Evidence for Changes in Climate and Environment in 1816 as Recorded in Ice Cores from the Quelccaya Ice Cap, Peru, the Dunde Ice Cap, China and Siple Station, Antarctica

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Abstract

The climate and environmental records preserved in three ice cores from three quite different sites (the tropical Quelccaya Ice Cap, Peru, the subtropical Dunde Ice Cap, China, and the Antarctic Ice Sheet, Siple Station) are examined for the period 1808-21. Emphasis is placed upon identifying potential changes in climate following the eruption of Tambora in 1815. Ice cores provide a multifaceted record of past variations in the Earth's climate and environment.

Historical documentation is scarce or absent for these three sites where the dust concentrations, electrical conductivity, net accumulation, oxygen isotopic abundances and seasonal ranges for 1808-21 are compared with the modern levels. For Siple Station $C\ell^-$ and SO^{2-}_4 levels are included as polar precipitation most closely represents atmospheric background levels.

The climatic and environmental variations of the early 1800s are discussed in the perspective of variations over the last 500 years available from each of these three ice-core sites. These records indicate that while there is an apparent global signal produced by the 1815 eruption of Tambora as recorded in the ice cores, the climatic response at each site is quite complex. The Dunde and Quelccaya sites reveal a cooling trend underway before the eruption; although the eruption may have strengthened the cooling trend that culminated in the coldest isotopic year (1819 at all three sites) of the decade 1810-20. Moreover, the year 1819-20 is the isotopically coldest year in the entire 1500-year record from the two Quelccaya ice cores. On the other hand, the mean isotopic temperatures for the 1810-20 decade appear to have been warmer at Siple Station in comparison to the modern "norm".

Dust records indicate no significant signal in insoluble particle concentrations above the high levels that characterized much of the Little Ice Age. A significant peak in conductivity for the Dunde Ice Cap, China records and in sulphate, excess sulphate and conductivity for the Siple Station, Antarctica records occur in 1817.

Introduction

Reliable meteorological observations for climate reconstruction prior to 1850 are scarce or absent for most of the globe. Ice caps and ice sheets provide an archive of atmospheric history which pre-dates human observations. It is recognized that much of the important climatic history of the Earth never reaches the polar regions and thus, would be lost if the poles were the only sites from which ice cores were recovered. Ice-core records from three sites: the Quelccaya Ice Cap, Peru (13°56'S; 70°50'W: 5670 m a.s.l.), the Dunde Ice Cap, China (38°06'M; 96°24'E: 5325 m a.s.l.) and Siple Station, Antarctica (75°55'S; 84°15'W: 1054 m a.s.l., Figure 1), are examined on an annual basis from 1808 to 1820 to ascertain the potential impact of the 1815 eruption of Tambora on climate and the environment.

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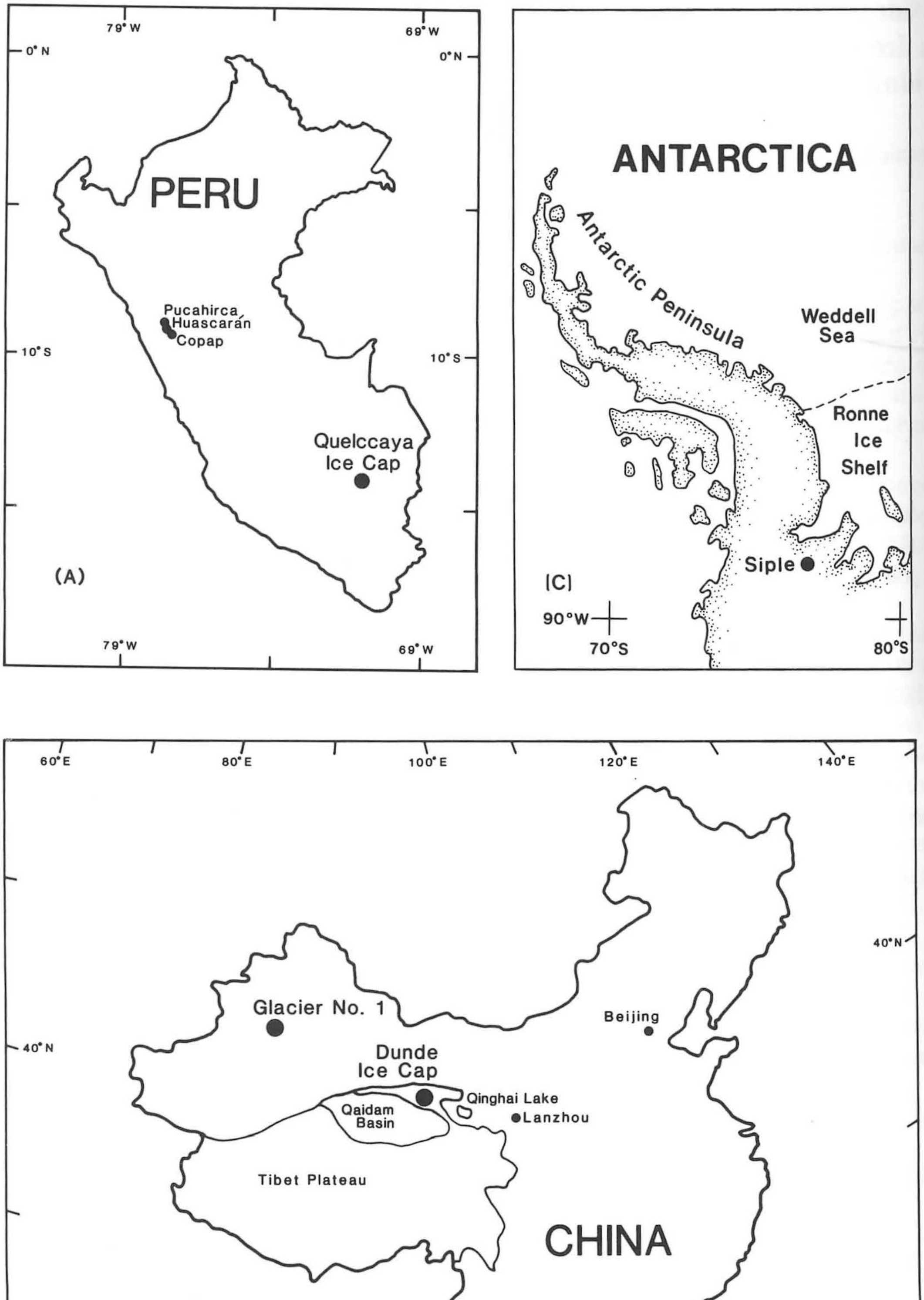

