

A Continuous 770-Year Record of Volcanic Activity From East Antarctica

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A 100-m ice core from site G 15 (accumulation rate 0.1 m water yr⁻¹, mean annual temperature -38°C) on the Mizuho plateau, Dronning Maud Land, East Antarctica, has been analysed using the dielectric profiling (DEP) technique. The capacitance and conductance of the core were measured at ac frequencies (20 Hz–300 kHz). The high-frequency conductivity profile shows variations that are primarily related to the strong acids derived from volcanic activity. The Tambora (1815) eruption can be identified with the aid of an approximate chronology based on the firm densification rate, other historic eruptions can then be recognised. Beyond about 300-years historical observations are very few, however if a constant overall accumulation rate is assumed, a well-known eruption of 1259 A.D. can be found near the bottom of the core. Other peaks in the conductivity profile can then be assigned dates accurate to within a few years. Using the conductivity profile it is possible to estimate the relative acid deposition fluxes produced by the main eruptions with reasonable accuracy. The estimated acid deposition fluxes relative to the Tambora (1815) eruption, of Agung (1963) is 27%, Krakatoa (1883), 25%, the signal of 1601, 28%, and that of 1259, 53%.

1. INTRODUCTION

Major volcanic eruptions often produce large amounts of SO₂ and other gases. The SO₂ is converted to sulphuric acid aerosol which is deposited globally. A violent eruption can eject SO₂ into the stratosphere and produce acid precipitation for several years after the eruption; less violent eruptions affect only the troposphere and fallout of the acid aerosol is much quicker. Volcanic eruptions that inject aerosols into the stratosphere can probably affect global climate in the short term [Lamb, 1970, Rampino and Self, 1982], primarily through reduction in atmospheric transmissivity. The acid precipitation from eruptions is recorded in Antarctic precipitation as peaks superimposed on an irregular nonvolcanic acid background. Atmospheric circulation patterns restrict interhemispheric transport, and this means that only volcanic eruptions from south of about 20°N produce changes in acid fall out in Antarctica. Previously, the volcanic record in Antarctica was well documented to about 1760 A.D. [Legrand and Delmas, 1987]; this study extends the record back to about 1220 A.D.

East Dronning Maud Land is a large elevated ice plateau containing the second highest dome in Antarctica. Kamiyama *et al.* [1990] show that the area is not unduly influenced by local cyclonic storm activity, and precipitation may be representative of a wide area of East Antarctica. The G 15 drilling site (71°12'S, 45°59'W, see Figure 1) was located at an elevation of 2544 m, mean annual air temperature -38.3°C. A 100-m core was drilled in January 1984 using an electromechanical drill. The core was cut into 0.5-m sections and returned to Japan where it was stored at -15°C in the Institute of Low Temperature Science. It was cut longitudinally in half; half of the core was used for stable isotope, density, and other measurements. The remainder was dielectrically profiled (DEP) at -21°C in October 1989; temperature variations during the course of the measurements were limited to 1°C.

The DEP technique has been described by Moore and Paren [1987] and Moore and Maeno [1991]. It involves the measurement of capacitance and conductance of ice cores at frequencies between 20 Hz and 300 kHz with an accuracy of about 3%. Spatial resolution of the system depends on the width of the electrodes used; 5-cm electrodes were used here. The high-frequency limit of conductivity, σ_{∞} , has been shown to be linearly related to both the acid and neutral salt concentrations in the ice [Moore *et al.*, 1989]. While these earlier studies analyzed complete cores, profiling of half cores should present no problems as the geometry of the electric field is identical in both configurations.

2. PRELIMINARY DATING OF THE CORE

The snow accumulation rate on the Mizuho Plateau is known to be very variable. Stake measurements over a period of several years show an accumulation rate of 0.1–0.15 m water yr⁻¹. At Mizuho station (Figure 1) a 700-m ice core has been recovered which shows periods when several years of accumulation have been lost. Kamiyama *et al.* [1990] report that in East Dronning Maud Land the effects of katabatic winds appear at altitudes below 3600 m, resulting in the loss of surface snow. This is a common problem in dating cores where the accumulation rate is below 0.1 m yr⁻¹.

