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A 1500 year record of accumulation at Amundsenisen western Dronning Maud Land, Antarctica, derived from electrical and radioactive measurements on a 120 m ice core

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Abstract. During the Nordic EPICA pre-site survey in Dronning Maud Land in 1997/1998 a 120 m long ice core was retrieved (76°00'S 08°03'W, 2400 m above sea level). The whole core has been measured using the electric conductivity measurement (ECM) and dielectric profiling (DEP) techniques, and the core chronology has been established by detecting major volcanic eruptions. In a nearby shallow core radioactive traces from nuclear tests conducted during the 1950s and 1960s have been identified. Altogether, 13 ECM and DEP peaks in the long core are identified as originating from specific volcanic eruptions. In addition two peaks of increased total β activity are identified in the short core. Accumulation is calculated as averages over the time periods between these dated events. Accumulation rate is 62 millimetres (w. eq./yr) for the last 181 years (1816 A.D. to present) and 61 mm w. eq./yr for the last 1457 years (540 A.D. to present). Our record shows an 8% decrease in accumulation between 1452 and 1641 A.D. (i.e. part of the Little Ice Age), compared to the long-term mean.

1. Introduction

The European Project for Ice Coring in Antarctica (EPICA) aims at obtaining one of the longest climate records from Antarctica which will aid studies of climate forcing, climate variability, long-term climate/ice sheet interactions, and the role of Antarctica in sea level change. The EPICA program is divided into two main areas, Dome C and Dronning Maud Land (DML). At Dome C, deep drilling has started; in DML the activities have been concentrated on presite survey studies.

This work presents the dating and calculated accumulation record of a 120 m deep ice core retrieved as a part of the EPICA DML presite survey program during 1997/1998 season at 76°00'S 08°03'W, Amundsenisen, western Dronning Maud Land (Figure 1) [*Bintanja et al.*, 1998; *Holmlund et al.*, 1999; *Tveraa and Winther*, 1999]. Volcanic signals detected by dielectrical profiling (DEP), electrical conductivity measurements (ECM), and radioactive horizons determined by total β activity are used for dating of the core. We have established a local accumulation record extending back 1457 years based on comparing data derived separately from DEP and ECM as well as data derived from merging results from both methods. Additionally, annual accumulation rates and variability for the last nine years (1989-1997) based on results of chemical analysis [*Stenberg et al.*, 1999] are presented.

2. Electrical Ice Core Measurements

Establishing a timescale for a newly retrieved core is fundamental and electrical property measurements have proven to be a powerful tool to use in this process. The electrical property measurements respond to the chemical compounds within the core and are based on two different continuous measurements; one applying a direct current to the ice core (ECM) and the other an alternating current (DEP). The aerosol fallout from major volcanic eruptions results in an increase of acidity (H^+), mainly sulfuric acid (H_2SO_4) and to a lesser degree, hydrochloric and hydrofluoric acid (HCl and HF) [*Clausen et al.*, 1997). The ECM method [*Hammer,* 1980] measures the direct current conductivity of the firn/ ice and essentially reflects the acidity of the firn/ice. In contrast, conductivity measurements on melted samples reflect the conductivity of all ions present in the water [*Hammer,* 1983]. The DEP method reacts to both the acidity content and the total salt content. It measures the AC capacitance and conductance, and from those parameters, it is possible to derive the conductivity, permittivity, and density of the core [*Moore and Paren*, 1987; *Moore et al.*, 1989, 1992; *Moore*, 1993; *Wilhelms et al.*, 1998].

Volcanic chronologies are established by measuring the chemical composition of ice, through direct chemical meas-

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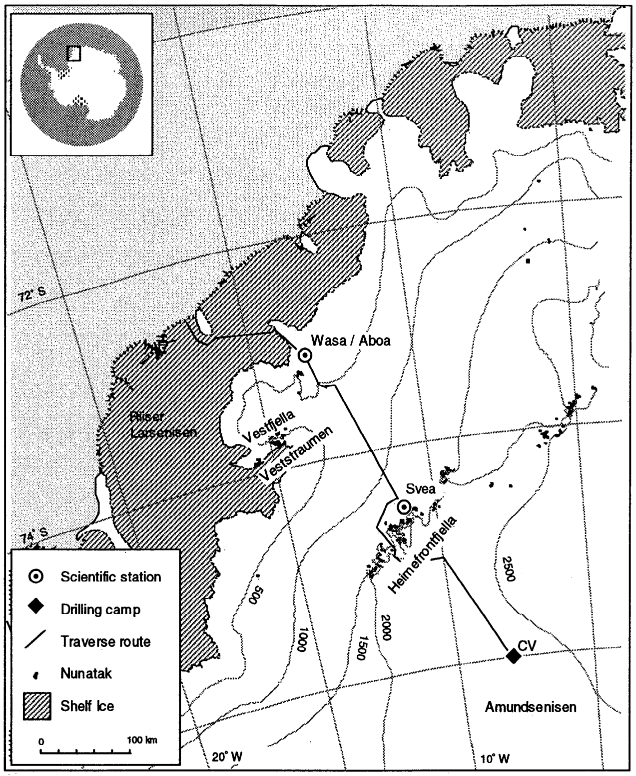

Figure 1. Map showing the study area, including the ground traverse route. The drilling site (CV) is located at 76° S 08° W, 2400 m above sea level on Amundsenisen.

urements and by measuring the conductivity of ice by electrical methods, and using peaks in the resultant data series as indicators of volcanic horizons. If they coincide with historically known volcanic eruptions, they are used as time markers and can consequently provide information on accumulation rates. By major element analyses of fine ash [*Palais et al.*, 1990] it is possible to unequivocally identify the origin of some volcanic events. Such volcanic particles can be used to date and cross-check events between different cores.

Volcanic chronologies for dating ice cores have been used in several previous studies from Antarctica, for example, ice cores from South Pole [*Delmas et al.*, 1992], and Byrd Station [*Hammer et al.*, 1994; *Langway et al.*, 1994]. The Byrd cores are probably the most accurately dated cores available from Antarctica covering the Holocene. This is due both to the large number of chemical analyses, including ECM, performed on the cores and the relatively high accumulation rate, about 100 millimetres (w. eq./yr), at this site. Several medium-long 100-150 m ice cores from DML are being analyzed within the EPICA programme. However, currently, the core retrieved closest to the site, discussed in this paper for which data are available, is the one presented by *Moore et al.* [1991], called G15, in eastern Dronning Maud Land (71°12' S, 45°59' E), who derived a chronology from a DEP record extending back to the 13th century. In that paper, acid fluxes for several eruptions as a fraction of the Tambora eruption 1815 were presented as well. At Dome F the highest dome in DML, preliminary ECM results [*Watanabe et al.*, 1997] identify peaks of volcanic origin which have all been observed and dated in the 1989 and 1968 Byrd ice cores [*Langway et al.*, 1994; *Hammer et al.*, 1994]. Two cores from Siple Dome in West Antarctica and Dyer Plateau on the Antarctic Peninsula [*Cole-Dai et al.*, 1997] are well dated but not fully representative for our site as the climatic conditions are significantly different from Dronning Maud Land [*King and Turner*, 1997].

At Law Dome (66°46' S 112°48' E), a 1196 m long ice core has been retrieved, and the data reveal a yearly signal in the ice core down to 399 m corresponding to 1304 A.D.. This is due to the high accumulation rate of 600 mm w. eq./yr and the absence of strong winds [*Morgan et al.*, 1997]. The core has been dated mainly by counting annual layers in the δ^{18}O record, but where the record is ambiguous, cross-checking has been done with the ECM record.

