East Antarctica (Figure 1). For this study, one of the two cores (PR-B) was sampled continuously along its length at approximately 4 cm per sample. All samples were melted and analyzed in the ice core analysis laboratory of the Byrd Polar Research Center at The Ohio State University. Concentrations of anions (chloride, nitrate, sulfate) were determined in all samples using ion chromatography, while selected portions of the core were analyzed for concentrations of cations (sodium, potassium, magnesium and calcium). A short section (23.14-24.14 m) of the core had been consumed for other measurements and was unavailable for ionic analysis. The samples were prepared and analyzed using stringent contamination control procedures, which have been described previously by *Dai et al.* [1995].

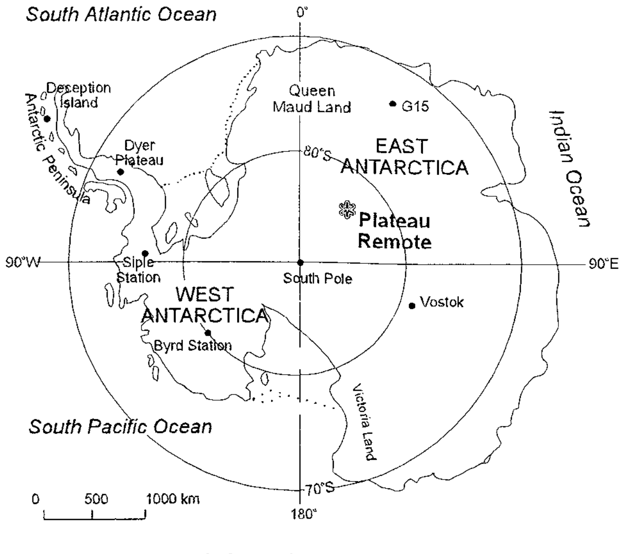

Figure 1. Location of Plateau Remote (84°S, 43°E) and other ice core sites in Antarctica referred to in text.

Ice core volcanic records are based on two types of measurements: (1) acidity or salt concentration determined by continuous electric conductivity measurements on ice [*Hammer*, 1980; *Moore et al.*, 1992], and (2) sulfate or sulfuric acid concentrations in discrete melted samples. In this study, sulfate concentrations were measured in 4958 samples to produce a continuous profile as a function of depth in core (Figure 2). The contribution by sea-salt aerosol particles to sulfate concentrations in snow can be estimated with sodium or chloride concentrations [*Dai et al.*, 1995]. Sodium and chloride concentrations are quite low (1.0 and 1.3 μeq kg^{-1}, respectively) in this core from the interior of East Antarctica, indicating a minimal sea-salt contribution (less than 5% of the total sulfate). Consequently, for the purpose of this study, no distinction is required between total sulfate and non-sea-salt sulfate. Density measurements along the entire length of the core and on numerous pit and shallow core samples made it possible to convert snow and ice depth to water equivalent (H_2O) depth [*Mosley-Thompson*, 1996].

3. Ice Core Dating and Error Estimates

The snow accumulation rate at Plateau Remote ($\approx$120 mm of snow or 40 mm H_2O per year) is among the lowest in Antarctica. As a result, the sampling resolution (approximately 1.2 samples per year) for ionic and other measurements [*Mosley-Thompson*, 1996] was insufficient to allow dating by counting annual layers. To develop a timescale for the sulfate profile (Figure 2), annual snow accumulation rates were determined empirically and used to date the ice core. Estimates of current accumulation rates were initially obtained from snow pit visible stratigraphy and the identification of the beta radioactivity horizons from atmospheric thermonuclear tests during the 1950s and early 1960s [*Mosley-Thompson*, 1996]. However, those estimates are typical of the mean accumulation rates during the most recent decades and may not be representative of the much longer time period covered by this core, for accumulation rates may vary significantly not only on an interannual basis but also on longer timescales [*Mosley-Thompson et al.*, 1999]. Time stratigraphic horizons from known volcanic eruptions provide another method for estimating mean annual accumulation rates. Several well-known, large volcanic signals in the PR-B sulfate profile (Figure 2) were identified by comparison with previous Antarctic ice core records [*Cole-Dai et al.*, 1997; *Delmas et al.*, 1992]. The ages and the corresponding depths of these known volcanic events are listed in Table 1. A large volcanic event was found at 103.8 m, and the preliminary dating suggested that this event occurred during the 100-300 A.D. period. According to *Simkin and Siebert* [1994], the most significant eruption in the Southern Hemisphere during this period is that of Taupo (Volcanic Explosivity Index (VEI)=6+) in New Zealand, with an estimated eruption date of 186±10 A.D. [*Wilson et al.*, 1980]. It has been suggested [*Zielinski et al.*, 1994] that this Taupo eruption was so explosive (ultraplinian) that its sulfate fallout was recorded in the Greenland ice sheet. Therefore, this event at 103.8 m is tentatively attributed to the 186 A.D. Taupo eruption and was included in the list of known volcanic eruptions used as time stratigraphic markers. A mean accumulation rate was calculated between two adjacent events in the list and was assumed constant to date the intervening snow layers. For the lower 100 m of the core, where no known volcanic horizons are available, the mean accumulation of 37.7 mm

