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THE LAKI AND TAMBORA ERUPTIONS AS REVEALED IN GREENLAND ICE CORES FROM 11 LOCATIONS

by

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ABSTRACT

Major volcanic eruptions deposit large amounts of strong acids in polar ice. Two such volcanic eruptions are Laki, A.D. 1783, at high latitude (64°N), and Tambora, A.D. 1815, close to the Equator (8°S). The acid ice layers from these eruptions are easily reached by shallow drilling, and the acidity of the ice cores obtained has been determined by a solid electrical conductivity method (ECM), and in some cases by liquid pH measurements. The strong acid is identified by chemical anion analysis. Sulfate is the dominant anion in both of these volcanic events.

Atmospheric thermonuclear-bomb tests ejected radioactive debris into the atmosphere. Two major groups of such tests are those carried out by the Americans in 1952–54 at low latitude (11°N) and by the Russians in 1961–62 at high latitude (75°N). Radioactive debris from these events was deposited in polar snow, and can be detected by specific total β activity measurements. The radioactive layers serve as dating horizons in the firn. The total β activities were measured at least 10 years after ejection, thus the measured activities were mainly due to ^{90}Sr and ^{137}Cs.

The amount of ^{90}Sr and ^{137}Cs ejected into the atmosphere is known. We assumed a similar global distribution pattern of bomb-produced total β activity and strong acids from violent volcanic activity, and were able to calculate that both major volcanic events produced some 300 million tons of sulphuric acid. This is in agreement with other estimates of the Tambora eruption, which are based on studies of ice cores from Antarctica.

INTRODUCTION

Polar snow is stratified by atmospheric impurities such as radioactive debris from nuclear-bomb test series in the atmosphere and strong acids from major volcanic eruptions, which are the subject of this paper. The strong acids are important for their volcanic and climatic significance, and the radioactive debris for their usefulness in estimating the production of volcanic acids in major eruptions. The areal deposition pattern of bomb-produced total β activity is inferred from specific total β activity measurements on ice cores. Ice-core samples from various locations in Greenland were analyzed for specific total β activity, which originated from atmospheric nuclear-bomb tests in the early 1950s and 1960s. The Greenland locations are shown in Figure 1.

The areal deposition pattern of volcanic strong acids is inferred from measurements of H^+ and anion concentrations in snow layers, which are stratified by strong acids injected into the atmosphere by the A.D. 1815 Tambora (8°S) and the A.D. 1783 Laki (64°N) volcanic eruptions. The choice of these two eruptions for investigation is based on two considerations: a reasonable amount of data exists and both belong to the class of major eruptions.

Detailed stable-isotope analyses ($\delta^{18}O$) have been performed on all the ice cores presented, in order to provide a reliable dating of the ice. $\delta^{18}O$ records exhibit seasonal oscillations in snow layers from regions where the annual rate of accumulation exceeds some 200 mm of ice equivalent per year. We obtain an absolute chronology by combining counting of $\delta^{18}O$ annual oscillations downward from the top (Dansgaard and others 1973), with fixed points determined by (for instance) bomb-produced radioactivity; see Figure 2, which shows a $\delta^{18}O$ record (thin curve) and a total β activity record (thick curve) from location Summit in central Greenland.