3. Study Area

The ice core location (76°00'S 08°03'W) is located on the polar plateau 2400 m above sea level, 550 km from the coast and 180 km south of the closest nunatak area, Heimefrontfjella (Figure 1). GPS measurements conducted during the expedition suggest ice-flow velocities of the order of 1 m/yr in this area (based on measurements conducted over 8 days and not statistically proven). Recent German airborne radar data show ice depths as low as 2240 m with a highly variable bedrock topography in the whole region [*Steinhage et al.*, 1999].

Understanding of the local climate parameters is rudimentary. Most of the low-pressure systems reaching this area originate in the northern part of the Weddell Sea [*King and Turner*, 1997]. Observed sastrugi orientations suggest that the predominant katabatic wind systems in the area of the core site are from east to south east. The closest available automatic weather station that has provided data over several years is located at the Finnish Aboa Station, 450 m above sea level, about 120 km from the coast and 400 km from the study area (Figure 1). In order to get a better understanding of the local climatic parameters, automatic weather stations have been erected during this and previous expeditions. Presently, nine automatic weather stations are operational in Dronning Maud Land [*Bintanja et al.*, 1998].

Glaciological work in this part of western Dronning Maud Land has been conducted during several Swedish expeditions and includes shallow cores documenting accumulation rates and climate interpretation during the last century [*Isaksson*, 1994; *Isaksson and Karlén*, 1994a,b; *Isaksson et al.*, 1996; *Stenberg et al.*, 1998] and snow radar work [*Richardson et al.*, 1997]. The immediate area around the core location presented in this paper was visited during SWEDARP 1991/1992 and during the Swedish International Trans-Antarctic Scientific Expedition (ITASE) 1993/1994. Measurements in 2 m snow pits along a west-east transect along 75° 30' S suggest an annual accumulation of 50-70 mm w. eq./yr with the lower value farthest east, following the altitude [*Stenberg et al.*, 1998]. At 75° 00' S 002° 00' E, 2900 m above sea level the mean annual accumulation is 77 mm/yr over the time period1865-1991, with large interannual variability [*Isaksson et al.*, 1996]. Several of the above mentioned studies use ECM for identification of volcanic eruptions, but only in one case was a parallel profile of the ion chemistry presented [*Isaksson*, 1994].

Researchers from Alfred Wegener Institut (AWI) für Polar und Meeresforschung, Germany, and British Antarctic Survey (BAS), England, have conducted extensive studies over large areas in DML with special focus on the areas around 75° S 00° E and 77° S 10° W, respectively. Their program consists of ice core drilling, snow pit studies, and airborne as well as surface ground penetrating radar [*Oerter et al.,* 1999; R. Mulvaney personal communication, 1999]. Similar studies using shallow cores have also been performed on the polar plateau farther east within the EPICA program [*Isaksson et al.,*1999; *Van den Broeke et al.,* 1999; *Winther et al.,*1997] and on Jutulstraumen ice stream, as part of the Norwegian Antarctic Research Expedition 1996/1997 [*Melvold et al.,* 1998].

4. Methods

4.1. Field and Laboratory

The core was retrieved with an electromechanical drill of a similar design to the electromechanical drills used previously in Antarctica and Greenland. The drill produces cores with 105 mm diameter and 90-120 cm length. The material used for the determination of total β activity was taken from a 16 m long core retrieved 15 m away from the deeper hole, using a light-weight core auger.

The electrical measurements were conducted in the ice laboratory at the Department of Physical Geography, Stockholm University. The temperature during the measurements was -20°C ±2°. Before the measurements started, the length of each core piece was remeasured to ensure a correct depth scale. Prior to the DEP measurements the core was unpacked and put together in 1-1.5 m increments by fitting breaks together (typically 0-6 breaks, with more breaks at greater depth). Next, all breaks were logged in order to simplify the interpretation afterward. Contamination due to core handling is most likely to happen at the end of each core section.

The DEP used in this study is a version developed at AWI and has a modified version of the electrodes used previously [*Wilhelms et al.,* 1998]. The frequency used for the DEP measurements was 250 kHz. When preparing for the DEP measurements, all core increments were wrapped in a thin plastic sleeve to enable the core to hang freely between the electrodes and to act as an insulator between the core and the electrodes. Part of the core was then sampled for $\delta^{18}O$, and on the remaining surface, ECM measurements were conducted. The ECM instrument used (Icefield Instruments Inc. Canada) consists of two electrodes with 20 mm spacing which are dragged along the core with an applied voltage of 947 V.

4.2. Dating Procedure

We date the core primarily by correlating observed peaks in the ECM and DEP signals with prominent volcanic eruptions. In addition, the upper part of the deep core is independently dated by assigning the total β activity peaks in the auxiliary core to the well-established 1955 and 1965 thermonuclear bomb horizons [*Delmas and Pourchet,* 1977; *Pinglot and Pourchet,* 1979], and assuming a perfectly continuous flat stratigraphy between the two cores.

Since we are primarily interested in isolating peak values from the background variations of the DEP and ECM signals, we must first remove their low-frequency components caused by the variations in density and long-term biogenicacidity. The relation between ice capacitance and density is relatively well understood, so the DEP signal is first corrected for density using the Looyenga mixing model [*Glen and Paren,* 1975]. There is no simple relation between ECM signal strength and density, and it is therefore treated as an unknown low frequency component.

We first detrend and then filter the raw ECM data and the density-corrected DEP data, using a high-pass filter with a cut-off for wavelengths >250 mm core length (Figure 2a.). The resulting residuals are then smoothed with a symmetric first-order Savitsky-Golay filter [*Press et al.,* 1992], which has the effect of eliminating peaks due to random noise or short-lived chemistry events while preserving the broad peaks expected from volcanic events (Figure 2b). The Savitsky-Golay filter width is three samples, or 15 mm core length, for the DEP signal and 51 points, or 51 mm core length, for the ECM signal. The difference in filter width is due not only to the sampling interval but also to the differing signal to noise ratio of the two data sets. The entire filtering operation is done in the sample domain (although the results are displayed in the figures in w. eq. depth). Data gaps are ignored; that is, the data on either side of a gap are treated as if they are adjacent. This has no effect on the low-pass-filtering operation and little effect on the Savitsky-Golay filtering, although in certain instances it does decrease or slightly smear an apparent peak. This was deemed less troubling, though, than smoothing through fictitious data inserted in the gap, and a few suspicious cases were eliminated from the data set. Finally, we normalize the resultant signals by subtracting their means and dividing by their standard deviations (Figure 3).

In order for a peak to qualify as being due to a volcanic event, we use criteria employed by other authors [*Delmas et al.,* 1992; *Mayewski et al.,* 1993; *Zielinski et al.,* 1994; *Cole-Dai et al.,* 1997], namely, that a peak has to have an amplitude higher than a certain threshold value. In this case we use a threshold value of $+2\sigma$ of the filtered data. Using these criteria, three data sets were created: 1) ECM peaks alone, 2) DEP peaks alone and, 3) peaks in both the ECM and the DEP records.

With the peaks identified and numbered, we now turn to the volcanic record. We use the index system of *Simkin et al.* [1994], based on the volcanic explosivity index (VEI) proposed by *Newhall and Self* [1982], the dust veil index (DVI) proposed by *Lamb* [1970], and well-dated events from other Antarctic cores [e.g., *Delmas et al.,* 1992; *Langway et al.,* 1994; *Cole-Dai et al.,* 1997]. The VEI is based on the magnitude, intensity, dispersive power, and the destructiveness of the eruption. It is divided into eight different levels, with each interval representing an increase around a factor of 10. The DVI, on the other hand, is related to the loss of incoming radiation to the Earth caused by each eruption, as observed from midlatitudes.