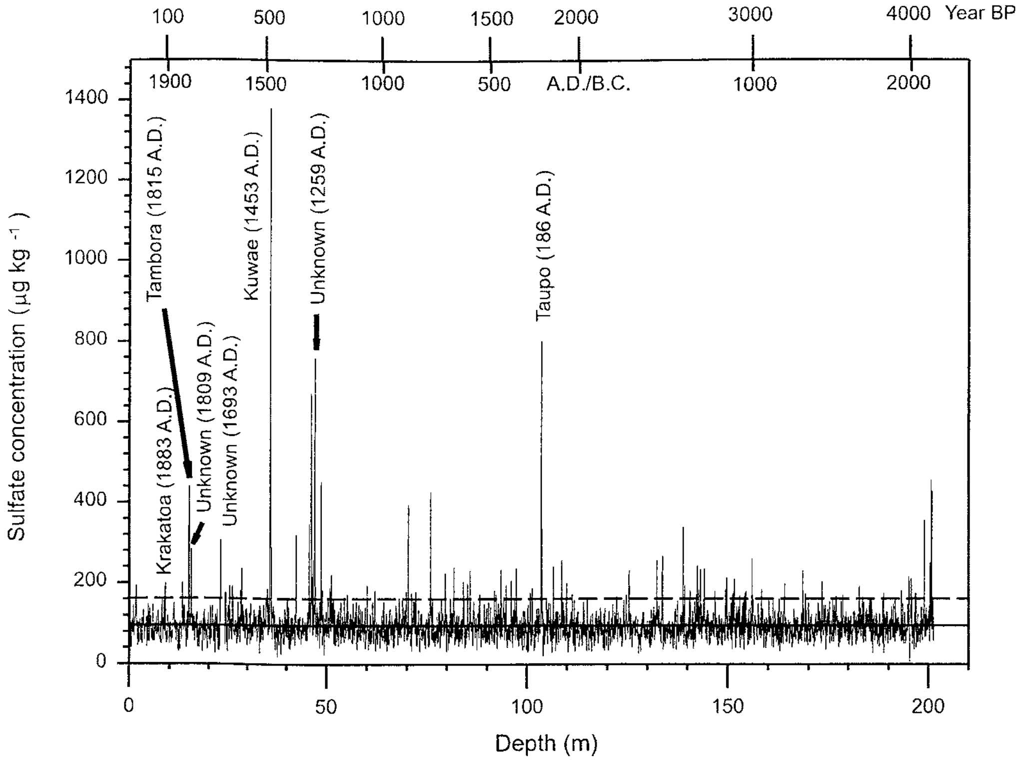

Figure 2. Continuous (except for a 1-m gap between 23.14 and 24.14 m) profile of sulfate concentrations ($\mu g\ kg^{-1}$) in the Plateau Remote core (PR-B) as a function of depth (bottom axis). Labeled volcanic events are known eruptions used as time stratigraphic horizons to construct the time-scale displayed as the top axis. The solid horizontal line indicates the nonvolcanic background and the dashed line represents the detection threshold (background $+2\sigma$).

$H_2O\ yr^{-1}$ was used. This value was obtained for the 1800-year interval between the snow surface (1986) and the date of the 186 Taupo eruption located at 103.8 m. A slightly different eruption date (177±10 A.D.) has been suggested [*Froggatt and Lowe,* 1990] for the Taupo eruption, although using 177 A.D. for dating would not change the conclusions of this work. The mean accumulation rates (Table 1) calculated from known volcanic stratigraphic horizons range from 30.8 to 41.8 mm $H_2O\ yr^{-1}$. The climatic implications of these accumulation rate variations, along with other relevant data, have been discussed previously by *Mosley-Thompson* [1996].

The construction of an ice core timescale is based on the assumption that the snow stratigraphy is temporally continuous and undisturbed. Continuous snow stratigraphy is usually the case with

Table 1. Mean Annual Accumulation Rates Calculated from Known Volcanic Stratigraphic Horizons in the PR-B Core.

Volcano/Year of Eruption	Depth in Core, m	Depth in H_2O, m	Date in Core (A.D.)	Period Covered	Mean Accumulation, mm $H_2O\ yr^{-1}$	Calculated Date (A.D.)	Difference, years
snow surface	0.00	0.000	1986				
Krakatoa/1883[a]	13.44	3.637	1884	1884-1986	35.3	1890	+6
Tambora/1815[a]	15.10	6.368	1816	1816-1883	40.2	1818	+2
Unknown/1809[a]	15.66	6.619	1810	1810-1815	41.8	1811	+1
Unknown/1693[a]	23.09	10.430	1694	1694-1809	32.8	1710	+16
Huaynaputina	28.45	13.400	1600				
Unknown/1593	28.66	13.510	1595				
Kuwae/1453[a]	36.13	17.824	1454	1454-1693	30.8	1514	+60
Unknown/1259[a]	47.28	24.960	1260	1260-1453	36.8	1324	+64
Taupo/186[a]	103.83	67.840	186	186-1259	39.9		
Taupo/186[a]	103.83	67.840	186	186-1986	37.7		

All dates are calendar years. The snow surface represents the end of 1986 or the beginning of 1987. The Huaynaputina and the 1593 unknown eruptions are dated according the dating procedures for the PR-B core. Calculated dates refer to event years computed using the 1800-year mean accumulation rate (37.7 mm $H_2O\ yr^{-1}$). The "difference" column represents the difference between the date in core and the calculated date.

[a] These volcanic events are used as time stratigraphic markers for dating, and their dates in core are determined by comparison with previously published records. The date of a volcanic eruption in the core lags the eruption date by 1 year, to allow for atmospheric transport of volcanic aerosols.

ice cores recovered from Antarctic locations with moderate to high rates of snow accumulation. Snow drift and redistribution after deposition, resulting from wind scouring of the snow surface, may cause partial loss of annual accumulation on the upwind side of sastrugi (small surface irregularities), and extra accumulation may be gained on the downwind side [*Black and Budd*, 1964]. This phenomenon is most pronounced at locations where the snow accumulation rate is extremely low, such as South Pole and Plateau Remote [*Van der Veen et al.*, 1999]. The average height of large sastrugi at Plateau Remote was estimated to be ~40 cm [*Mosley-Thompson,* 1996]. This suggests that at the mean accumulation rate of approximately 10 cm snow per year, surface smoothing would take place in 4-5 years and, under ideal conditions, the high- and low-accumulation points would be reversed in 8-10 years. Therefore accumulation averaged over several decades should contain no net loss or gain resulting from the small-scale surface irregularities. Snow drifting and redistribution may also occur due to larger-scale topographic undulations, and the resulting accumulation changes require a much longer time period (≥ 100 years) to be smoothed out in low-accumulation areas [*Van der Veen et al.*, 1999]. However, this larger-scale effect is difficult to quantify [*Van der Veen et al.*, 1999] and is not considered in this study.

With the mean annual accumulation rates for the various periods listed in Table 1 and the dating procedure outlined above, the depth scale shown in Figure 2 was converted to a timescale, as indicated on the top axis of Figure 2. According to this timescale, the 200-m core covers the last 4144 years before present (BP, present = end of 1986 A.D.). For the top 16 m of the core marked by the 1815 A.D. Tambora eruption, dating errors are no more than a few years, as the variation in accumulation rate appears to be very small. From 16 m to approximately 103 m, where the Taupo volcanic horizon is located, the variation in accumulation rate is relatively large (Table 1). Errors would be significant, if a single mean accumulation rate were used for dating. For instance, the ages of the known volcanic horizons were calculated (Table 1) using the 1800-year mean annual accumulation rate (37.7 mm H_2O yr^{-1}) determined using the 186 A.D. Taupo eruption. Comparison of these calculated dates with the known dates of the volcanic eruptions suggests that dating errors could be large (right column, Table 1). Fortunately, the actual dating errors for this period are very small, due to the identification of four or five well known volcanic horizons. For example, two closely timed volcanic signals (the 1600 A.D. Huaynaputina eruption and a 1593 A.D. unknown eruption at 28.45 and 28.66 m, respectively) are dated at 1600 and 1595 A.D., respectively. These are very similar to the dates of a corresponding doublet in a South Pole core [*Delmas et al.,* 1992] and in two West Antarctica cores [*Cole-Dai et al.,* 1997]. Additionally, the dates of a series of volcanic events between 1234 and 1285 A.D. are corroborated by similar events dated by *Langway et al.* [1995] in a West Antarctica core (see later discussion on volcanic events during the last 1000 years).

