EVIDENCE OF ABRUPT CLIMATIC CHANGE DURING THE LAST 1,500 YEARS RECORDED IN ICE CORES FROM THE TROPICAL QUELCCAYA ICE CAP, PERU

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ABSTRACT. Reliable observations of climatic variation prior to 1850 are limited or absent for many regions, especially *South America*. Ice sheet and ice caps can provide a valuable supplement to historical and other proxy records. The *tropical* Quelccaya ice cap in Peru (5,670m) has provided a *1500-year* record of *climatic variability*. Abrupt climatic events are recorded in this ice by *microparticle concentrations*, *conductivities* and *oxygen isotopes* which are discussed in detail for three periods: A.D. 1928-1947, 1864-1905 and 1452-1550. These data suggest that both the onset and termination of the "*Little Ice Age*" were abrupt in tropical South America.

INTRODUCTION

Climate fluctuations over the last 1,000 years represent the most probable range of natural variability for the next century and are of great interest. Therefore historical records chronicling the extent of past climatic changes over the last 1,000 years are ideal for assessing the time scales and amplitudes of change. Unfortunately, long historical records are geographically restricted to the Orient (China and Japan) and West Europe (Gribbin and Lamb, 1978). In the Southern Hemisphere, and especially in South America, the reconstruction of global climate changes depend almost entirely upon proxy records such as ice cores, tree rings and lake sediments.

Tropical and subtropical conditions inhibit the formation of seasonal rings (Stockton et al., 1985), thus, dendroclimatological records from Ecuador, Peru, and Brazil and southward along the eastern flank of the Andes to about 23°S are very limited. Fortunately, some ice fields in the Andes contain records of tropical and subtropical climatic variability with high temporal resolution over several millennia. In an effort to obtain such a record, a field program has been conducted on the Quelccaya ice cap each summer for the period 1976 through 1984 with one central objective - to recover an ice core to bedrock. It was anticipated that a 1,000-year climatic history for tropical South America could be reconstructed. The Quelccaya ice cap program was designed as a

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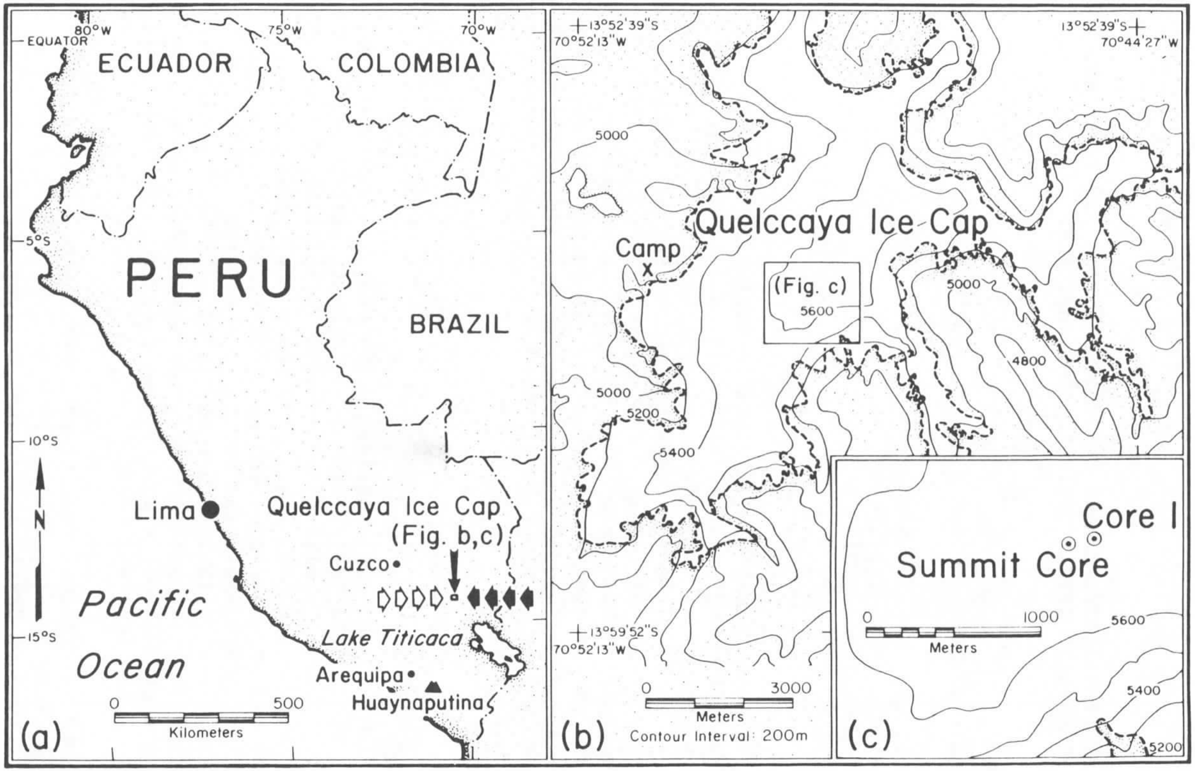