To correlate the ECM and DEP peaks with the volcanic index, we make a plot with time on the x axis and w. eq. depth on the y axis. Lines are drawn upward from the dates of candidate volcanic eruptions, and across from the peaks in the ECM, DEP or both records on the y axis. Every intersection represents a potential match (Figure 4), but a number of criteria can be used to guide us through this checkerboard of possible correlations.

In the cross-plot we draw a line from the origin to the point that connects the distinctive double-peaked electric signature found in our core, and over much of Antarctica [*Cole-Dai et al.,* 1997], to the well-known eruption of Tambora in 1815 A.D. (see below for further discussion). This line is equivalent to a long-term average of 62 mm w. eq./yr. Then, we draw two lines representing a possible ± 15% accumulation rate variability from 62 mm w. eq./yr between two consecutive eruptions. These outer lines give us the envelope in which

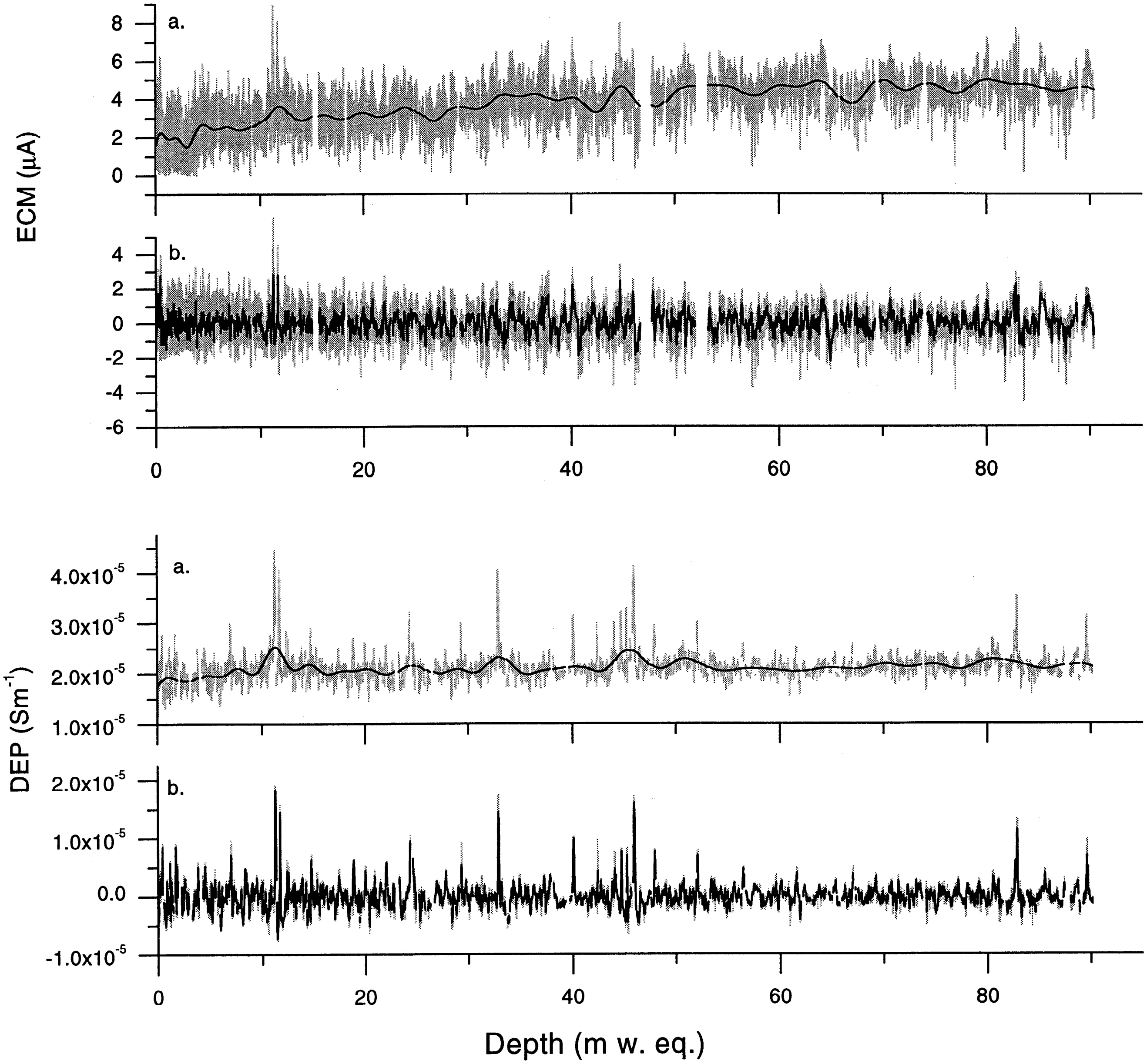

Figure 2. (a) The original data (light shade) and its low frequency component (black). (b). The unfiltered residuals (light shade) and the Savitskey-Golay filtered residual (black) (see text for discussion).

we consider possible volcanoes. The interpretation is further supported by results of the total β activity analysis, which yield a shorter-term accumulation average of 68 mm w. eq./yr for the time period 1965-1997. When an intersection has been dated, the envelope is moved to start from that intersection. If several intersections were listed within the envelope area then a criterion system adapted from *Delmas et al.* [1985] was used. First, eruptions located between 20° N and 20° S and with VEI ≥ 4 were used. For smaller eruptions with VEI < 4, north of 20° N, which aerosols is transported in the troposphere, the equator act as a barrier and prevents the aerosols to reach Antarctica. Thus these eruptions are not considered. Second eruptions with VEI ≥ 4 south of 20° S were considered. Eruptions south of 20° S with VEI <4 are believed not to reach Antarctica due to the circumpolar circulation. Third, Antarctic and sub Antarctic eruptions have only a local impact, even though the fact that the low altitude of the troposphere over Antarctica can permit small eruptions to be spread over the whole continent. If several eruptions ended up as possible, then we used dates suggested from other Antarctic chronologies.

5. Volcanic Chronology

In DEP and ECM records volcanic peaks are recognized by their generally short duration and their fairly symmetrical shape [*Moore et al.*, 1991]. Along the 120 m core, 29 peaks of increased electrical conductivity are listed from the combined data sets. For seven of these we have not been able to tie them to an indexed eruption and they are therefore considered unidentified. The fact that four of the unidentified peaks are at depths, which are more than 800 years old may, reflect