Density measurements on the top 40 m of the core were made on samples of typically 60 cm³. Below this depth the density was measured on 0.5-m lengths of the core. We have used the firm densification model of Herron and Langway [1980] to model the density data. The model predicts that plots of $\ln[\rho/(\rho_i - \rho)]$, where ρ_i is the density of solid ice = 0.917 Mg m⁻³ and ρ is the density of firm, versus depth consist of linear segments. The first segment is for $\rho < 0.55$ Mg m⁻³, the second is a shallower slope for 0.55 Mg m⁻³ $< \rho < 0.82$ Mg m⁻³, corresponding to the first and second stages of densification. Pore close off occurs at $\rho = 0.82$ – 0.84 Mg m⁻³, below which densification occurs more slowly. The accumulation rate A can be found from the slope of the second stage of densification, b as

$$A = (\rho_i k_1 / b)^2 \quad (1)$$

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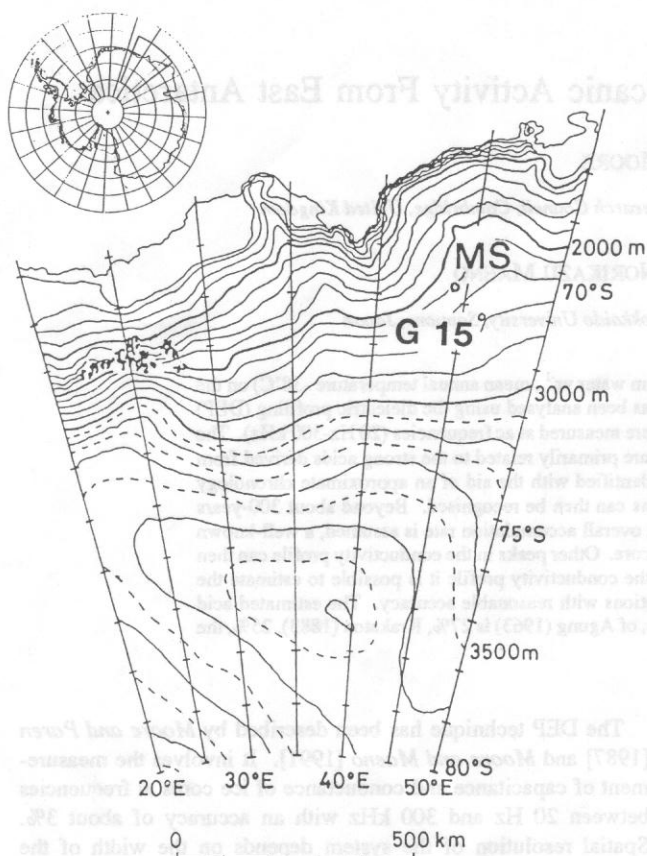


Fig. 1. Map showing the location of the G 15 drilling site in East Dronning Maud Land, East Antarctica. MS denotes Mizuho Station.

where k_1 is an empirical constant found from measurements on many cores, *Herron and Langway* [1980] give

$$k_1 = 575 \exp(-21400/RT) \quad (2)$$

where R is the gas constant and T is the mean annual temperature, which is 234.8 K at G 15. The best fit of the model to the data was found with the second stage of densification starting at about 12 m depth. This gives a value for b of 0.0234, and $A = 0.13 \text{ m yr}^{-1}$ water equivalent. The density of the surface snow is found to be 0.39 Mg m^{-3} and the depth where $\rho = 0.55 \text{ Mg m}^{-3}$ is 11.24 m, corresponding to an age of 42 years. The depth at pore close off, $\rho = 0.82 \text{ Mg m}^{-3}$ is 83 m. A provisional depth age relationship was constructed to establish an approximate chronology for the core.

3. CONDUCTIVITY RECORD

The measured high-frequency conductivity was corrected for densification effects using the Looyenga model for ice / air mixtures [*Glen and Paren, 1975*]:

$$\sigma_{\infty} = \frac{\sigma_{\text{mf}}}{\rho/\rho_i(0.68 + 0.32\rho/\rho_i)^2} \quad (3)$$

where σ_{mf} is the measured high frequency conductivity of firm with density ρ . The σ_{∞} response is determined by both acid and neutral salt concentrations [*Moore et al., 1989*]. Salt is not a significant factor in the conductivity of ice from the inland areas of Antarctica where marine ion concentrations are generally $< 1 \mu\text{eq l}^{-1}$ [*Legrand, 1987*]. However, contamination introduced during core handling can introduce levels of NaCl far higher than those

