NEAR SURFACE VARIATIONS IN MEAN ANNUAL MICROPARTICLE CONCENTRATION AND OXYGEN ISOTOPE AS A FUNCTION OF TIME

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ABSTRACT

The Quelccaya Ice Cap in Peru (13°56′S; 70°50′W) has been the focus of a paleoclimatic and glaciological program since 1976 (Thompson, 1979; Thompson et al., 1984a). The central objective of the Quelccaya program was accomplished with the extraction of a 1500-year paleoclimatic record for tropical South America determined from microparticle concentration, oxygen-isotope, accumulation and conductivity measurements from ice cores (Thompson et al., 1984 a,b; 1985a; 1986). However, accurate interpretation of details of individual parameters within this record requires knowledge of how the annual signals extracted from deep cores reflect the original input signal. This paper deals only with microparticle concentrations and oxygen isotopes by determining post-depositional changes in their signals. This study attempts to ascertain the degree to which natural near surface processes and sampling procedures affect the initial input signal. The included data exhibit relatively consistent trends for which possible explanations are explored.

INTRODUCTION

The purpose of this study is to characterize the effect diagenetic and other processes have upon the initial microparticle concentrations (MPC). MPC are very susceptable to contamination by human activities. Therefore it is necesary to consider another parameter, oxygen isotopic abundance ($\delta^{18}O$), for which the impact of human activity is greatly reduced. This will help determine the relative effects of human activity and naturally occuring processes. The Quelccaya data are sufficient to observe changes in MPC and $\delta^{18}O$ with respect to time (years after deposition). The data employed here consist of pit samples representing the annual input (fresh) signal and shallow core samples representing the annual post-depositional signals. There is a sufficient overlap of annual measurments from pits with respective annual measurements from firn cores to gain an understanding of time related signal changes.

These comparisons suggest consistent trends for which possible explanations are explored. A prerequisite for interpretion of the data is a thorough examination of sampling and processing procedures which, along with naturally occurring near-surface processes, are responsible for the observed trends. These factors must be further examined and tested to (1) ascertain the degree to which natural processes affect the input signal and (2) to develop improved field collection and handling procedures to ensure attainment of more representative data.

MATERIALS AND METHODS

The pit and core data compared in this study are from sampling sites in close proximity to the summit (Fig. 1). This is essential to reduce the possible effect of spatial variability on preserved signal levels. The pits' microparticle and $\delta^{18}O$ values most closely resemble original input as the samples consist of the most recent year's accumulation. Pits were excavated to the previous year's accumulation which is well defined by a visible dust horizon representing the dry season (June-September). Samples of both microparticle and $\delta^{18}O$ were collected from the pit wall with a plexiglas tube inserted into the wall at regular intervals. The samples were placed in plastic bags, melted and poured into 4oz Polyethylene bottles. To avoid vapor loss or exchange with the atmosphere, bottle lids were sealed with wax. Sampling procedures were consistent throughout the program except for 1976 when a 5cm sampling interval was used instead of the 10cm interval used from 1977 through 1984. Investigations of data have suggested that while a 10cm sampling interval may miss more microparticle events than the 5cm interval, the annual concentratons do not significantly differ. However, no valid test has been performed to verify this.

The 1976 core (SC-76) was drilled with a teflon coated SIPRE (Snow, Ice, and Permafrost Research Establishment) drill barrel while the 1979 cores (S4-79 and S3-79) and the 1983 shallow core were drilled with a PICO (Polar Ice Coring Office) fiberglass light-weight auger. The deep core involved in this study, the 1983 Summit core (SC-83), was drilled with a solar-powered electro-mechanical drill. Each drill run recovered approximately 1 meter of core which was then cut into vertical sections 10cm in length. This provided a continuous sampling profile as opposed to the discontinuous profiles from the pits. Like the pit samples, the core samples were placed in plastic bags, melted and transferred to 4oz Polyethylene bottles.

The $\delta^{18}O$ samples were sent to the Quaternary Research Laboratory at the University of Washington and the Geophysical Institute, University of Copenhagen. Annual $\delta^{18}O$ values are expressed in parts per mil.

Oxygen has three stable isotopes (^{16}O, ^{17}O, and ^{18}O) of which ^{16}O is the most abundant. The relative amount of ^{18}O to ^{16}O in a water sample, when compared to that of standard mean ocean water (SMOW), is the oxygen isotopic ratio designated as $\delta^{18}O$. Thus $\delta^{18}O$ may be expressed as

$$\delta^{18}O = \frac{R^{18}O_{sample} - R^{18}O_{SMOW}}{R^{18}O_{SMOW}} \times (10^3)$$

where R is the ratio of $H_2{}^{18}O/H_2{}^{16}O$.

Due to the higher vapor pressure of $H_2{}^{16}O$, water vapor evaporated from the ocean is enriched in ^{16}O relative to ^{18}O. Likewise, during condensation ^{18}O is removed preferentially leaving the precipitating air mass or remaining vapor depleted in ^{18}O. Many factors affect the magnitude of the ^{18}O depletion. For example, ascension, poleward movement of an air mass, and distance from moisture source result in depletion of ^{18}O. Bromwich (1983) demonstrated this relationship for Antarctic coastal precipitation. In general, the precipitation at both high elevation and high latitude sites is very depleted in ^{18}O

resulting in lower (more negative) $\delta^{18}O$ ratios.

Seasonal variations are reflected in $\delta\ ^{18}O$ (Delta) such that winter precipitation is more negative than summer precipitation. This provides a mechanism by which to date the stratigraphic layers in ice cores (Epstein and Sharp, 1967; Hammer et al., 1978). Note that Delta also provides a means for dating the Quelccaya core but the most negative Delta values occur during the summer wet season (Thompson and Dansgaard, 1975). On Quelccaya the original Delta input signal reflects (1) the elevation effect and (2) air mass precipitation history during transit over the Amazon Basin and to a lesser extent (3) atmospheric temperatures (Thompson et el., 1984a). In addition to seasonal variations Delta records from long (deep) ice cores have demonstrated that the precipitation deposited during extended cold or glacial periods has a more negative Delta signature than precipitation during warmer periods (Epstein et al., 1970; Thompson et al., 1986). The $\delta^{18}O$ signature of ice provides a powerful tool for dating as well as interpretation of paleoclimates.

Microparticle analyses were performed at the Institute of Polar Studies, The Ohio State University as part of the Quelccaya research program (Thompson et al., 1984a,b; 1985a). Microparticles are a valuable parameter with which to reconstruct climate history. Seasonal variations in MPC in the atmosphere are reflected in the stratigraphy of glaciers and thus provide a means of recognizing and dating annual units. Ice core records of MPC may also reflect turbidity levels in the atmosphere at the time of deposition. Morphologic studies of the microparticles can be used to link them to source areas which provides further information about the nature of past local and global circulation patterns. Microparticles have been used to characterize climates during the Wisconsinan Glacial Stage (Thompson and Mosley-Thompson, 1981), the 'Little Ice Age' in the last 1000 years (Mosley-Thompson, 1982), and even the drought conditions prevalent in the Peruvian Andes during the 1940s (Thompson et al., 1986).

Microparticle analyses involve the addition of an electolyte solution to each sample to create a standard conductive medium. A Coulter Counter TAII is used to obtain actual microparticle counts. The liquid is drawn through an aperture tube through which a current passes between two foil plates. Suspended particles passing through the aperture between the plates cause deflections from the standard resistivity by momentarily displacing the electrolyte solution. The increase of resistance in the path of the current is proportional to the particles cross-sectional area. The Coulter Counter records concentrations and size distributions in 16 size ranges.