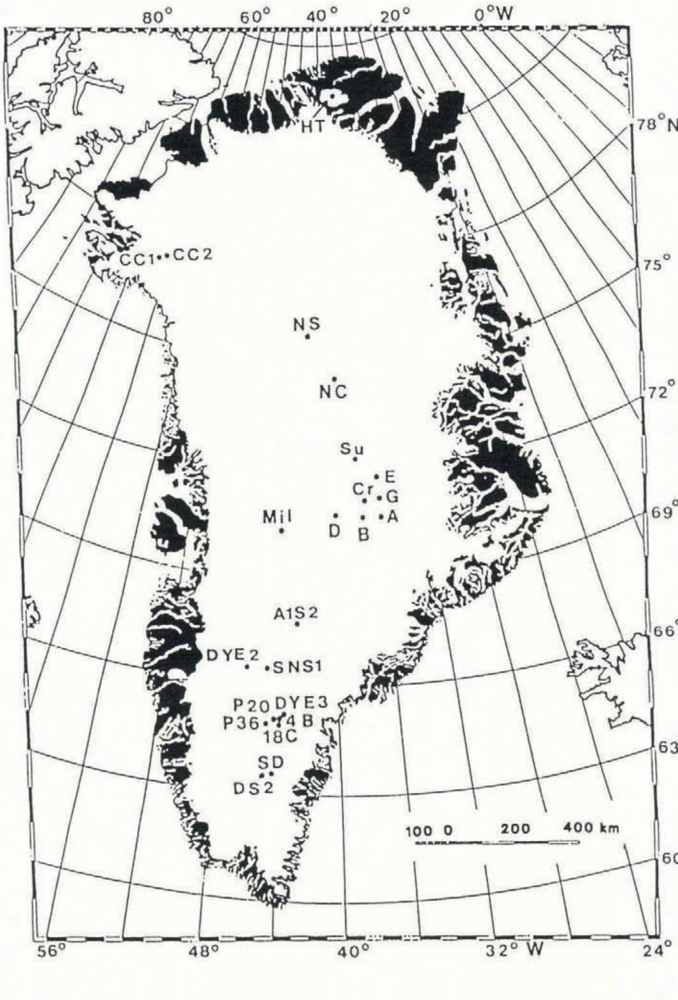

Fig.1. Map of Greenland locations where ice cores have been obtained for this study. HT, Hans Tavsen ice cap; CC, Camp Century; NS, North Site; NC, North Central; Su, Summit; Mil, Milcent; Cr, Crête; A, Site A; B, Site B; D, Site D; E, Site E; G, Site G; P20, Dye 3 pit 20; P36, Dye 3 pit 36; SD, South Dome.

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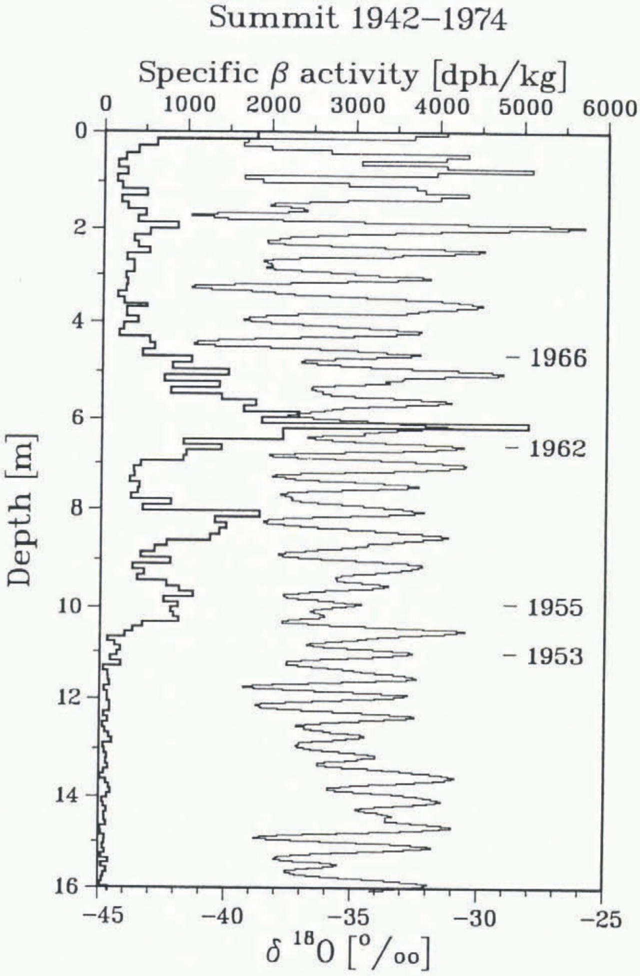

Fig.2. The thin curve shows $\delta^{18}O$ seasonal variations in the top 16 m of an ice core from location Summit, central Greenland, covering the period 1942–74, scale at bottom. The thick curve shows the measured specific total β activity (in disintegrations per hour per kg of ice, dph/kg), scale at top. The area above the natural background during e.g. 1962–66 represents the total β deposition from the atmospheric test series in the early '60s, corrected for radioactive decay.

DEPOSITION OF BOMB-PRODUCED TOTAL β ACTIVITY

The deposition of bomb-produced total β activity in the years 1962–66 and 1953–55 is of particular importance, because the total β activity in these years originates from geographically rather well-defined atmospheric bomb tests (the 1961–62 and the 1952–54 test series). Because the measurements were made at least 10 years after the bomb tests, the measured specific total β activities (in disintegrations per hour per kg of ice, dph/kg) are mainly due to ^{90}Sr and ^{137}Cs. According to the UNSCEAR Report (1982), the total fission yields from the atmospheric bomb tests in 1961 and 1962 were 102 MT TNT, mainly due to Russian test series at a high northern latitude (HNL) 75°N, and American test series at low northern latitudes (LNL) 17° and 2°N.