occurring naturally in ice from central Antarctica. This contamination is most severe at the ends of the core where it is most often touched. If contamination has occurred the σ_{∞} profile will show high levels at the ends of a core that will be discontinuous with levels in the adjacent core (as long as that core has not also been contaminated). This effect was observed in a few places in the σ_{∞} profile. The σ_{∞} profile is also determined by other events than volcanic eruptions or contamination, for example biogenically derived acid. Figure 2 shows two peaks: the peak at 25.4 m is probably volcanic in origin, while the peak at 25.9 m is probably due to other factors. Volcanic events are recognized by their generally short duration and their fairly symmetrical shape, this is seen in the peak at 25.4 m in Figure 2 (compare the peaks in Figure 4). The second peak in Figure 2 showing a steady rise over 20 cm and then an abrupt fall in σ_{∞} at 25.9 m is not typical of a volcanic event, nor contamination, and temperature fluctuations are too small to cause the effect. The cause may be one of the other influences on σ_{∞} . Other areas showing discontinuities at core ends are at 12 and 13 m depths producing an apparent double peak, where the highest levels are at the ends of the cores, and the peak at 14 m is another example. The peaks that appear to be a result of contamination or other nonvolcanic factors have not been removed from the σ_{∞} profile shown in Figure 3 because such data manipulation is a very subjective procedure.

3.1. Core Chronology From Major Volcanic Horizons

Figure 3 also shows the major eruptions (dust veil index (DVI) > 400) given by *Lamb* [1970] from volcanoes south of 20°N . Lamb's DVI appears to be more useful than the *Newhall and Self* [1982] volcanic explosivity index (VEI) in describing the impact of eruptions recorded in Antarctic precipitation [*Legrand and Delmas, 1987*]. The conductivity profile shows eight large peaks in the core covering the last 180 years as estimated from the preliminary dating found from the densification profile. The great eruption of Tambora (1815) should be an obvious feature near the estimated depth of the 1815 horizon. The largest, peak 7 together with peak 8 correspond to a pair of peaks often seen in Antarctic

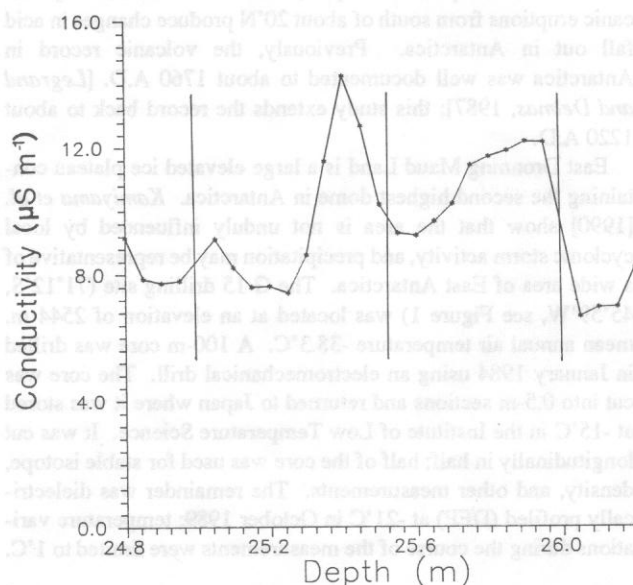


Fig. 2. Detailed DEP conductivity profile for the G 15 core showing a probable volcanic peak at 25.4 m and a feature due to a nonvolcanic cause reaching a maximum at 25.9 m. The ends of the cores are shown by vertical lines.

cores [Legrand and Delmas, 1987]. Recently, a consensus has been reached that the upper peak is actually the 1815 eruption of Tambora, and the second is an unknown eruption that occurred around 1808. The acid flux in cores from different areas of Antarctica, produced by the 1808 eruption indicates a local eruption, [Legrand and Delmas, 1987]. This conclusion also agrees with the analysis of glass shards from the two events in a South Polar ice core [Palais et al., 1990], where the glasses from the younger peak matched glasses known to be from the Tambora eruption.

With the knowledge that peak 7 is Tambora 1815 we can use simple linear interpolation assuming a constant accumulation rate to provide dates for the top 30 m of the core. This chronology can be improved using the established record of the largest volcanic eruptions covering the probable time interval covered by the core. Results from other cores suggest that the most reliable volcanic eruption to use as reference horizon in addition to the 1815 eruption of Tambora, is the near surface eruption of Agung (1963). On the basis of the accumulation rate found from the identification of peak 7 as Tambora, peak 2 is likely to be Agung. It would also be desirable to have a reference horizon from a much earlier eruption. This would be before any historical records, and therefore it should be as widely observed and as accurately dated as possible. Langway et al. [1988] identify large volcanic signals in 8 ice cores from different areas of Antarctica and Greenland which appear to be from the same eruption. The eruption has been dated by counting annual layers in the Milcent and Crete (accumulation rates 0.49 and 0.26 m yr⁻¹) Greenland cores at A.D. 1258-9. The 1259 eruption was a very large, probably tropical eruption, and Hammer et al. [1980] report that it is the third largest acidity spike in the Crete core acidity record, which is generally dominated by local Icelandic eruptions. In Antarctica, accumulation rates are generally much lower than in Greenland, and annual layers can be easily lost. Langway et al. [1988] report that the second largest signal in the last 1000 years recorded in South Polar precipitation may be the 1259 eruption. They compared their dating of the 1259 volcanic peak with dating of annual horizons at South Pole (0.08 m yr⁻¹ accumulation rate) by Mosley-Thompson and Thompson [1982] and report a loss of about 40 years precipitation over the last 700 years. This degree of loss is entirely reasonable, and so it seems likely that the 1259 eruption should be seen as a major event at G 15, if the core reached this horizon. The sharp peak at 95 m depth is close to the expected depth of the 1259 event assuming an accumulation rate based on the Tambora horizon. The peak observed here is not so large in relation to Tambora as observed at South Pole (Table 1), however, part of the peak may have been missed in the DEP analysis because almost 5 cm of the core immediately after the peak maximum was unfortunately not measured. The peak at South Pole is also a very sharp feature