This paper deals only with the smallest size range (.63-.80 micrometer(μm) diameter). Samples were processed to yield annual MPC data given in populations per milliliter (ml) of sample. These data as well as that for δ ^{18}O values and ranges are included for SC-83 for years 1970-1982, S4-79 for years 1973-1978, S3-79 for years 1976-1978, SC-76 for years 1970-1975, and pits for years 1976-1982 (Table I, II and III). The 1983 electro-mechanical drill's core recovery of near surface snow was so poor that the PICO fiberglass light-weight auger was used to drill a 10m core to provide data for upper annual units. Measurements of samples from the upper 5m of this 1983 shallow core are used to represent annual measurements for the 1982 and 1981 accumulations of the SC-83 record. There was approximately 5m of overlap between the shallow core and usable electro-mechnical core. Over this interval it was found that the electro-mechanical drill produced core dirtier by 32 percent than that drilled with the light-weight auger. Therefore included with the data are SC-83 values which have been reduced to coincide with the light-weight auger values. These adjusted data may be more representative of actual particulate levels. The core to pit correlations are step curve comparisons illustrating how annual signals change with time. The input signals are compared to post-depositional signals. All pit data represent the input signal for an annual unit while core data represent signals of respective annual layers in successive post-depositional years (PDY). The value of the 1982 unit in SC-83 is a 1 year post depositional signal (PDS), the 1981 value is a 2 year PDS, and so forth. The 1978 unit in S4-79 and S3-79 is represented by a 1 year PDS as is the 1975 unit in SC-76. The core to core comparisons are more complicated as the same annual unit of x-years post-deposition in one core is compared to that of y-years post deposition in another.

DATA

The input MPC of successive pits are plotted with the post-depositional values of the SC-83 in Fig. 2a. Although the profiles are very similar in trend the MPC of the core are much higher than those in the pits. The concentration differences peak the 1st post-depositional year, afterwhich the differences decrease very steadily as core values begin to approach those of the pits. However, for the 1976 unit (PDY-7), the difference increases. It must be noted that the 1976 input was determined by a 5cm sampling interval whereas input signals for following years were determined by 10cm intervals. The percent differences between pit and core MPC are illustrated in Fig. 3.

The comparison of pit and SC-83 $\delta^{18}O$ annual average data show a similarity in both trend and magnitudes for the first three PDY afterwhich greater and more random variance is evident (Fig. 4a). The pit values, on the average, are higher than those of the 1983 core by only 3.4 percent. Comparison of the $\delta^{18}O$ ranges reveal a sharp decrease the 3rd PDY. For PDY > 3 the differences between ranges increase as post-depositional values drop well below input levels (Fig. 5a). As expected, the range of the input signal greatly exceeds that of the respective post-depositional signal.

The comparison of pit signals with those of S4-79 supports the SC-83 relationships discussed above. The MPC in the core are considerably higher than corresponding pit values (Fig. 2b). These data exhibit the greatest MPC differences between pit and core values in PDY-2. Unfortunately, before 1976 there is no overlap of pit and core data thus limiting this comparison to only the 1st, 2nd, and 3rd PDY.

The $\delta^{18}O$ data show the annual input signal to be much more negative (more depleted) than all 3 consecutive PDY signals in S4-79 (Fig. 4b). In the core, $\delta^{18}O$ range differences increase sharply in the 2nd PDY with the percent difference between the pit and core rising to 434 percent.

S3-79 MPC are elevated above the input values of the pit by an average of 87 percent. The percent difference between pit and core values peaks in PDY-3 with a value of 175 percent. For the $\delta^{18}O$ data the annual signal of PDY-1 is nearly equivalent to that of the pit while PDY-2 and PDY-3 signals are much less negative than the input signals of the pits. The $\delta^{18}O$ ranges show the greatest difference between pit and core values to occur in PDY-2.

All pit to core comparisons exhibit essentially the same trend; that is, in all instances the post-depositional MPC are greatly enhanced relative to the input (pit) MPC. The greatest percent difference of annual concentrations occurs in PDY-1 in SC-83, PDY-2 in S4-79, and PDY-3 in S3-79. SC-83 is the only core for which there is extended overlap with pit data. The pit and SC-83 MPC comparison show a steady decrease in the percent difference between pit and core beginning after PDY-1) when core values begin to approach pit values. This suggests that the most recent PDY is a period or region of relatively higher concentrations than previous post-depositional units.

The post-depositional annual $\delta^{18}O$ signals are generally less negative than the input signals except for PDY-1 in SC-83 and S3-79. Ranges of input $\delta^{18}O$ are consistently greater than PDY values. Post-depositional range values drop considerably after PDY-2 and PDY-3. This isotopic smoothing is expected and is evident in all three comparisons. Isotopic smoothing is has been investigated extensively for other regions (Johnsen, 1977; Hammer <u>et al</u>, 1978).

To accurately interpret core to core comparisons of MPC and $\delta^{18}O$ it is necessary to realize that the comparisons will be of PDY-X signals in one core to PDY-Y signals in the other. For example, comparing the 1978 annual unit of S4-79 with the 1978 unit in SC-83 is a comparison of a PDY-1 signal (S4-79) with a PDY-5 signal (SC-83), and for the 1977 annual unit, a comparison of a PDY-2 signal (S4-79) to a PDY-6 signal (SC-83), etc. The data show that MPC of PDY-1 and PDY-2 of S4-79 are enhanced above the PDY-5 and PDY-6 signals of SC-83. However, subsequent comparisons of respective MPC demonstrate that the values converge with neither core exhibiting consistently higher concentrations (Fig. 6a).

The annual $\delta^{18}O$ signals of S4-79 are very similar to those of SC-83 in both trend and magnitude of actual values (Fig. 7a). The $\delta^{18}O$ ranges of the more recent firn in S4-79 are higher than those of the older firn in SC-83 as expected (Fig 8a). S4-79 and S3-79 compare similarly with SC-83. The S3-79 MPC are consistently higher than those of respective annual units in SC-83 (Fig. 6b). The greatest percent difference between S3-79 and SC-83 MPC occurs in PDY-2 (S3-79). The annual $\delta^{18}O$ signals of S3-79 are similar in magnitude to those of the 1983 core (Fig. 7b). The post-depositional $\delta^{18}O$ ranges of S3-79 core are consistently higher than those of the 1983 core (Fig. 8b).

The comparison between the 1976 and 1983 cores break trends established by previous comparisons in this study. The younger post-depositional firn of SC-76 yield annual MPC lower than in respective units in the older firn of SC-83 (Fig. 6c). Similarly, the average MPC over the 1970 to 1975 period is lower for the 1976 core than the 1983 core by 57 percent.

Post-depositional annual $\delta^{18}O$ values are similar in magnitude with the exception of two years which differ significantly (Fig 7c). The annual unit $\delta^{18}O$ ranges in the younger firn of SC-76 are much higher than those in correlative units in the older firn of SC-83 (Fig. 8c). These differences are greater than for any other core to core comparison.

Comparisons of both S4-79 and S3-79 to the SC-83 show essentially the same trends. Although not true in every year, the 1979 cores' MPC are generally higher than those in the 1983 core.

However, SC-76 MPC compare differently to SC-83, almost opposite to that of both 1979 cores. The MPC of SC-76 after PDY-1 are consistently lower than the correlative annual units of SC-83.

All core to core comparisons of annual $\delta^{18}O$ values show similar trends. Except in a few instances, actual annual $\delta^{18}O$ values are very similar in magnitude. In every case, the annual ranges in the younger post-depositional units are higher than in the older respective post-depositional units in SC-83.

INTERPRETATION OF DATA

Proper interpretation of these data requires that several factors be considered. The observed trends may be attributed to a combination of any number of processes. Two major groups of influencing factors are those induced by human activity and those caused by naturally occuring surface or near-surface processes. The human factor includes a whole spectrum of variables that may affect signal values. These include (1) inconsistencies in annual unit definition, (2) comparison of data obtained by different sampling procedures or collected with different drill types, (3) the comparison of pit profiles collected discontinuously to the continuos samples of core, and (4) the handling procedures including bagging, melting, and bottling. The second category, surface and near-surface processes, are those which may result in either a loss or redistribution of mass. These are sublimation and melting with subsequent percolation.