In 1952 and 1954 an atmospheric fission yield of 36.2 MT TNT was almost entirely due to American test series at LNL 11°N. Also according to the UNSCEAR Report (1982), production of the fission products ^{90}Sr and ^{137}Cs was 0.105 MCi/MT and 0.159 MCi/MT respectively. The yield distribution of the Russian and American test series and of the total bomb-produced β activity (the sum in MCi of the ^{90}Sr and ^{137}Cs produced) at HNL and LNL is shown in Table I.

TABLE 1. TOTAL FISSION YIELD AND BOMB-PRODUCED TOTAL β ACTIVITY.

Years of injection	Fission yield MT TNT HNL	Fission yield MT TNT LNL	Bomb-produced total β activity MCi HNL	Bomb-produced total β activity MCi LNL
1952–54		36.2		9.6
1961–62	85.5	16.5	22.6	4.4

Detailed specific total β activity measurements were made on all ice cores from the Greenland locations listed in Table II. An example of one of these detailed records is shown in Figure 2 (thick curve). These total β activity measurements are the basis for the deposition rate values given in Table II. All measured values (e.g. in Fig.2) are corrected for radioactive decay since formation (using a half-life of 29 years) and for natural β activity background. The background is mainly due to ^{210}Pb and ^{40}K (^{40}K is the long-lived background component). For all sites the value of 150 dph/kg is used as an initial natural background (^{210}Pb: 100 dph/kg; ^{40}K: 50 dph/kg). In the following, the actual snow depths are converted into meters of ice equivalents, using the measured density profiles to calculate annual deposition rates. In order to estimate the HNL part of the 1962–66 deposition, the contribution from the LNL tests must be subtracted. The latter contribution is calculated as the ratio 16.5/36.2 of the 1953–55 deposition (LNL) (see Table I for the fission yields).

The deposition rates of bomb-produced total β activity (in mCi/km²) integrates the deposition over the years 1953–55 and over 1962–66. Table II shows the deposition rate for the period 1962–66 (from the Russian test series, 85.5 MT TNT at HNL in 1961 and 1962 (column 5)), and for the period 1953–55 (from the American test series, 36.2 MT TNT at LNL in 1952 and 1954 (column 7)). For comparison, data from a few locations in Antarctica have been added. In Antarctica the 5 year deposition period starts around mid-1963. The 1½ year shift is due to the inter-hemispheric stratospheric exchange of the radioactive debris which originated at HNL.

Columns 6 and 8 in Table II show the deposition rate which corresponds to the injection of 1 MCi of total β activity at HNL and LNL respectively. The deposition in the Milcent–Crête region shows a decreasing trend of some 40% in the west–east direction (see next section). This difference is explained by the accumulation at Crête being ≈40% less than at Milcent, whereas the specific total β activity is the same at the two sites. The data in columns 6 and 8 of Table II are further treated in Table III, where the Greenland data are averaged within latitude bands. The Antarctica values are means of 4, 13 and 2 sites in the vicinity of Byrd Station, J-9 and South Pole respectively. Table III then shows the deposition rate of total β activity at various latitude bands from a 1 MCi test at a HNL or LNL test site.

Table III shows, for Greenland, generally uniform deposition rates of bomb debris injected into the stratosphere at HNL and LNL. In Table III the ratio f between the deposition from a HNL and a LNL injection of a given magnitude is ≈2 in Greenland, and in Antarctica ≈1 and ≈0.5 for Byrd Station – J-9 and South Pole respectively.

The ratio between Greenland and Antarctica depositions from a HNL injection is ≈10 and 6 for Byrd Station – J-9 and South Pole respectively. This suggests that large volcanic events at HNL (e.g. Laki, Iceland) will be difficult to identify in Antarctic ice cores, even at South Pole, because the volcanic deposition is expected to be of the same order of magnitude as the background.

DEPOSITION OF VOLCANIC H_2SO_4

Detailed H^+ concentrations were obtained by the ECM method (Hammer 1980) from all the ice cores from

TABLE II. DEPOSITION RATES OF TOTAL β ACTIVITY IN GREENLAND AND ANTARCTICA.