Figure 1: Ice core location maps: (A) Quelccaya Ice Cap, Peru (B) Dunde Ice Cap, China and (C) Siple Station, Antarctica.

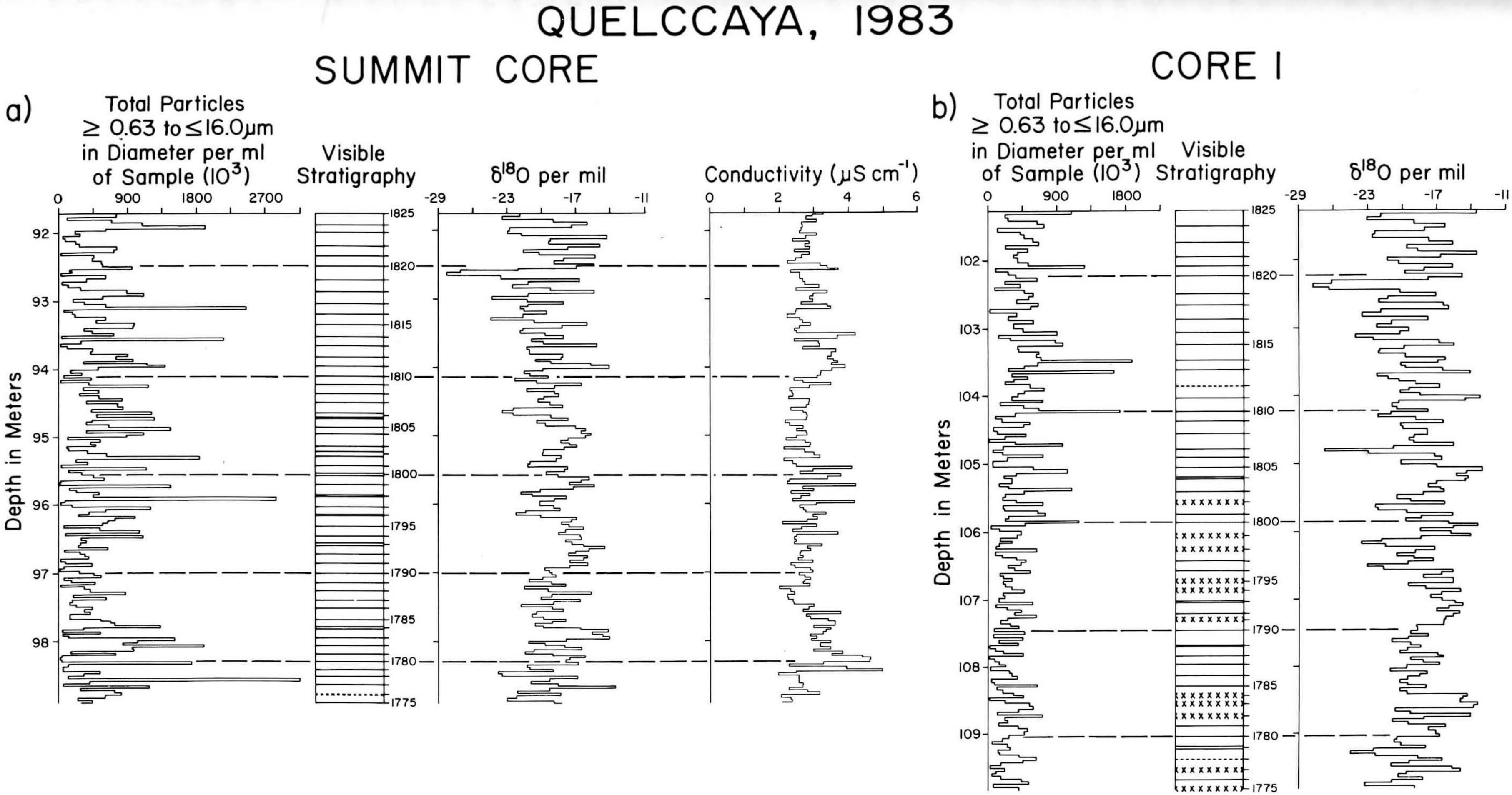

Figure 2: The stratigraphic parameters used to date ice cores are illustrated for the period 1775-1825 in the Quelccaya summit core (A) and core 1 (B). Annual signals are recorded in microparticle concentrations (particles from 0.63 to 16.0 μm in diameter per ml sample), oxygen isotopic ratios, electrical conductivity (summit core only), and visible stratigraphy. For stratigraphy, a single solid line represents a normal dry-season dust layer; a single dashed line and a double dashed line represent very light and light dust layers, respectively. Series of Xs