Figure 1a. Location of the Quelccaya ice cap. Black arrows indicate dominant wet season wind direction while the open arrows indicate dominant dry season wind directions (Schwerdtfeger, 1976), 1b shows map of ice cap and 1c illustrates the locations of two long cores drilled in 1983.

field and laboratory study to acquire data for the reconstruction of this climatic record. Results from snow pit and shallow ice core studies have been published (Thompson et al., 1979, 1984a, b; Thompson, 1980) These studies demonstrate seasonal cycles in microparticle concentrations, conductivities and oxygen isotope ratios.

In 1983, the central objective was accomplished by recovering one 154.8m summit core (SC) containing 1,350 years and another 163.6m core (C-1) containing 1,500 years. The cores were dated using a combination of visible annual dust layers, microparticle concentrations, conductivity and oxygen isotope ratios. Thompson et al. (1985) present a synthesis of the 1,500-year precipitation record from both cores, while Thompson et al. (1986) present the decadal variations of microparticle concentrations, conductivity and oxygen isotopes for the last 1,000 years. Here we focus on three abrupt events recorded within the last 1,000 years in the visible stratigraphy, microparticle concentrations, conductivity variations and oxygen isotopes preserved in the summit core.

The Quelccaya ice cap (13°56'S; 70°50'W) rests on the easternmost rise of the Andes (Fig. 1) on the western margin of the Amazon Basin. On this ice cap there is a distinct seasonality in snowfall which is ultimately preserved in the ice stratigraphy. The elevation (5,670m) results in a near zero net surface energy balance and an annual mean temperature of -3°C, and consequently there is an insignificant amount of melting and percolation. This has been confirmed by dry season field observations using *in situ* percolation pans. Distortion of the preserved record by ice flow is minimized as the ice cap rests on an extensive plateau with gentle topography. The plateau has been mapped using a monopulse radar system. A maximum thickness of 180 meters and an annual net balance of 1.15 meters $(H_2O)a^{-1}$ result in a long and temporally well-resolved, proxy climate record.

Precipitation on the Quelccaya ice cap falls as snow throughout the year. The major moisture source for wet season snowfall (November-April) is from air masses advected from the Amazon Basin (Thompson et al., 1984b). The 500mb cloud flow patterns across South America during the wet season indicate the major moisture source is ultimately the Atlantic Ocean (Schwerdtfeger, 1976; Virji, 1979). Meteorological data from an automatic weather station maintained on the summit of Quelccaya from 1976 to 1984 indicate a dominant wind direction out of the east during the wet season and wind direction from the west during the dry season. Thus, the main source for the dust is from the west from the dry altiplano of Southern Peru and the snowfall from the east from the vast Amazon Basin and ultimately the Atlantic Ocean.

In this paper dealing with abrupt climatic events we focus upon three different time intervals in which abrupt deviation from average microparticle concentrations, conductivities and oxygen isotopes are recorded contemporaneously in all three parameters. The periods discussed include the greatest drought recorded in southern Peru (A.D. 1933 to 1945) and the onset (A.D. 1452 to 1550) and termination (A.D. 1864-1905) of the "Little Ice Age".