As seen in the pit to core MPC comparisons, the core MPC are significantly and consistently higher. Considering the sampling procedure, and especially the steps involved in the transfer of the melted sample from the plastic bag to the 4oz Polyethylene bottle, the enhanced core values may be partially explained. This step introduces a potential problem because when melted, the pit samples produced more volume than needed to fill the bottles. If the bagged fluid, even though shaken before pouring, is not homogenous, that is if a stratification of the particles develop with respect to their density or size, an unrepresentative sample is obtained. The small size range (.63-.80 μm) was chosen for the above comparisons as the smaller particles will remain in suspension longer than the larger ones. The core sections were processed by the same procedure although the resulting sample mass was such that, in most cases, the entire melted volume was necessary to fill the 4oz bottle, thus reducing the possibility of obtaining an unrepresentative sample. The result would be diluted concentrations for pit samples and more accurate concentrations for core samples. The transfer of liquid sample occurred again in the laboratory procedures. Portions of the samples were transfered into containers for analyses with the Coulter Counter, repeating the possibilty of obtaining an unrepresentative sample; however, this should affect pit and core samples identically causing a fairly uniform dilution of MPC.

The enhanced core concentrations partially result from coring procedures which yield dirtier samples than pit procedures. Even the step-like nature of percent differences that occur between pit and SC-83 values may result from drilling procedures. Since drilling through the surface causes the unconsolidated near surface snow to be knocked loose from the borehole wall, debris from upper layers may be packed into the porous firn of underlying layers. This would bias the MPC of underlying units in the direction of the upper unit's MPC. The input MPC in 1983, as determined by the 1983 pit is 272274 particles per ml which is well above the input MPC of all previous years (Table I). Drilling through the 1983 unit and incorporating its snow into underlying units would cause their MPC to be enhanced above the initial values. The greatest amount of debris is generated during the first few runs before the drill hole is firmly established. Therefore the greatest affect on MPC would be observed in the upper units and if the surface layer is dirtier than those below, would result in enhancement of the post-depositional MPC above the input value. Quelccaya data shows that the greatest percent difference between input (pit) and post-depositional (SC-83) occurs in the first PDY and decreases therafter (Fig. 3a).

The drill composition and design must also be considered. As stated before, the electro-mechanical drill used in 1983 produced MPC which were 32% higher than those produced by the PICO light-weight auger. This presents a potential problem, making core to core comparisons more difficult to analyze than pit to core comparisons. It is important to note that in the case of the S4-79 to SC-83 comparisons the 1st, 2nd, and 3rd PDY units established as periods or regions of greatly enhanced MPC by pit to core comparisons also are elevated when compared to the 5th, 6th and 7th PDY units respectively (Fig. 6a). The 5th, 6th, and 7th PDY are shown by pit to core comparisons to exhibit relatively lower MPC.

The 1976 to 1983 core comparison does not show this relationship and MPC for all PDY of SC-76 are depressed below the signals in the older firn of SC-83 (Fig. 6c). The 1976 core is anomalous as the average MPC is much lower than levels in all other cores. These low values may partially be due to the drill type used in 1976. As shown earlier, drill types can greatly influence MPC. In 1976 a teflon coated SIPRE drill was used. It may be that this drill produces cleaner core relative to drills used in subsequent years. For whatever the reason, the trends observed in the SC-76 comparison with SC-83 are juxtaposed those established by all pit to core and 1979 to 1983 core comparisons.

The above discussion considers only human introduced factors while naturally occuring, surface and near-surface processes may contribute to the observed trends. Because particles are assumed to remain in their respective annual units except under conditions of extreme melting and percolation, the processes discussed here are those which may affect microparticle concentrations through loss or transfer of mass. These processes are sublimation and melting which result from the thermal regime of the near-surface zone and both involve the loss, transfer, and compaction of mass. Both processes are driven in varying degrees by the radiation receipt at the snow surface. Due to Quelccaya's summit elevation of 5670m and average albedo in excess of 80% the amount of radiation available at the surface is very small. In fact, Hastenrath (1978) reported that the radiation receipt at the summit is insufficient to initiate either sublimation or melting. However, the extreme decrease in $\delta^{18}O$ range values occurring during PDY-1 and PDY-2 suggest some vapor transport. Observations of structures and textures suggestive of sublimation have also been observed within the firn (Thompson, personal communication).

For sublimation to occur a temperature gradient must exist which in turn creates a water vapor pressure gradient (Yen, 1969). Ice crystals in regions of low water vapor pressure lose molecules to the gaseous state. Along with vapor pressure gradients, high porosity encourages sublimation in that it provides void regions which are able to accomodate free molecules. Therefore sublimation occurs more readily in the upper snow and firn layers.

Sublimation processes can persist over a broad range of temperatures. Influences of sublimation processes have been detected in laboratory tests (Shumskii, 1964) at temperatures near -80 °C. However, sublimation resulting in significant mass transfer generally occurs at temperatures near 0 °C. Near-surface temperatures (upper 2m) on Quelccaya are approximately -7 °C which may inhibit mass transfer. Nevertheless, Quelccaya data show a great increase in MPC during the 1st, 2nd, and 3rd PDY which may suggest a loss of mass within the annual unit which may possibly be attributed to sublimation. After PDY-1 MPC decrease and approach the original input signals (inferred by pit values). It is postulated here that the downward transfer of mass, depleting surface layers and replenishing lower layers, may partially explain the observed trends. The amount of mass that can be transferred by sublimation processes is not fully known. Therefore it is impossible to predict whether enough mass can be moved to produce the trends observed in Quelccaya data. It is important to note that in the process of sublimation perecrystallization (redistribution of material between non-contiguous crystal surfaces through the vapor phase, and in migration of material along crystal surfaces) there is a transfer of an enormous amount of thermal energy in the direction of redeposition of material (Shumski, 1964). Thus the proposed scheme of downward mass transport would result in a general downward warming of lower firn layers due to the release of latent heat of recrystalization. The Quelccaya temperature profile exhibits such a temperature inversion (Fig. 9).

Melting and subsequent percolation of water through the intergranular voids of permeable firn is another mechanism for the transportion of mass. The three reasons for the presence of the liquid phase in ice are: (1) influx of heat or another form of energy converted to thermal enrgy, (2) increased pressure which reduces the melting point of ice, and (3) a concentration of salts which also reduces the melting point (Shumskii, 1964). The effect of increased pressure must be ignored for near surface studies and, in this case, so shall salt concentrations since unnaturally high concentrations would be necessary to depress the melting point to approach Quelccaya's near surface temperature of -7 °C. Therefore the only factor which remains as an explanation for the presence of the liquid phase on Quelccaya is the influx of solar energy.

As previously noted, Quelccaya's summit has very little available radiation and while particulates at or near the snow surface will absorb and subsequently transfer heat to surrounding snow, this is insufficient to account for the large mass transfer necessary to explain the data. Even though surficial melt occurs during periods of relatively intense radiation the -7 °C temperatures of the near surface firn should prevent extensive percolation. Additionally, there have been no observations of percolation or percolation features in the firn. In 1983 a test for percolation was conducted by inserting plastic trays at various depths under an undisturbed surface. The only tray in which water was collected was 4cm below the surface. In this tray, a minor ice layer formed. While this test may demonstrate that there is minor percolation to very shallow depths, it is invalid in that, since solar radiation can penetrate snow and firn to depths of 40cm (Shumskii, 1964,) the tray itself may have absorbed energy therby creating the contained melt (Thompson, personal communication). Current evidence suggests that percolation cannot be seriously considered to explanation of the observed data trends.