For each site, identical samples were analyzed for microparticle concentrations and size distributions, electrical conductivity and oxygen isotopic abundances. The microparticle, conductivity and chemistry measurements were made under class 100 clean room conditions at Ohio State University, and $\delta^{18}0$ analyses were conducted at the University of Copenhagen and at the University of Washington.

Dating of the ice cores was accomplished using several stratigraphic features that exhibit seasonal variability. For the Dunde and Quelccaya cores, stratigraphic dating was possible using visible, annual dust layers in conjunction with annual variations in microparticle concentrations, conductivity, chemistry and oxygen isotopes. Using Quelccaya as an example, Figure 2 illustrates how both the Quelccaya and Dunde cores were dated. Here the annual record over a 50-year period from 1775 to 1825 for two cores, the summit core and core 1, is illustrated. Thus, the dating is confirmed through a series of cross-checks and allows evaluation of the reproducibility of the ice-core records (Thompson *et al.* 1986). The initial dating of the Siple core is based only on the seasonality of $\delta^{18}0$ (Mosley-Thompson *et al.* submitted). Sulphate and nitrate concentrations also exhibit an excellent seasonal signal (Dai *et al.* submitted), and the final time scale will be produced using cross-checks among these three constituents ($\delta^{18}0$ $S0^{2-}{}_4$, $N0_3^-$).

The Little Ice Age recorded in the northern hemisphere earlier in this millennium was characterized by colder temperatures and expanded glaciers. Little Ice Age dates, determined from historical and proxy climatic records, vary depending on location and observed parameters (Thompson *et al.* 1986; Grove 1988). However, here we used the term Little Ice Age for the period 1500-1880.

The eruption of Tambora (8°S, 118°E) on 10 and 11 April 1815 was the largest and most deadly eruption in recorded history (Stothers 1984). Moreover, it is believed to have been the greatest ash eruption in the last 10,000 years. It is significant that this eruption can be seen in records presented here for both Greenland (Hammer *et al.* 1978) and Siple Station, Antarctica. A potential temperature response to this eruption is seen in oxygen isotope records at such widely dispersed ice-core sites as the Andes of Peru and the Qinghai-Tibetan Plateau of China. These records, when viewed in terms of the well-documented period of unusual temperatures in parts of North America and Europe, including "the year without a summer, 1816" (Milham 1924; Hoyt 1958; Stommel and Stommel 1983; and Stothers 1984), strongly suggest a global impact. The instrumental, historical, and proxy data (including the ice-core data presented here) also indicate that although global in scale, the specific climatic response at any given site was quite complicated. This was documented in the northern hemisphere instrumental records (Deirmendjian 1973; Landsberg and Albert 1974). Thus, the first step to understanding the impact on global climate of a volcanic eruption the magnitude of Tambora requires the compilation of existing data sets and the acquisition of new data sets from regions where such information is absent.

In Figures 3-6 and Tables 1 (A-C), the period 1808-21 is compared to modern "norms" for the Quelccaya Ice Cap, Peru, the Dunde Ice Cap, China, and the Antarctic Ice Sheet at Siple Station. These figures and tables allow comparisons of: (1) large, small and total particles and electrical conductivity indicating variations in concentration of insoluble and soluble dust, respectively; (2) relative changes in precipitation as recorded by average net accumulation in metres of ice equivalent; and (3) proxy temperatures as recorded by oxygen isotopes. These data are presented both as annual means and annual ranges between extreme values. In Figure 5 and Table 1 (C), $C\ell^-$, $S0^{2-}{}_4$ and excess $S0^{2-}{}_4$ values are presented for 1808-21 for Siple Station, Antarctica. Remote from local sources, Antarctica provides an ideal site for recording major volcanic eruptions.