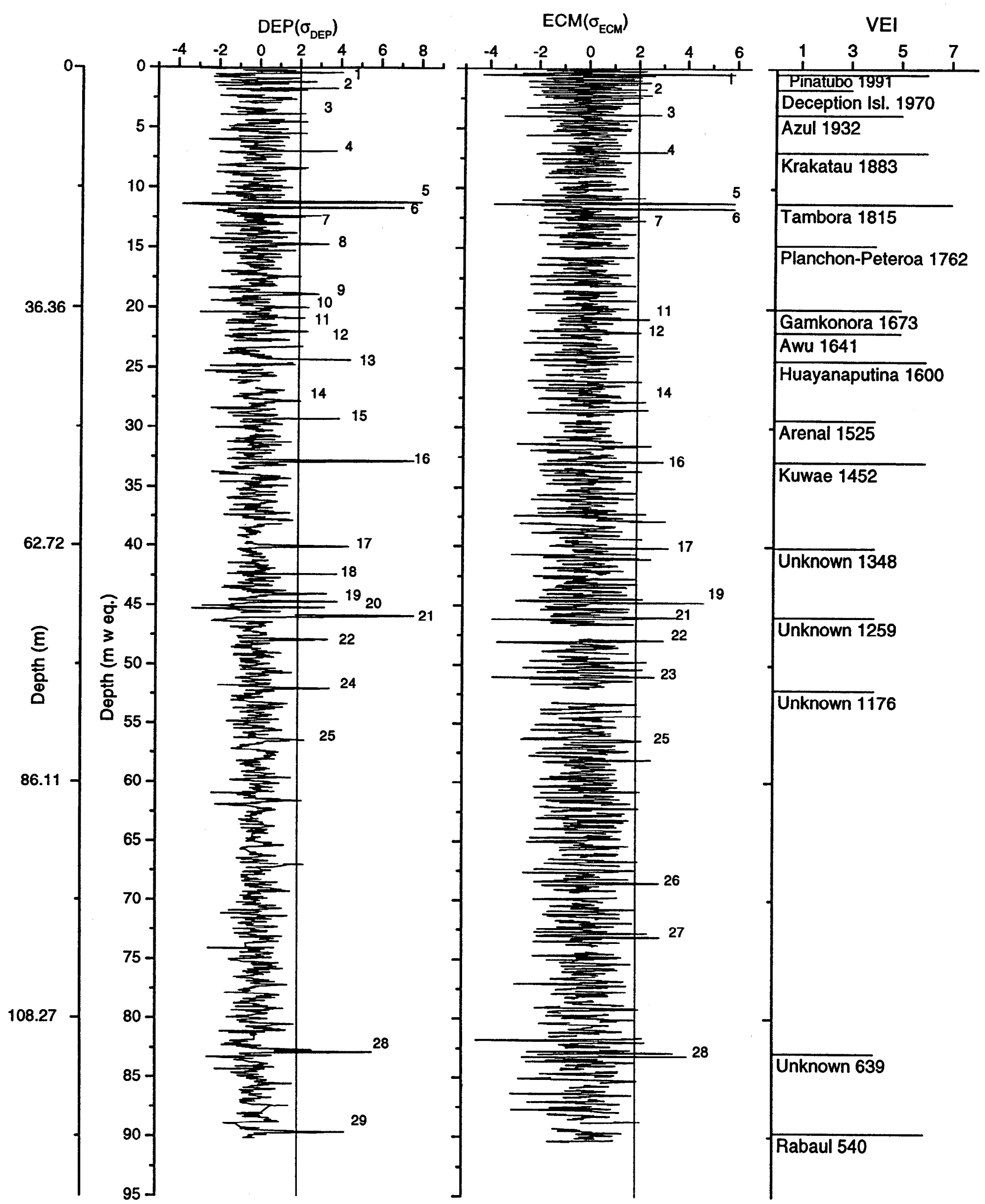

Figure 3. Dielectrical profiling (DEP) and electric conductivity measurement (ECM) conductivity profile of the CV core, and the major volcanic eruptions used for dating. Volcanic explosivity index (VEI) number according to *Simkin et al.* [1994].

the incompleteness of the volcanic chronology available. The fact that one of the unidentified peaks is only seen in the DEP record may reflect that it has a different chemistry than the other volcanic aerosols, but this cannot be determined without chemical data available. However, 18 peaks have been identified in both electrical systems (Figure 3), and 13 of these peaks have been used to calculate accumulation rates. The most prominent identified events will be discussed below in chronological order and numbered in accordance to Table 1.

5.1. Peak 1 (1991)

This peak is dated by counting layers from chemical analysis adapted from *Stenberg et al.* [1999], in the neighbouring pit (see section *Pit studies*). The chemical analysis reveals an in crease in sulfate and methanesulphonate (MSA) formed in two peaks corresponding to the years 1991/1992 and 1992/1993. The MSA indicates a marine biogenic contribution due to the extended 1991-1993 El Niño, while the sulfate also indicate a possible volcanic origin. Thus the peak corresponds to both marine and volcanic input [*Dibb and Whitlow,* 1996]. The volcanic input corresponds to the two eruptions of Mount Pinatubo (Philippines) and Mount Hudson (Chile) in July and August 1991 A.D., respectively. Both eruptions increased the stratospheric aerosol over Antarctica during 1991-1993. The aerosol cloud from Mount Hudson and Pinatubo were observed by SAGE II [*Saxena et al.,* 1985] and a lidar at the South Pole [*Cacciani et al.,*1993]. The aerosol cloud from Mount Hudson was centred over the South Pole already in September 1991 and had disappeared by the end of January 1992. The Pinatubo cloud arrived later

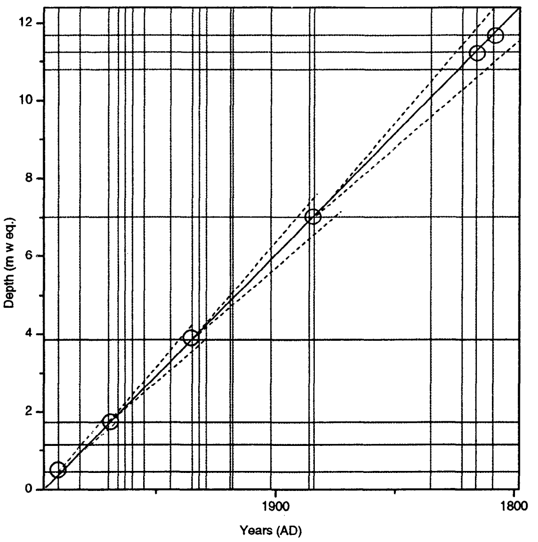

Figure 4. Plot used for the identification of peaks with a volcanic origin. The dotted lines represents the envelope that was used (see text for discussion).

in 1991. It is probable that deposition of volcanic aerosol may have occurred already during late 1991 and first half of 1992 also at the Camp Victoria (CV) drill site. (Figures 5a and 7).

5.2. Peak 3 (1932 or 1935)

There are two possible candidates for this peak (1) Cerro Azul in Central Chile (April 1932), earlier identified by both *Delmas et al.* [1985] and *Isaksson et al.* [1996] with a VEI of 5 and (2) Bristol Island (December 1935), the second southern-most island in the South Sandwich Islands, with a VEI of 2. This event does not give a strong signal in any of our electrical records. In the record from *Delmas et al.* [1985] the peaks are not sufficiently marked to be absolute certain about this eruption. Even though the subantarctic eruption has a low VEI number, the relative distance is much shorter compared to Cerro Azul, and the aerosol impact of the eruption would leave a signal already during the same year. This is in contrast to aerosols from eruptions farther away, which enter the polar stratosphere in spring after the breakdown of the polar vortex [*Deshler et al.*, 1992]. Further, the duration of the peak in our electrical records is short, which suggests a more local input. With the data on hand it is not possible to distinguish which one of the suggested eruptions it is. We have chosen 1933 as the date for peak 3. (Figure 5b).

5.3. Peak 4 (1883)

Peak 4 at 7 m w. eq. depth covers the years around the eruption of Krakatau 1883 (VEI 6). The peak is not distinct. However, other possible eruptions in the same time period (Cotopaxi 1877, Ecuador, VEI 4; Tarawera, 1886, New Zealand, VEI 5; Tungurahua, 1886, Ecuador, VEI 4) cannot be seen in the record. We therefore assigned peak 4 as Krakatau simply because it is the strongest eruption in this time period and has been identified in other ice core chronologies [e.g. *Langway et al.*, 1988; *Moore*, 1991; *Wilkinson*, 1994]. One reason for the relative low signal can be the low sulfur content reported from studies on magma from the Krakatau eruption [*Rampino and Self*, 1982] (Figure 5c).