For the lower 100 m of the core where no time horizons are available, dating uncertainty is determined by the selection of the mean accumulation rate of 37.7 mm H_2O yr^{-1} derived from the Taupo horizon and, more importantly, by the variability of accumulation rate during the time period covered by this part of the core. Unfortunately, this variability can not be estimated using available data. Nonetheless, the mean annual accumulation rates in Table 1 for the upper half of the core may provide an indication of the long-term (decadal to century and millennium) variability (the inter-annual variability is substantially larger). Assuming that the long-term variability of accumulation rate in the lower half is similar to that in the upper half of the core, dating errors such as those listed in Table 1 (right column) can be expected for the lower 100 m of the core.

4. Results

4.1. Criteria for Detecting Volcanic Signals in an Ice Core

Antarctic snow contains sulfate from sources other than explosive volcanic eruptions [e.g., *Delmas*, 1982]. The concentrations of the nonvolcanic or background sulfate vary temporally in an ice core, and the sulfate from volcanic eruptions is superimposed on this variable background. The detection of a volcanic signal therefore requires estimating the background and its variability. Previous ice core studies [*Legrand,* 1995; *Legrand et al.,* 1991] have shown that background sulfate concentrations in Antarctic snow have remained relatively constant over the entire Holocene period, suggesting that interannual background sulfate variations are not controlled by any dominant sources or systematic aerosol transport and deposition processes. Therefore the "normal" background may be assumed constant and equal to the average nonvolcanic concentration, and its range of variation may be approximated assuming a random (Gaussian) distribution. Different approaches have been used in previous studies to approximate the nonvolcanic background and to define a volcanic threshold in ice core data (see summary by *Cole-Dai et al.* [1997]). *Cole-Dai et al.* [1997] proposed that a sample contain potential volcanic sulfate when the sulfate concentration exceeds the background by 2 times the standard deviation (σ), while others used somewhat lower thresholds (e.g., average plus 1σ by *Delmas et al.* [1992]). The average-plus-2σ threshold used in this work would exclude 95.5% of the random background fluctuation, if the distribution is truly Gaussian. For the PR-B core the average background sulfate concentration is calculated to be 95.0 $\mu g\ kg^{-1}$ (indicated by the solid line in Figure 2), with a standard deviation of 33.1 $\mu g\ kg^{-1}$. The threshold of 161.2 $\mu g\ kg^{-1}$ is indicated by the dashed line in Figure 2. This criterion was used to detect samples of unusually high sulfate concentrations in the entire PR-B sulfate profile. A second criterion is that to be considered volcanic in origin, the sulfate concentration must be elevated above the threshold for at least two consecutive samples. This criterion is necessary to reduce the probability of false volcanic signals due to single samples with a spuriously high background sulfate concentration. Using the above detection criteria, a total of 54 volcanic events were found in this core. These volcanic events are listed in Table 2 and are hereby designated as the PR volcanic record. Events are numbered according to their appearance in the core and are referred to by their numbers in subsequent discussions. As a result of the second criterion and the relatively low sampling resolution (~1 year per sample for most of the core), a volcanic event detected in this core lasts a minimum of 2 years, and volcanic events with shorter durations are excluded from this record. Net volcanic sulfate concentrations are obtained when the average background sulfate concentration (95.0 $\mu g\ kg^{-1}$) is subtracted from the total sulfate concentrations of samples containing volcanic sulfate.

4.2. Date and Duration of a Volcanic Event

A volcanic eruption can enhance the atmospheric sulfate aerosol reservoir for up to 3 years, or longer in the case of megascale eruptions such as the prehistoric Toba eruption (~72,000 years BP). Therefore a volcanic event lasting less than 3 years in an ice core is usually considered to have resulted from a single volcanic eruption, although it is possible that closely timed multiple eruptions could appear as a single volcanic signal [*Cole-Dai and Mosley-Thompson*, 1999]. The date for a volcanic event in Table 2 is assigned to the year containing peak sulfate concentration during the event. The appearance of the volcanic signal in Antarctic snow usually lags the date of a low-latitude eruption by 1 or 2 years [*Cole-Dai and Mosley-Thompson*, 1999; *Legrand and Wagenbach*, 1999].

Table 2. Volcanic Events Found in the Ice Core from Plateau Remote, East Antarctica.