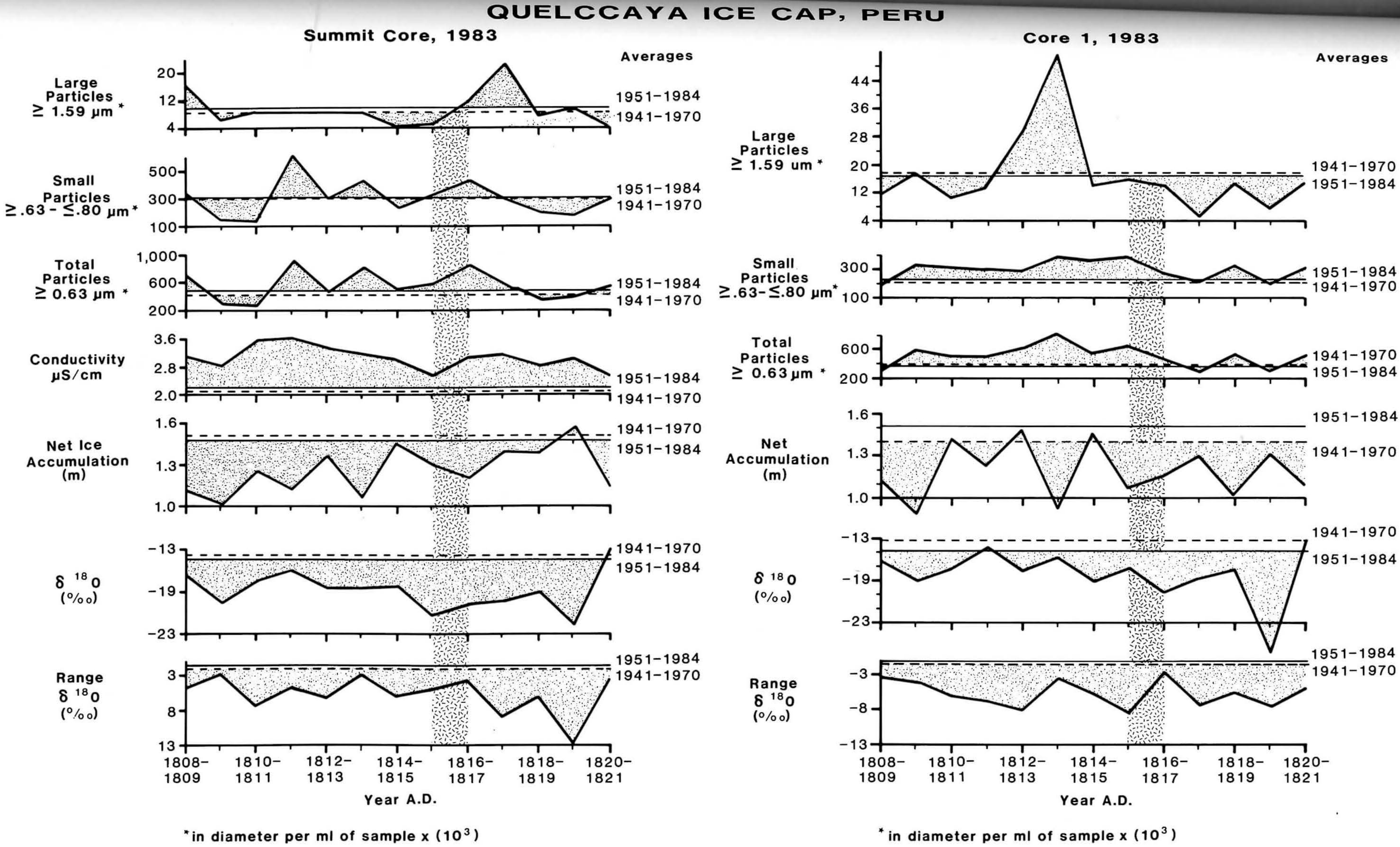

Figure 3: Quelccaya Ice Cap, Peru ice-core record of summit core and core 1 for the period 1808-21 of microparticle concentrations, conductivity, net ice accumulation, $\delta^{18}0$ and range of $\delta^{18}0$. Solid line indicates the 1951-84 mean and the dashed line indicates the 1941-70 mean.

Table 1 (A): Quelccaya Ice Cap, Peru.[1]

Summit Core	$\delta^{18}O$‰	.63-.80 μ	≥.63 μm	≥1.59 μm	Cond. (μS/cm)	Accumulation Ave-ice (m)	Accumulation Range $\delta^{18}O$‰
1941-1970 31 years	-17.4	300734	475840	8308	2.145	1.516	1.71
1951-1984 33 years	-17.6	305948	489378	9441	2.098	1.486	1.54
1808-1821	-19.9	316271	551253	9278	2.900	1.259	5.70
Δ	-2.5	+15537	+75413	+163	+0.755	-0.257	+3.99

Core 1	$\delta^{18}O$‰	.63-.80 μm	≥.63 μm	≥1.59 μm	Accumulation Ave-ice (m)	Accumulation Range $\delta^{18}O$‰
1941-1970 31 years	-17.2	215641	382217	17401	1.398	1.31
1951-1984 33 years	-17.9	230380	357874	17243	1.513	1.27
1808-1821	-19.7	295731	516310	16778	1.166	5.86
Δ	-2.5	+80090	+134073	-623	-0.232	+4.55

[1] Tables 1 (A), (B) and (C) represent modern averages for 1941-70 and 1951-84, averages for 1808-21 and the differences between 1941-70 and 1808-21 period (Δ) of $\delta^{18}O$, number of small, medium and large diameter particles per ml of sample, conductivity, average accumulation in metres of ice equivalent and the range of $\delta^{18}O$ for the three sites mentioned. In addition, for the Siple Station, Antarctica site, modern averages for of 1965-85, averages for 1808-21, and the differences between the modern average and the 1808-21 period (Δ) of $C\ell^-$, SO^{2-}_4 and excess SO^{2-}_4 are presented.

