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TEPHRA LAYERS IN THE BYRD STATION ICE CORE AND THE DOME C ICE CORE, ANTARCTICA AND THEIR CLIMATIC IMPORTANCE

PHILIP R. KYLE[1], PETER A. JEZEK[2], ELLEN MOSLEY-THOMPSON[1] and LONNIE G. THOMPSON[1]

[1]*Institute of Polar Studies, The Ohio State University, Columbus, Ohio 43210 (U.S.A.)*
[2]*Department of Mineral Sciences, Smithsonian Institution, Washington, D.C. 20560 (U.S.A.)*

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ABSTRACT

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Volcanic glass shards from tephra layers in the Byrd Station ice core were chemically analyzed by electron microprobe. Tephra in seven layers have similar peralkaline trachyte compositions. The tephra are believed to originate from Mt. Takahe, on the basis of their chemical similarity to analyzed rocks from Mt. Takahe and because dated rock samples from the volcano are younger than 250,000 years old. Glass shards from 726 m deep in the Dome C ice core, which is 2400 km from Byrd Station, are composed of peralkaline trachyte and may have also been derived from Mt. Takahe. The tephra could have resulted from eruptions which were triggered by increased ice loading during the late Wisconsin glaciation. Preliminary grain size data suggest the eruptions were only minor and they were unlikely to have instantaneously altered global climate as have explosive eruptions in the tropics. Nevertheless, the effect of this localized volcanic activity upon the Antarctic energy budget warrants further investigation.

INTRODUCTION

Volcanic eruptions during historic times have been associated with temporary surface cooling and stratospheric warming at some latitudes. Particulate matter (dust) and aerosols injected into the stratosphere can scatter and absorb shortwave radiation and scatter, absorb and emit longwave radiation. The resulting alteration of the atmosphere's optical properties may create a temporary imbalance in the radiation budget resulting in an adjustment of the globally averaged surface temperature (Pollack et al., 1976). A major problem is to determine the long-term effects of prolonged, explosive volcanism on global climate. The study of ice cores offers a means to evaluate the frequency of volcanic eruptions and their possible relationship to climate over the last 100,000 years or so.

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Tephra (a collective term for all volcanic pyroclastic ejactamenta) are abundant as microparticles in the Byrd Station ice core from Antarctica especially in the interval from 16,000 to 30,000 years (Gow and Williamson, 1971). The purposes of this paper are firstly to describe microprobe analyses of volcanic glass shards from the Byrd Station ice core and the Dome C ice core and secondly to evaluate the possible climatic importance of the responsible eruptions.

BYRD STATION ICE CORE (BSIC)

A 2164 m deep ice core was drilled at Byrd Station (Fig.1) on the West Antarctic Ice Sheet during 1967/68 (Gow et al., 1968). Gow and Williamson (1971) described 25 distinct dirt layers and an estimated 2000 cloudy (dust) layers within the core. Age estimates of the ice core are controversial; however the time scale used by Gow and Williamson (1971) suggests the majority of the tephra layers are between 16,000 and 30,000 years old. The dirt layers were characterized by particles large enough to see with the eye whereas this was not the case for the cloudy layers. Particle size analyses (Thompson, 1977) of cloudy layers and those reported below for the dirt layers are different.