CONCLUSIONS

MPC and $\delta^{18}O$ are valuable indicators of past climatic conditions and events. This study was designed to determine how these signals might change with respect to time. The Quelccaya data show that MPC measured from core samples are significantly higher than those of pits with the maximum concentration difference occurring in the 1st PDY in SC-83, 2nd in S4-79, and 3rd in S3-79. Similarly, the core to core comparisons of 1979 cores to SC-83 show that the younger post-depositional signal of the 1979 cores are, in most cases, greater than the older post-depositional signals of respective annual units in SC-83. The maximum enhancement occurs in PDY-2 for both 1979 cores. However, the SC-76 comparison shows the younger post-depositional MPC to be less than the older signals in SC-83 and reasons for this were previously discussed.

$\delta^{18}O$ data show the annual input signals from pits to be more negative than post-depositional signals from cores. Core to core comparisons are such that neither core has consistently more negative $\delta^{18}O$ values than the other. The input (pit) $\delta^{18}O$ ranges are much greater than the cores' post-depositional ranges. Similarly, the the younger post-depositional $\delta^{18}O$ ranges of the 1979 and 1976 cores are greater than that for respective units in SC-83.

This study has evaluated some of the factors which possibly affect these trends. In future field programs an attempt should be made to test these factors to determine their effects on MPC and $\delta^{18}O$ values and ranges.

The possible problem created by melting and transferring pit samples to other containers may be alleviated by collecting the sample from the pit wall with a pre-cleaned sample container which will be sealed until the time of analysis. This method of collection would eliminate the problem caused by the melting and transfer of samples. The problem of comparing pit to core values remains to be that of comparing discontinuous (pit) and continuous (core) sampling profiles. To avoid this problem in the future, it is best to avoid using a 10cm or even a 5cm sampling interval. Instead, the diameter of the cylindrical sampling container should define the sampling interval which will reduce the amount of missed snow and result in a more representative sample.

There is a problem inherent with cylindrical sampling containers. Stratigraphic horizons that fall at or near the container's center contribe more to the sample's signal than horizons near the container's periphery. Unfortunately, a suitable rectangular container has not been found that would solve this problem.

A test of these different sampling procedures would involve the excavation of one pit in which 4 side by side profiles for microparticles and 4 side by side profiles for $\delta^{18}O$ are sampled. For each parameter, there should be (1) a profile sampled at 10cm intervals and processed the same way as on Quelccaya, (2) one sampled at 10cm intervals by inserting the pre-cleaned sampling containers, (3) one sampled at 5cm intervals using containers, and (4) one sampled with a sampling interval equal to the diameter of the sampling container. A test to find the drill which produces the cleanest core must also be performed. This would require side by side coring using available drill designs and materials. The resolution of these problems will help in the design of future programs with improved sampling procedures.

Apparently, for Quelccaya, sublimation is the only naturally occurring process that might affect the input signals. A test for sublimation would require a several year program and the development of a very accurate means by which to determine the water equivalence of an annual unit. Knowing the initial water mass of an annual accumulation unit (measured from a pit excavation) and measuring its water equivalence in subsequent years should reveal the amount of mass being removed or added by transfer. The accuracy of this test is limited by the ability to define and recognize the same annual unit in subsequent years. Nevertheless, the effect of such near surface natural processes on both MPC and $\delta^{18}O$ must be known as it is undoubtedly propagated into the longer record.

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REFERENCES

Bromwich, D.H. and C.J. Weaver. 1983. Latitudinal displacement from main moisture source controls delta-O-18 of snow in coastal Antarctica. Nature, 301(5896), 145-147.

Epstein, S. and R.P. Sharp. 1967. Oxygen-and hydrogen-isotope variations in a firn core, Eights Station, Western Antarctica. Journal of Geophysical Research, 72, 5595-5598.

Epstein, S., R.P. Sharp and A.J. Gow. 1970. Antarctic Ice Sheet: stable isotope analysis of Byrd Station cores and interhemispheric climatic implications. Science, 168, 1570-1572.

Hammer, C.U., H.B. Clausen, W. Dansgaard, N. Gundestrup, S.J. Johnsen, and N. Reeh. 1978. Dating of Greenland ice cores by flow models, isotopes, volcanic debris and continental dust. Journal of Glaciology, 20, 3-26.

Johnsen, S.J. 1977. Stable isotope homogenization of polar firn and ice. International Association of Hydrological Sciences, Publication No. 118, 210-292.

Mosley-Thompson, E. and L.G. Thompson. 1982. 900 years of microparticle deposition at the South Pole. Quaternary Research, 17(1), 1-13.

Shumskii, P.A. 1964. Principles of Structural Glaciology. Dover Publications, Inc., N.Y., pp. 497.

Thompson, L.G. 1980. Glaciological investigations of the tropical Quelccaya Ice Cap. Journal of Glaciology, 25(91), 69-84.

Thompson, L.G. and W. Dansgaard. 1975. Oxygen isotope and microparticle investigation of snow samples from the Quelccaya Ice Cap, Peru. Antarctic Journal of the U.S., X(1), 24-26.

Thompson, L.G. and E. Mosley-Thompson. 1981. Temporal variability of microparticle properties in polar ice sheets. International Union of Geodesy and Geophysics Proceedings of a Symposium on Volcanism and Climate. Canberra, Australia. Journal of Volcanology and Geothermal Research, 11(1), 11-27.

Thompson, L.G., E. Mosley-Thompson, P. Grootes, and M. Pourchet. 1984a. Tropical glaciers: potential for paleoclimatic reconstruction. Journal of Geophysical Research, 89(D3), 4638-4646.

Thompson, L.G., E. Mosley-Thompson and Benjamin Morales Arnao. 1984b. Major El Niño/Southern Oscillation events recorded in stratigraphy of the tropical Quelccaya Ice Cap. Science, 226(4670), 50-52.

Thompson, L.G., E. Mosley-Thompson, J.F. Bolzan and B.R. Koci. 1985a. A 1500 year record of tropical precipitation recorded in ice cores from the Quelccaya Ice Cap, Peru. Science, 229(4717), 971-973.

Thompson, L.G., E. Mosley-Thompson, W. Dansgaard, and P.M. Grootes. 1985b. Evidence of abrupt climatic change during the last 1500 years recorded in ice cores from the tropical Quelccaya Ice Cap, Peru. (Abstract). In: The Book of Abstracts and Reports from the Conference on: Abrupt Climatic Change, (Biviers, France, Oct. 1985). Scripps Institution of Oceanography, Reference 86-8, 248-252.

Thompson, L.G., E. Mosley-Thompson, W. Dansgaard, and P.M. Grootes. 1986. The "Little Ice Age" as recorded in the stratigraphy of the tropical Quelccaya ice cap. Science, accepted for publication.

Yen, Yin-Chao. 1969. Recent Studies on Snow Properties. Advances in Hydroscience, 5, 173-214.