MATERIALS AND METHODS

The two long ice cores (see Fig. 1b and c for location) were recovered without contaminating the pristine environment or the core samples by use of a newly-developed, sun-powered drilling system. Approximately 6,000 samples were collected from pits, shallow cores, and the two long cores. The samples were melted by passive solar-heating in a laboratory tent, placed in polyethylene bottles, sealed in wax, and shipped to The Ohio State University. In the laboratory, samples were divided so that microparticle concentrations and size distributions, conductivity, and oxygen isotope measurements could be made on the same samples.

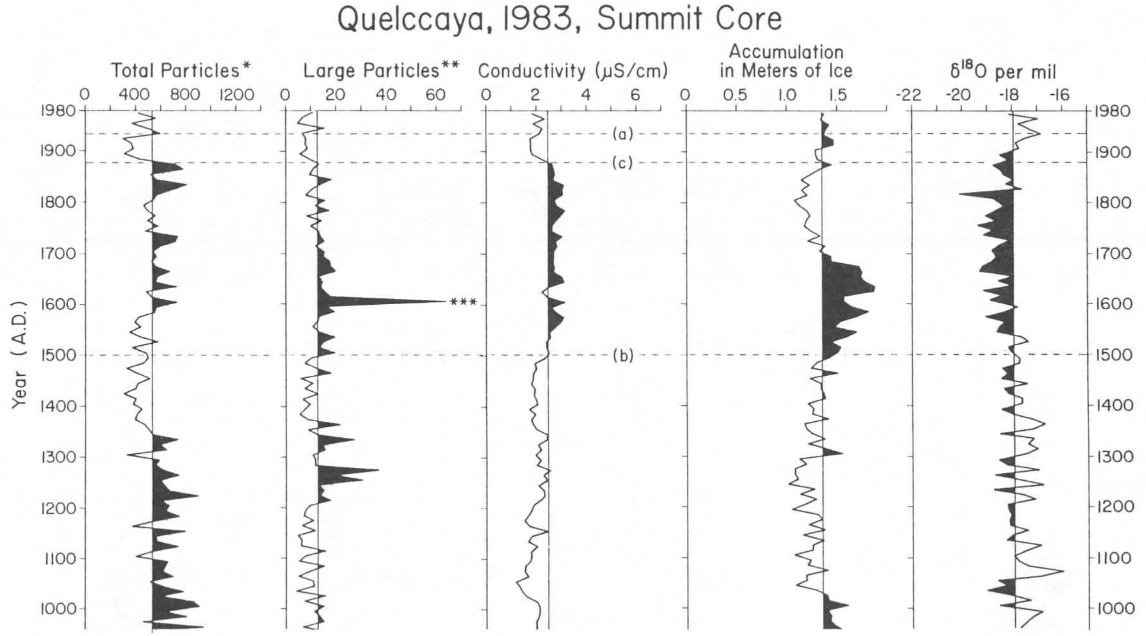
The analysis of microparticle concentration and size distribution (Thompson, 1977) is conducted under Class 100 clean room conditions using two Model TA II Coulter Counters, which electronically separate particles into 15 size ranges between 0.4 and 16μm in diameter. The microparticle concentration (MPC) data are presented as total particles $\geq$ 0.63μm diameter per milliliter (ml) sample. Electrolytic conductivity (S), measured under Class 100 clean room conditions using an Altex RC-16C Conductivity Bridge, furnishes an excellent estimate of the soluble impurities in the meltwater. Conductivity (S) measurements, in microsiemens cm^{-1}, have an accuracy within 1% of the reading. All measurements were conducted under temperatures of 21 ± 1°C, and with replicate analyses. The oxygen isotope analyses for the SC were conducted at the University of Copenhagen (Denmark) and at the University of Washington for the C-1. The oxygen isotope results are expressed as $\delta^{18}O$, the relative difference in isotopic abundance ratio $^{18}O/^{16}O$ between the sample and the Vienna Standard Mean Ocean Water (VSMOW) expressed in per mil (^{o}/oo). Control samples for interlaboratory comparison indicate a maximum difference of 0.30 ^{o}/oo.

