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THE VOLCANIC RECORD OF ANTARCTIC ICE CORES: PRELIMINARY RESULTS AND POTENTIAL FOR FUTURE INVESTIGATIONS*

by

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ABSTRACT

Occurrences of tephra layers in four ice cores from Antarctica are reviewed. A new tephra, informally named the Vostok tephra, is described from a depth of 100.85 m in an ice core from Vostok station. Ice associated with four tephra layers at depths between 1390 and 1450 m in the Byrd station ice core shows increased levels of sulfate and nitrate which correlate well with peaks in particle concentrations. High levels of sulfate and nitrate are also associated with the Vostok tephra.

Tephra offer great potential as stratigraphic markers and should be useful in providing time planes as well as assisting in correlation between widely spaced ice cores.

INTRODUCTION

Tephrochronology is a relatively new field which is concerned with the establishment of time-related sequences of geological events based on the characterization of tephra layers (Westgate and Gold 1974). The term tephra was initially defined by Thorarinsson (1944) and is now used as a collective term for all airborne volcanic ejectamenta.

Interest in volcanism has increased with the realization that volcanic eruptions may affect the global climate (Lamb 1970, Pollack and others 1976). Therefore, the identification and characterization of tephra in ice cores offer a method of studying the relationship between volcanism and climate during the late Pleistocene and Recent times. Ice cores are also useful for such a climatic interpretation since they preserve information on past temperature variations, as recorded by fluctuations in stable isotope ratios. In addition to the insoluble particulate record, the record of soluble aerosols, such as sulfate and nitrate, is preserved in ice cores. Secondary aerosols formed from volcanic gases when injected into the stratosphere in large quantities may have an important role in modifying the Earth's climate following a major volcanic eruption (Pollack and others 1976).

In Antarctica, numerous studies (Thompson 1977, Mosley-Thompson 1980, Thompson and others 1981) have shown that good microparticle records can be obtained. Tentative correlations with major eruptive events have been suggested. A combination of static electrical conductivity (Hammer 1980), to locate layers, followed by analyses of the soluble impurity and microparticle concentrations offer great potential for evaluating the southern hemisphere volcanic record.

In this paper we review the known occurrences of tephra layers in Antarctic ice cores (Fig.1). We also present preliminary grain-size analyses of tephra layers and values for the concentrations of soluble impurities (SO_4^{2-} and NO_3^-) of the associated ice from several Antarctic ice cores. The potential for future studies is discussed.

TEPHRA IN ANTARCTIC ICE CORES

Byrd station ice core (BSIC)

The 2 164 m deep BSIC (Gow and others 1968) contains 25 distinct dirt layers and an estimated 2 000 cloudy layers. The cloudy layers contain increased levels of particulate material and have been referred to as dust layers by Gow and Williamson (1971). Preliminary size analyses suggest that there is a graduation in the number and size of particles between the dirt and dust layers so we refer to them all collectively as dust layers. Once the particles from the layers have been examined and shown to be composed of airfall volcanic material, they are termed tephra layers. To date, all dust layers have been shown to