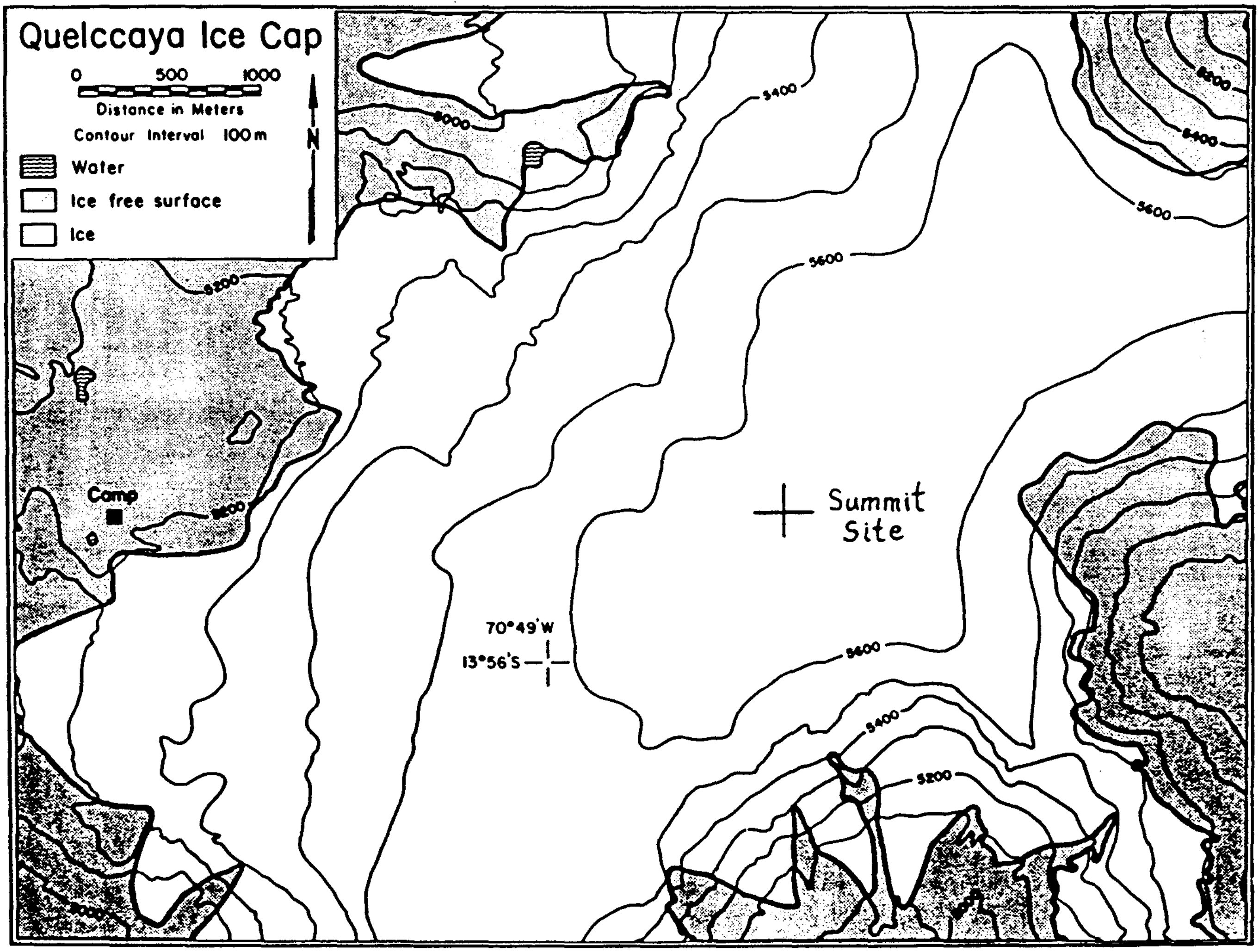

Figure 1.

Overview of the Quelccaya Ice Cap showing the location of the base camp and the summit site.

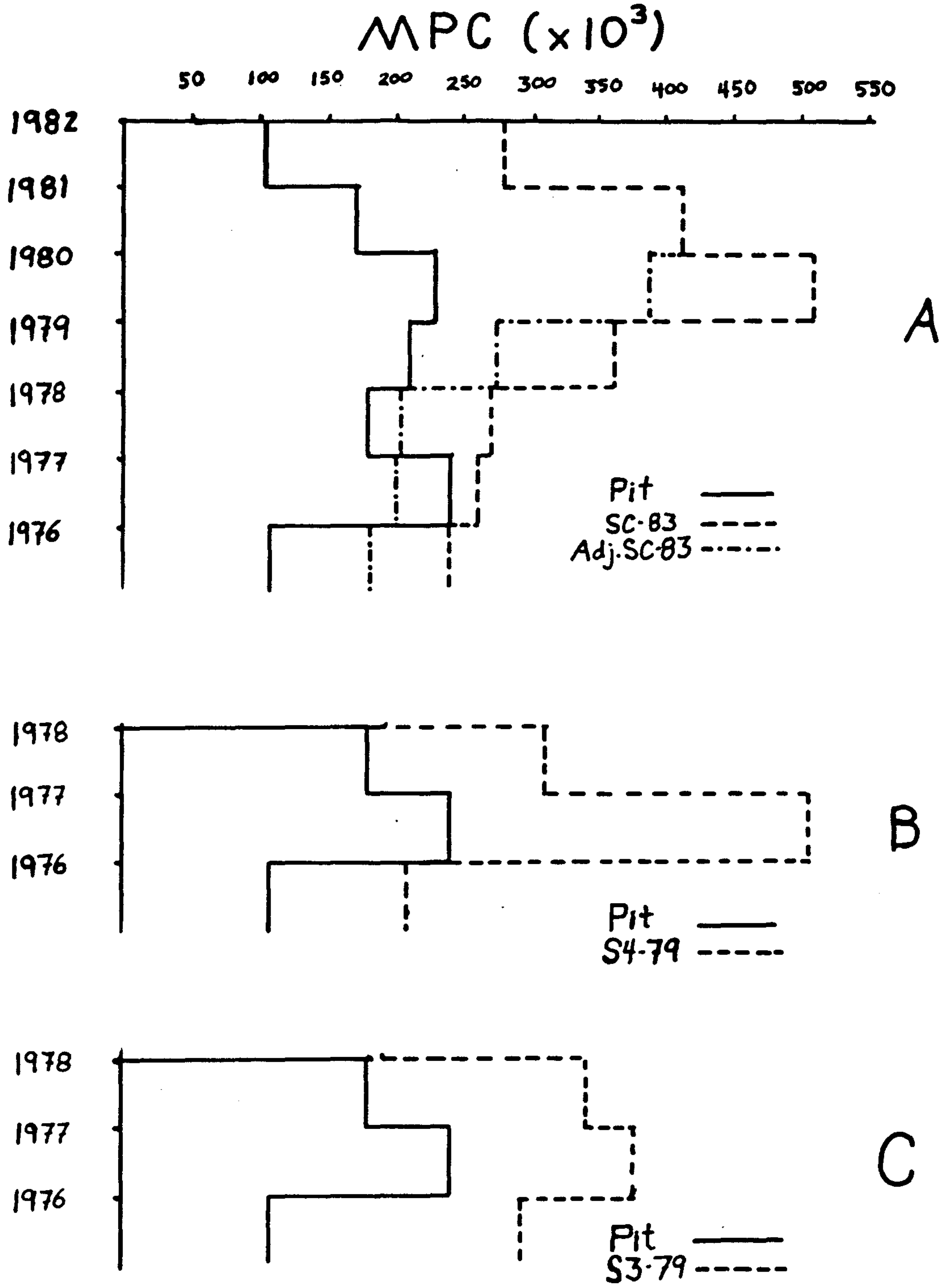

Figure 2.

Graph of MPC (.63-.80 μm) comparing (A) Pit to SC-83, (B) Pit to S4-79, and (C) Pit to S3-79.