RESULTS AND CONCLUSIONS

"Little Ice Age" in Peru

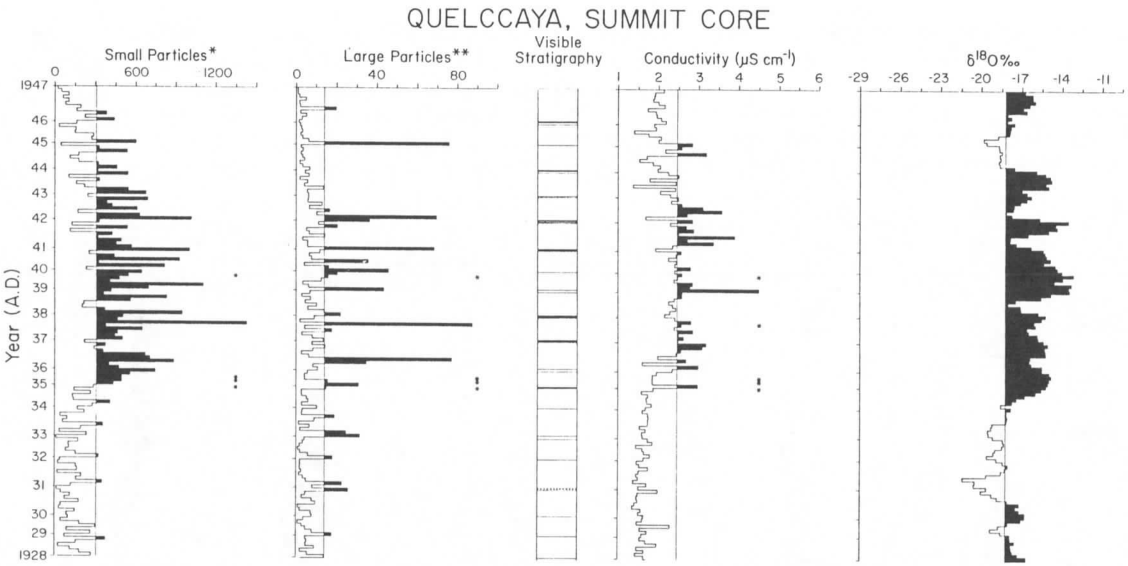
Figure 2 illustrates the decadal averages of MPC (both >.63 and >1.59μm diameter particles), conductivity, *accumulation* and $\delta^{18}O$ isotope records for the last 1,000 years in the summit core. These records suggest that in the last millenium the most significant climatic event in tropical South America coincided with the "Little Ice Age" here recorded between A.D. 1490 and 1880 (Thompson et al., 1986).

In the Northern Hemisphere the "Little Ice Age" (LIA) lasted from approximately the early 1500's to the late 1800's and was characterized by colder-than-usual temperatures and expanded glaciers. The dates of the LIA determined from historical and proxy climate records vary depending on location and the observed parameter, for example 1550-1850 (Flohn and Fantechi, 1984) and 1430-1850 (Gribbin and Lamb, 1978). This period, corresponding to the Northern Hemisphere LIA, is a prominent feature in the microparticle concentrations, conductivities and $\delta^{18}O$ features of the Quelccaya ice core record. Microparticle and conductivity averages are as much as 30% higher during the LIA than during the 14th, 15th and 20th centuries (Fig. 2). In addition, the average $\delta^{18}O$



* Total Particles ≥ 0.63 to ≤ 16.0μm in Diameter per ml of Sample (10^3)
** Large Particles > 1.59μm in Diameter per ml of Sample (10^3)
*** Huaynaputina (Peru) eruption of Feb. 19,-March 6, 1600 A.D.

Figure 2. Decadal variations of total microparticles (>0.63μm and >1.59μm diameter), liquid conductivities, net accumulation and $\delta^{18}O$ over the last 1,000 years (modified from Thompson et al., 1986). The solid line represents the 1,000 year averages. The "Little Ice Age" appears as the largest climatic event in the last 1,000 years in tropical South America. The periods interpreted as representing abrupt climatic changes which are discussed in this paper are indicated as a, b and c. These are enlarged in Figures 3, 4 and 5, respectively.