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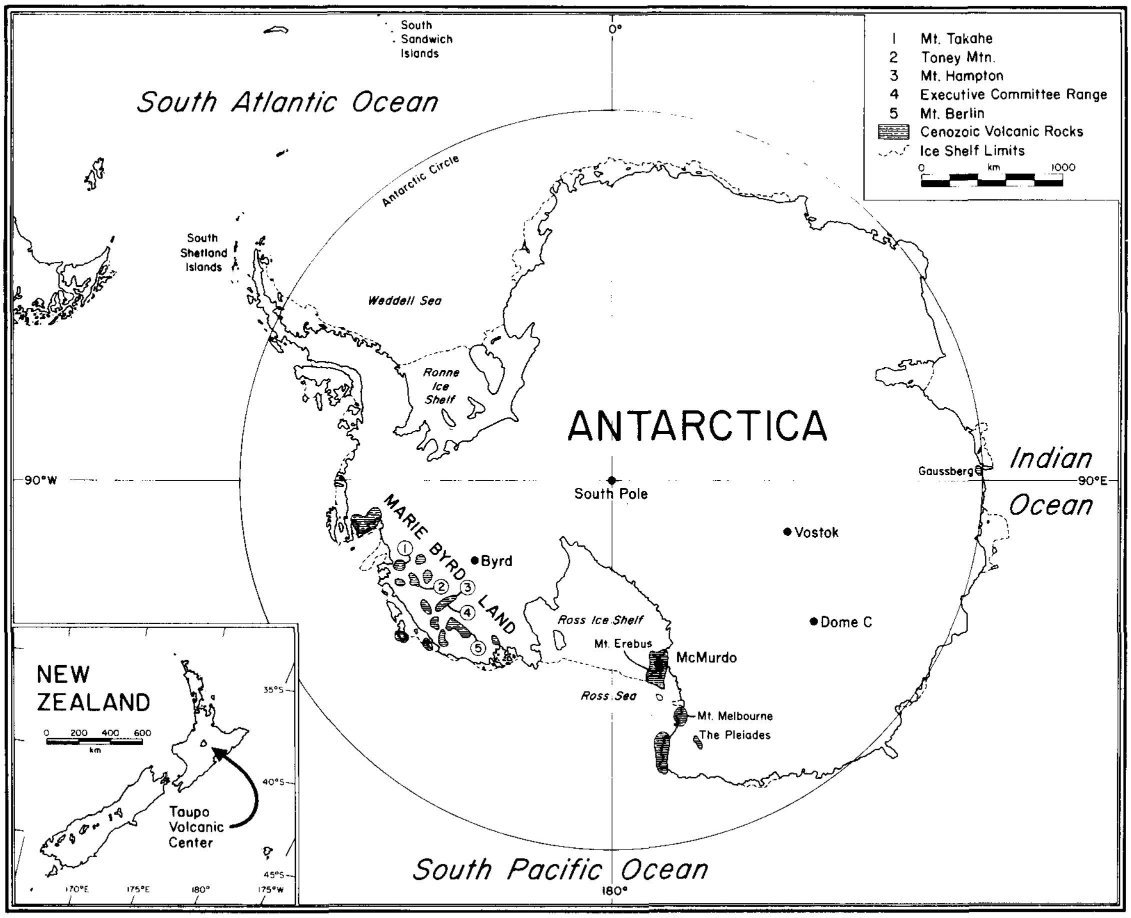

Fig.1. Map of Antarctica showing the location of four ice cores known to contain tephra layers. Areas of Late Cenozoic volcanic rocks are indicated along with possible volcanic centres which are known to have had explosive eruptions in the last 1 Ma.

be tephra layers; it is likely that the majority of the dust layers consist of tephra. Using the time scale given by Gow and Williamson (1971) the great majority of the dust layers occur between 14 and 30 ka BP.

Electron microprobe analyses of volcanic glass shards from six tephra layers in the BSIC, show they are composed of peralkaline trachyte (Kyle and others 1981). Mt Takahe, a young volcano 450 km from the drill site, was suggested as the source for the six tephra layers.

Dome C ice core (DCIC)

Large (~70 μm) volcanic glass shards were reported by Kyle and others (1981) at 726 m depth in the 905 m deep DCIC (Lorius and others 1979). Microprobe analyses of the shards show that they have compositions similar to those analyzed in the BSIC, and a source in Marie Byrd Land, possibly Mt Takahe, was suggested by Kyle and others (1981). The occurrence at Dome C of volcanic glass shards which apparently originated in Marie Byrd Land indicates that local volcanism can result in the widespread distribution of particulate material within Antarctica.

High levels of static electrical conductivity, due to elevated levels of sulfate were reported in the DCIC by Maccagnan and others (1981) at depths of 104 and 713 m, corresponding to ages of about 2 and 24 ka BP respectively. The younger layer may represent the AD 131 Taupo eruption from New Zealand (Walker 1980). The 713 m deep layer occurs at a time of significant volcanism in Marie Byrd Land, although, if an error exists in the time scale, this layer may in fact correspond to the Oruanui eruption from New Zealand which occurred 20 ka BP (Vucetich and Pullar 1969).