Table 1. Volcanic Events Detected Along the Core

Peak No.	Depth (m w. eq.)	Name	Location	Eruption M/Y AD	VEI	DVI	Error Years	Method
1	0.45	Mt.Pinatubo,	Philippines,	June 1991	6	n.a.	± 0	ECM DEP
		Mt. Hudson	central Chile	Aug. 1991	5	n.a.	± 0	
2	1.72	Deception Island	Antarct. Penin.	Aug. 1970	3	n.a.	± 0	ECM, DEP
3	3.84	Cerro Azul	central Chile	April 1932	5	n.a.	± 0	ECM, DEP
4	7.01	Krakatau	Indonesia	Aug. 1883	6	1000	± 0	ECM,DEP
5	10.80	unidentified						ECM
6	11.24	Tambora	lesser Sunda Is.	April 1815	7	3000		ECM, DEP
7	11.68	unknown		n.a. 1809	n.a.	n.a.	± 2	ECM, DEP
8	14.70	Planchon-Peteroa ?	central Chile	Dec. 1762	4	n.a.	± 0	DEP
9	18.85	unidentified						DEP
10	20.02	Gamkonora ?	Indonesia	May 1673	5?	1000	± 0	DEP
11	20.89	Long Island	New Guinea		6	n.a.	± 20	ECM, DEP
12	22.00	Awu,	Indonesia,	Jan. 1641	5?	1000	± 0	ECM, DEP
		Deception Island	Antarct. Penin.	n.a. 1641	n.a.	n.a.	± 3	
13	24.34	Huyanaputina	Peru	Jan. 1600	6?	n.a.	± 0	DEP
14	27.78	unidentified						ECM, DEP
15	29.29	Arenal	Costa Rica	n.a. 1525	4	n.a.	± 20	DEP
16	32.85	Kuwae	SW Pacific	n.a. 1452	6	n.a.	± 10	ECM, DEP
17	40.07	unknown		n.a. 1348	n.a.	n.a.	± 9	ECM, DEP
18	44.04	unknown		n.a. 1287	n.a.	n.a.	± 2	ECM, DEP
19	44.69	unknown		n.a. 1278	n.a.	n.a.	± 2	ECM, DEP
20	45.20	unknown		n.a. 1269	n.a.	n.a.	± 2	ECM
21	45.91	El Chichon?	Mexico	n.a. 1259	n.a.	n.a.	± 2	ECM, DEP
22	47.91	unknown		n.a. 1227	n.a.	n.a.		ECM, DEP
23	50.98	unidentified						ECM
24	52.06	unknown		n.a. 1176	n.a.	n.a.	± 16	DEP
25	56.40	unidentified						ECM, DEP
26	68.50	unidentified						ECM
27	73.09	unidentified						ECM
28	82.83	unknown		n.a. 639	n.a.	n.a.	± 25	ECM, DEP
29	89.63	Rabaul	SW Pacific	n.a. 540	6	n.a.	± 100	DEP

The year is that used for final dating. Error ± year as estimated from literature [*Simkin et al.*, 1994]. n.a., not available.

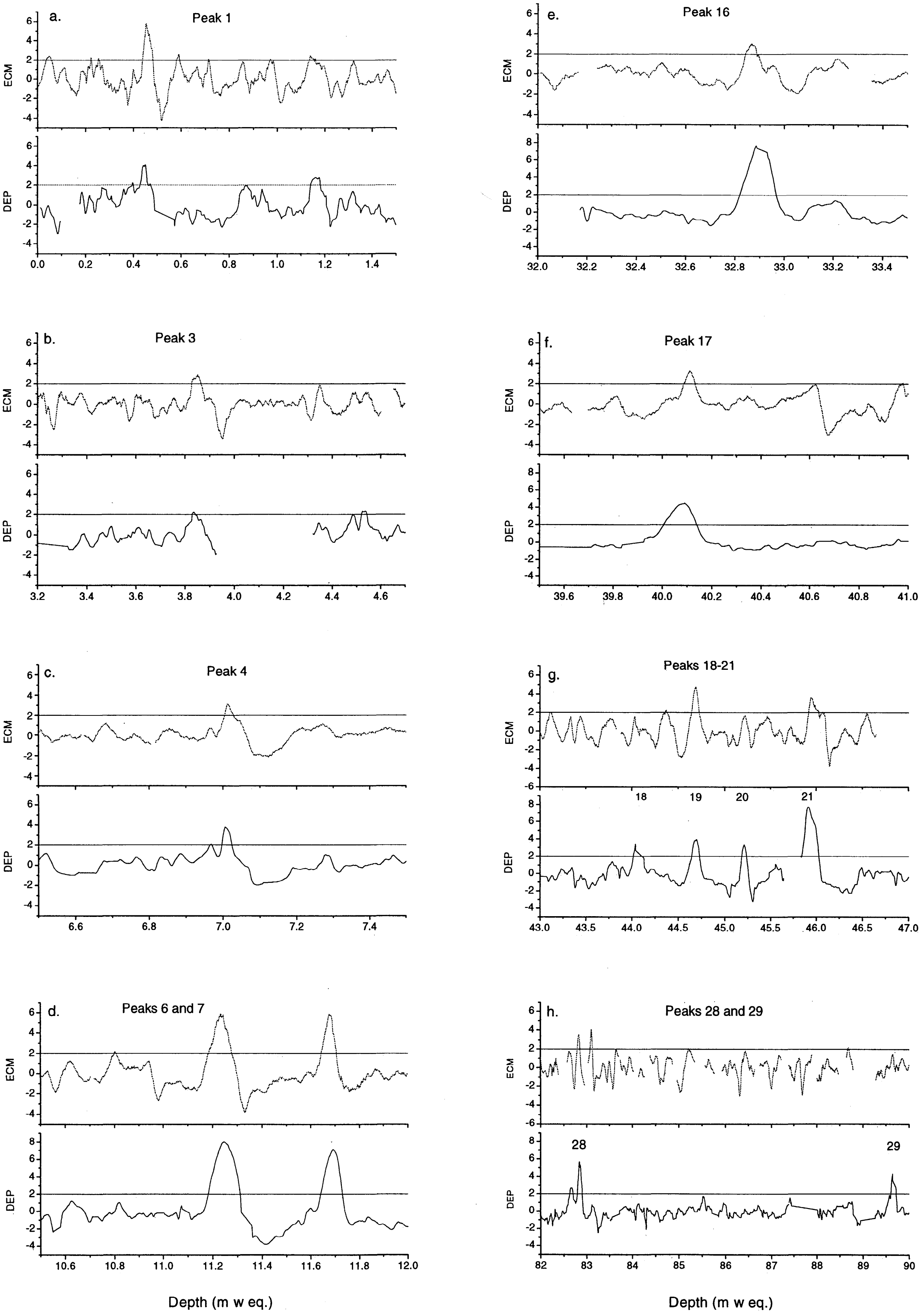

Figure 5. Detailed plots of the ECM and DEP peaks discussed in the text.

5.4. Peaks 6 and 7 (1815 and 1809)

The most pronounced peaks in the uppermost 25 m are a doublet at 11.1-11.8 m w. eq., corresponding to 22.5-23.5 m snow depth. Such a doublet has been found in most Antarctic cores [e.g., *Cole-Dai et al.*, 1997] and Greenland cores [e.g., *Clausen and Hammer*, 1988]. The upper peak is assigned to the eruption of Tambora, Lesser Sunda Island, Indonesia, in April of 1815 A.D., with deposition in Antarctica during 1816 A.D., [e.g., *Handler*, 1989]. This eruption gives an increased acidity level for at least 4 years. In the VEI the eruption is given a ranking of 7, which is the second highest level, [*Simkin et al.*, 1994]. The peak preceding the Tambora peak is an unknown eruption dated to 1809. *Palais et al.* [1990] identified these two eruptions by analyses of glass shards, and *Dai et al.* [1991] compared sulfate fluxes to show that the 1809 eruption precedes Tambora. *Cole-Dai et al.* [1997] suggests that it is a low-latitude eruption that attributes to the 1809 signal since it is a bipolar signal. This is in contrast to *Moore et al.* [1991] who suggested that the 1809 eruption was the result of two different high-latitude events (Figure 5d).