1	2	3	4	5	6	7	8
Site	Elevation m a.s.l.	Latitude °N (bottom 3 = °S)	Longitude °W	Corrected deposition 1962–66 mCi/km²	Deposition 1962–66 from 1 MCi injected at HNL mCi/km²	Deposition 1953–55 mCi/km²	Deposition 1953–55 from 1 MCi injected at LNL mCi/km²
Hans Tavsen	1200	82.40	38.15	11.1	0.49	1.63	0.17
Camp Century 2	1914	77.22	60.80	16.1	0.71	2.32	0.24
Camp Century 1	1885	77.18	61.11	18.0	0.80	3.42	0.36
North Site	2850	75.77	42.44	11.3	0.50	2.51	0.26
North Central A	2930	74.62	39.60	12.6	0.56	1.54	0.16
North Central E	2930	74.62	39.60	–	–	1.21	0.13
Summit	3210	72.30	38.00	13.8	0.61	3.81	0.40
Crête A	3172	71.12	37.32	14.4	0.64	3.64	0.38
Crête B	3172	71.12	37.32	17.0	0.75	3.07	0.32
Milcent	2450	70.30	44.55	24.6	1.09	4.79	0.50
A1–S2	2600	67.85	43.12	16.2	0.72	–	–
Dye 2 A	2100	66.48	46.33	12.9	0.57	4.65	0.48
Dye 2 B	2100	66.48	46.33	12.4	0.55	6.66	0.69
SNS 1	2450	66.47	44.83	15.7	0.69	–	–
Dye 3 pit P	2465	65.19	43.77	17.9	0.79	–	–
Dye 3 A	2480	65.18	43.83	11.2	0.50	3.02	0.31
Station 1	2480	65.18	43.83	12.2	0.54	–	–
Dye 3 B	2480	65.18	43.83	16.3	0.72	2.94	0.31
4 B	2491	65.17	43.93	16.0	0.71	–	–
Dye 3 pit H	2512	65.16	43.94	15.9	0.70	3.11	0.32
Dye 3 pit 20	2600	65.08	44.34	15.2	0.67	–	–
Dye 3 pit 36	2570	64.95	44.87	12.8	0.57	–	–
South Dome	2821	63.55	44.60	20.2	0.89	2.38	0.25
DS 2	2760	63.55	44.93	13.0	0.58	–	–
South Pole	2835	90.00	–	2.55	0.11	2.19	0.23
Byrd Station	1530	80.02	119.52	1.58	0.07	0.89	0.09
RISP J-9	55	82.38	168.63	1.50	0.07	0.58	0.06

TABLE III. TOTAL β ACTIVITY DEPOSITION RATES IN GEOGRAPHIC LATITUDE BANDS FROM A 1 MCi TEST AT A HNL OR LNL TEST SITE.

	Latitude	HNL test site Deposition mCi/km²	LNL test site Deposition mCi/km²	f "HNL/LNL"
Greenland	82°–75°N	0.62 ± 0.08	0.26 ± 0.04	2.4 ± 0.5
	69°–75°N	0.73 ± 0.10	0.31 ± 0.06	2.3 ± 0.6
	63°–69°N	0.66 ± 0.03	0.40 ± 0.07	1.7 ± 0.3
Antarctica				
Byrd Station	80°S	0.07 ± 0.01	0.09 ± 0.01	0.8 ± 0.1
Ross Ice Shelf, J-9	82°S	0.06 ± 0.02	0.06 ± 0.01	1.0 ± 0.3
South Pole	90°S	0.11 ± 0.03	0.23 ± 0.06	0.5 ± 0.2

Greenland locations, listed in Table IV. Furthermore, pH measurements were made on selected ice samples from the Laki and Tambora annual layers. Anion concentrations (SO_4^{2-}, NO_3^- and Cl^-) were measured on four ice-core sequences which showed high acid concentrations due to the Laki eruption (Site A, Dye 3, 4B and 18C). Anion concentrations in acid layers caused by the Tambora eruption were measured at two sites (Site A and 18C). The data from 18C is from Langway (1988, this volume). Along with these chemical ion-chromatographic analyses, liquid pH measurements were made and used to calibrate the ECM results. ECM data, converted into H^+ concentrations (in μeq/kg) by the calibration mentioned above, are shown as the thick curves in Figure 3a and b for the time interval A.D. 1782–85 and A.D. 1815–18 respectively.

The anion analyses show that sulfate was the dominant anion during both eruptions. The nitrate level is similar to that found in other time intervals and other ice cores from central Greenland (Steffensen 1988, this volume). No increase of NO_3^- takes place during the time of deposition of volcanic acid. Also the level of chloride concentration is similar to that observed in cores from other locations in Greenland (Langway and others 1988, this volume). The thin curves in Figure 3a and b show the sum of NO_3^- and excess SO_4^{2-} concentrations in μeq/kg, excess SO_4^{2-} is that left after the marine contribution has been removed. The marine contribution is defined as 0.10 × Cl^- concentration, when it is assumed that all Cl^- is of marine origin. This sum also reflects the acidity of the ice (Finkel and others 1986).

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TABLE IV. H_2SO_4 DEPOSITION IN GREENLAND FROM THE LAKI AND TAMBORA ERUPTIONS.