Volcanic Eruption	Event	Year A.D.	Duration, years	Depth in Core, m	Depth in H_2O, m	Peak Sulfate, $\mu g\ kg^{-1}$	Volcanic Flux f, kg km^{-2}	f/f_T[a]	Signal Strength[b]
Deception and Agung	PR1	1968	3.0	1.81	0.67	194.2	6.68	0.30	S
Krakatau[c] and Tarawera	PR2	1884	3.9	9.11	3.64	200.4	9.42	0.42	M
Coseguina	PR3	1836	2.4	13.44	5.60	201.3	6.31	0.28	S
Tambora[c]	PR4	1816	3.4	15.10	6.39	442.0	22.39	1.00	L
Unknown/1809[c]	PR5	1810	2.7	15.66	6.66	285.5	8.30	0.37	M
Unknown[c]	PR6	1694	3.0	23.09	10.45	308.8	10.74	0.48	M
	PR7	1671	3.1	24.45	11.18	175.4	5.55	0.25	S
	PR8	1653	3.1	25.47	11.73	195.3	6.14	0.27	S
Parker and Deception	PR9	1639	3.9	26.31	12.20	192.1	7.06	0.32	S
Huaynaputina	PR10	1600	3.3	28.45	13.40	181.5	4.91	0.22	S
	PR11	1595	2.5	28.66	13.51	237.7	7.34	0.33	S
Kuwae[c]	PR12	1454	7.2	36.13	17.92	1380.4	133.37	5.96	L
	PR13	1343	3.1	42.56	21.94	321.8	14.88	0.66	M
	PR14	1285	3.6	45.88	24.09	349.0	21.05	0.94	L
	PR15	1277	9.0	46.49	24.49	672.1	55.39	2.47	L
	PR16	1269	3.9	46.81	24.70	259.8	11.85	0.53	M
Unknown/1259[c]	PR17	1260	5.8	47.28	25.01	566.8	46.30	2.07	L
	PR18	1234	5.2	48.90	26.09	453.4	31.21	1.39	L
	PR19	1197	4.4	50.90	27.56	188.6	10.62	0.47	M
	PR20	847	3.6	70.54	41.79	397.4	21.27	0.95	L
	PR21	742	7.1	76.24	45.81	428.0	44.97	2.01	L
	PR22	672	2.3	79.74	48.50	226.4	11.51	0.51	M
	PR23	630	5.0	81.91	50.19	240.7	15.78	0.70	M
	PR24	583	6.3	84.36	52.11	205.3	15.12	0.68	M
	PR25	564	2.6	85.26	52.81	201.5	6.77	0.30	S
	PR26	550	2.5	85.89	53.32	233.4	8.99	0.40	M
	PR27	396	5.1	93.65	59.55	235.1	16.89	0.75	M
	PR28	370	4.2	94.91	60.57	196.1	10.22	0.46	M
	PR29	343	2.6	96.16	61.60	206.9	6.57	0.29	S
	PR30	317	3.7	97.41	62.62	238.7	13.93	0.62	M
Taupo[c]	PR31	186	6.2	103.83	67.94	804.0	69.38	3.10	L
	PR32	74	5.5	108.82	72.14	256.9	20.51	0.92	L
	PR33	46	3.6	109.95	73.10	200.4	7.89	0.35	S
	PR34	-314	6.6	125.62	86.70	232.7	18.01	0.80	M
	PR35	-476	6.3	132.60	92.95	257.7	15.03	0.67	M
	PR36	-509	3.9	133.85	94.07	267.5	22.44	1.00	L
	PR37	-631	5.1	139.00	98.71	338.3	24.70	1.10	L
	PR38	-672	4.3	140.67	100.24	182.3	9.37	0.42	M
	PR39	-719	9.8	142.58	102.00	243.6	21.12	0.94	L
	PR40	-736	4.0	143.27	102.63	234.4	10.55	0.47	M
	PR41	-761	3.1	144.26	103.55	236.3	11.43	0.51	M
	PR42	-897	2.0	149.79	108.63	214.8	9.27	0.41	M
	PR43	-932	2.7	151.24	109.97	173.8	7.03	0.31	S
	PR44	-1050	2.8	156.05	114.40	261.9	9.98	0.44	M
	PR45	-1109	2.0	158.46	116.62	185.3	6.41	0.29	S
	PR46	-1248	6.8	164.17	121.87	198.4	15.39	0.69	M
	PR47	-1357	3.0	168.94	125.98	231.6	9.36	0.28	M
	PR48	-1476	2.9	173.49	130.45	203.6	10.36	0.46	M
	PR49	-2003	5.9	195.21	150.43	217.6	18.03	0.80	M
	PR50	-2019	5.2	195.74	150.92	210.7	13.85	0.62	M
	PR51	-2099	5.4	199.07	153.99	357.0	18.98	0.85	M
	PR52	-2134	3.0	200.50	155.30	252.1	11.86	0.53	M
	PR53	-2140	4.0	200.67	155.46	457.2	28.51	1.27	L
	PR54	-2144	4.0	200.94	155.61	428.8	14.21	0.63	M

Dates are years of peak volcanic sulfate concentrations in core. Negative event dates represent years B.C.

[a] Here f denotes volcanic flux; f_T denotes volcanic flux of the 1815 A.D. Tambora eruption.

[b] L denotes large, M denotes moderate, and S denotes small.

[c] These volcanic events are used as time stratigraphic markers for dating.

Therefore the actual eruption years probably predate the event dates in Table 2 by 1 or 2 years. The duration data (Table 2) reveal that volcanic events in this core last significantly longer than the typical duration of 1-3 years observed in other Antarctic ice cores [*Cole-Dai et al.*, 1997; *Delmas et al.*, 1992; *Langway et al.*, 1995]. As discussed earlier, drifting and redistribution of surface snow at Plateau Remote tend to mix snow layers deposited within the most recent 4-5 years, due to the development and smoothing of small surface irregularities. The combined effect of the long atmospheric residence time of volcanic aerosols and postdeposition surface modification is that the signal from a single volcanic eruption could potentially last as long as 7 or 8 years at Plateau Remote. Events in Table 2 with an estimated duration of longer than 8 years, such as events PR15 (9.0 years) and PR39 (9.8 years), are suspected to contain multiple eruptions, which could be further explored with more detailed sampling.

4.3. Volcanic Flux

The volcanic sulfate mass flux of a sample is obtained by multiplying the net volcanic sulfate concentration by the sample length representing time in water equivalent. The volcanic flux of an event is the sum of volcanic sulfate mass flux of all samples contained in that event (Table 2). The sampling resolution (approximately one sample per year) does not allow the calculation of annual sulfate flux. The volcanic flux data in Table 2 represent the cumulative or total sulfate deposit from an event. A number of recent studies have used volcanic flux [*Zielinski,* 1995; *Zielinski et al.,* 1997] and volcanic acid/sulfate concentrations [*Robock and Free,* 1995] to estimate mass aerosol loadings and to infer the climatic forcing of volcanic eruptions, although caution is essential when such extrapolations and inferences are made from ice core data. *Cole-Dai et al.* [1997] used a relative scale (volcanic flux normalized against the 1815 Tambora eruption) to compare the magnitude of volcanic events found in different ice cores. An eruption is considered large if its volcanic flux is comparable to or exceeds that of Tambora. A similar approach is taken here. The PR events are categorized (Table 2, right column) as from either large (L, volcanic sulfate flux ≥ 20 kg km^{-2}), moderate (M, $9 \leq$ flux < 20 kg km^{-2}) or small (S, flux < 9 kg km^{-2}) eruptions. It is worth noting that volcanic flux in polar snow depends strongly on the latitude location of the erupting volcano [*Langway et al.,* 1988]. For example, a moderate eruption in the Antarctic or subantarctic region may result in a volcanic flux larger than that of a comparable eruption in the low latitudes, due to the loss of volcanic aerosols from the atmosphere during the longer transport time from the latter. Therefore the signal strength designations in Table 2 are applicable only to low-latitude eruptions. A large (L) event may result from a small or moderate eruption in the Antarctic and subantarctic regions. Fortunately, as only a few volcanoes are known to be active in the Antarctic and subantarctic regions [*LeMasurier and Thomson,* 1990], few such events are expected, and they may be differentiated by comparison with other Antarctic ice core records.