5.5. Peak 12 (1641)

This peak is identified in both electrical systems. In the VEI there is an eruption with VEI number 5 listed corresponding to an eruption at Awu, Indonesia, in January 1641 A.D.. In an ice core retrieved on James Ross Island (64°12'S, 57°40' E), *Aristarain and Delmas* [1998] report similarities between tephra particles found in layers corresponding to this time in the James Ross Island ice core, in a South Pole ice core [*Delmas et al.*, 1992], with tephra samples collected on Deception Island. This comparison suggests that these layers of tephra particles originate from Deception Island. Since Deception Island is located in the source area of low pressure system it would be possible to assign peak 12 to the Deception Is. eruption. In the South Pole core the detection of the peak dated to 1641 A.D. is further supported by ECM and ion-chemistry (ion chromatography). However, peak 12 could also be a combined signal from the Deception Island eruption and the low-latitude eruption of Awu, Indonesia. We have used 1641 A.D. as the date of peak 12.

5.6. Peak 13 (1600)

At 24.34 m depth there is a strong signal in the DEP. Unfortunately, the signal is incomplete in the lower end, because bad core quality. In the ECM record there is a peak, but it does not reach the threshold value. This peak could correspond to the major eruption of Huyanaputina, Peru, 1600 A.D., which leads to cold summers in the years after reported by Briffa *et al.* [1998] and also recorded in other Antarctic ice cores [e.g. Delmas *et al.*, 1992; Cole-Dai *et al.*, 1997].

5.7. Peaks 14 and 15 (Unknown and 1525)

Peak 14 is found in both data sets, while peak 15 is only seen in the DEP data set. In the DVI and VEI, several possible eruptions can be attributed to these peaks. Peak 14 could be Pichincha (Ecuador), which had several eruptions during the mid-16th century. After the 1553 eruption there are reports of purple sunset afterglows in Scandinavia [*Royal Society*, 1888]. However, the eruptions of Pichincha during this time period are never given a VEI value above 2. There is also an estimated error in the date of the VEI of ±20 years. Because of these uncertainties we have chosen to classify peak 14 as unidentified.

Peak 15 is assigned to Arenal in Costa Rica, which has a VEI of 4, but the error in the date according to the VEI is ± 20 years here as well. Moving the eruption date for peak 15 within the error limits of the eruption date, it is possible to produce a smooth accumulation record in this time period. In the accumulation calculations, neither peak 14 nor peak 15 has been used because of the poor precision in the eruption date.

5.8. Peak 16 (1452)

In the DEP record this peak is well defined, occurring at 32.9 m w. eq. depth. The ECM record, on the other hand, does not show an equally clear increase in the conductivity signal (Figure 5e). The peak is assigned to the eruption of Kuwae, Vanuatu, in the SW Pacific. This eruption has been dated by various authors to have occurred between 1450 and 1460 A.D.. Recently, reported dendrochronological evidence puts the date for this eruption at 1452 A.D. [*Briffa et al.*, 1998]. *Morgan et al.* [1997] used a $\delta^{18}O$ record with yearly resolution from the Law Dome core, to date the Kuwae eruption to the austral summer of 1457 A.D. They state that their record has to be "generously" interpreted to find the extra four years between 1815 and 1457 A.D. to date it to 1453 A.D. In the well-dated cores of *Cole-Dai et al.* [1997] a core section with extremely high nss-SO_4^{2-} concentrations were found at depths corresponding to an age between 1451 and 1456 A.D. The increase in sulfate lasts for 4 full years. We have used the year 1452 A.D. as the date for the Kuwae eruption.

5.9. Peak 17 (1348?)

Peak 17 is well defined in both electrical records (Figure 5f). *Langway et al.* [1995] report peaks in the nss-SO_4^{2-} records from the New Byrd Core (NBY 89), and cores from South Pole and Greenland drilled in 1989, 1978, and 1974, respectively. There are dating discrepancies of nine years among the various cores; we use the date 1348 from NBY 89 since that core is supposed to be the best dated of the two Antarctic cores [*Langway et al.*, 1995]. An eruption candidate for peak 17 is difficult to find since the DVI does not include this time period. In the VEI there is an eruption of El Chichon in Mexico. No Index number is given, but it is stated to have been a Plinian eruption. However, the dating error is stated to be as high as ±75 years.

5.10. Peaks 18-21 (1287, 1278, 1269, 1259)

These are prominent events showing up in several cores from Antarctica and Greenland [*Hammer et al.*, 1980; *Langway et al.*, 1988; *Moore et al.*, 1991; *Palais et al.*, 1992; *Langway et al.*, 1994]. The shape of the DEP signals at depths from 46 to 44 m w. eq. is very similar to the shape of the nss SO_4^{2-} data from NBY 1989 [*Langway et al.*, 1995]. That core is reported to have a dating error of ±2 years at this depth. A quadruple electrical peak also shows up in the Dome Fuji core [*Watanabe et al.*, 1997], although not in the G15 core retrieved from the same region but closer to the coast [*Moore et al.*, 1991]. The 1259 A.D. horizon has been assigned to originate from an eruption by El Chichon based on chemical analyses of glass shards, in cores from both Antarctica and Greenland [*Palais et al.*, 1992] (Figure 5g).

5.11. Peaks 28 and 29 (639 and 540)

The difficulties of dating the lowest peaks are due to the limited amount of ice cores reaching this far back in time in Antarctica, as well as the meager number of dated eruptions listed in the VEI. We have assigned peak 28 to an unknown eruption of 639 A.D.. In Antarctica this event has been identified in both the Byrd Station core from 1968 and in the deep core from Dome Fuji [*Hammer et al.*, 1997; *Watanabe et al.*, 1997]. The dating error of this eruption is ±25 years according to the VEI [*Simkin et al.*, 1994] and is based on the dating of the GISP 2 core [*Zielinski et al.*, 1994]. Peak 30 located at 89.30 m w. eq. and 118.7 m snow depth is only seen in the DEP record. The ice core quality was poor at these depths, therefore the ECM data are not considered. In the volcanic chronology from the 1968 Byrd core there is a volcanic event identified at 191 m depth which *Hammer et al.* [1997] dated to 534. In the VEI there is an eruption Rabaul, in the Southwest Pacific listed with a VEI of 6. We have used the date 540 A.D. for peak 29 and assigned it to the eruption of Rabaul (Figure 5h).

6. Dating by Total β-Activity and Pit Studies

To obtain accumulation rates for the last 30 to 40 years the well-known radioactive reference layers of 1965 and 1955 were identified by means of Total β-radioactivity measurements on a shallow (16 m) core drilled 15 m away from the 120 m core. The length of the pieces melted for filtering was 100-110 mm. The results of the total β activity show an increase in the natural radioactivity at 7.45 m and 6.1 m depth (3.02 and 2.25 m w. eq.) and their corresponding peaks at 7.31 m and 5.9 m (2.95 and 2.19 m w. eq.), which corresponds to nuclear test fallouts in January 1955 and January 1965 (Figure 6).