Site	Camp Century	North Central	Crête	Site A	Site B	Site D	Site E	Site G	Dye 3	4 B	18 C	Dye 2
Elevation m a.s.l.	1885	2930	3172	3092	3139	3018	3086	3098	2480	2491	2620	2100
Latitude °N	77.18	74.62	71.12	70.63	70.65	70.64	71.76	71.15	65.18	65.17	65.03	66.48
Longitude °W	61.11	39.60	37.32	35.82	37.48	39.62	35.85	35.84	43.83	43.93	44.39	46.33
Year ice core drilled	1977	1977	1974	1985	1984	1984	1985	1985	1979	1983	1984	1977
LAKI A.D. 1783												
L1 H^+ mean μeq/kg	32.22	9.61	8.21	8.97	11.06	15.19	6.50	11.91	13.39	16.94	12.43	23.43
L2 H^+ background μeq/kg	1.51	1.40	1.00	1.18	2.06	2.58	1.88	1.43	1.25	1.36	2.14	3.14
L3 H^+ volcanic μeq/kg	30.71	8.21	7.21	7.79	9.00	12.61	4.62	10.48	12.14	15.58	10.29	20.29
L4 Depth of volcanic event m	91.50	44.10	74.75	80.85	83.70	93.80	62.95	69.40	128.75	129.10	110.25	85.30
L5 Length of event: cm of core	21.7	35.0	47.3	30.0	45.0	55.0	35.0	35.0	33.0	25.0	42.8	26.0
L6 Density kg/m^3	899	709	823	836	841	857	786	807	881	881	880	895
L7 H^+ deposition meq/m^2	5.99	2.04	2.81	1.95	3.41	5.94	1.27	2.96	3.53	3.43	3.88	4.72
L8 H_2SO_4 deposition (H^+) kg/km^2	294	100	138	96	167	291	62	145	173	168	190	231
L9 H_2SO_4 background (H^+) kg/km^2	14	17	19	15	38	60	25	20	18	15	40	36
L10 H_2SO_4 deposition kg/km^2	–	–	–	150	–	–	–	–	168	170	190	–
L11 H_2SO_4 background kg/km^2	–	–	–	6	–	–	–	–	11	8	11	–
TAMBORA A.D. 1815												
T1 H^+ mean μeq/kg	7.81	4.81	4.13	4.18	6.17	6.96	2.63	5.16	2.78	4.37	2.85	
T2 H^+ background μeq/kg	1.71	1.93	1.36	1.92	2.92	2.46	1.73	1.86	1.30	2.08	2.12	
T3 H^+ volcanic μeq/kg	6.10	2.88	2.77	2.26	3.25	4.50	0.90	3.30	1.48	2.29	0.73	
T4 Depth of volcanic event m	78.50	38.00	64.70	70.90	73.00	81.50	53.40	60.50	111.60	111.65	95.20	
T5 Length of event: cm of core	24.0	50.0	49.3	65.0	55.0	70.0	40.0	75.0	85.0	99.0	79.0	
T6 Density kg/m^3	883	684	791	812	816	839	749	778	880	880	872	
T7 H^+ deposition meq/m^2	1.29	0.98	1.08	1.19	1.46	2.64	0.27	1.93	1.11	2.00	0.50	
T8 H_2SO_4 deposition (H^+) kg/km^2	63	48	53	58.41*	71	129	13	94	54	98	25	
T9 H_2SO_4 background (H^+) kg/km^2	18	32	26	50.23*	64	71	25	53	48	89	72	
T10 H_2SO_4 deposition kg/km^2	–	–	–	39	–	–	–	–	–	–	25	
T11 H_2SO_4 background kg/km^2	–	–	–	10	–	–	–	–	–	–	24	