Another factor important to the Plateau Remote site is the potential partial loss or gain of an annual layer due to drifting and redistribution of surface snow at this low-accumulation site, as discussed earlier. At the drilling point, accumulation can be either reduced or enhanced for any given year. Therefore the volcanic deposit from a particular event may be underestimated or overestimated if the net accumulation for that year is affected by surface redistribution. Consequently, volcanic flux data listed in Table 2 may contain large errors and could potentially underestimate or overestimate the true mass flux of volcanic aerosols. The normalized volcanic fluxes for several known events (Table 2) appear quite different from those estimated for the same events in other Antarctic cores [*Cole-Dai et al.,* 1997; *Delmas et al.,* 1992]. For example, the flux ratio of the 1453 Kuwae eruption and the 1815 Tambora is 0.92 in a core from Siple Station, West Antarctica [*Cole-Dai et al.,* 1997], close to the ratio of 1.10 in a South Pole core [*Delmas et al.,* 1992], whereas the ratio is 5.96 in the PR record. The high ratio implies a much larger atmospheric mass loading by Kuwae, relative to Tambora, than the estimates from the other cores. This discrepancy highlights the potential large flux errors resulting from the partial loss or gain of snow within annual layers at Plateau Remote. The flux data in Table 2 should be used only for qualitative comparisons until the extent and significance of the loss or gain can be evaluated in future work.

5. Discussion

Owing to the various limitations discussed earlier, volcanic records from ice cores obtained at a single location must be scrutinized carefully, especially when small and moderate events are considered. Spurious acidity or sulfate signals may arise from atmospheric and glaciological effects which may be locally important, but unrelated to volcanic aerosols. To discount or eliminate local effects, it is necessary to compare ice core records from sites across Antarctica or Greenland. Intercore and bipolar comparisons can also contribute to the identification of large eruptions of hemispherical and global significance. However, caution is required when such comparisons are undertaken. Dates of detected eruptions may not match directly due to differences in dating accuracy and uncertainty. Furthermore, ice core records often are based on different measurement techniques, as mentioned previously, which may result in substantially different quantitative estimates of the volcanic deposits.

The following discussion of the PR record is divided into three time periods, depending on the availability and quality of existing ice core records for comparison. Several volcanic records from previous Antarctica ice cores are compared with the PR record to corroborate the volcanic events in the most recent 1000 years of the 4100-year record. Comparison is also made with Greenland records to identify low-latitude eruptions with global climatic implications. For the period of 2000-1000 years BP, for which no continuous Antarctic records are available, the PR record is compared with two detailed Greenland records of explosive volcanic history: the Greenland Ice Core Project (GRIP) record by *Clausen et al.* [1997] and the Greenland Ice Sheet Project 2 (GISP2) record by *Zielinski et al.* [1994]. Finally, some characteristics of the older part (4100-2000 years BP) of the PR record are examined against the lengthy GISP2 and GRIP records.

5.1. The Last 1000 Years (1000-1986 A.D.): Comparison with Existing Antarctic and Greenland Ice Core Volcanic Records

Delmas et al. [1992] presented a detailed, continuous volcanic record for the last 1000 years using sulfate concentration measurements in two 1982 South Pole ice cores. Two Antarctic sites (South Pole in East Antarctica and Byrd Station in West Antarctica, Figure 1) were included by *Langway et al.* [1995] in a bipolar ice core comparison of volcanic records for the last 1000 years, although their focus was on the most prominent volcanic events. *Moore et al.* [1991] used the technique of dielectric profiling (DEP) to measure total ionic concentrations in an ice core from Queen Maud Land in East Antarctica (site G15, Figure 1). Abrupt conductance increases in DEP were attributed to volcanic acidity, and a 770-year volcanic record was obtained from that core. The DEP technique detected far fewer volcanic events than the sulfate measurements in other Antarctic cores. The South Pole record by *Delmas et al.* [1992], henceforth referred as the SP record, and the record from the Plateau Remote core (the PR record) are similar in a number of important characteristics: (1) both are from central East Antarctica sites, (2) both are based on continuous and detailed sulfate measurements throughout, and (3) a similar approach is used to assess the nonvolcanic sulfate background. These similarities offer an excellent opportunity to compare in detail ice core volcanic records from two different Antarctic sites. All volcanic events in the last 1000 years of these two records are listed in Table 3. Also included in Table 3 are volcanic events found in ice cores from several West Antarctica sites: Byrd Station reported by *Langway et al.* [1995] and Siple Station (denoted as S events) and Dyer Plateau (denoted

Table 3. Volcanic Events During the Last 1000 Years Found in Ice Cores from Several Antarctic Locations.

	Plateau Remote, East Antarctica *this work*		South Pole, East Antarctica *Delmas et al.* [1992]		Siple and Dyer, West Antarctica *Cole-Dai et al.* [1997]		Byrd Station, West Antarctica *Langway et al.* [1995]
Volcanic Eruption	Event Number[a]	Year A.D.	Event Number[a]	Year A.D.	Event Number[a]	Year A.D.	Year A.D.
Agung and Deception	PR1	1968	SP1	1964	S1/D1	1965	
Tarawera	PR2	1884	SP2	1886	S3/D3	1886	1884
Krakatoa[b]	PR2	1884	SP3	1884	S4/D4	1884	
Coseguina	PR3	1836	SP5	1836	S5/D5	1836	1835
Tambora[b]	PR4	1816	SP7	1816	S7/D7	1816	1816
Unknown[b]	PR5	1809	SP8	1809	S8/D8	1810	1811
			SP9	1795			
	PR6	1694			S9/D9, S10/D10	1695,1693	
	PR7	1671			S11	1673	
	PR8	1653					
Parker and Deception	PR9	1639	SP10	1641	S12	1640	
			SP11	1621	S14	1619	
Huaynaputina[b]	PR10	1600	SP12	1601	S15	1599	
	PR11	1595	SP13	1596	S16	1593	
Kuwae[b]	PR12	1454	SP14	1450	S17	1454	1464
	PR13	1343	SP15	1340			1348
Unknown[b]	PR14	1285					1287
	PR15	1277	SP16	1279			1278
	PR16	1269	SP17	1269			1270
Unknown/1259[b]	PR17	1260	SP18	1259			1259
Unknown[b]	PR18	1234					1227
	PR19	1197	SP19	1191			
			SP20	1177			1168?
			SP21	1118			
			SP22	1047			

Dates indicated are eruptions years given in each core. No adjustments are made based on inter-core correlation.

PR, events found in the 1986 Plateau Remote core (this work); SP, events founds in the 1982 South Pole core [*Delmas et al.*, 1992]; S and D, events found in Siple Station and Dyer Plateau, West Antarctica cores [*Cole-Dai et al.*, 1997].

[a] Events in each core are numbered sequentially.

[b] These events are low-latitude eruptions that have been found in bipolar ice core records.

as D events) by *Cole-Dai et al.* [1997]. The Siple Station and Dyer Plateau (designated SD) records cover the most recent 500 years.