similar to that seen here. We therefore feel confident in assigning the 95-m peak to the 1259 eruption.

The fallout from historically known eruptions has been found to take about a year to reach the Polar regions, therefore the start of the conductivity spike assigned to the volcano was dated as the beginning of the year following the eruption. The fixed marker horizons of Agung, Tambora and the large eruption of 1259 were used to calculate an optimum dating for the core shown in Figure 3. The water equivalent accumulation rates found using the three volcanic reference horizons are 0.116 m yr⁻¹ between 1964 and 1984, 0.086 m yr⁻¹ from 1816 to 1964, and 0.092 m yr⁻¹ between 1259 and 1816. Our assumption that the spikes in Figure 3 are correctly assigned to the marker eruptions is strengthened by the similar accumulation rates deduced for periods between them. The apparent increase in accumulation rate of 25-30% between 1963 and the present is in agreement with the findings of Petit et al., [1982] that the accumulation rate at Dome C, East Antarctica was 30% higher since 1965 than it had been in the 1955-1965 period. The accumulation rates are lower than found using the densification model by around 30%. One of the reasons for this is the sensitivity of the accumulation rate to the chosen break between the first and second stages of densification. Starting the second stage at about 17 m depth decreases the deduced accumulation rate to about 0.11 m yr⁻¹.

3.2. Identification of Volcanic Signals

Peak 1 is a very sharp feature, a characteristic often observed in local nonstratospheric eruptions. The most likely candidate is Deception Island in the Antarctic Peninsula which erupted several times in 1969 and 1970. The Deception Island eruption was not observed in cores from the Antarctic Peninsula, much closer to the eruption, however, evidence of the fall-out pattern from islands around Deception Island suggests that a southwesterly wind carried the plume away from the Peninsula [Baker et al., 1975, p 58]. The plume could then have been transported in the zonal circulation to East Antarctica. Peaks 3 and 4 are probably Tarawera, (1886) and Krakatoa (1883). Legrand and Delmas [1987] report these eruptions as a broad peak in the Dome C acidity profile. Here the two eruptions are clearly separated.

Peak 5 is probably Coseguina (1835), but peak 6 is rather difficult to assign to a specific eruption using compilations of volcanic activity. The Dome C acidity record showed a similar feature to peaks 5 and 6 at the same separation from Tambora. Several possible eruptions are available from the compilations of Lamb [1970] or Newhall and Self [1982], particularly Armagora, South Pacific (1846), Coseguina, Nicaragua (1835) and Galunggung, Java (1822). Legrand and Delmas [1987] assigned peak 5 to Armagura and peak 6 tentatively to Coseguina. The best dating for the G 15 core gives dates of 1835 for peak 5 and 1829 for peak

TABLE 1. Relative Fluxes of Eruptions as a Fraction of Tambora

Eruption	G 15 DEP Acid Flux	South Pole Estimate	Reference
Agung 1963	27%	22%	Legrand and Delmas [1987]
Unknown 1808	18%	45% and 55%	Legrand and Delmas [1987] Legrand and Kirchner [1990]
Krakatoa 1883	25%	20-30% and 13%	Legrand and Delmas [1987] Langway et al. [1988]
Unknown 1259	53%	200% and 110%	Legrand and Kirchner [1990] Langway et al. [1988]