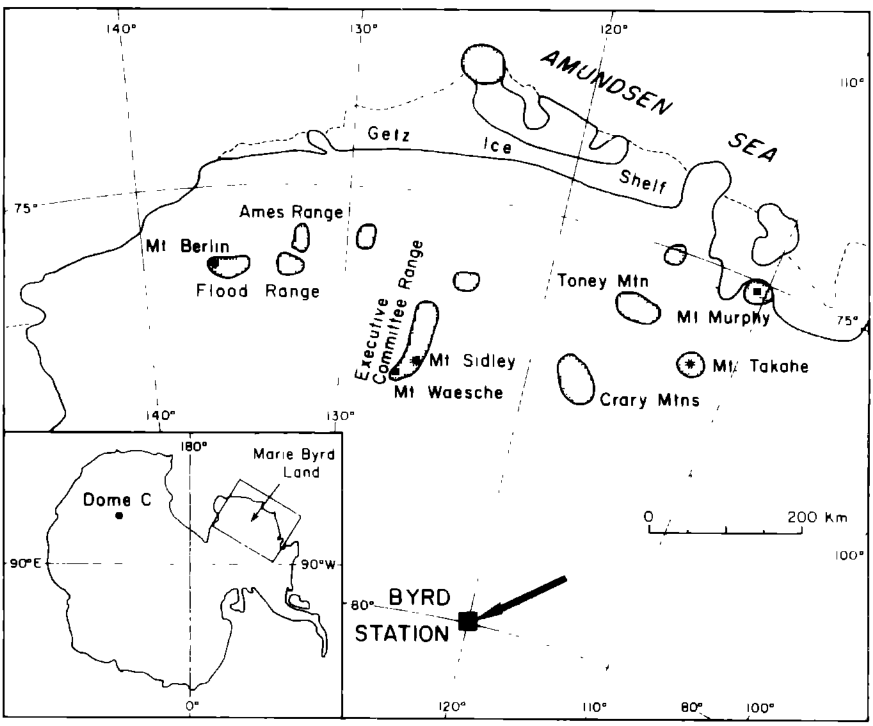

Fig.1. Location map of Marie Byrd Land showing Byrd Station and the distribution (shaded) of Late Cenozoic alkali volcanics. Arrows indicate estimated direction and extent of ice flow during the last 25,000 years (Whillans, 1979).

Dirt layers tend to exhibit high concentrations of both small and large particles while cloudy layers contain high concentrations of only the smaller particles. All layers whether visible or cloudy are here referred to as dust layers. Particles in some of the dust layers have been examined by scanning electron microscopy and the petrographic microscope, and consist predominantly of volcanic glass shards and lithic fragments with rare crystals. Where an airfall mode of formation is inferred the layers are called tephra layers. Some dust layers could also be wind-blown material, not associated with volcanic eruptions, although none have been identified to date.

DOME C ICE CORE (DCIC)

The 906 m deep Dome C (Fig.1) ice core was drilled during 1977/78 by the French on the East Antarctic Ice Sheet. The oxygen isotope record and its climatic interpretation is described by Lorius et al. (1979), and the microparticle record in 51 sections each 0.8 m long is discussed by Thompson et al. (1981). During the microparticle analyses a section at 726 m depth was found to contain a considerable number of volcanic glass shards large enough for microprobe analyses. Using the time scale of Lorius et al. (1979) the tephra layer is about 25,000 years old, similar to tephra layers in the BSIC.

GRAIN SIZE

Preliminary size distribution of the insoluble particles was measured using a Coulter counter and followed the procedures described by Thompson (1977). Only particles between 0.5 and 16 μm were counted. Microscopic examination revealed that some samples contained a few particles greater than 16 μm; these are believed to be relatively insignificant in the total volumetric size distribution. A total of 76 individual ice samples, each about 10 mm thick, were analyzed. The number of particles is reported relative to an ice volume equivalent of 500 μl of water sample volume. A typical profile across a tephra layer (Fig.2) shows the particles are confined mainly to one or two 10-mm sample intervals, and define a sharp peak above an undulating background. Using the time scale established by Whillans (1979) for the BSIC, a 10-mm ice sample at a depth of 1500 m represents approximately four to five months.

Representative grain size distributions of the tephra layers, based on the number of particles, show a range of median grain size from 1.5 to about 1.0 μm. Median grain size increases as the total number of particles increases. Microparticle analysis of background samples are characterized by about 90% of their particles being less than 0.7 μm.

The grain size distributions were determined by counting the number of particles within a given size range. However, in order to compare these data with published grain size distributions for other tephra it is necessary to convert the number of particles to weight or volume percent. This was done

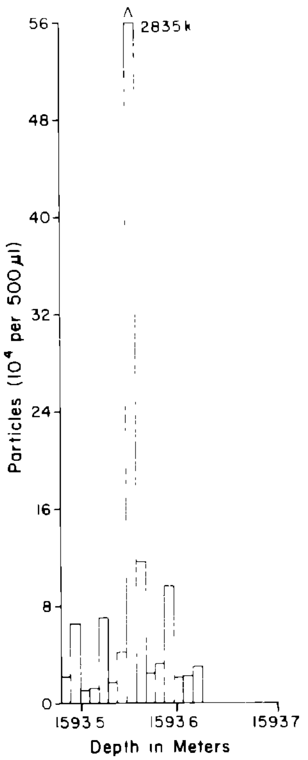

Fig.2. Representative profile showing the number of particles (>0.50 μm) across a tephra layer at 1593.58 m depth in the BSIC. The sample interval of about 10 mm represents approximately four to five months. The peak contains 2835 thousand (*k*) particles. Total number of particles is based on a sample size of 500 μl.

by assuming a size range was represented by the mean of the limiting values and that the particles were spheres. On a volumetric basis the range in median size was about 8—5 μm.