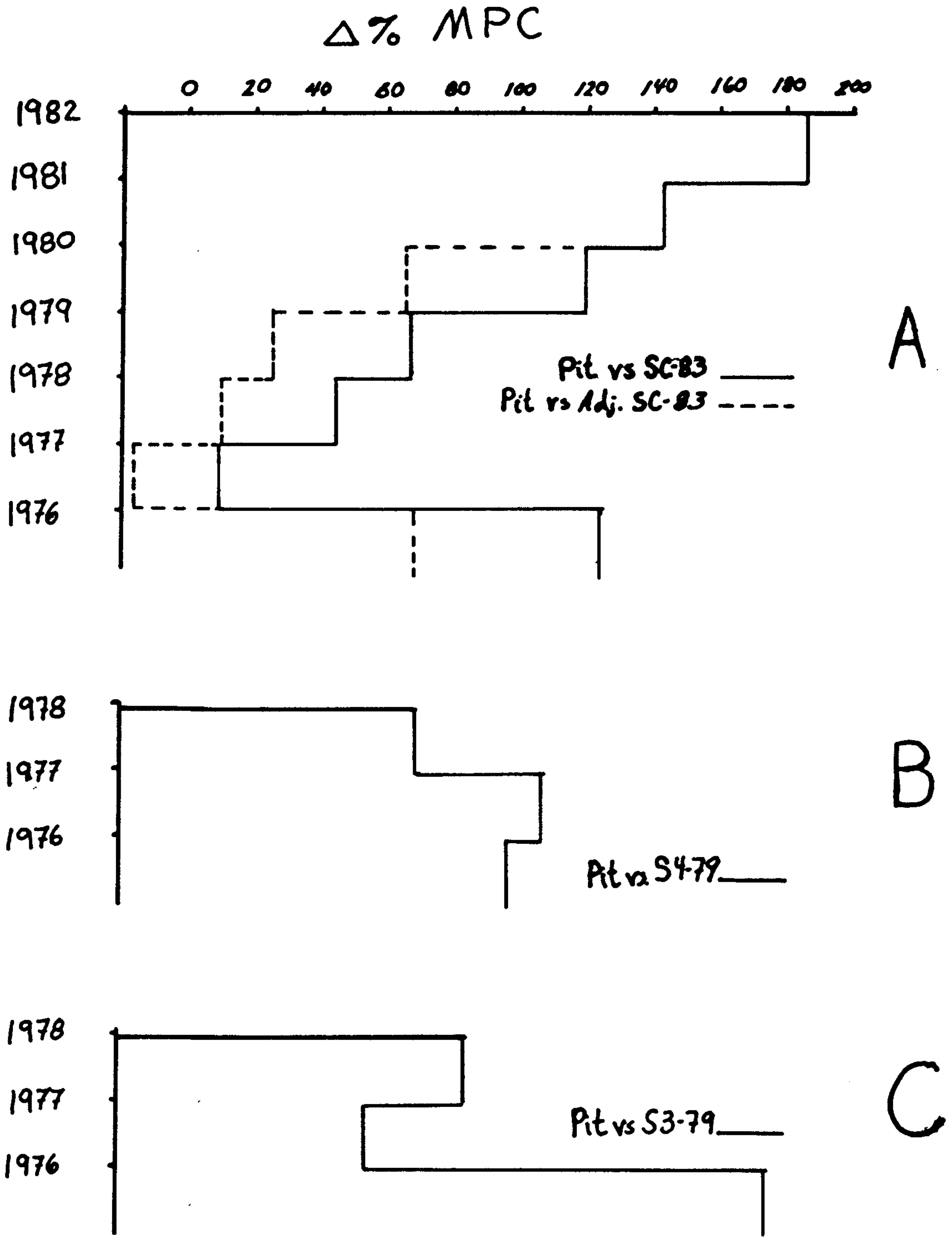

Figure 3.

Graph of percent differences in MPC between (A) Pit and SC-83, (B) Pit and S4-79, and (C) Pit and S3-79.

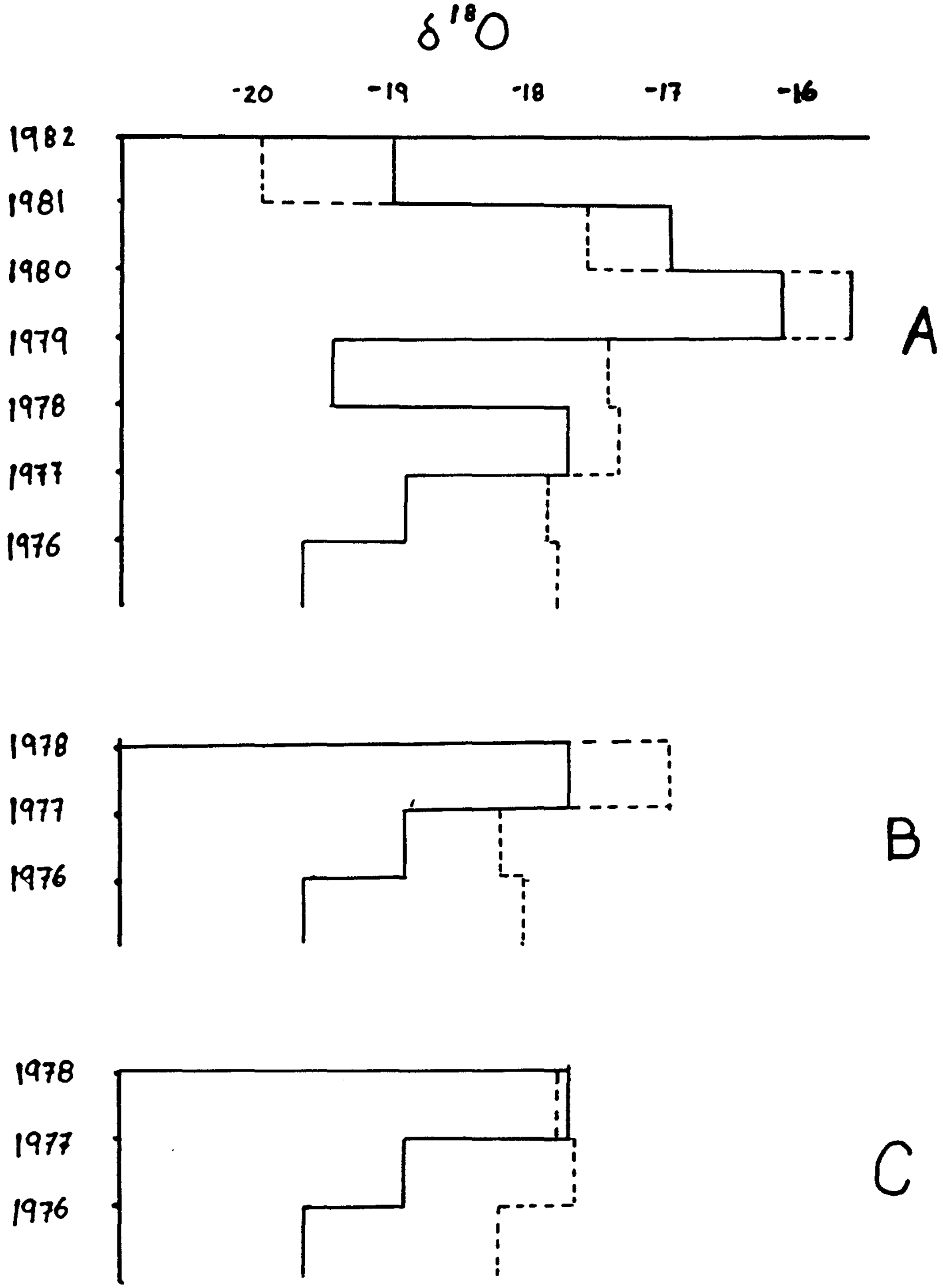

Figure 4.

Graph of annual $\delta^{18}O$ values comparing (A) Pit to SC-83, (B) Pit to S4-79, and (C) Pit to S3-79.