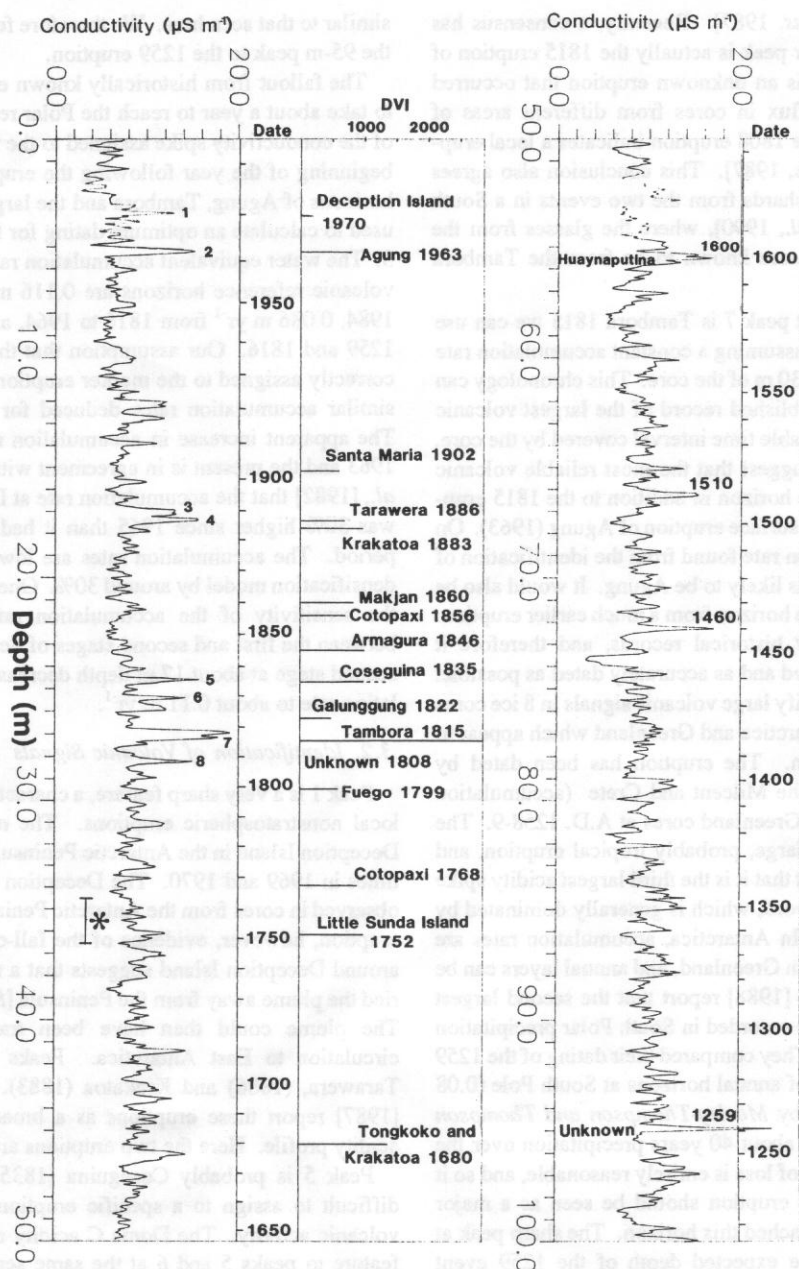


Fig. 3. The DEP conductivity profile at -21°C of the G 15 core, and the major volcanic eruptions south of 20°N from Lamb's [1970] dust veil index (for events south of 20°N with DVI>400). There is no DVI earlier than 1680. The eruption of Deception Island in 1970 is smaller than the others but is included as it is relatively near G 15. The DVI given for Coseguina (1835) is 4000, but this seems too large according to other work [see Legrand and Delmas, 1987]. The large spikes numbered 1 to 8 are assigned to volcanic eruptions. The estimate based on the densification rate, of the depth corresponding to the 1815 horizon is shown as an asterisk at 35.5 m; the error bar represents the scatter in the density data. The eruptions called "unknown" have been observed and well dated in cores from Antarctica (1808) or at both poles (1259), but the source volcano is unknown. The spikes denoted by only a date have not been well observed previously. The dating uses the eruptions of 1963, 1815, and 1259 to fix dates for the conductivity spikes and dates for the core are interpolated between these points.

6. It is interesting to note that with our dating Armagura apparently produced no significant deposits at G 15. This contrasts with Legrand and Delmas [1987] interpretation of the Dome C record where they assigned Armagura to one of the most prominent peaks.