QUELCCAYA, SUMMIT CORE

*Small Particles ≥ 0.63 to ≤ 0.80μm in Diameter per ml of Sample (10^3)

**Large Particles ≥ 1.59 to ≤ 16.0μm in Diameter per ml of Sample (10^3)

Figure 3. Ice core parameters measured in the summit core for the period A.D. 1928 to 1947. Shaded areas here and in Figures 4 and 5 represent positive deviations from the averages calculated over the entire core record. The drought in southern Peru, A.D. 1933 to 1945, is recorded by increases in both soluble (conductivity) and insoluble (microparticle concentrations) particulates and less negative $\delta^{18}O$ ratios. The ice core visible stratigraphy is illustrated on the right of Figures 3, 4 and 5 where: a single solid line represents a normal dry season dust layer; a single dashed line and double dashed line represent very light to light dust layers, respectively; and a triple dashed line and quadruple dashed line represent distinct and very distinct dust layers, respectively. The drought of the 1930's and 1940's is characterized by as many as five closely spaced dry season layers. The dots identify missing samples.

values average 0.9 $^{o}/oo$ more negative than for the last 100 years or the 1,000 years prior to 1500 A.D. The Quelccaya ice core records of precipitation and conductivity suggest that the onset of the LIA occurred rather abruptly (Fig. 2b) although the δO^{18} change is more gradual. However, the termination of the LIA is abrupt in all the ice core parameters measured (Fig. 2c).

As this paper deals with abrupt climatic events, emphasis is placed upon three time intervals in which contemporaneous, abrupt deviations from the average are recorded in microparticle concentrations, conductivities, precipitation and oxygen isotopes. Special attention is given the first period, 1928 to 1947 (Fig. 2a, Fig. 3) as it may provide a modern analog facilitating better interpretation of older parts of the ice core records.

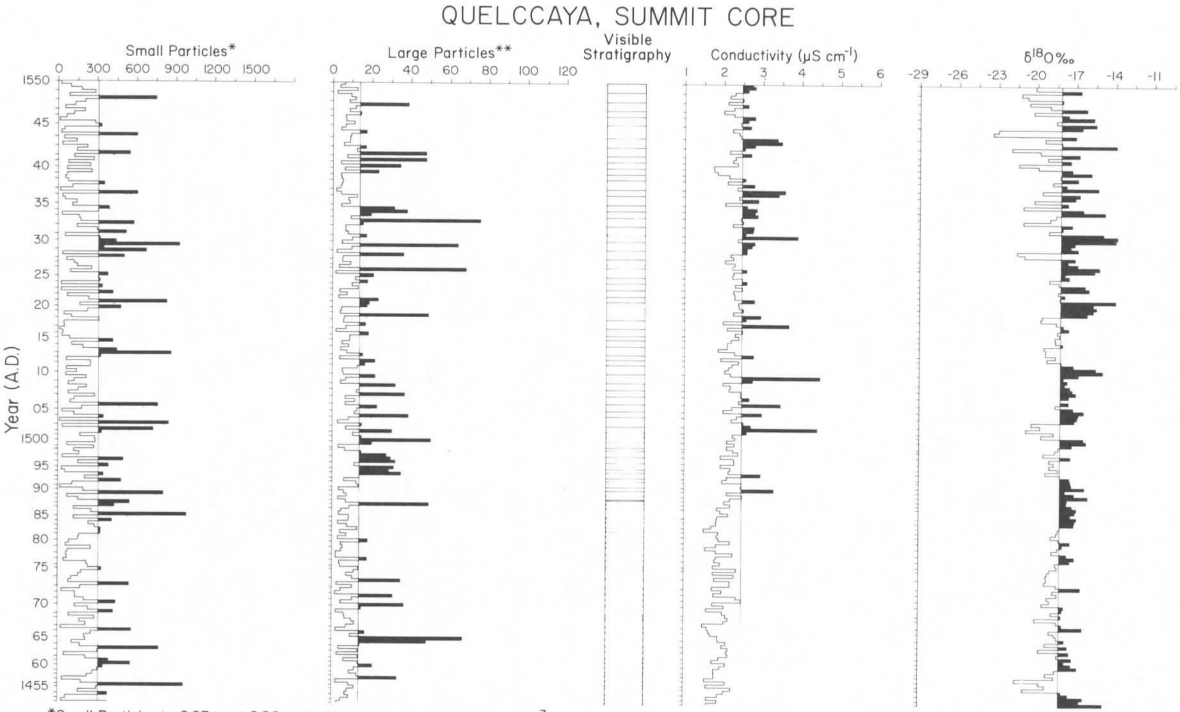
Twentieth Century Drought

The period A.D. 1933 to 1945 encompassed the greatest drought recorded in southern Peru. The drought is reflected by a large drop in Lake Titicaca water levels over this period (Newell, 1949) and in the precipitation record from El Alto in Bolivia. Lake Titicaca, the highest (3,812m) large lake in the world, covers 8,446km. From 1933 to 1945 water levels dropped almost 5m (Newell, 1949; see pages 10-17) causing extreme difficulties for the Peruvian Corporation which operated a fleet of steamboats. The lake was closed to traffic for several years and installations were abandoned because of the shallowing.