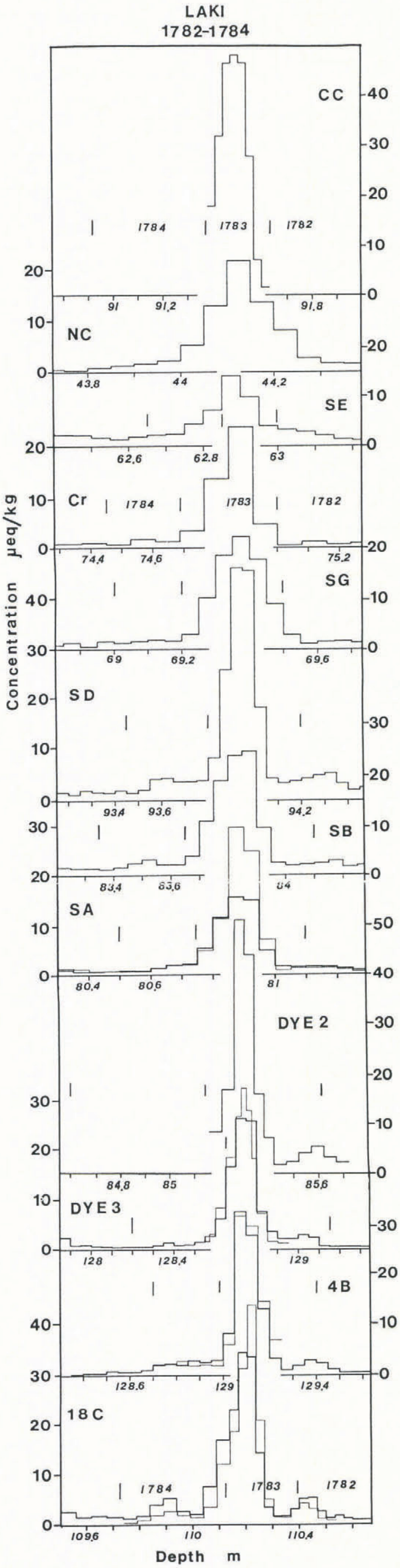

Fig.3a. The thick curve shows the H^+ concentration, in µ equivalent per kg of ice (µeq/kg), in the years around 1783 for the Greenland sites listed in Table IV. The H^+ concentration is determined by the ECM method. The thin curve (Site A, Dye 3, 4B and 18C) shows the sum of nitrate and excess sulfate, which reflects the acidity of the ice. The vertical bars indicate the start of a calendar year as determined by seasonal $\delta^{18}O$ variations.

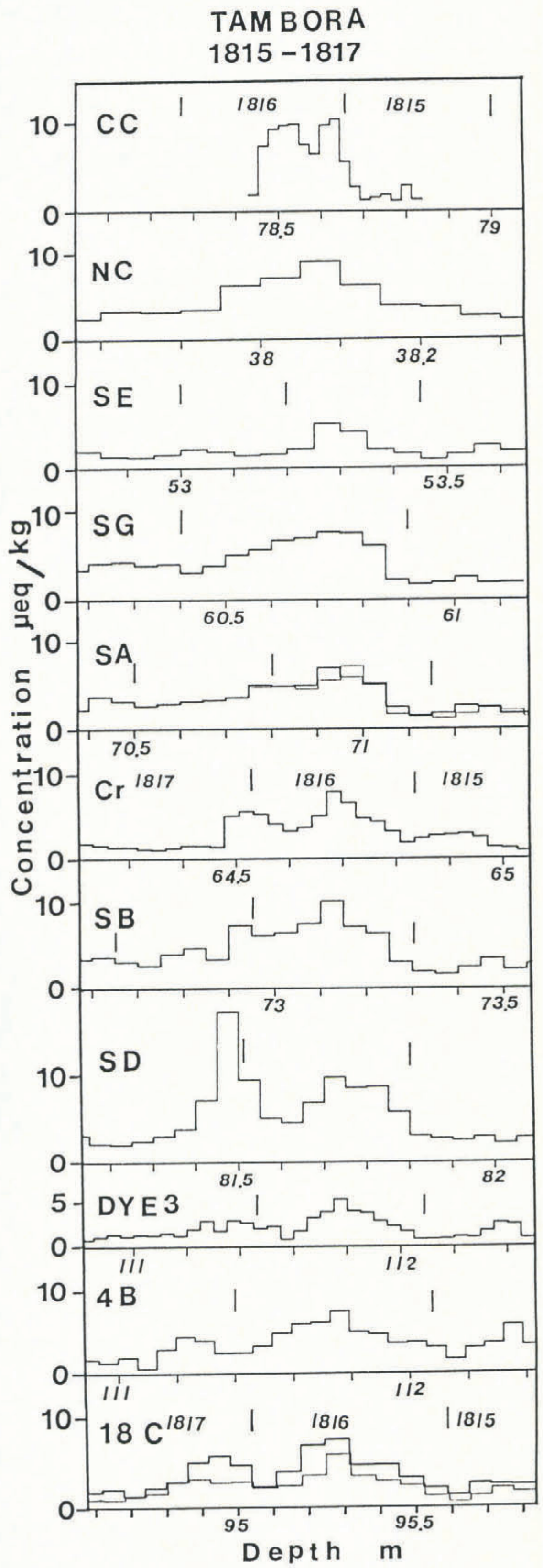

Fig.3b. H^+ and the sum of nitrate and excess sulfate concentrations for the Greenland sites listed in Table IV, in the years around maximum volcanic H_2SO_4 deposition, originating from the Tambora eruption. See also Figure 3a.