As discussed in section 3.1, peaks 7 and 8 form a well-known doublet in Antarctic ice core records, the younger peak 7 being Tambora, the older probably caused by a local volcanic eruption around 1808. Palais *et al.* [1990] analyses of the glass shards in the older horizon shows a distinct alkaline affinity (high Na₂O +

K₂O) which may be classified as a benmoreite. During Cenozoic times volcanism was widespread in West Antarctica and predominantly of alkaline nature [LeMasurier and Thomson, 1990]. Although over-interpretation should be avoided, extensive rocks of benmoreite composition have been reported from Deception Island (Antarctic Peninsula) and several volcanoes in the McMurdo group (Ross Sea) [LeMasurier and Thomson, 1990]. Deception Island and two volcanoes in the McMurdo group are thought to have been active during the 19th and 20th centuries. Hence there are no geological factors that require the 1808 (peak 8) volcanic eruption to be from a non-Antarctic volcano. Legrand and Delmas [1987] show that the distribution of acid flux fallout from the eruption is not homogeneous over the continent. Higher levels are found in Adelie Land, lower values at Siple (Ellsworth Land) and perhaps South Pole. Table 1 shows that low values are also found at G 15. The atmospheric circulation patterns around Antarctica suggest a location for the eruption in the Ross Sea region, rather than the Antarctic Peninsula. Of the volcanoes in the McMurdo group, Mt. Erebus is known to be presently active but generally produces more alkaline material than that found by Palais *et al.* [1990] in the South Pole core. Although no historic eruptions of Mt. Melbourne have been witnessed, a major (5 m thick) volcanic ash layer is well exposed in the ice near the summit cone, and has been tentatively dated at 70–200 years [Lyon, 1986]. The material from the summit area is less alkaline than found at Mt. Erebus [LeMasurier and Thomson, 1990] and similar to that found in the ice cores.

Beyond 1800, historical data on eruptions that are likely to be recorded in Antarctic cores become sparse and unreliable, especially in magnitude estimates. Lamb [1970] does not give any DVI information covering the period before 1680.

The large peak at 56 m depth at a date of 1600 is probably the signal of a well dated (± 1 year) eruption in 1601 seen in the Crete core and reported by Hammer *et al.* [1980]. Ash from probably the same eruption was analyzed by Palais *et al.* [1990] in South Pole ice, and glass shards were found by Thompson *et al.* [1986] from the Quelccaya ice cap Peru. Palais *et al.* [1990] identify the eruption as likely to be Huaynaputina (1600). Palais *et al.* [1990] indicate that the 1601 peak is part of a doublet at South Pole with another eruption about 8 years earlier, tentatively identified as Ruiz (1595). However, there is no obvious evidence of a doublet in the σ_{a} profile near this date.

The peak at 46 m depth could be the Tongkoko, Celebes and Krakatoa (1680) eruptions. Beyond this the remaining eruptions cited by Newhall and Self [1982] show no clear correlations with the σ_{a} profile. Zanolini *et al.* [1985] report acidity measurements on the D 57 core, Terre Adelie, Antarctica. The core was not well dated, but they found two large eruptions separated by about 80 years. The oldest was about 1400, while the second appeared to have a more local characteristic in its sharp rise and fall. The dating of the core was very uncertain and it is possible that the two eruptions are the peaks at 1460 and 1510, Legrand and Kirchner [1990] report a large event at South Pole which they estimate to be about 1450.

4. VOLCANIC FLUX

The DEP conductivity profile could be used to compute the acidic flux of the main volcanic eruptions. The only core in which σ_{a} has been directly calibrated to acidity is from Dolleman Island, Antarctic Peninsula. The relationship found at -22°C was

$$\sigma_{\text{a}} = C + 0.4[\text{salt}] + 1.425[\text{H}^+] \quad (4)$$

where the σ_{a} is expressed in $\mu\text{S m}^{-1}$, salt and H^+ are in $\mu\text{eq l}^{-1}$ [Moore *et al.*, 1989]. The salt term represents marine cation