The Quelccaya Ice Cap is situated immediately east of the high dry Altiplano (Thompson *et al.* 1984) whereas the Dunde Ice Cap has the Gobi Desert to the north and west and the dry Qaidam Basin to the southwest. Thus the dust records at both sites are dominated by local sources (Thompson *et al.* 1988a). Figure 3 and Table 1 (A) compare the 1808-21 period with two modern "norms", 1951-84 and 1941-70 for two cores from the Quelccaya Ice Cap, Peru. The year 1815-16 is shaded. In Peru 1810-20 is characterized by high dust concentrations, more negative oxygen isotopic ratios, and reduced accumulation. Note that these are characteristic of most of the Little Ice Age on this Ice Cap (Thompson *et al.* 1986; Thompson *et al.* 1988c; Thompson and Mosley-Thompson, in press). Thus, this decade is believed to have been colder, drier and dustier than present at this tropical site. Although there is no obvious indication of the Tambora eruption in the dust record, this is not unexpected in view of the predominance of the Altiplano as a major local source of dust. However, the oxygen isotope records show a cooling that reaches a minimum in 1819-20. This minimum is the lowest in the entire 1500 years preserved in the two ice cores.

Figure 4 and Table 1 (B) compare the 1808-21 period with the modern "norms" 1951-84 and 1941-70 for the Dunde Ice Cap, China. The year 1815-16 is shaded. 1810-20 is characterized in central China with lower (more negative) oxygen isotope values, low accumulation and higher dust concentrations. Again, these features are also characteristic of much of the Little Ice Age in this part of the world, and are consistent with records from the Quelccaya Ice Cap. Thus, the ice-core record suggests that conditions were colder, drier and dustier than present. However, the period following the eruption of Tambora shows: (1) a decrease in oxygen isotopes, with the most negative values occurring in 1819-20; and (2) an increase in conductivity (soluble dust) in 1817-18.

For Siple Station, Antarctica, Figure 5 and Table 1 (C) compare the characteristics of 1808-21 period with the modern "norms" 1941-70, except for anion concentrations for which the period 1965-85 is used. The decade 1810-20 is characterized by less insoluble dust, and more soluble dust, generally less accumulation, higher (less negative) oxygen isotope values, generally lower chloride values and higher sulphate and excess sulphate levels than found in the modern record. Thus, the only common features of the Little Ice Age with those in the China and Quelccaya ice cores are the higher electrical conductivity values and lower accumulation. The isotopic values may reflect warmer temperatures near the Siple Station, Antarctica during this period. The $\delta^{18}O$ is also subject to other interpretations possibly related to changes in sea-ice extent and hence, changes in distance from the moisture source. Following the eruption of Tambora in 1815-16, there is a major increase in conductivity, sulphate and excess sulphate between 1817 and 1819 that can probably be attributed to the eruption of Tambora. The mean oxygen isotope values actually rise (less negative) after the eruption with the lowest (most negative) values of the decade occurring in 1819-20, consistent with the Dunde and Quelccaya ice-core results.

Figure 6 illustrates the interannual variability in sulphate and oxygen isotopes for the period 1810-27. These plots of actual sample measurement illustrate the distinct seasonal record in both the sulphate (shown for two cores, A and B), and oxygen isotopic ratios used to date these cores. Evidently the Siple Station, Antarctica record has the clearest signal of the Tambora eruption, which is recorded in the sulphate signature and is reproducible in two cores. The sulphate deposited during 1817-19, essentially two years after the eruption, is consistent with the time lag in transport of stratospheric radioactivity to Antarctica (Lambert *et al.* 1977). However, the oxygen isotope record shows no apparent response to this eruption. The only meteorological parameter that potentially shows a change following the eruption is a rather sharp decrease in accumulation in 1817, which may or may not be related to the eruption of Tambora.

Discussion

Ice sheets and ice caps are now recognized as libraries for proxy climatic and environmental histories that can be used to extend historical records. Attempts to describe global climatic changes have been hampered by the lack of historical records from the southern hemisphere and the tropics. The Dunde, Quelccaya and Siple Station ice-core records allow, for the first time,