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Based on the measured H^+ and sulfate concentrations, we calculated the total deposition of volcanic H_2SO_4. This deposition is defined by the area above the background in Figure 3a and b. The results are listed in Table IV. Horizontal rows with the prefix L and T relate to data from Laki and Tambora respectively, and similar information is given in rows with the same number. Rows L1 and T1 show the mean concentration of H^+ over the interval of the volcanic deposition (row L5 and T5). In a similar way, rows 2 and 3 express the background H^+ concentrations and the volcanic H^+ concentrations of the Laki and Tambora eruptions.

If we compare the volcanic H_2SO_4 depositions determined by the H^+ and SO_4^{2-} measurements for the two eruptions (Table IV, rows 8 and 10), we see that the two sets of data are in close agreement even though the H^+ measurements are mainly based on a physical surface measurement (ECM), whereas the chemical data are based on "bulk" measurements.

If a similar comparison is made between the background H_2SO_4 depositions (rows 9 and 11), a clear difference is displayed. The H_2SO_4 background determined by the H^+ method (row 9) is significantly higher than the background determined by the SO_4^{2-} analysis (row 11), because HNO_3 makes up a substantial amount of the natural-acidity background. Volcanic and background H_2SO_4 deposition values (58 and 50 kg/km^2) for Tambora at Site A have to be corrected. This is because the anions were not measured over the entire ice-core sequence (see Fig.3b, Site A). If corrected, the volcanic H_2SO_4 and background depositions (marked with an asterisk) are 41 and 23 kg/km^2 respectively.

The west–east (Site D – Site B) change in the volcanic-acid deposition rates from the Laki and Tambora eruptions shows a decreasing trend of some 40%, similar to that found from the total β measurements. Quite different from this is the decreasing trend in volcanic-acid deposition of some 70% across the ice divide from Site B to Site E, where both volcanic-acid concentration and accumulation show decreasing trends. $\delta^{18}O$ and accumulation-rate studies reported by Clausen and others (1988, this volume) imply that Site E is located in an accumulation "shadow" area, i.e. it has a relatively low rate of accumulation as compared to, for instance, the corresponding region west of the ice divide.

ESTIMATE OF THE MAGNITUDE OF THE LAKI AND TAMBORA ERUPTIONS

The assumption of a similar global distribution pattern of the bomb-produced "total β activity" (i.e. ^{90}Sr + ^{137}Cs) and strong acids (e.g. H_2SO_4) injected into the atmosphere by violent volcanic activity at a given latitude, makes it possible to calculate the magnitude of the volcanic eruption in terms of millions of tons of H_2SO_4. The magnitude of the Laki and Tambora eruptions is calculated by comparing the volcanic H_2SO_4 deposition from these events with the total β deposition originating from known fission yields injected at HNL and LNL respectively (Table I).

All locations for which both total β data (Table II) and volcanic-acid data (Table IV) exist, are combined in Table V. The total β data used for Laki and Tambora are HNL and LNL values respectively.

Column 3 in Table V shows that the HNL injection of 22.6 MCi total β activity (Table I), e.g. at Camp Century, is equal to 1.32 × 10^9 times the total β deposition per km^2 at this site. In a similar way, column 7 in Table V shows that the LNL injection of 9.6 MCi total β activity (Table I), e.g. at Camp Century, is equal to 3.34 × 10^9 times the total β deposition per km^2 at this site.

Calculated in this way, the total amount of H_2SO_4 injected by the Laki and Tambora eruptions is 280 × 10^6 tons and 220 × 10^6 tons respectively.

The standard deviations of the magnitudes listed in columns 4 and 8 in Table V correspond to 30 and 17% of the Laki and Tambora mean magnitudes respectively. Sastrugi (or snow-drift) noise in Greenland typically results in accumulation-series noise of about 40% of the yearly value (Fisher and others 1985), which to some degree must be reflected in the estimated magnitude.

The magnitude of the Tambora eruption is calculated to be 360 × 10^6 tons by Langway and others (1988, this volume), based on Antarctic ice-core data from South Pole. Legrand and Delmas (1987) estimate the magnitude to be 150 × 10^6 tons of sulphuric acid, based on ice-core evidence from Dome C in Antarctica. Our estimate of the magnitude will probably underestimate the acid production because the total β injection and the volcanic eruption occur at different latitudes, i.e. the site of the volcanic eruption was more distant from Greenland than the bomb-test site, and the opposite is the case in Antarctica.