Most of the volcanic events found in the SP record are also detected in the PR-B core. These include all of the well-known events during the last 1000 years: two eruptions (Agung and Deception Island) during 1963-1967, Krakatoa (1883), Coseguina (1835), Tambora (1815) and an unknown eruption (1809), Huaynaputina (1600), Kuwae (1453), and Unknown (1259, El Chichon?). A doublet (1884 and 1886) was found in the SP record and the SD records, but only one event is seen in the PR record at the end of the nineteenth century. The two volcanic eruptions in the doublet, identified as Krakatoa (1883) and Tarawera (New Zealand, 1886), occurred within a 3-year interval. Owing to the low accumulation and mixing of surface snow layers at Plateau Remote, two volcanic signals within a few years of each other are likely combined to appear as a continuous event, as discussed earlier. The 1884 event in PR therefore probably represents both the Krakatoa and Tarawera eruptions. The signals of the 1815 Tambora eruption and the 1809 unknown eruption (PR4 and PR5) are detected separately in the PR-B core, as in other Antarctica cores. This suggests that the mixing of snow layers at Plateau Remote is probably limited to less than 5 years, at least during this time period. Event PR9 (1639) is close in age to a moderately large event (SP10) dated at 1640-1641 at South Pole. A contemporaneous event (S12 and D12) was found in the SD records [*Cole-Dai et al.*, 1997]. This event in ice cores, which was incorrectly attributed to an eruption of Awu (4°S, 125°E) in Indonesia, probably originates from a large (VEI=6) 1641 eruption of Mount Parker (6.1°N, 124.9°E) in the Philippines [*Briffa et al.*, 1998]. Recent evidence from an Antarctica Peninsula ice core suggests that the subantarctic volcano on Deception Island (64°13'S, 57°40'W) may have erupted explosively at about the same time [*Aristarain and Delmas,* 1998]. This Deception Island eruption, although small, may have distributed a significant amount of aerosols to Antarctica snow due to its subantarctic location. The volcanic event dated around 1640 in these Antarctic cores probably reflects the coincident Mount Parker and Deception Island eruptions. A third doublet at the end of the sixteenth century, well resolved in the PR record (PR10 and PR11), the SP record (SP12 and SP13), and the SD records (S15, D15 and S16, D16), corresponds to the well-known 1600 eruption of Huaynaputina (17°S, 71°W) in Peru [*Thompson et al.*, 1986] and an eruption 6 years prior to Huaynaputina [*Cole-Dai et al.*, 1997].

The largest volcanic event in PR is the 1453-1454 eruption of Kuwae, Vanuatu (17°S, 168°E) in the South Pacific [*Pang,* 1993]. Both the maximum sulfate concentration (1380 $\mu g\ kg^{-1}$) and the volcanic sulfate flux (133 $kg\ km^{-2}$) are unmatched in this 4100-year record (Figure 3). However, *Delmas et al.* [1992] found that the Kuwae volcanic flux (74.4 $kg\ km^{-2}$) at South Pole is much less than that of the 1259 Unknown eruption (135.7 $kg\ km^{-2}$). One possible explanation for the difference in relative signal strength between the PR and SP records is the possible loss of the 1259 Unknown volcanic mass at PR due to snow drift and redistribution. This difference highlights the potential impact of local glaciology on ice core volcanic records and also underscores the need to compare records from multiple sites before extrapolating ice core volcanic fluxes to atmosphere mass loadings by volcanic eruptions.

The thirteenth century appears exceptional in that it is marked by several conspicuous volcanic signals, the 1259 eruption being the most outstanding. The prominent 1259 signal found in all Antarctic ice cores has been tentatively attributed to El Chichon (17°N,

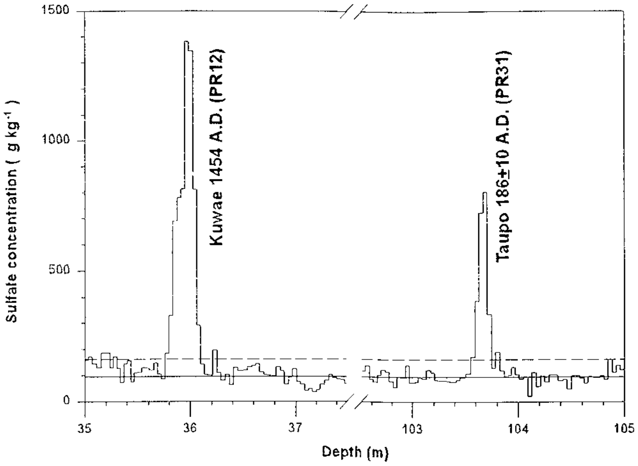

Figure 3. Two prominent volcanic events in the Plateau Remote core: Kuwae (1454 A.D.) at 35.9 m, and Taupo (186±10 A.D.) at 103.8 m.

93°W) in Mexico [*Palais et al.,* 1990] and used as a bipolar time stratigraphic horizon in ice cores [*Langway et al.,* 1988]. In the PR-B core, five events are detected during the thirteenth century (Figure 4), similar to the findings by *Langway et al.* [1995] in a 1989 Byrd Station, West Antarctica core. If the largest of the five events (PR17 at 47.28 m) is assigned to the 1259 Unknown eruption, the resulting chronology for the five events appears to be consistent with that reported by *Langway et al.* [1995] in the Byrd Station core and in another 1978 South Pole core. The oldest of the 5 events, PR18, is dated at 1234 A.D. in PR, compared to 1227 A.D. in the Byrd Station core and 1231 A.D. in the 1978 South Pole core. These dates are well within the range of dating uncertainties in these cores. In comparison, *Delmas et al.* [1992] found only three events during the same time period in the 1982 South Pole core. Those three events appear to correspond to PR15, PR16, and PR17 (Table 3). Missing in the SP record are PR14 (1285) and PR18 (1234), both relatively large events. The fact that signals probably corresponding to PR17 (Unknown, 1259) and PR18 (1234) were found in several Greenland cores (Crête by *Langway et al.* [1995], Dye 3 and GRIP by *Clausen et al.* [1997], and GISP2 by *Zielinski et al.* [1994]) indicates that they both are likely from large low-latitude eruptions. A moderate signal has been reported in the Crête record [*Langway et al.,* 1995] and in the GISP2 record [*Zielinski et al.,* 1994] around the date of PR14 (1285) and may represent either a large, low-latitude eruption or coincident eruptions in middle or high latitudes of both hemispheres. PR15 and PR16 are likely moderate eruptions in the middle or high southern latitudes.

The oldest event during the last 1000 years in the PR record is a small signal (PR19) dated around 1197 A.D. Two events, SP19 (1191) and SP20 (1174), were found in the SP record near the end of the twelfth century. Given that the dating accuracy is high at this depth due to the identification of the 1259 Unknown eruption about 60 years later in both cores, PR19 and SP19 are essentially contemporaneous and are probably from the same eruption. The similarity in the relative signal strength (volcanic flux relative to that of the 1453 Kuwae eruption) of these two signals also suggests that the same eruption is likely the common source of the volcanic sulfate. *Zielinski et al.* [1994] reported a moderate signal dated at 1194 in the central Greenland GISP2 core, but no corresponding event was found by *Clausen et al.* [1997] in either the GRIP (central Greenland) core or the Dye 3 (southern Greenland) core. This suggests that PR19 is probably not from a low-latitude eruption that could have affected both hemispheres.