species. The constant, C , is made up of a pure ice component, possible contributions from physical properties such as grain size, and contributions from chemical species not accounted for in the salt or acid terms. For pure single crystals of ice at -22°C , C is $4.5 \mu\text{S m}^{-1}$ [Glen and Paren, 1975], this is the value we have taken for C in producing Figure 4. The acid in the Dolleman core does not come from volcanic sources but from biogenic activity. The principal acid in the Dolleman core is H_2SO_4 which makes up about 60% of the total, but there are important (about 25% on average, [Moore *et al.*, 1989]) quantities of HCl , probably produced from the reaction between H_2SO_4 and NaCl . The remainder of the acid is HNO_3 . The acid deposition from volcanic events is mainly H_2SO_4 , while in some eruptions HCl and HF are also produced. Because the acid in the G 15 core may not follow exactly the same calibration equation established for the Dolleman Island core, we present the acid fluxes for several eruptions expressed as a fraction of the Tambora eruption. This will be a valid approach if the eruptions have the same balance of acids in their fallout. A further complication is the level and variability of neutral salts in the ice. Kamiyama *et al.* [1989] report measurements of marine ions in surface snow from an area 500 km west of G 15 at similar altitudes. Total marine ions are about $6 \mu\text{eq l}^{-1}$, much greater than values typical of inland areas of Antarctica [Legrand, 1987]. Equation (4) predicts that this level of neutral salt would contribute about $3 \mu\text{S m}^{-1}$ to σ_{a} . The variability of salt concentrations between the volcanic eruptions is not known, but seasonal variations are probably much larger than annual variability. The large eruptions considered in this section are thought to have produced significant deposits for at least 1 year, therefore errors in relative flux caused by salt variations are likely to be small.

The detailed σ_{a} profiles for the Agung (1963), Tarawera and Krakatoa doublet (1886, 1883), Tambora and unknown (1808) pair, Huaynaputina (1600), and unknown (1259) eruptions, are shown in Figure 4. The deposition fluxes were calculated for the peaks after subtracting the background levels of σ_{a} . Table 1 shows the fluxes as a percentage of the Tambora flux. Table 1 also shows flux estimates from South Pole acidity data based on liquid conductivity and ion chromatography measurements [Langway *et al.*, 1988, Legrand and Delmas, 1987, Legrand and Kirchner, 1990]. Percentages of the Tambora flux are shown in Table 1 because there are large differences in absolute acid fluxes given by different authors. For example, for the Tambora 1815 eruption at South Pole, Langway *et al.*, [1988] give a value of 83 kg km^{-2} for the H_2SO_4 deposition, while Legrand and Delmas [1987] give 42 kg km^{-2} for the event. In addition, any doubt about the application of (4) would make absolute values of flux calculated dubious. Nevertheless, for the sake of completeness, the Tambora deposition flux for the G 15 core using (4), assuming all the acid is H_2SO_4 , and integrating over the area shown in Figure 4 is 95 kg km^{-2} . South Pole has a similar accumulation rate to G 15 (about 0.08 m yr^{-1} water equivalent), and would be expected to have similar acid fluxes. The relative fluxes of Agung, Krakatoa, and Tambora agree well those of Legrand and Delmas [1987] and support their estimate of sulphate aerosol ratios between the eruptions as 1:1:5, respectively. The estimate for Krakatoa of Langway *et al.* [1988] is rather lower than our estimate. The flux estimate for the unknown 1808 eruption given here is lower than observed at South Pole, supporting the suggestion that the eruption was from the Antarctic area. The estimate for the 1259 eruption based on Legrand and Kirchner [1990] and Langway *et al.* [1988] non-sea-salt sulphate measurements disagrees with our estimate. As discussed in section 3.1, this may be due to the incomplete analysis of the peak, a loss of precipitation at G 15, or