South Pole

A 101 m firn core from South Pole was analyzed over its whole length for microparticle (>0.63 - 16 μm) concentrations (Mosley-Thompson 1980, Thompson and Mosley-Thompson 1981) and showed several large peaks. Thompson and Mosley-Thompson (1981) compared the microparticle record with the volcanic dust veil index of Lamb (1970) and tentatively correlated microparticle peaks with eruptions of Krakatau (1883), Cosequina (1835), Tambora (1815), and Mayon (1766). Volcanic glass shards from the 1834±5 AD interval are andesitic in composition and have been attributed to the Cosequina eruption by King and Wagstaff (1980). We doubt this interpretation because: (1) the peak in the microparticle record is insignificant, compared to general fluctuations in the background, (2) recent field work (Self and others 1981) has shown that the Cosequina eruption was insignificant in size, and (3) a particle illustrated by King and Wagstaff (1980) is extremely large (perhaps >50μ m) and because of its high terminal velocity would settle out before reaching Antarctica.

Vostok core

In 1979-80 a 101 m firn core was obtained at Vostok station (Parker and Zeller 1980) in East Antarctica. A 0.05 m thick dust band was located at 100.8 m in the core has has been identified as tephra. Details are discussed below.

GRAIN-SIZE ANALYSES

Results

Preliminary analyses have been made on samples containing dust layers using a Coulter counter, following methods described by Thompson (1977). Two separate sample aliquots were analyzed to measure the

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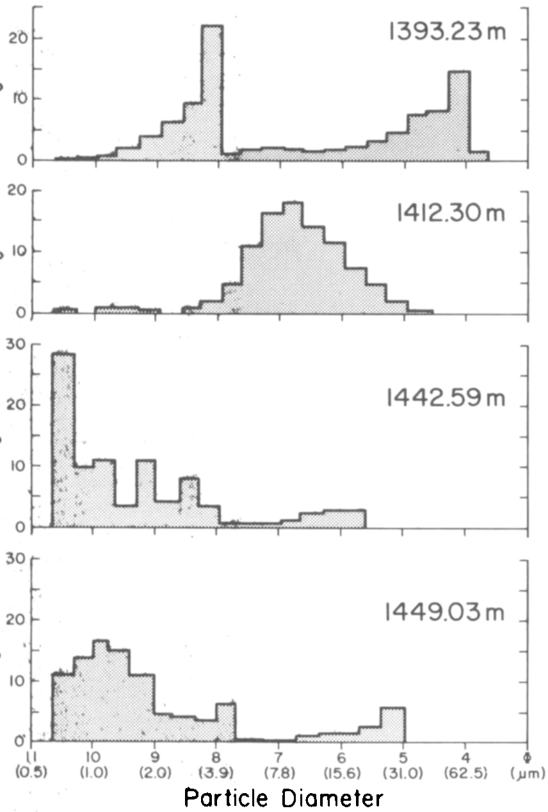

Fig.2. Histograms of grain-size distribution for four dust layers in the BSIC at depths of 1 393.23, 1 412.30, 1 442.59, and 1 449.03 m. The per cent by volume in each grain-size interval was computed assuming a spherical shape for the particles. Note the size axis is logarithmic, whereas the volume per cent of particles is linear.

0.63 to 5.0 μm size range and the 5.0 to 80 μm range. The size distributions are given as histograms (Fig.2) for four tephra layers from 1 393.23, 1 412.30, 1 442.59, and 1 449.03 m in the BSIC. Profiles across the tephra layers showing the number and volume of particles are given in Figure 3. Volumes were calculated assuming the particles were spheres.

Discussion

The four tephra layers all show different grain-size distributions. The sample at 1 393.23 m is bimodal and there is a weak indication of bimodality in the samples at 1 442.59 and 1 449.03 m. A sample from 1 412.30 m has a normal distribution with a median grain size of about 8 μm. The nature of the distributions is probably a function of the eruption size. The bimodality of the sample at 1 393.23 m may be due to the presence of two individual layers.

There is usually a close correlation between the total number and volume of particles (Fig.3), although this is not always the case. For example, at 1 442.52 to 1 442.535 and 1 448.99 to 1 449.00 m depth, the total number of particles is low relative to the volume. This implies the presence of several large particles. The reverse, a large number of small particles with a small total volume, is rarely seen (e.g. 1 448.98 to 1 448.99 m).

The four tephra samples analysed were all from cloudy bands. It is apparent that these contain a significant number of particles greater than 12 μm in diameter. Previous grain-size analyses, over a restricted grain-size range of 0.63 to 12 μm, of several dust layers were presented by Thompson (1977) and Kyle and others (1981). These analyses are now considered unrepresentative because of the presence of particles larger than 12 μm.