Three events (PR6, PR7, PR8) in the PR record are not found in the SP record. Two closely timed events (S9 and D9, S10 and D10) were found in the SD records in the last decade of the seventeenth century [*Cole-Dai et al.,* 1997]. Given the small dating uncertainty at this depth and the mixing of surface snow layers at Plateau Remote, the moderate event PR6 (1694) may well be the combined signal of the two late seventeenth century events found in the SD records (Table 3). Event PR7 (1671) is small (~5 kg km^{-2}) and contemporaneous with a similarly small event in Siple and Dyer (S11 and D11, 1673), and they may be the result of the same moderate volcanic eruption [*Cole-Dai et al.,* 1997]. This small or moderate eruption is likely from a volcano in the middle to high southern latitudes, as a corresponding signal is not found in any Greenland cores during 1670-1675 [*Clausen et al.,* 1997; *Zielinski et al.,* 1994]. No volcanic events have been reported around 1653 A.D. in previous Antarctica ice cores. Therefore PR8 (1653), with a very small flux, is likely a spurious signal or a very minor volcanic event.

Several events (SP9, SP11, SP20, SP21, SP22) found in the SP record are not present in the PR record. In yet another South Pole core drilled in 1996, *Cole-Dai and Mosley-Thompson* [1999] did not find any volcanic signals around 1795 A.D. to support event SP9 found by *Delmas et al.* [1992]. Event SP9 is so small that it may be either a spurious signal or easily missed in other cores. In the SD records, an event (S14 and D14) was dated at 1619, possibly corresponding to SP11, and has been tentatively attributed to a subantarctic eruption by *Cole-Dai et al.* [1997]. It is probable that this very small event is either missing in PR or below the detection threshold. Events SP21 and SP22 are both very minor, and may not be detectable in PR for the same reason as SP11. Although no event in PR corresponds to SP20 (1177), this moderate event is supported by *Langway et al.* [1995], who found a moderate-to-large event in both the 1989 Byrd Station core (1168) and the 1978 South Pole core (1176). A moderate event was also found in various Greenland cores at around 1175-1180, but has been attributed to an Icelandic eruption [*Clausen et al.,* 1997; *Zielinski et al.,* 1994].

5.2. The Period of 1-1000 A.D. (2000-1000 Years BP): Comparison With Greenland Records

No Antarctic ice core volcanic records are available for comparison with the PR record during this period. Therefore the comparison below focuses on finding large, low-latitude eruptions in both the PR record and GRIP/GISP2 records and on the frequency of eruptions and the scale or relative magnitude of individual eruptions. Of the 16 events in the GRIP record [*Clausen et al.,* 1997]

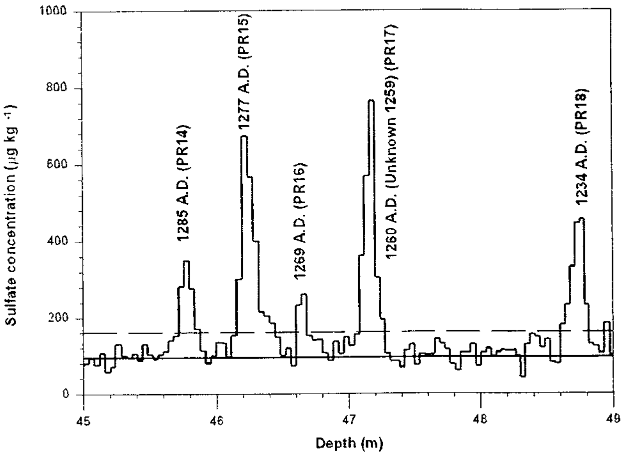

Figure 4. Five volcanic events detected in the Plateau Remote core during the thirteenth century. Event PR17 is assigned to the interhemispheric volcanic time stratigraphic marker of the 1259 A.D. Unknown eruption. All dates indicated are years of the events according to the timescale of this core.

during this 1000-year period, only seven have potential corresponding events in the GISP2 record (a total of 21 events) [*Zielinski et al.*, 1994], according to the reported eruption dates. The lack of better event-to-event correlation between these two cores drilled approximately 30 km apart in central Greenland illustrates the difficulty in comparing ice core volcanic records using different analytical techniques (Electric Conductivity Measurement (ECM) in GRIP and sulfate measurement in GISP2) and with low time resolution and relatively large dating uncertainty.

When the Greenland records are further compared with events in the PR record, only two events emerge as possibly contemporaneous (within 15 years of each other) in all three records. A large volcanic event (PR32) was detected at 108.82 m. This event (74 A.D.) appears temporally correlative with an event in GRIP (79 A.D.) and in GISP2 (77 A.D.). *Zielinski et al.* [1994] proposed that the 77 A.D. event in GISP2 may have resulted from the earliest historically documented eruption, the 79 A.D. Mount Vesuvius (40.8°N, 14.4°E) eruption that buried the Roman city Pompeii. However, this Northern Hemisphere eruption (VEI=5) appears only as a moderate signal in both Greenland records [*Clausen et al.*, 1997; *Zielinski et al.*, 1994] and is undetectable at Dye 3 [*Clausen et al.*, 1997], suggesting that the atmospheric mass loading from this eruption was insufficient to sustain the long transport from a middle northern latitude across the equator to the Southern Hemisphere and to Antarctica before being removed from the atmosphere. Therefore event PR32 probably represents a moderate-to-large eruption in the Southern Hemisphere, perhaps coincidental to the Mount Vesuvius eruption. The other event possibly common in all three records is PR23 at 630 A.D. in the PR record, close in age to an unknown eruption at 639 A.D. in the GISP2 record and a large signal at 645 A.D. in the GRIP record. These signals may result from either a large, low-latitude eruption around 640 A.D., or coincidental eruptions in both hemispheres. Further evidence from other ice cores is required to distinguish between these scenarios.