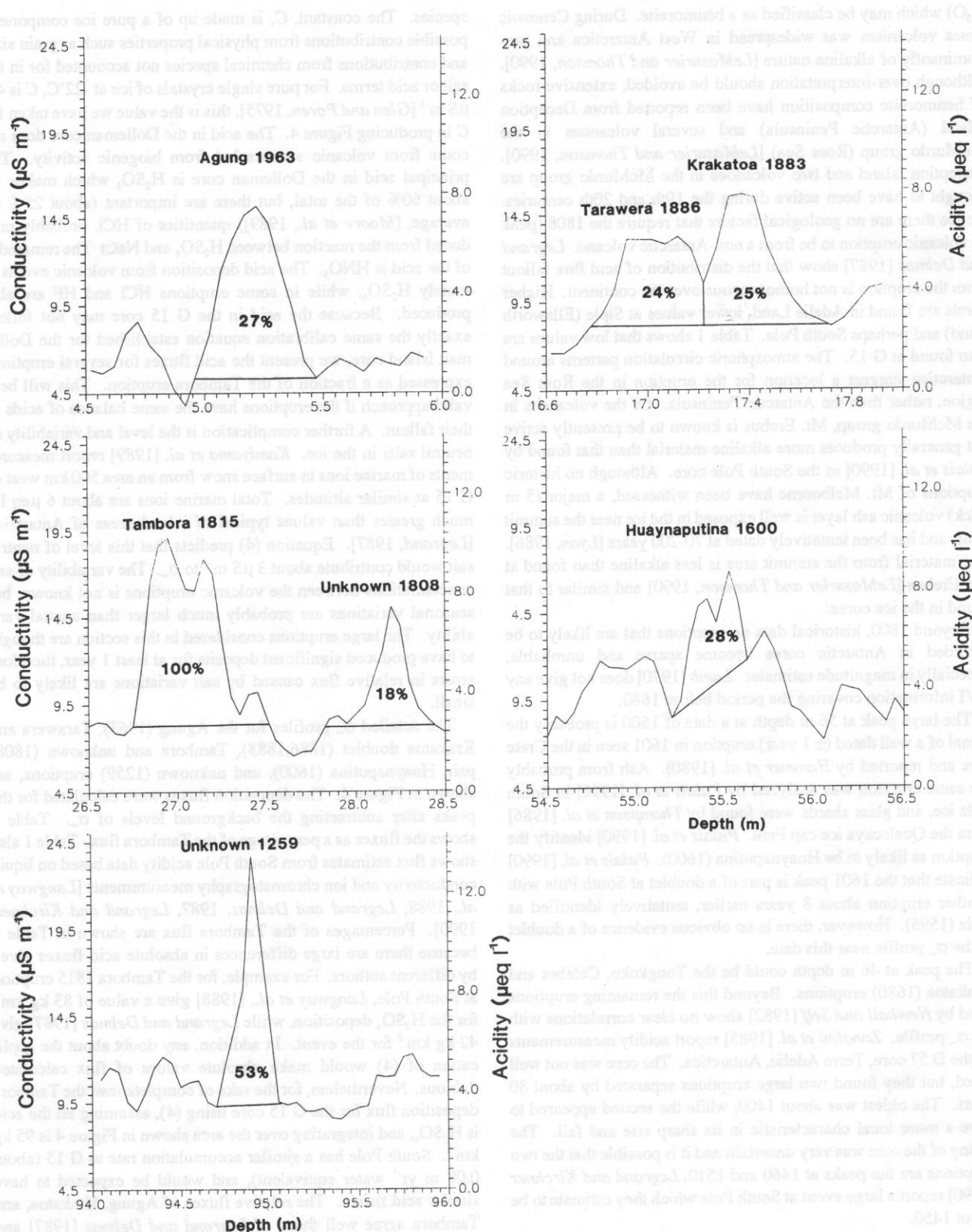


Fig. 4. Detailed DEP conductivity profiles (upper curves) for seven eruptions well known in Polar ice cores. The conductivity can be converted to a strong acid concentration (lower curves) using equation (4). The relative acid flux for each eruption as a percentage of that of Tambora is shown, assuming the balance of acids in each eruption is similar to the Tambora eruption. The deposition fluxes in Table 1 were found by integrating between the curve and the estimated background shown by the straight lines.

a differing balance of acids and/or salts. Alternatively, the σ_{m} spike may not be correctly identified as the 1259, though it is a large peak and misidentification seems unlikely. There is evidence of local changes in the deposition of artificial tritium (a stratospherically derived impurity) at South Pole, with differences in concentration for the 1966 horizon of 1.5:1 in two pits a few hundred meters apart [Jouzel et al., 1979]. There appears to be a large discrepancy (a factor of 2) in the 1259 flux between the two South Pole cores, so the difference between them and the G 15 core may be due to small-scale changes in deposition.

5. CONCLUSIONS

The accumulation rate based on eruptions over the last 800 years is about 0.09 m yr^{-1} water equivalent, and the averages over several hundred years are quite constant for the period from 1250 to the 1960s. There seems to have been a 25% increase in accumulation rate from about 1964 to the present in agreement with observations from Dome C, East Antarctica [Petit et al., 1982]. There seems to be little net loss of accumulation through wind scouring as the pattern of eruptions spanning the last 200 years seems well preserved. The 700-m core from Mizuho Station (Figure 1) shows many events of accumulation loss which makes accurate dating difficult. The area around G 15 appears not to suffer in this way.

We have used the density profile of the G 15 core to obtain a basic chronology of the core. The chronology has been refined using the DEP σ_{m} profile which displays the well-dated eruptions of Agung (1963), Tambora (1815), and the unknown (1259) event. While the final dating of the core cannot be checked without further analysis, the dating of the probable signal from the Huaynaputina (1600) eruption was correct to within 2 years. The dates of some large spikes in the σ_{m} record that have been observed in other ice cores have been estimated. The DEP method has been used to estimate the acid flux from volcanic eruptions. These data seem generally consistent with earlier estimates based on direct measurement of acidity in ice cores. Hence DEP offers a very rapid way of semiquantitatively measuring strong acid in ice cores. We recommend a similar study on a better dated ice core.

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