The magnitude of the Laki eruption may be overestimated because the gases ejected by this lava eruption barely reached the stratosphere and thus in this case the assumption of a similar distribution of volcanic gases and total β does not hold. This may also be the explanation of the difference between our estimate and that of Hammer and others (1980) (a factor of 2–3), as they used the total β deposition over the year 1962 as a basis for their calculation. In the case of Tambora this error should not occur, because the acid gases reached the stratosphere.

CONCLUSIONS

The acid layers in Greenland ice from the two major volcanic eruptions, Laki (A.D. 1783) and Tambora (A.D. 1815), are easy to reach by shallow drilling and are therefore well suited for the study of deposition rates of volcanic acids. The suite of Greenland sites which has been investigated exhibits a uniform rate of deposition of total β activity from atmospheric bomb tests and of sulphuric acid from major volcanic eruptions (except for the region north-east of Crête, at Site E). Combination of the deposition patterns determined by bomb-produced total β activity and volcano-produced strong acid allows one to calculate the magnitude of these volcanic events. The total global deposited amount of sulphuric acid from the Laki and Tambora eruptions (281 and 222 × 10^6 tons

Table V. MAGNITUDE OF THE LAKI AND TAMBORA ERUPTIONS.

	LAKI				TAMBORA			
	1	2	3	4	5	6	7	8
Region	Deposition volc.H_2SO_4 kg/km^2	Deposition total β mCi/km^2	$\left(\frac{22.6\ MCi}{Dep.total\ \beta}\right)$ × 10^9	Magn. 10^6 tons H_2SO_4	Deposition volc.H_2SO_4 kg/km^2	Deposition total β mCi/km^2	$\left(\frac{9.6\ MCi}{Dep.total\ \beta}\right)$ × 10^9	Magn. 10^6 tons H_2SO_4
Camp Century	294	17.1	1.32	389	63	2.87	3.34	211
North C	100	12.0	1.88	188	48	1.75	5.49	263
Crête	137	15.1	1.50	205	69	3.51	2.74	189
Milcent	291	24.6	0.92	267	129	4.79	2.00	259
Dye 3	177	14.7	1.54	272	59	3.02	3.18	188
Dye 2	231	14.3	1.58	365	–	–	–	–
Mean				281 ± 82				222 ± 37

respectively) is among the largest recorded in the continuous acidity record from Dye 3, which covers the last 10 000 years. The magnitude of the Tambora eruption presented here is in agreement with other reported values based on ice-core evidence from Antarctic data.

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REFERENCES

Clausen H B, Gundestrup N S, Johnsen S J, Bindschadler R, Zwally J 1988 Glaciological investigations in the Crête area, central Greenland: a search for a new deep-drilling site. *Annals of Glaciology* 10: 10-15

Dansgaard W, Johnsen S J, Clausen H B, Gundestrup N 1973 Stable isotope glaciology. *Meddelelser om Grønland* 197(2)

Finkel R C, Langway C C Jr, Clausen H B 1986 Changes in precipitation chemistry at Dye 3, Greenland. *Journal of Geophysical Research* 91(D9): 9849-9855

Fisher D A, Reeh N, Clausen H B 1985 Stratigraphic noise in time series derived from ice cores. *Annals of Glaciology* 7: 76-83

Hammer C U 1980 Acidity of polar ice cores in relation to absolute dating, past volcanism, and radio-echoes. *Journal of Glaciology* 25(93): 359-372

Hammer C U 1984 Traces of Icelandic eruptions in the Greenland ice sheet. *Jökull* 34: 51-65

Hammer C U, Clausen H B, Dansgaard W 1980 Greenland ice sheet evidence of post-glacial volcanism and its climatic impact. *Nature* 288(5788): 230-235

Langway C C Jr, Goto-Azuma K 1988 Temporal variations in the deep ice core chemistry record from Dye 3, Greenland. *Annals of Glaciology* 10: 209

Langway C C Jr, Clausen H B, Hammer C U 1988 An inter-hemispheric time-marker in ice cores from Greenland and Antarctica. *Annals of Glaciology* 10: 102-108

Legrand M, Delmas R J 1987 A 220-year continuous record of volcanic H_2SO_4 in the Antarctic ice sheet. *Nature* 327(6124): 671-676

Steffensen J P 1988 Analysis of the seasonal variation in dust, Cl^-, NO_3^- and SO_4^{2-} in two central Greenland firn cores. *Annals of Glaciology* 10: 171-177

United Nations Scientific Committee on the Effects of Atomic Radiation 1982 *Ionizing radiation: sources and biological effects. Report to the General Assembly, with annexes.* New York, United Nations. Annex E: 211-248