For accumulation estimates over the last nine years chemistry data from a nearby pit was used [*Stenberg et al.*, 1999]. Errors in the accumulation data from the pit are due primarily to density measurements. In this case, the total density error is estimated to be ±3%. The second source of error is due to the uncertainty in the depth of the peak used as a time marker (±4 cm). This uncertainty is the combined effect of sampling resolution and accuracy in the depth measurement (Figure 7 and Table 4).

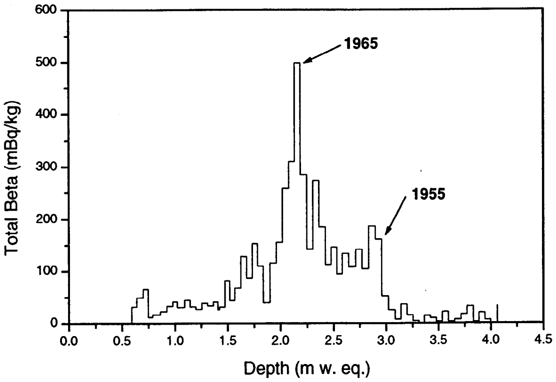

Figure 6. Total β activity in a shallow (16 m) firn core drilled ~15 m from the main core. The arrows indicate the years with an increase in activity.

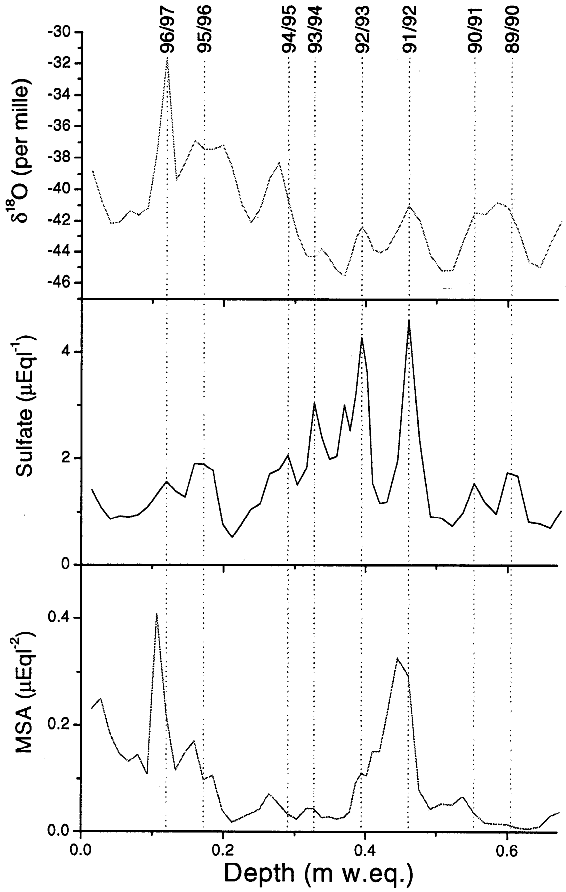

Figure 7. Methanesulfonate (MSA), sulfate, and $\delta^{18}O$ from a 2 m snow pit. The samples have 40 mm vertical resolution. Transition between different years are marked with a dotted line. From *Stenberg et al.* [1999].

7. Accumulation

Average accumulation is calculated by dividing the time span between the core retrieval and the dated stratum with the w. eq. depth of the core section above the dated horizon. We have not taken into account layer thinning due to vertical strain, because the ratio of the core depth to the entire ice thickness is ~ 5%. A 10% decrease in the height of the layer above the bed results in a 10% layer thinning [*Nye*, 1963].

Errors in accumulation derived from the electrical record are due to incorrect identification or to errors in the volcanic chronology. All eruptions between 1600 A.D. and the present were used for ice core dating, except one (Unknown, 1809), are dated with a yearly precision (Table 1). Given the uncertainty due to the depth resolution and the various measurement errors, the maximum error in the total β activity dates is ±1 year.

For both the 1816-1997 and the 1259-1997 A.D. period the yearly accumulation rate is 62 mm w. eq. while it is 61 mm w. eq., for the longer-term 540-1997 A.D. period. The accumulation for different time increments are listed in Tables 2 and 3 and shown graphically in Figure 8. There is an 8% decrease in accumulation between 1452 and 1641 A.D. compared to the 1259-1997 A.D. mean. Then, the accumulation rate rises back towards the long-term mean with a few periods of higher accumulation (1810-1816 and 1884-1933 A.D.). In the period

Table 2. Average Accumulation Rates

Year A.D.	Average Accumulation to 1998 mm. w. eq.	Years
1997	119	1
1996	85	2
1995	96	3
1994	81	4
1993	78	5
1992	76	6
1991	78	7
1990	75	8
1989	78	9
1970	61	28
1965	68	33
1955	70	43
1933	60	65
1884	61	114
1816	62	182
1810	62	188
1641	62	356
1600	61	398
1525	62	473
1452	60	546
1340	62	658
1287	62	711
1278	62	720
1269	62	728
1259	62	739
1227	62	771
1176	63	822
639	61	1359
540	61	1458

The first nine years correspond to horizons in the chemical record, 1955 and 1965 correspond to the radioactive horizons found in the 20 m core. Note that some of the years of volcanic eruptions differ from Table 1 because a 1 year delay from eruption to deposition in Antarctica has been accounted for.

1348-1452 A.D. there is an 11% higher accumulation rate than the 1259-1997 A.D. mean. Between the more established horizons of 1259 A.D. and 1452 A.D. the mean accumulation is 9% higher than the 62 mm w. eq. This indicates that the higher accumulation over the ~100 year period is most probably not an artefact of erroneous identification of peak 17.

The accumulation averages derived from total β activity yield slightly higher values than the long-term mean. From 1965 to 1997 A.D. the average accumulation is 68 mm w. eq./yr ±2 mm, while from 1955 to 1997 it is 70 mm w. eq./yr ±2 mm. The accumulation between 1955 and 1965 is 77 mm w. eq./yr ±6 mm. Since the 1955-1965 accumulation is higher than the mean for the 1955-1997 value, there must also have been periods of lower accumulation during the last 43 years. Such a period with lower accumulation is identified in the volcanic-dated record between 1970 and 1992 (Table 3). A source for discrepancies in our obtained accumulation rate record might be that the samples for the total β activity study are derived from another core. Thus part of the variations in accumulation might be the spatial accumulation variation at the drill site.

The snow pit study yields an average annual-accumulation rate for the last nine years of 78 mm, which is 10 mm higher than during the last four decades (from total β analysis, i.e. 1955 to 1997). The relative σ for that period is 39%. The accumulation value obtained from the pit for the last 6 years from the Mount Pinatubo/Mount Hudson eruption is 76 mm w. eq./yr.

Since the period 1955-1997 has a higher average accumulation rate than the more recent period 1965-1997, it indicates a decrease in accumulation the last three decades. However as the data from the pit suggests higher average accumulation rates during the last 9 years (Table 4) there seems to have been a shift during the last decade.