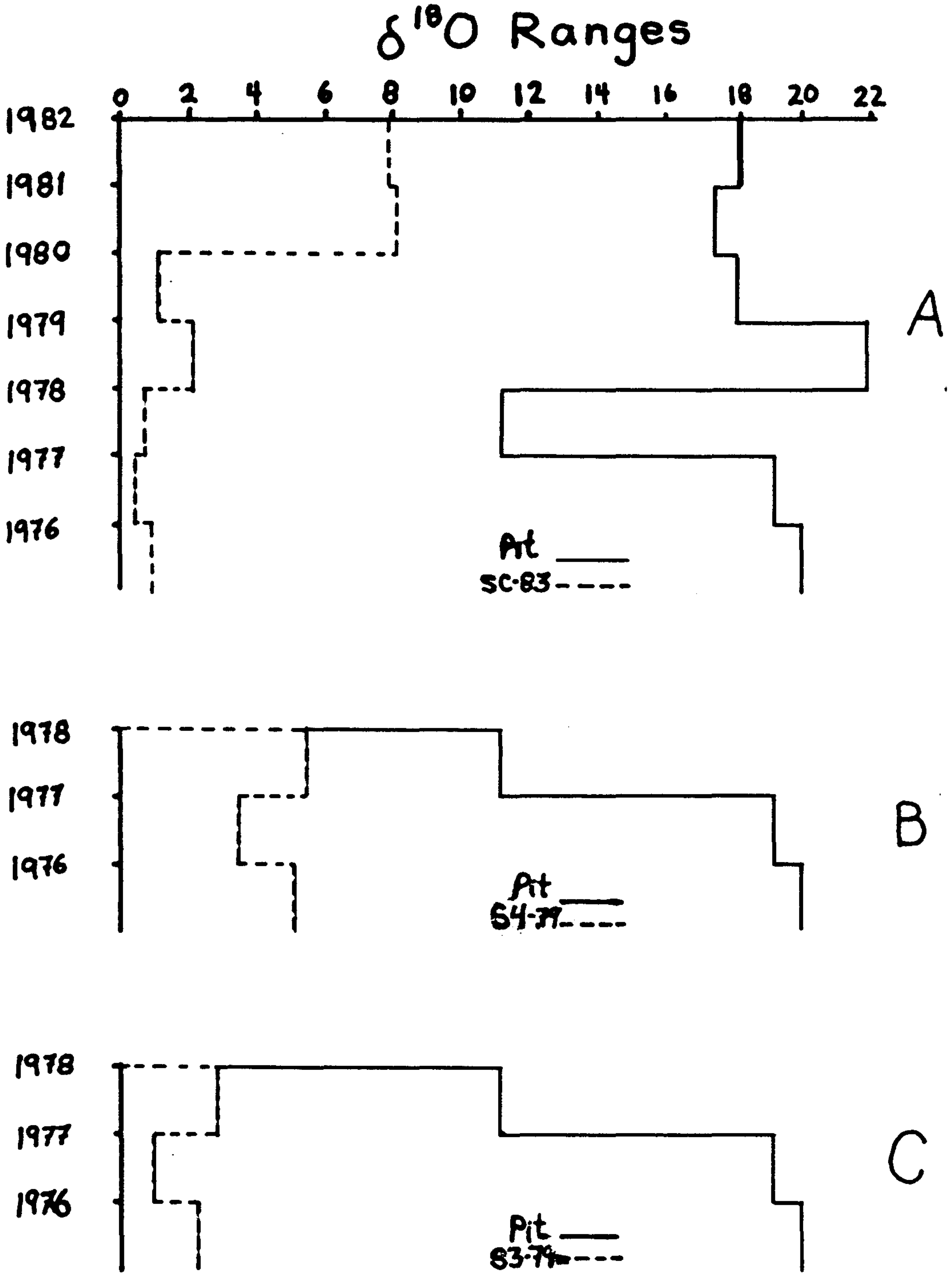

Figure 5.

Graph of annual $\delta^{18}O$ ranges comparing (A) Pit to SC-83, (B) Pit to S4-79, and (C) Pit to S3-79.

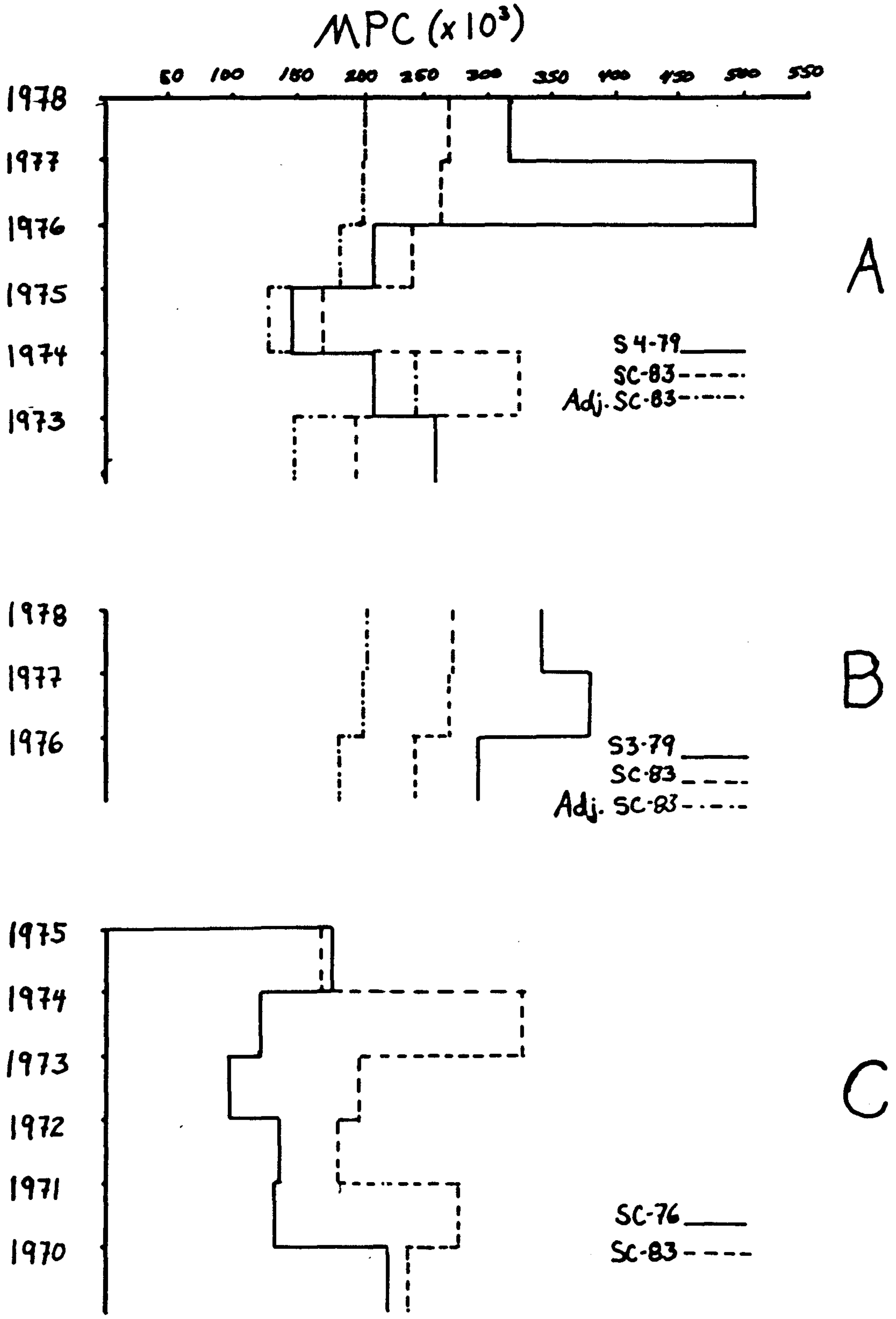

Figure 6.

Graph of MPC (.63-.80 μ m) comparing (A) S4-79 to SC-83, (B) S3-79 to SC-83, and (C) SC-76 to SC-83.