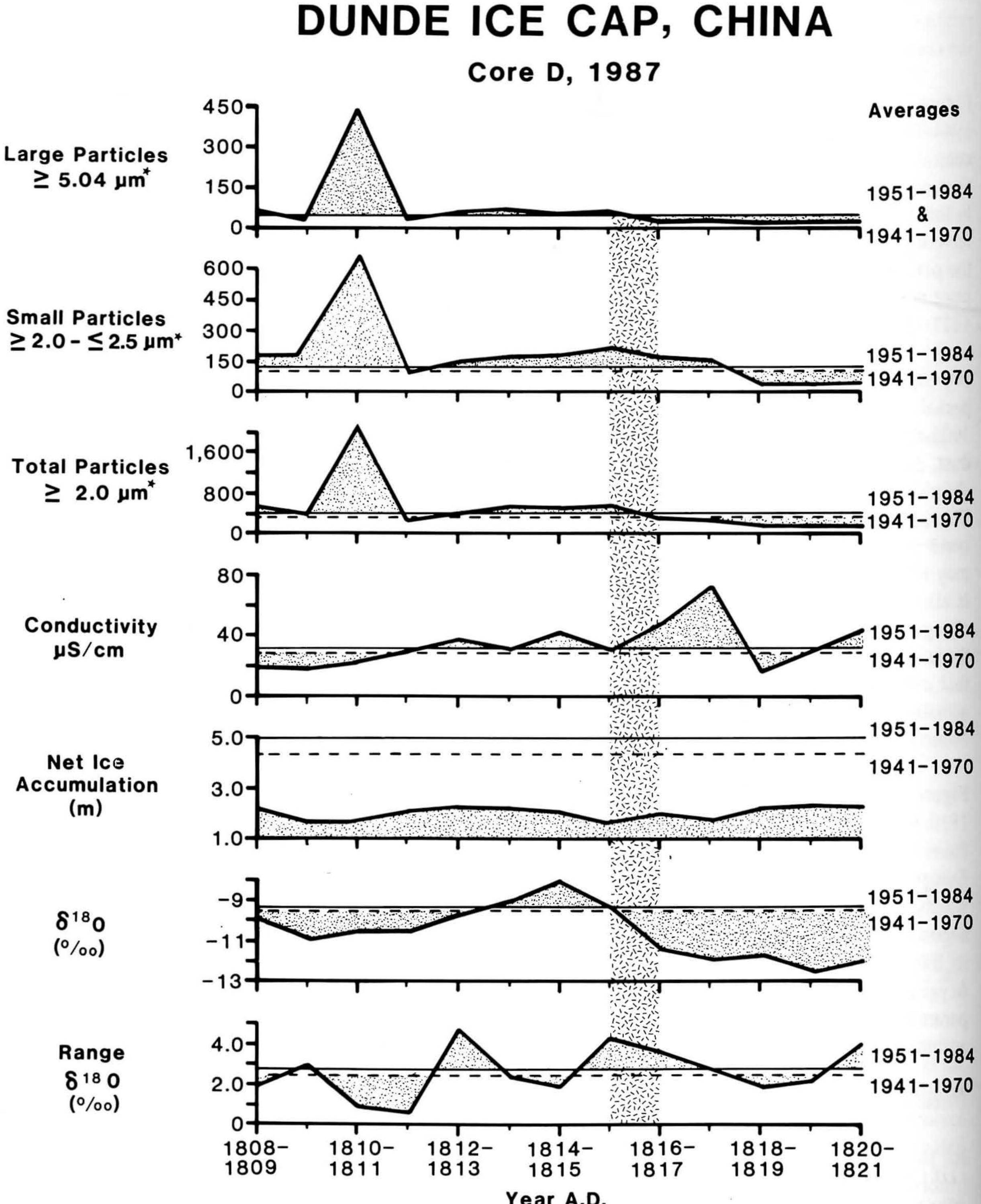

Figure 4: Dunde Ice Cap, China ice-core record for the period 1808-21 of annual variations in microparticle concentrations, conductivity, net ice accumulation, $\delta^{18}O$ and range of $\delta^{18}O$. Solid line indicates the 1951-84 mean and the dashed line indicates the 1941-70 mean.

Table 1 (B): Dunde Ice Cap, China.[1]

Core 1	$\delta^{18}0$‰	2.0-2.52 μm	$\geq$2.0 μm	$\geq$5.04 μm	Cond. (μS/cm)	Accumulation Ave-ice (m)	Accumulation Range $\delta^{18}0$‰
1941-1970 31 years	-9.6	94106	245031	35052	26.946	0.43	2.25
1951-1984 33 years	-9.5	106728	275643	35820	28.220	0.50	2.56
1808-1821	-10.8	+152769	+424538	+66154	+32.300	0.20	2.51
Δ	-1.2	+58663	+179507	+31102	+5.54	-0.23	-0.26

[1] For explanation see Table 1 (A) footnote.

annual reconstruction of events at all three sites. These records permit a preliminary assessment of change and environmental variations for the early 1800s in general, and the year 1816, in particular.

In the subtropical and tropical sites of Dunde and Quelccaya, respectively, the period 1808-21 was colder, drier and dustier than modern levels. These conditions are deduced from a 14% decrease in oxygen isotope values at both the Dunde and Quelccaya sites, an average increase of 60% for insoluble particles on the Dunde Ice Cap, an average increase of 20% for insoluble particles on the Quelccaya Ice Cap, an average increase of 35% in soluble dust for both Dunde and Quelccaya, and an accumulation decrease of 50% for Dunde and 17% for Quelccaya when compared to the modern period 1941-84. For both Quelccaya cores the 1910-20 decade is characterized by the most negative $\delta^{18}0$ (coldest temperatures). The lowest mean decadal values are -20.14 in the summit core and -20.01‰ in core 1, which are 0.63 and 0.67‰ lower than the next coldest decade (1750-60). Additionally, the lowest $\delta^{18}0$ values measured in both cores occur during the southern hemisphere wet season of 1819-20. The lowest values are -28.25‰ (summit core) and -27.90‰ (Core 1) which are 2.65‰ and 1.02‰ lower than the next lowest value in their respective cores. The Dunde oxygen isotope values are low for the decade, with the low value of -12.80‰ occurring in 1819-20. However, in the China record, many years during the Little Ice Age have lower values, with 1779 and 1852 exhibiting significantly lower values of -14‰.