Evidence of this drought is excellently preserved in the Quelccaya ice core records. It is characterized by reduced accumulation, by an increase in the concentration of both large and small particles, and by higher conductivities for the years from 1934 to 1945 (see Fig. 3). In association with this drought the $\delta^{18}O$ ratios are distinctly less negative than under the wetter conditions prevailing several decades prior to and since that time. The substantial increase in particle concentrations and conductivities probably reflect the increased dryness of the altiplano in association with the drought. The drought is also evident in the visible stratigraphic record as an increase in the frequency of multiple dust bands (produced during the dry season) within a single year (Fig. 3). It should be possible to isolate other extensive drought periods in this region from the longer ice core using distinct characteristics of the microparticles, conductivities, $\delta^{18}O$ and net annual accumulation.

Onset of the "Little Ice Age"

The onset of the LIA in Peru, inferred from the increase in microparticles and the sharp increase in conductivities (Fig. 2b; Fig. 4) occurred around 1490 A.D. The high and typically more extreme values which characterize the $\delta^{18}O$ signal throughout the LIA, did not begin until the 1520's, 30 years after the initial increase in both soluble and large-diameter insoluble particulates. From these ice core records it appears that a profound and lasting change in climate took place within a few decades. The atmosphere became far more dust laden, both with insoluble particles but particularly with soluble particulates,



*Small Particles $\geq$ 0.63 to $\leq$ 0.80μm in Diameter per ml of Sample (10^3)
**Large Particles $\geq$ 1.59 to $\leq$ 16.0μm in Diameter per ml of Sample (10^3)

Figure 4. Ice core parameters measured in the summit core for the period A.D. 1452 to 1550. The increase in soluble (conductivity) and insoluble (microparticle concentrations) particulates characterize the "Little Ice Age" (LIA) inferred as beginning about 1490 A.D. The visual stratigraphy recorded in the field reveals a change in the characteristics of the annual dust layers at this time. High seasonal oscillations and more negative $\delta^{18}O$ values which characterize the LIA begin around 1520 A.D.

precipitation increased abruptly around A.D. 1490. Thirty years later the lower oxygen isotopes suggest colder temperatures, while the greater interannual variability is due at least in part to greater seasonal variability during the Little Ice Age. The initial increase in the concentration of microparticles and the sharp increase in conductivity, characterizing the entire LIA, were very abrupt at about 1490 A.D. The dry season dust layers are very distinct in the visual stratigraphy before 1490 A.D. The general increase in soluble and insoluble particles at the onset of the "Little Ice Age" may have reduced the overall clarity of the ice core making the dry season dust layers appear less distinct.

Termination of the "Little Ice Age"

One of the most abrupt events recorded in the Quelccaya ice cores is the termination of the LIA (Fig. 2c; Fig. 5). Centered nearly on A.D. 1880 there is a sharp reduction in both the insoluble and soluble particulate concentrations from the higher levels characterizing the LIA. These reduced levels are more characteristic of the last 100 years. Additionally, the amplitudes of the seasonal $\delta^{18}O$ variations which characterized the LIA period rapidly decrease just before A.D. 1880, while mean oxygen isotope values become less negative. These data indicate that for the last 100 years: (a) reduced mean wind velocities resulted in a sharp drop in insoluble and soluble particles, (b) an increase in annual snowfall and, (c) an increase in annual mean temperatures (as inferred from less negative oxygen isotope values).