GLASS COMPOSITION

Electron microprobe analyses of glass shards, from six BSIC tephra layers and a tephra layer 726 m deep in the Dome C ice core are given in Table I. All the BSIC glasses have high normative acmite (Ac), which exceeds about 5—6 wt.%; the glasses are classified as peralkaline trachyte. The analyses are all very similar and with the exception of the 788-m layer cannot be distinguished from each other. The 788-m tephra layer has higher TiO_2, MgO and CaO than the other five analyzed BSIC tephra layers.

An additional tephra layer at 1377.4 m in BSIC is composed predominantly of lithic particles, together with glass shards and crystals of pyroxene, magnetite and feldspar. Insufficient glass analyses were made to give a good estimate of the average composition. However, two glass populations are

TABLE I

Major element analyses (in weight percent) of volcanic glass from tephra layers in the Byrd Station Ice Core, Dome C Ice Core and comparative analyses of volcanic rocks from Marie Byrd Land volcanoes

Sample	1	2	3	4	5	6	7	8	9
Depth (m)	788	1457	1487	1500	1594	1711			
n	29	30	4	9	10	19	16		
SiO_2	60.42 (0.68)	61.56 (0.66)	63.22 (0.83)	62.76 (0.77)	61.90 (0.88)	61.55 (0.63)	61.67 (0.64)	61.22	61.51
TiO_2	0.85 (0.07)	0.50 (0.05)	0.47 (0.03)	0.48 (0.05)	0.43 (0.03)	0.51 (0.06)	0.52 (0.04)	0.61	0.38
Al_2O_3	15.44 (0.25)	14.52 (0.37)	14.44 (0.28)	14.45 (0.39)	15.37 (0.24)	15.82 (0.34)	14.11 (0.38)	15.16	16.03
FeO[a]	8.52 (0.16)	8.49 (0.29)	7.76 (0.62)	8.23 (0.48)	7.36 (0.40)	7.02 (0.18)	8.79 (0.36)	7.07	6.17
MnO	n.a.[b]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.29	0.14
MgO	0.38 (0.06)	0.04 (0.03)	0.06 (0.03)	0.05 (0.02)	0.07 (0.03)	0.14 (0.04)	0.06 (0.03)	0.12	0.22
CaO	1.91 (0.07)	1.22 (0.09)	1.14 (0.16)	1.16 (0.08)	1.11 (0.06)	1.14 (0.07)	1.21 (0.07)	1.30	1.45
Na_2O	7.22 (0.30)	8.65 (0.58)	7.51 (0.51)	7.56 (0.22)	7.58 (0.25)	8.43 (0.35)	6.58 (0.76)	7.97	6.93
K_2O	4.45 (0.14)	4.26 (0.11)	4.53 (0.16)	4.60 (0.12)	4.70 (0.18)	4.49 (0.16)	4.40 (0.16)	4.80	5.20
P_2O_5	0.17 (0.05)	0.07 (0.04)	0.08 (0.02)	0.07 (0.03)	0.07 (0.03)	0.06 (0.04)	0.07 (0.03)	0.11	0.06
Total	99 36	99.31	99 21	99.36	98.59	99.16	97.41	98.65[c]	98.09[d]
CIPW norms (wt. %)									
Q	—	—	2.35	1.32	—	—	1.94	—	—
Or	26.30	25.17	26.77	27.18	27.77	26.53	26.00	28.36	30.73
Ab	49.41	50.97	49.05	48.72	52.89	51.74	48.08	50.15	49.76
Ne	2.83	—	—	—	—	2.51	—	0.60	2.03
Ac	5.68	6.83	6.25	6.63	5.90	5.64	6.69	5.67	4.53
Ns	—	3.37	1.72	1.80	1.06	1.99	—	2.27	—
Di	7.35	4.98	4.57	4.72	4.49	4.66	4.93	5.08	6.00
Hy	—	3.04	7.64	8.16	0.57	—	8.67	—	—
Ol	5.42	4.08	—	—	5.13	5.17	—	5.29	4.15
Mt	0.59	—	—	—	—	—	0.18	—	0.29
Il	1.61	0.95	0.89	0.91	0.82	0.97	0.99	1.16	0.72
Ap	0.39	0.16	0.18	0.16	0.16	0.14	0.16	0.26	0.14
Total	99.60	99.55	99.42	99.60	98.79	99.36	97.65	98.84	98.26
D.I.[f]	78.5	76.1	78.2	77.2	80.7	80.8	76.0	79.1	82.5