Particle analyses for the Quelccaya and Dunde ice cores for the decade 1810-20 show no significant change in particle concentrations above the high levels that characterize much of the Little Ice Age. Probably abundant local dust sources mask any potential change due to distance from particle sources such as the eruption of Tambora. The liquid conductivity profile for the Dunde site shows a prominent peak for the decade in the year 1817-18.

The $\delta^{18}0$ records from Siple Station, Antarctica, have an average oxygen isotope value for the 1810-20 decade which is 0.50‰ higher than the modern "norm" (1941-70). Moreover, these

Table 1 (C): Siple Station, Antarctica.

	$\delta^{18}O$‰	.63-.80 μm	$\geq 0.63\ \mu m$	$\geq 1.59\ \mu m$	Cond. ($\mu S/cm$)	Accumulation H_2O eq. (m)	Accumulation Range $\delta^{18}O$‰
1941-1970 30 years	-29.94	1347	3089	257	2.16	0.540	-6.43
1951-1984 33 years	-29.85	NA	NA	NA	2.16	0.556	-7.21
1808-1821	-29.44	777	1905	176	2.33	0.468	-6.55
Δ	+0.50	-570	-1184	-81	+0.17	-0.07	1.12

	Cl^-	SO^{2-}_4	Excess SO^{2-}_4
1965-1985 20 years	2.46	0.77	1.37
1808-1821	1.77	1.35	1.17
Δ	-0.69	+0.58	-0.20

[1] For explanation see Table 1 (A) footnote.

records show a major electrical conductivity and SO^{2-}_4 peak associated with the years 1817-19. Thus, while the Siple Station record contains the strongest physical evidence of the Tambora eruption, there is little evidence of a coding response in the oxygen isotopes, and in fact, the $\delta^{18}O$ values actually *rise* (warming) after the eruption. On the other hand, note that 1819 ($\delta^{18}O$ -13.5‰) contains the lowest annual value for the decade which is consistent temporally with the Quelccaya and Dunde ice-core records.