SOLUBLE IMPURITIES

Concentrations of SO_4^{2-} and NO_3^- were measured in ice associated with tephra layers, using an ion chromatograph (Delmas and others 1982). Three sections from the BSIC (Fig.3) and one from the Vostok ice core (Fig.4) were measured.

The three BSIC sections show large peaks in SO_4^{2-} concentrations, which coincide closely with the particle peaks (Fig.3). There is a correlation between the size of the SO_4^{2-} peak and the number of particles present, if the largest peaks are compared (Fig.3). Thus, the sample at 1 412.30 m, which has the largest SO_4^{2-} peak, also has the largest number and volume of particles. In the other two layers, there are slight offsets between the largest particle peaks and the largest SO_4^{2-} peaks. There are too few data currently available to attach any significance to these offsets.

The BSIC samples show peaks in SO_4^{2-} concentrations of between 180 and 250 μg ℓ^{-1}, whereas the Vostok core (Fig.4) shows considerably higher SO_4^{2-} values (corrected for blank) of 420 to 560 μg ℓ^{-1}. Nitrate also shows significant peaks which correlate well with the SO_4^{2-} and particle peaks. The Vostok sample has a peak of 250 μg ℓ^{-1} NO_3^- whereas the large peak for BSIC sample 1 412.30 is about 185 μg ℓ^{-1}.

PARTICLE COMPOSITIONS

Chemical analyses of volcanic glass shards provide a means of evaluating the source of tephra layers. Kyle and others (1981) have reported electron microprobe analyses of glass from six tephra layers in the BSIC and a zone in the DCIC.

Preliminary semi-quantitative analyses, using an energy dispersive X-ray analyzer on a scanning electron microscope, were made of particles from layers at 22.90 and 23.35 m depth in the South Pole core, for which a continuous microparticle profile is available (Thompson and Mosley-Thompson 1981). Both layers were considered as possibly resulting from the 1815 eruption of Tambora. No volcanic glass was identified, although one particle was rhyolitic in composition. This is quite unlike the composition of the phonolite eruption from Tambora (Bemmelen 1949). The sample from 23.35 m contained many Mg-silicate particles, which are possibly olivine or orthopyroxene. Olivine was a known mineral phase in the Tambora eruptive products (Bemmelen 1949). The presence of mineral phases and no observed volcanic glass can be reconciled by observations of Rose and others (1980) on small particles in volcanic eruption clouds. They reported that tephra in three Central American volcanoes had a bimodal distribution, with glass occurring in a 2 to 10 μm size range, whereas crystal fragments and acid droplets were found in a 0.2 to 0.8 μm size range. It is conceivable that the 23.35 m microparticle layer in the South Pole core could be from Tambora. If so, it suggests that large distant eruptions may be characterized in ice cores by the presence of acid and mineral particles rather than volcanic glass.

VOSTOK TEPHRA

Vostok tephra is proposed as an informal name for a 0.05 m thick tephra layer which occurs at a depth of 100.8 m in an ice core drilled in 1979 at Vostok station. The estimated age of the tephra is about 3.2 ka BP (Parker and others 1982). Based on preliminary microscope examination, the tephra is composed of about 55% lithic material, 40% clear volcanic glass shards, and 5% crystals. The average grain size is about 30 μm with a range from <5 to >45 μm. The lithic material is mainly brown glass, which is often cryptocrystalline and well-rounded. Alkali feldspar is the main crystal phase observed.

Although the source of the Vostok tephra is unknown, the discovery may be significant. The grain size and thickness of the tephra is greater than most of those observed in the BSIC; sulfate is also higher.