Key: 1—6 = tephra from the Byrd Station Ice Core; 7 = tephra from the Dome C Ice Core, 726 m depth; 8 = peralkaline trachyte (66A), Mt Takahe (W. LeMasurier, (pers. comm.); 9 = peralkaline trachyte (53b), Mt. Sidley (LeMasurier and Wade, 1976); *n* = number of analyses value in parentheses represents one standard deviation.

[a]total Fe as FeO, [b]n a. = not analyzed; [c]includes H_2O^+ = 0 37, FeO = 2.35, Fe_2O_3 = 5 24; [d]includes H_2O^+ = 1.73, FeO = 2.34, Fe_2O_3 = 4.26, [e]for the norm calculations, Fe_2O_3 standardized at 0.25 × FeO[a], [f]differentiation index (Thornton and Tuttle, 1960).

Analytical procedures are described by Kyle and Jezek (1978).

present. One appears similar to analyses given in Table I. The other is more basic with SiO_2 about 57—58%, TiO_2 1.4, Na_2O 4.7—5.1, and K_2O 4.35, and could represent eruptions from another volcano or else changes in composition during the same eruption.

Glass shards from the Dome C tephra layer are chemically similar to those from the BSIC (Table I). Some minor differences are the slightly higher FeO and lower Na_2O. More significant is the low analytical total which suggests the glass may be hydrated. It is difficult to explain why the glass shards in the DCIC are hydrated whereas this is not the case in the BSIC. The implication is that hydration may have occurred during transportation of the glass. This seems unlikely as transport time was probably in the order of days, at least for the larger (>30 μm) particles. Further analyses of glass shards in Dome C are necessary before the significance of the hydration can be assessed.

TEPHRA SOURCE

Cenozoic alkali volcanics are common throughout much of Marie Byrd Land (LeMasurier and Wade, 1976) and are the most probable source of the tephra as previously suggested by Gow and Williamson (1971). No other possible source having compositions comparable to the analyzed glass shards is presently known in Antarctica.

Kyle and Jezek (1978) suggested that Mt. Takahe (Fig.1) was the source volcano for the tephra layers because an analyzed rock sample (Table I) was nearly identical in composition to the tephra, and radiometric dates indicate the volcano is younger than 250,000 years old. Four other volcanoes: Mt. Berlin, Mt. Sidley, Toney Mountain and Mt. Waesche (Fig.1) must be considered, but are less likely sources. Mt. Sidley appears to be too old (4—5 m.y., W. LeMasurier, pers. comm.), although a tuffaceous apron of unknown age occurs around a summit caldera and has a similar composition (Table I). Trachytes have not been recorded from Toney Mountain or Mt. Waesche, and an analysis of a rock sample from Mt. Berlin is unlike the tephra from Byrd Station or Dome C. However, as the exposure on these volcanoes is limited due to ice cover, and as only reconnaissance studies have been made, they cannot be completely dismissed.

NATURE OF THE VOLCANIC ERUPTIONS

The preceding discussion suggests the tephra layers may have been erupted from Mt. Takahe, which is about 350 km from the likely site of tephra deposition at Byrd Station. This distance takes into account ice flow movement of about 140 km during the last 25,000 years (Fig.1). Considering the close proximity of Mt. Takahe, the median sizes of the tephra are small and suggest the responsible eruptions were only minor.