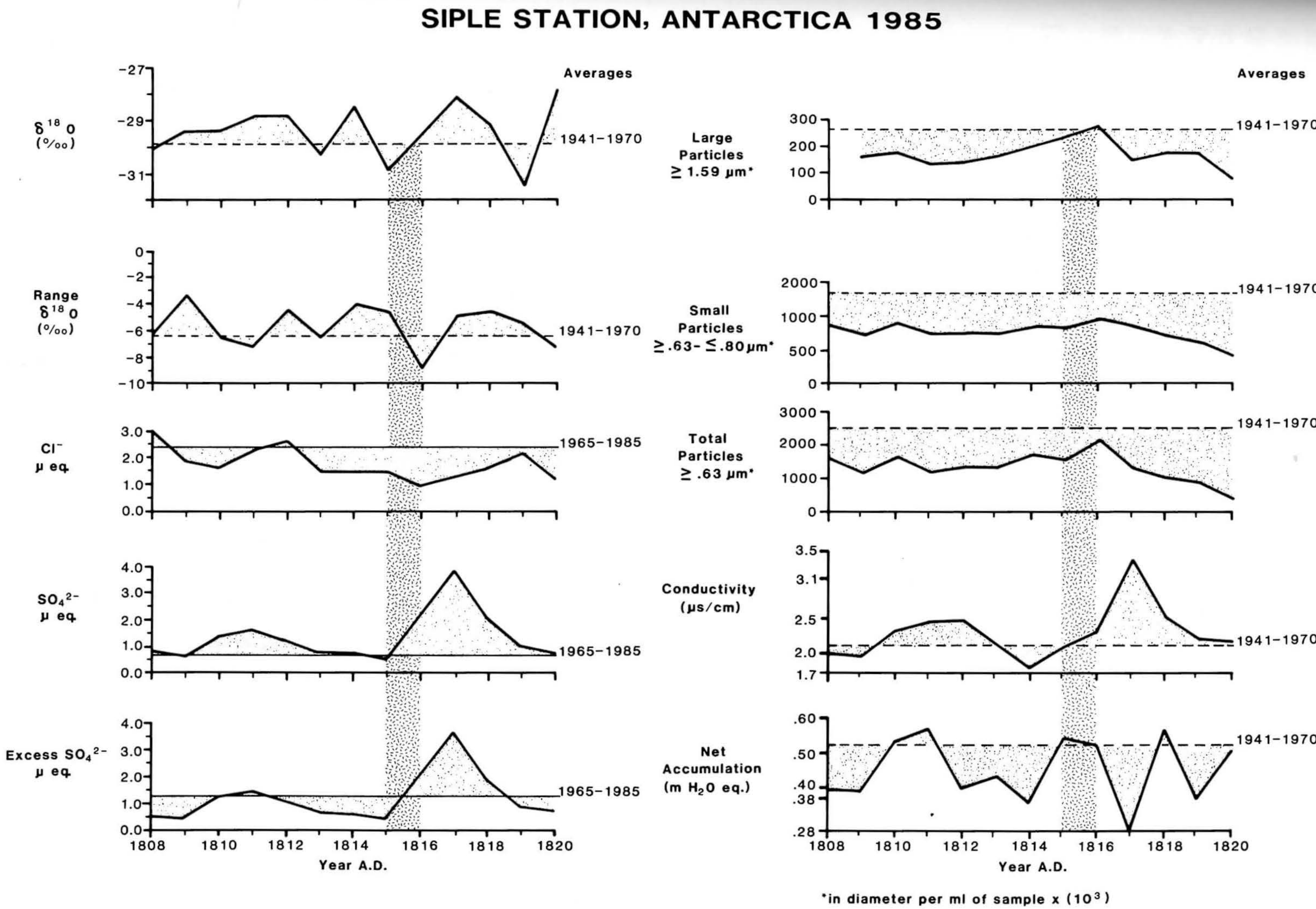

Figure 5: Siple Station, Antarctica, ice-core record of $\delta^{18}0$, range of $\delta^{18}0$, $C\ell^-$, SO^{2-}_4 and excess SO^{2-}_4, expressed as μ equivalents per litre, microparticle (insoluble) concentrations, electrical conductivity and net accumulation for the period 1808-20. The solid line is the 1965-85 mean for anion concentrations and the dashed line is the 1941-70 mean for all other analyses.

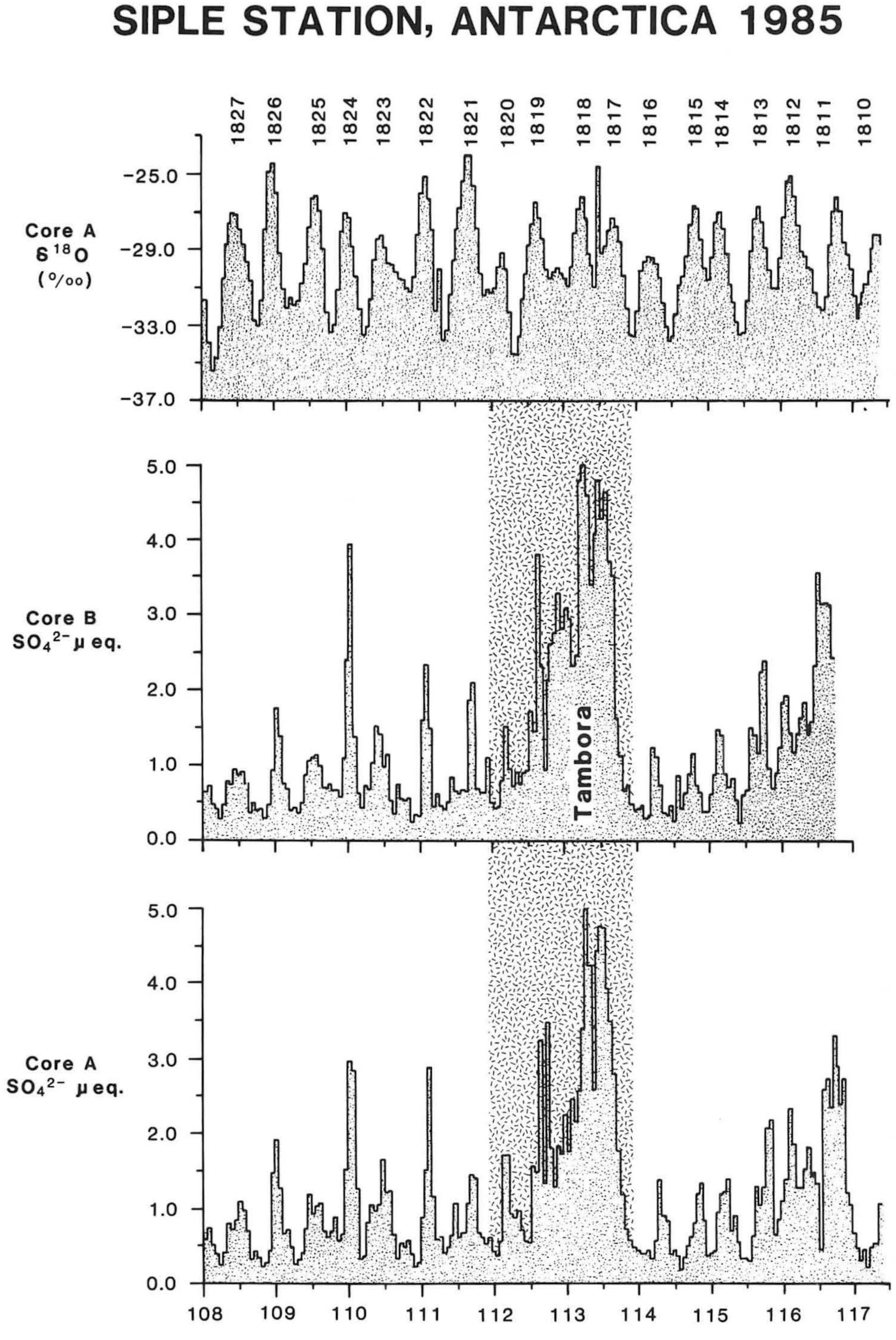

Figure 6: A 10-meter section from cores A and B drilled at Siple Station, Antarctica. These show individual sample measurements of SO^{2-}_4, concentration and demonstrate the reproducibility (and hence the reliability) of the chemistry record. Individual analyses of $\delta^{18}O$ are also given for core A. The annual variation in $\delta^{18}O$ and SO^{2-}_4 data are readily apparent and illustrate the methods by which the cores were dated. Tambora stands out in both cores A and B as a period of enhanced concentrations of SO^{2-}_4 for 1817-19.

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