Isaksson et al. [1996] could see no trend in accumulation rate in a core retrieved at 75° 00' S 002° 00' E during the 1865-1991 A.D. period. However, the last 3 years in the record suggested an increase. By comparing the data from *Isaksson et al.* [1996] with our data over similar time periods, we can note a discrepancy in the changes between different periods. The average accumulation for the four periods 1991-1965, 1965-1955, 1955-1933 and 1933-1884 A.D. is 76, 66, 85, 74 mm w. eq. for the *Isaksson et al.* [1996] core, while for the core in this study, the values are, 66, 77, 59, 65 mm w. eq., respectively. The relative changes between the different periods are not the same, which implies the possibility that changes in accumulation at one site are not necessarily of the same magnitude and direction as at another site during the same period. In this, case the sites were 300 km apart with a

Table 3. Accumulation Rates for Periods Between Dated Layers

Period	Year	Accumulation mm w eq. yr^{-1}	Dating Method	Percentage Deviation From 62 mm
1	1992-1997	76	ECM, DEP	26%
2	1970-1992	58	ECM, DEP	- 6%
3	1965-1997	68	β	9%
4	1955-1997	70	β	13%
5	1955-1965	77	β	24%
6	1933-1970	57	ECM, DEP	-8%
7	1884-1933	65	ECM, DEP	3%
8	1816-1884	62	ECM, DEP	0%
9	1810-1816	73	ECM, DEP	18%
10	1641-1810	62	ECM, DEP	0%
11	1600-1641	57	ECM, DEP	- 8%
12	1452-1600	57	ECM, DEP	- 8%
13	1348-1452	69	ECM, DEP	11%
14	1259-1348	65	ECM, DEP	5%
15	639-1259	59	ECM, DEP	- 5%
16	540-639	68	DEP	10%

Accumulation rates (mm w eq./yr) for periods between identified and dated layers. The deviation is calculated based on the 1259-1997 mean. Note the relatively low accumulation rate between 1452 and 1641.

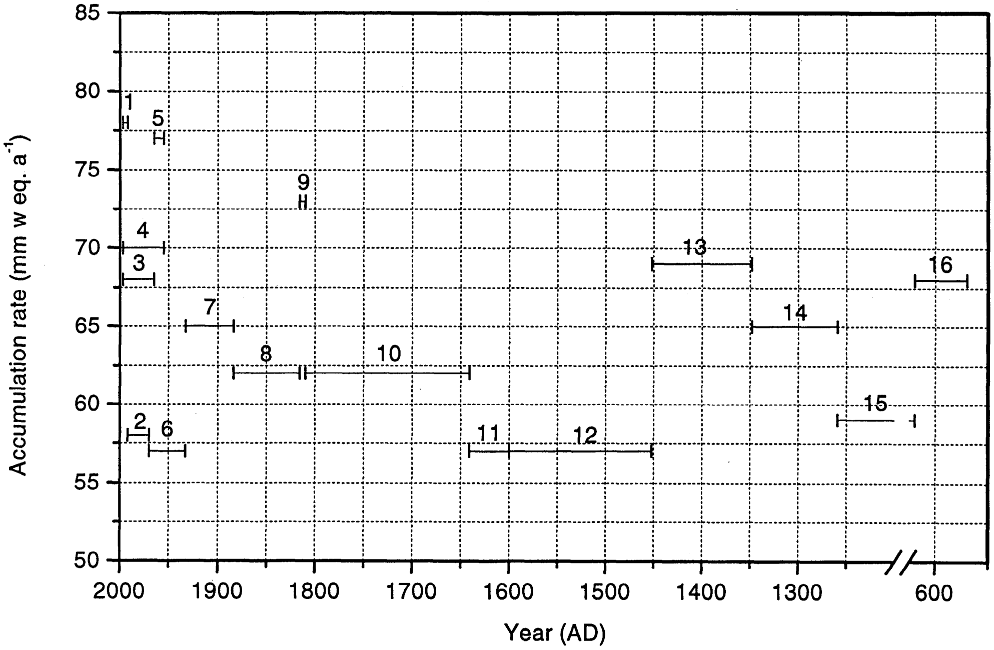

Figure 8. Derived mean accumulation from electrical and total β-measurements for periods between identified and dated volcanic eruptions and atmospheric nuclear tests. The corresponding data are listed in Table 3.

450 m elevation difference, both located on the polar plateau. Whether this observed pattern over four short periods is consistent at other sites in DML remains to be seen when more core data have become available.

In the work of *Isaksson et al.* [1996] a more coastal core from Ritscherflya showed a clear decrease in accumulation rate for the 1932-1991 period. This is in agreement with recent results from the Jutulstraumen area which shows a 10-30% decrease in accumulation rate for the period 1965 to 1996 [*Melvold,* 1999]. These recorded decreases can be the result of the fact that both coastal records begin in the years when a time-local increase in accumulation rate ends (around 1940) [*Lunde*, 1961]. This decreasing trend can, to some degree be seen in our core as well; Periods 7, 6, 2 and for the radioactive layers 5, 4, and 3 (Figure 8).

Table 4. Accumulation for the Last Nine Years

Year	Accumulation mm w. eq.
1997	119 ±14
1996	51 ±12
1995	119 ±14
1994	36 ±10
1993	67 ±13
1992	66 ±12
1991	92 ±13
1990	46 ±9
1989	106 ±15

Yearly accumulation values from 1989 to 1997 as derived from counting layers in the sulfate and $\delta^{18}O$ record. The error range is based on the sampling resolution and the accuracy of the weight used. The transition between winter and summer layers is expected to be at the peak value. Year 1997 means the period between austral summers of 1996/1997 and 1997/1998.

Increasing accumulation during recent decades has been reported by others. At Dome C there is seen an increase in accumulation from 1965 according to earlier work presented by *Petit et al.* [1982]. The increase is 30% from 1965 to the late 1970's compared to the 1955-1965 period. Our new accumulation data includes the period from late 1970 up to 1997, which was not included in the Dome C study. *Petit et al.* [1982] also show that there are large spatial variabilities on the 1-year scale (72%), but averaged over 10 years or more the spatial variability is reduced to 8%. From a study at the Dyer Plateau (Antarctic Peninsula) an increase in accumulation of 20-25% is found for the 1950-1992 period compared to the 1950-1900 period [*Weertman*, 1993]. *Mosley-Thompson et al.* [1995] also report an increase of 30% in accumulation at the South Pole since 1955. Even though some of the increase may be due to drifting, reflecting the presence of the South Pole station, most of the upwind measurements also showed an increase. However, two ice cores from, James Ross Island, Antarctic Peninsula, indicate that no change of accumulation occurred for the respective time periods extending from 1965 to 1981 and from 1965 to 1991 [*Aristarain et al.*, 1987; A.J. Aristarain personal communication, 1999].

Naturally, the temporal variability decreases with longer averaging increments. Therefore we consider the 8% decrease during the 189 year period (1452-1641) to be of greater significance than the more recent increases which may simply reflect the natural variability of accumulation occurring over shorter time periods.

8. Conclusions

We have presented a volcanic and radioactive chronology, and the resultant accumulation record from a 120 m deep core retrieved at Amundsenisen in western Dronning Maud Land. The precision in the given accumulation values is based on the accuracy of the date for the identified eruption and how well we can correlate DEP and ECM peaks with the volcanic record. The values from the deeper parts (beyond 1259 A.D.) of the core are considerably less reliable than the more recent ones.

Comparisons over four periods between two cores retrieved at two different sites on Amundsenisen reveal no similarity in changes in average annual accumulation over the respective periods. The record shows stable accumulation rates throughout the core, with a decrease in accumulation between the dated horizons of 1452-1641, i.e. part of the little ice age. The long-term mean accumulation (540 to present) is 61 mm w. eq./yr while it is 62 mm w. eq./yr for the 1259-1997 period. We found a 15-20% higher average accumulation rate during the last nine years. However, the 1933 volcanic and the 1955 and 1965 radioactive layers demonstrate that the accumulation decreased for the respective time periods extending from 1933 to 1997.

There is a complicated pattern of accumulation changes over the Antarctic continent. Part of this is probably caused by the differing time periods the different cores cover. This highlights the need for a conclusive study of accumulation rates in Antarctica covering comparable time periods between well-dated horizons.

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