Fisher (1964) has shown a correlation between median diameter and distance travelled for a large number of tephra samples (Fig.3). The BSIC

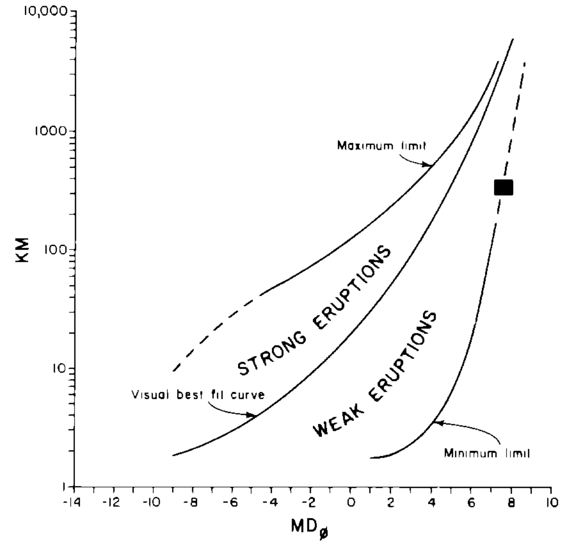

Fig.3. Empirically derived relationship between median grain size and distance from eruptive source (after Fisher, 1964). Extrapolation of minimum limit given by Fisher (1964) is shown by a dashed line and intersects the field for BSIC tephra samples.

tephra date correspond to near the extrapolated minimum limit suggested by Fisher (1964) and support the suggestion that the eruptions were probably small in size. No quantitative estimation of eruption size can be made, but empirically it is concluded that the eruptions were unlikely to have been very large and that they were not globally significant. This is supported by LeMasurier (1972b), who, based on field studies, concluded that there was no evidence that volcanoes in Marie Byrd Land were very explosive or that they produced significant quantities of tephra.

Mt. Takahe, the favored source of the tephra layers, is composed predominantly of felsic hyaloclastite with basaltic parasite cones around the lower flanks (LeMasurier, 1972a). Eruptions may therefore have occurred subaquatically, possibly in a water-filled cavity within the West Antarctic Ice Sheet. Periodically the eruptions may have reached the atmosphere to allow the dispersion of the tephra found in the ice cores. It is possible that the eruptions were of the phreatomagmatic or surtseyan types.

DOME C TEPHRA

Tephra in the DCIC range up to 70 μm in size and have an inferred source in Marie Byrd Land, possibly Mt. Takahe. Such large particles, similar or only slightly smaller in size to those found in the BSIC, seem to suggest that the responsible eruptions were considerably larger than inferred from the grain size of tephra in the BSIC. Several explanations seem possible to elucidate this apparent contradiction:

(1) The site of deposition of tephra in the BSIC is downwind from Mt. Takahe. If there were consistently strong winds then deposition may have been limited at Byrd Station.

(2) Atmospheric paleocirculation may have been significantly stronger than present, so that even though eruptions may have been small, particles were transported rapidly around Antarctica.

(3) The tropopause in Marie Byrd Land is now in the range of 7—10 km high (Weyant, 1966). Mt. Takahe is 3400 m high, so that small eruptions may be capable of injecting material into the stratosphere, thus allowing a rapid and widespread distribution over Antarctica.

(4) The tephra may have been transported by a cyclonic storm.

(5) Whereas the BSIC tephras may have been erupted by surtseyan-type eruptions, the DCIC tephra could have been the result of a larger subaerial eruption, which for some unknown reason was not recorded as a thick deposit in the BSIC.

DISCUSSION

Gow and Williamson (1971) have speculated that about 30,000 years ago a period of prolonged volcanism, represented by the dust and tephra bands in the BSIC (Fig.4), resulted in the injection of large amounts of particles into the Antarctic stratosphere. They suggested the eruptions may have been responsible for a decrease in temperature of the troposphere, as inferred from the oxygen isotope analyses of the ice enclosing the tephra. Gow and Williamson (1971) suggested that "it is conceivable that widespread eruptions of volcanic ash in Antarctica during the latter part of the Wisconsin may have triggered world-wide cooling during this period — effectively intensifying the existing glacial regime". While this speculation is not disputed the cause and effect relationship can be viewed from an alternative point of view.

A thickening of the West Antarctic Ice Sheet may have been responsible for the initiation of volcanic eruptions in Marie Byrd Land. Crustal loading due to an increase in ice thickness would cause isostatic depression with a resulting increase in pressure on any high level magma chamber. The glass shards are composed of peralkaline trachyte, a composition which is highly evolved and presumably formed by differentiation from a basaltic parent in a low pressure regime in the upper crust.