SUMMARY

Many geological records of climate variability covering the last 1,000 years lack good temporal resolution. This reinforces the conventional expectation of gradual climatic change. The relatively large annual accumulation on ice sheets and ice caps and especially on Quelccaya (1.15 meters water equivalent a^{-1}) allows reconstruction of both high frequency (annual) and longer-term climatic variations. Some evidence of abrupt changes within the climate system have been reported from polar ice cores, e.g., Camp Century (Thompson, 1977) and Dye 3 in Greenland (Dansgaard et al., 1982; Herron and Langway, 1985). These results and those from the tropical Quelccaya ice cap strongly suggest that atmospheric conditions can change substantially over only a few years. Ice cores offer the most direct evidence of the past variations in atmospheric aerosols. The dust records provide a unique opportunity to acquire the information essential for the reconstruction of conditions of drought, volcanic activity and variations in past circulation patterns. The insoluble and soluble particulates from the Quelccaya ice cores have been used to identify a historical volcanic eruption (Thompson et al., 1986) and in this paper increases in particle concentrations have also been shown to be one of the ice core indicators of drought conditions. The oxygen isotope data suggest a significant cooling in the tropics during the "Little Ice Age" and the large seasonal range during the LIA may indicate greater sublimation of surface snow during the dry season and/or greater seasonal variability in moisture source during this period.

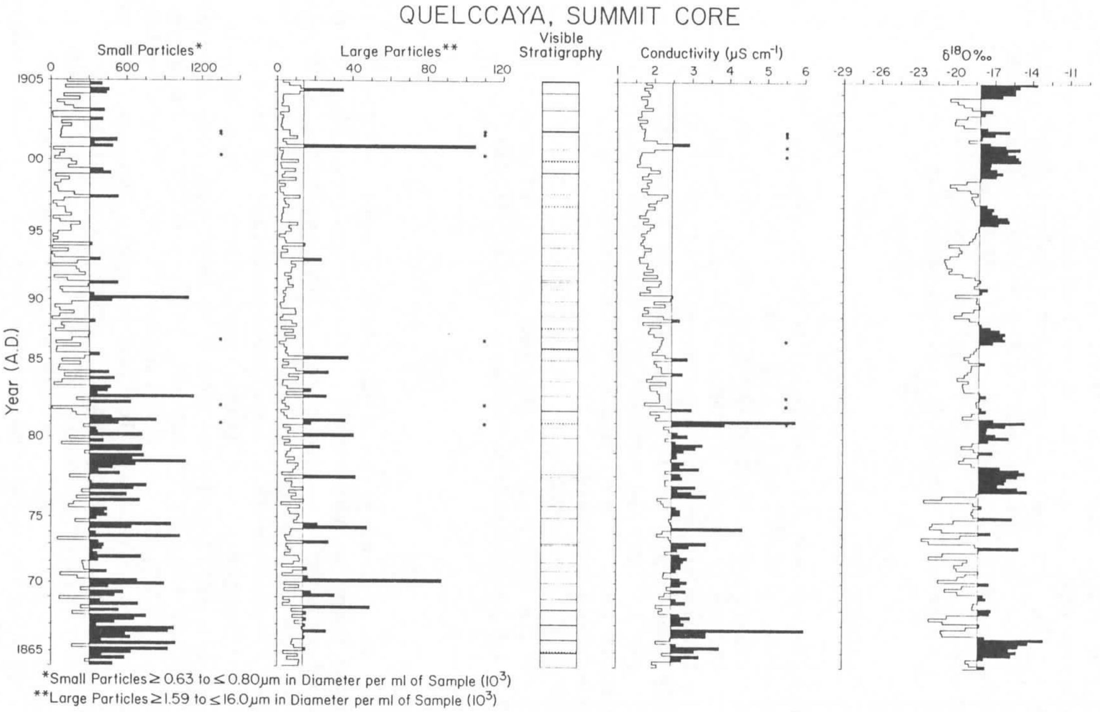


Figure 5. Ice core parameters measured in summit core for the period A.D. 1864 to 1905. The soluble (conductivity) and insoluble (microparticle concentrations) particulates drop abruptly from the elevated LIA levels around A.D. 1880. From A.D. 1875 to 1880 there is an abrupt reduction in the annual amplitude of the $\delta^{18}O$ signal from the large seasonal ranges characterizing the LIA to lower amplitudes and less negative average values characteristic of the last 100 years.

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