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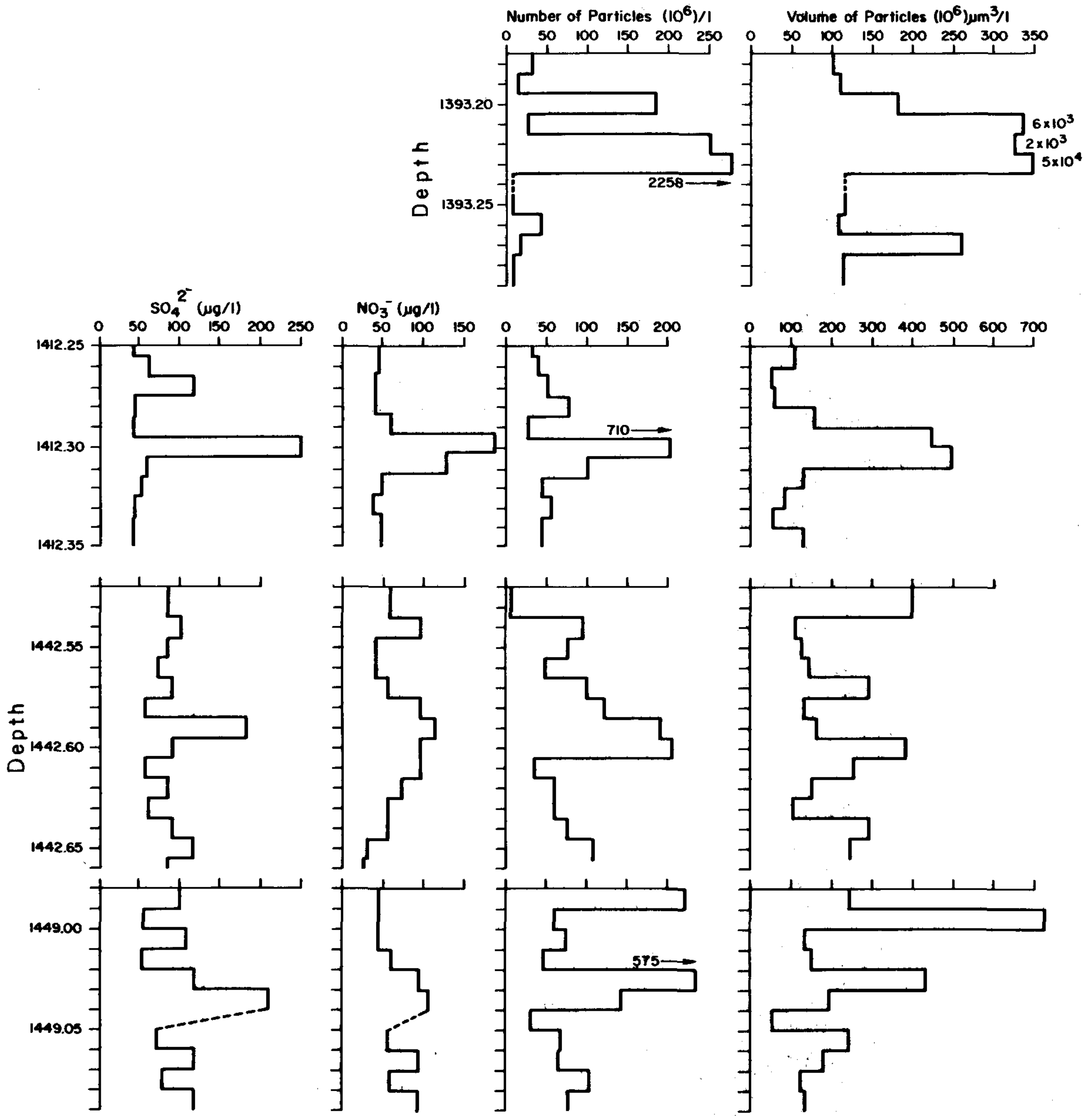

Fig.3. Sulfate, nitrate, and microparticle (by volume and number) concentrations vs depth (m) in the BSIC. No blank corrections for sulfate or nitrate have been applied.

The tephra may be extremely widespread and could act as an excellent stratigraphic marker over a wide area of East Antarctica. Because its age is about 3.2 ka, it is accessible using shallow (less than 150 m) drill cores. Further work is presently underway to characterize the material.

ERUPTIVE SOURCES

Tephra layers have been found in several shallow and deep ice cores and on the surface in Antarctica. Preliminary observations have suggested that the tephra may represent both local (within Antarctica) (Gow and Williamson 1971, Orheim 1972, Keys and others 1977, Kyle and Jezek 1978) and distant (non-Antarctic) (Delmas and Boutron 1980, Mosley-Thompson 1980) eruptive sources. Within Antarctica the likely source volcanoes (Fig.1) for the tephra are well known from geologic mapping (Craddock 1972) and include (1) volcanoes of the McMurdo volcanic group in the western Ross Sea (Kyle and Cole 1974), (2) volcanoes in Marie Byrd Land (LeMasurier and Wade 1976), (3) volcanoes in the Antarctic Peninsula (Baker 1976), and Scotia Arc (Federman and others in press), and (4) a small volcanic vent at Gaussberg in eastern Wilkes Land (Sheraton and Cundari 1980).