The largest PR volcanic event (PR31) during this 1000-year period is detected at 103.8 m in the core and lasts approximately 6 years in the second century A.D. (Figure 3). This event, as stated earlier, is attributed to the most explosive eruption in the Southern Hemisphere at that time, that is, the 186 A.D. Taupo eruption. *Zielinski et al.* [1994, 1996] found a large volcanic signal at 182 A.D. in the annually dated GISP2 core. Although Taupo is located in the Southern Hemisphere (38.8°S, 176.1°E), this signal in GISP2 was attributed to the Taupo eruption because of the explosive type (ultraplinian) of the eruption and the exceptional height (≥50 km) of its eruption column [*Wilson and Walker*, 1985]. The extraordinarily large magnitude (VEI=6+) of the eruption and the mid-southern latitude location of Taupo suggest that an unusually large signal would be detected in Antarctic ice cores, particularly if the aerosols from this eruption were found in Greenland. However, the total volcanic sulfate flux for Taupo (69.4 kg km^{-2}) in the PR-B core is only about 50% higher than that of the 1259 Unknown eruption (46.3 kg km^{-2}) and is only half the Kuwae flux (133.4 kg km^{-2}). Such a moderate flux may indicate that the 186 A.D. Taupo eruption was not particularly sulfur-rich and probably had a very limited climatic impact, as compared to the low-latitude 1259 Unknown and Kuwae eruptions. It is important to note that owing to the large errors in volcanic flux data derived from this core, conclusions such as this must remain tentative until they can be confirmed by other ice core records.

The frequency of volcanic eruptions during this millennium (14 events in 1000 years) is comparable with the average of 1.3 eruptions per century for the entire 4100 years covered by the PR record. In comparison, the eruption frequency in the most recent millennium (1000-1986 A.D.) is relatively high, averaging almost two detectable eruptions per century.

The half millennium from 700 to 1200 A.D. appears to be relatively quiet. Only two eruptions (PR20 and PR21) are detected at 70.54 and 76.24 m, in the middle of the ninth and the eighth centuries, respectively (Table 2). Both eruptions are relatively large (L), with respective peak sulfate concentrations of 397 and 428 μg kg^{-1}. A small event at 970 A.D. in the SP record does not appear to match PR20 or PR21 either by date or by relative volcanic flux. No events are found in Greenland records that may correspond to either PR20 or PR21, suggesting that they result from moderate or large eruptions in the middle to high southern latitudes. From 300 to 700 A.D., a series of small and moderately large events (PR22-PR30) marks a period of increased volcanic activity in the Southern Hemisphere.

5.3. The Period of 4100-2000 Years BP (2100-1 B.C.)

A detailed bipolar comparison of the older part (4100-2000 years BP) of the PR record with the lengthy GISP2 and GRIP records would be difficult and therefore is not attempted here for the following reasons. First, Greenland ice cores contain many more volcanic events than Antarctic cores, because the Greenland ice sheet receives abundant volcanic deposit from frequent eruptions in nearby Iceland and in other Northern Hemisphere volcanic zones (e.g., Kamchatka, Japan, Alaska). Numerous events in the GISP2 and GRIP records were suspected, but could not be confirmed (owing to the declining number and accuracy with age of eruptions in historical records), to be from these Northern Hemisphere eruptions [*Clausen et al.*, 1997; *Zielinski et al.*, 1994]. A search for large, low-latitude eruptions with bipolar volcanic deposit would only be speculative, because of the difficulty in separating the large and climatically important low-latitude eruptions from contemporaneous eruptions in both hemispheres, although simultaneous eruptions in both hemispheres may also impact the global climate. Second, as discussed earlier, owing to the lack of time stratigraphic horizons, dating errors for events in the older part of PR may be too large to permit a direct comparison and correlation with specific events in the Greenland records. Therefore the discussion of this period (4100-2000 years BP) focuses on the frequency and the relative magnitudes of the eruptions.

A total of 21 volcanic events (PR34-PR54) are detected during this 2100-year period. No significant difference is seen in the frequency of eruptions between the first half (11 events) and the second half (10 events) of this period. The average of 1.0 eruption per 100 years during this period is well below the frequency of 1.6 eruptions per century for the most recent two millennia (1-1986 A.D.). Of the 21 events, only three or four are considered large eruptions with high volcanic sulfate flux (≥20 kg km^{-2}). No exceptionally large eruptions, comparable to Taupo, Kuwae, or 1259 Unknown, are found during the period. In comparison, 33 events (PR1-PR33) are observed in the most recent 2000 years, and 10 of these events produced a volcanic flux greater than 20 kg km^{-2}.

The frequency of 21 events during this 2100-year period in the PR record appears to be well below the number (69) of volcanic events reported in the GISP2 record in the same period. This is not unexpected owing to the numerous volcanoes in nearby Iceland and other middle northern latitude locations. Large eruptions by these volcanoes, which may result in significant sulfate deposits in the Greenland ice sheet, would not be recorded in Antarctic ice cores. On the other hand, a slightly different approach was used by *Zielinski et al.* [1994] to detect volcanic signals in the GISP2 core, that is, the nonvolcanic background was defined using a mean residual concentration. A somewhat lower threshold (1σ above the mean residual sulfate concentration) was used [*Zielinski et al.*, 1994] to detect volcanic events in the GISP2 core. At a threshold of 2σ above the mean residual concentration, only 20 events remain in the GISP2 record. Of these 20 events, seven are in the interval of 500-1 B.C., compared to only two in PR. There are nine moderate or large (2σ above the background) events seen in GISP2 during 2000-1500 B.C., while no events are detected in PR during the same period.

Similarly, during 300-1 B.C., four moderate-to-large events are seen in GISP2, while no eruptions are detected in PR. In general, the agreement between the PR record and the GISP2 record is poor for this time period. This likely reflects inherent differences between the records (e.g., significant dating errors, different volcanic signal detection thresholds, or different hemispheric eruptions recorded).

6. Conclusions

A total of 54 volcanic events are found in a central East Antarctica ice core covering the last 4100 years. Of these events, 14 may be considered large eruptions with volcanic fluxes comparable to or larger than that of the 1815 Tambora eruption (VEI=7). However, owing to extremely low snow accumulation rates at the ice core site and considerable postdeposition changes, flux estimates from this core are highly variable when compared with estimates from previous Antarctic ice cores. Therefore the flux data reported in this study should be considered tentative and used with caution.

This 4100-year record demonstrates that there were more frequent volcanic eruptions (33) and more large eruptions (10 large) in the most recent 2000 years than in the previous 2100 years (21 eruptions, three or four large). The climatic implications of this difference may be significant and need to be explored in future work, although the validity of the difference requires verification from additional ice core records.

Comparison with Greenland ice core volcanic records indicates that during the most recent 1000 years, nine large eruptions in the low latitudes of either hemisphere may have contributed significant amounts of volcanic aerosols to the atmosphere of both hemispheres, potentially affecting global climate. In contrast, only one or possibly two such eruptions are found in the first millennium A.D. Unfortunately, deficiencies in all the available ice core records preclude similar examinations of the older part (4100-2000 years BP) of the record. Better dated Antarctic ice cores, ideally from sites with higher snow accumulation rates, are needed to corroborate the older events in the PR records and to compare with the extended Greenland records.

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