The frequency of tephra layers and dust bands show a strong correlation with a decrease in the oxygen isotope composition of the enclosed ice (Fig. 4). The onset of sustained volcanism occurs simultaneously with the decline in $\delta^{18}O$ (Gow and Williamson, 1971). The decline in $\delta^{18}O$ corresponds to a temperature change of about 2—3°C (Gow and Williamson, 1971). What the temperature change results from is unknown. It could be due to a decrease in the temperature of the troposphere or it could reflect a gain in altitude of the site of deposition due to thickening of the ice sheet or a combination of

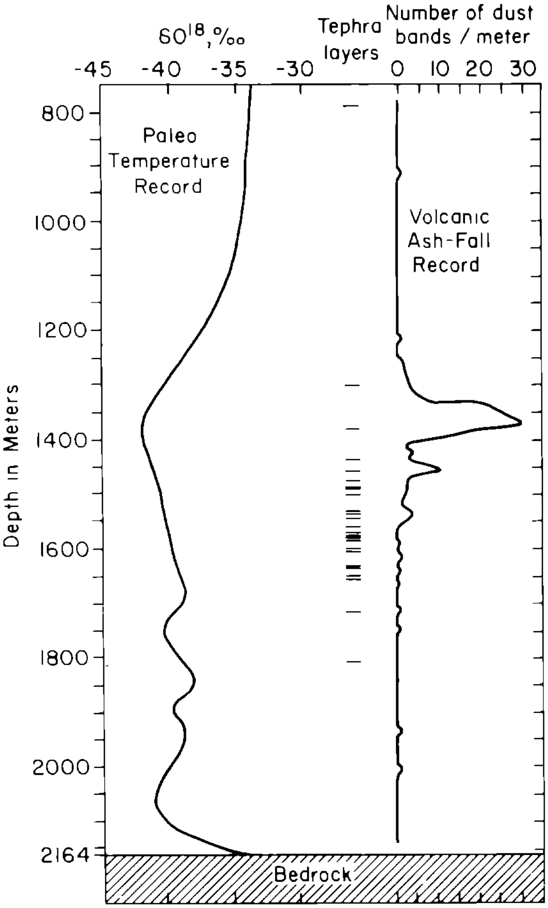

Fig.4. Correlation of the number of tephra and dust bands in the BSIC with the oxygen isotope profile of Epstein et al. (1970), from Gow and Williamson (1971). Tephra layers and visible dust bands recognized by Gow and Williamson (1971). Note the onset of tephra layers with the decrease in $\delta^{18}O$.

both. The present temperature lapse rate of 0.5 to 1°C per 100 m (Bentley et al., 1964) would indicate a maximum ice thickness increase of 300—600 m in the vicinity of Byrd Station. Mt. Takahe is situated closer to the sea than Byrd Station. Therefore if ice thickening occurred near Byrd Station it would be even greater at Mt. Takahe or sites closer to sea level, in order to attain an equilibrium profile.

Very little is known about the mass balance of the West Antarctic Ice Sheet during the Wisconsin glaciation. However, studies of the variations in the amount of air trapped in ice samples taken from the BSIC (Gow and Williamson, 1975; Raynaud, 1977) suggest that the West Antarctic Ice Sheet may have increased in thickness during the Wisconsin.

Therefore on the basis of the present data it is possible for thickening of the ice sheet to have occurred. It is tentatively suggested that such thickening increased the lithostatic pressure on an upper crustal magma chamber(s) and caused minor eruptions of Mt. Takahe. Thus, glaciation may have been the cause of volcanism and not vice versa as suggested by Gow and Williamson (1971).

CONCLUSIONS

(1) Tephra layers in the BSIC and DCIC were possibly derived from eruptions of Mt. Takahe in Marie Byrd Land.

(2) The eruptions may have been of the surtseyan type and although they were not likely to be extremely violent they may have had sufficient energy to inject tephra into the stratosphere. The eruptions were probably too small to cause any rapid response from the global climate system although the effect of prolonged activity upon the Antarctic energy budget or the world's climate has not yet been assessed.

(3) It is suggested that an increase in ice thickness in Marie Byrd Land during the late Wisconsin glaciation may have caused crustal subsidence which initiated volcanic eruptions.

(4) The recognition in the DCIC of a possible tephra eruption in Marie Byrd Land is perhaps of greater significance than stated here. Given more analyses of tephra in both the DCIC and BSIC it may be possible to correlate individual tephra layers and thus define a common time plane within each ice core. The occurrence of such large particles, which probably travelled about 5000 km, suggests the possibility of a more vigorous stratosphere circulation pattern in the past. It may be possible to examine the paleoclimatic conditions which prevailed during the Wisconsin, if further size analyses and chemical analyses are made of tephra in the DCIC.

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