Only a limited record of non-Antarctic volcanic eruptions has yet been identified in Antarctic ice cores. Extremely large volcanic eruptions in the southern hemisphere which would have a global impact should be recorded in Antarctic ice cores across the continent. Many of these large eruptions are dated by historic and radiometric methods, and would therefore also provide important time planes.

Although it is not intended to give a comprehensive list of major eruptions, it is worth noting a few of potential importance. The Taupo Pumice eruption from New Zealand (Fig.1) was of exceptional size and had an eruption column that exceeded 50 km in height. It is probably one of the most widely dispersed tephra known (Walker 1980). ^{14}C age determinations suggest an age for the Taupo of about AD 131, although recent correlations with historic records

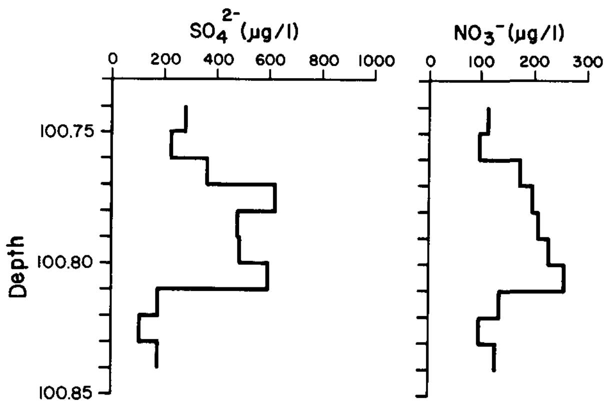

Fig.4. Sulfate and nitrate concentrations vs depth (m) in the Vostok core; no blank corrections have been applied.

suggest an age of AD 186 (Wilson and others 1980).

The Oruanui Formation is an extensive tephra deposit erupted about 20 ka BP (Vucetich and Puller 1969), also from the Taupo Volcanic Center. It is estimated to have had an eruptive volume of 75 km^3 and is believed to have been widely dispersed (Self and Sparks 1978). The positive identification of the Oruanui Formation in any Antarctic ice cores may be masked by local Antarctic tephra from Marie Byrd Land volcanoes, which, based on the tephra record in the BSIC, were undergoing frequent eruptions at this time. The rhyolitic composition of glass shards from the Oruanui Formation should be characteristic and easily distinguished from volcanic glass from the peralkaline volcanoes of Marie Byrd Land.

An older tephra layer which may be recorded in ice cores is that from the eruption in 75 ka BP of Toba, Sumatra (Ninkovich and others 1978). It is the largest magnitude eruption documented from the Quaternary and produced about 1 000 km^3 of tephra and ignimbrite. This tephra has the potential for providing a time plane in the basal section of the BSIC.

CONCLUSIONS

The potential for the application of tephrochronology to glaciological problems has yet to be realized. Tephra are useful for defining dated horizons and in providing correlations between various ice cores. Dated horizons are difficult to derive within ice bodies, because material suitable for dating is lacking. On the other hand, the age of many tephra layers are known from historic records and radiometric dates. This is particularly true for the non-Antarctic eruptions.

Tephra layers are known from most Antarctic ice cores. To date only tephra from Antarctic volcanic eruptions have been identified. Larger eruptions, having global impact, from volcanoes in the southern hemisphere should also be present in the cores and tentative correlations have been suggested. A concerted effort should be made to locate these tephra as they will provide valuable stratigraphic markers, and known time planes. These large eruptions are potentially the most valuable because they should be recorded across all of Antarctica.

Little is known about the volcanic record of Antarctic volcanoes during the last 50 ka or so. An extensive period of volcanic eruptions occurred in Marie Byrd Land during the period 30 to 14 ka BP. The resulting tephra are recorded as over 2 000 layers in the BSIC. Because of the proximity of the BSIC to active volcanoes it must be considered unrepresentative of Antarctica and care should be taken in interpreting any microparticle record in terms of climatic variations (cf. Thompson 1977).

The preliminary results discussed above indicate that tephra layers can be characterized using grain size, ice chemistry, and particle composition. In some cases the eruptive sources have been inferred. Further work should contribute to an understanding of the volcanic record of the southern hemisphere (including Antarctica) and the impact of major eruptions on climate.

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