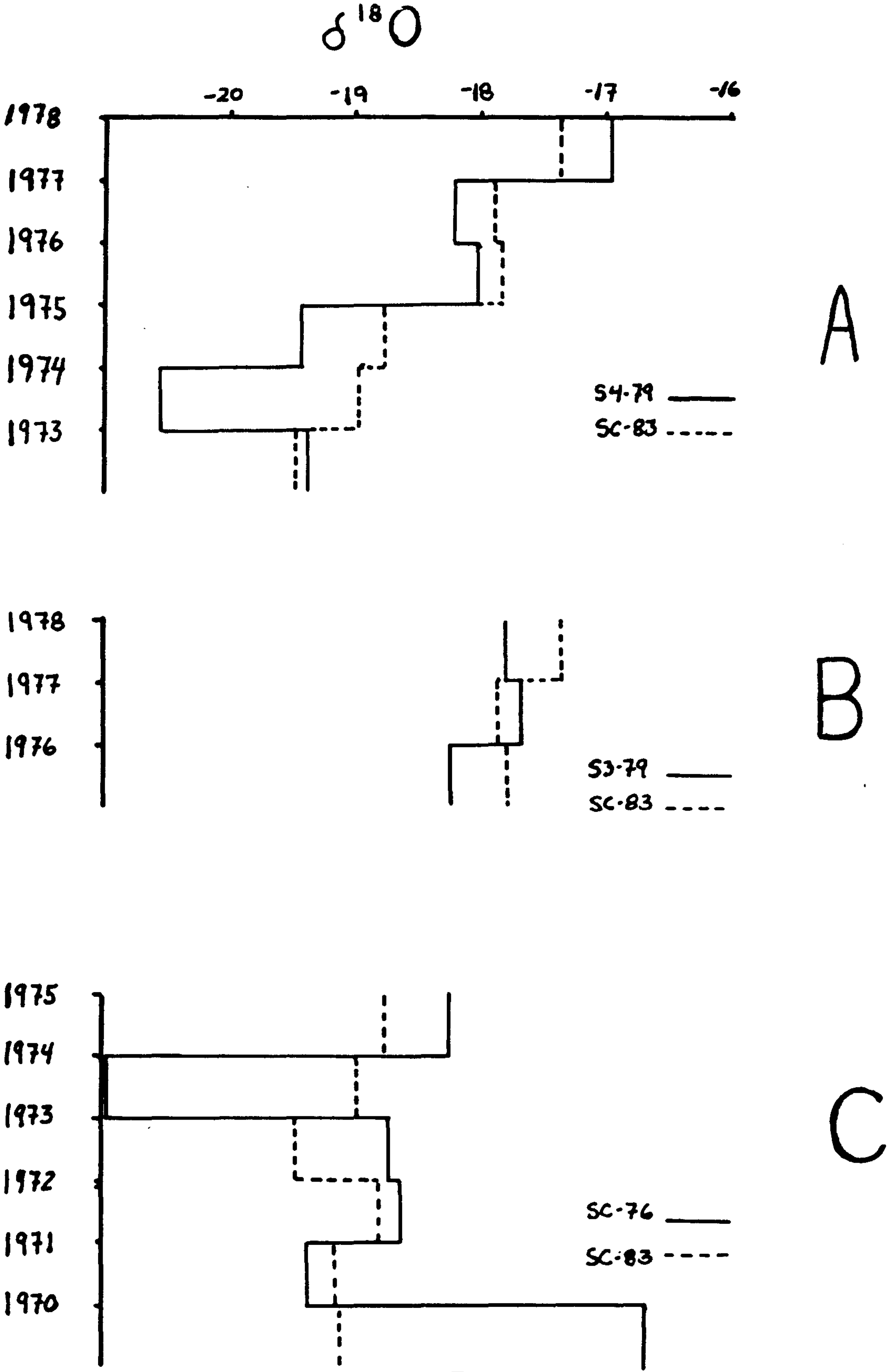

Figure 7.

Graph of annual $\delta^{18}O$ values comparing (A) S4-79 to SC-83, (B) S3-79 to SC-83, and (C) SC-76 to SC-83.

Figure 8.

Graph of annual $\delta^{18}O$ ranges comparing (A) S4-79 to SC-83, (B) S3-79 to SC-83, and (C) SC-76 to SC-83.

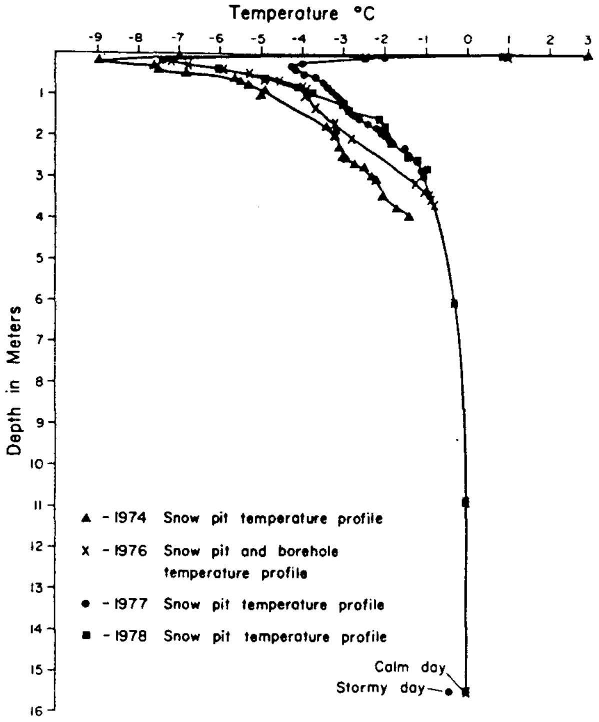

Figure 9.

Firn temperature profiles from the summit dome of the Quelccaya ice cap demonstrating a temperature inversion. (Thompson, 1980.)

TABLE 1

ANNUAL MICROPARTICLE (.63-.80μm) CONCENTRATIONS

		ADJUSTED				
Ann. Unit	SC-83	SC-83	S4-79	S3-79	SC-76	PITS
1982	288856	288856	-	-	-	100917
1981	418787	418787	-	-	-	172144
1980	512448	387329	-	-	-	233710
1979	361637	273341	-	-	-	217392
1978	270300	204304	315275	342908	-	187394
1977	267463	202159	507358	377312	-	245704
1976	240705	181935	209144	295594	-	107661
1975	171430	129574	146845	-	172410	-
1974	324545	245304	213231	-	124873	-
1973	197702	149431	260828	-	97329	-
1972	180730	136603	-	-	139557	-
1971	274250	207289	-	-	130162	-
1970	236036	178405	-	-	220139	-

TABLE II.

ANNUAL $\delta^{18}O$ VALUES

ANN. UNIT	SC-83	S4-79	S3-79	SC-76	PITS
1982	-19.99	-	-	-	-19.02
1981	-17.58	-	-	-	-16.96
1980	-15.65	-	-	-	-16.14
1979	-17.42	-	-	-	-19.46
1978	-17.36	-16.97	-17.80	-	-17.72
1977	-17.89	-18.21	-17.67	-	-18.92
1976	-17.82	-18.05	-18.24	-	-19.67
1975	-18.76	-19.44	-	-18.27	-
1974	-18.99	-20.56	-	-20.97	-
1973	-19.49	-19.38	-	-18.75	-
1972	-18.80	-	-	-18.64	-
1971	-19.15	-	-	-19.36	-
1970	-19.13	-	-	-16.69	-

TABLE III.

ANNUAL $\delta^{18}O$ RANGE VALUES

ANN.UNIT	SC-83	S4-79	S3-79	SC-76	PITS
1982	7.95	-	-	-	18.20
1981	8.11	-	-	-	17.40
1980	1.13	-	-	-	18.00
1979	2.16	-	-	-	21.90
1978	0.67	5.46	2.84	-	11.30
1977	0.56	3.59	1.14	-	19.20
1976	0.91	5.09	2.31	-	20.00
1975	0.48	7.16	-	14.20	-
1974	3.02	7.40	-	16.30	-
1973	2.45	2.51	-	9.50	-
1972	0.47	-	-	6.40	-
1971	0.82	-	-	9.00	-
1970	1.51	-	-	3.80	-