# LATE GLACIAL INPUT OF EOLIAN CONTINENTAL DUST IN

# THE DOME C ICE CORE: ADDITIONAL EVIDENCE FROM

# INDIVIDUAL MICROPARTICLE ANALYSIS

by

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ABSTRACT

399 individual microparticles in nine samples from the Dome C ice core were studied under a scanning electron microscope and analysed by an energy dispersive X-ray system. The studied particles were either continental quartz or various silico-aluminates of continental or volcanic origin. Observations lead to the conclusion that the increase in microparticle concentration by a factor of 10 to 20 during the last glacial stage is explained by a large input of continental dust, as already indicated by trace element analysis (Petit and others 1981) and previously suggested by chemical analysis of other polar ice cores (Cragin and others 1977). This increase is considered to be a consequence of the ice-age climate and earth surface conditions which were characterized by the increase of arid regions and more vigorous atmospheric circulation. Both these conclusions are further supported by the existence of a higher quartz content in the Antarctic ice core as was already found in tropical deep-sea core studies.

## INTRODUCTION

Assuming that chemical concentrations in Antarctic air and snow are correlated (Pourchet and others in press), the atmospheric composition in the past can probably be deduced from the chemical composition of ice samples taken from pit walls (hundreds of years old) or deep ice cores (thousands of years). In order to study the possible link between atmospheric aerosol content and climate we measured the trace element composition and microparticle concentration of ice samples from the Dome C (74°S,124°E) core, each one covering a 3 to 10 a period. The 905 m deep ice core spans approximately 30 ka. The depths corresponding to the last glacial maximum (≈18 000 BP), to the climatic transition, and to the Holocene period were taken from the isotopic profile by Lorius and others (1979) (see periods 3, 2, and 1 on Figure 1). The first step in our experiment involved removing the outer part of the samples, contaminated by field procedures, and measuring components already known to be of crustal origin (Al, V, Mn, Zn, insoluble microparticles) and marine origin (Cl and Na). The detailed analytical procedure along with complete results and discussion have been published elsewhere (Petit and others 1981). The main results are that the continental (see Fig.1) and marine inputs were respectively about 20 and 5 times higher during the late
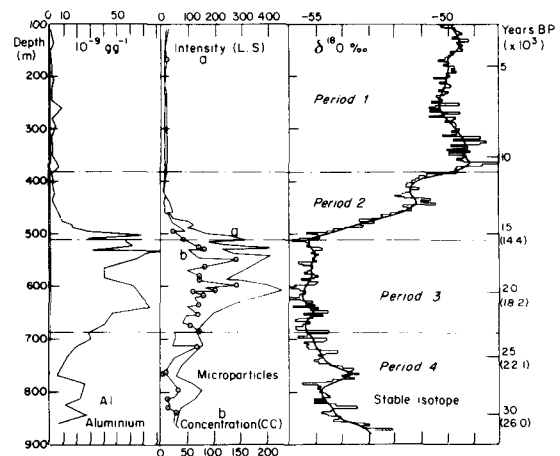


Fig.1. Stable isotope content ($\delta O^{18}o/oo$), microparticle and aluminium (continental indicator) concentrations for the Dome C ice core: (a) microparticle data from light-scattering technique (LS) in relative units, (b) Coulter counter concentrations (CC), units in $10^3$ particles ($r>0.4\mu m$) $g^{-1}$ of snow. Data from Thompson and others (1931) were also used. The chronology and isotope profile with distinct isotopic periods were presented by Lorius and others (1979).

glacial period than during the Holocene period. Similar trends were observed in deep ice cores from Byrd station (West Antarctica) and Camp Century (Greenland) by Cragin and others (1977) but with lower ratios between the glacial and Holocene periods. These authors suggested that the enhancement of the crustal flux over polar regions during the glacial stage could be due to stronger atmospheric circulation and larger production areas, the volcanic contribution over Antarctica remaining low during the last hundred thousand years.

In this paper we present and discuss detailed results concerning the trace element composition and morphology of individual particles randomly chosen from filtered aliquots of samples from both the glacial and postglacial periods.

27

## ANALYTICAL PROCEDURE

One to three aliquots of several samples previously analysed for microparticle concentrations by Coulter counter and light scattering techniques (Petit and others 1981) and corresponding to low (Holocene stage samples) and high (glacial stage samples) insoluble dust content were filtered by aspiration through a nuclepore filter (filter diameter: 13 mm, pore diameter: 0.2 to 0.4 $\mu$m). The volume of each aliquot varied from 10 to 100 $cm^3$ depending on their microparticle content. The filters containing the particles were taped to aluminium stubs, coated with a carbon film and observed using a scanning electron microscope equipped with an X-ray energy dispersive system (EDAX). This procedure enabled us to study the elemental composition of particles >0.5 $\mu$m in diameter for elements having an atomic number Z >10. For each particle analysed, data acquisition was stopped when the integration count of the most abundant element reached 1 000 or 2 500 (this corresponds to integration times varying from 40 to 120 s). Taking the most abundant element (silicon in our samples) as a reference we were then able to compare quantitatively the relative abundance of the other components when their concentrations were higher than 2%. Quantitative measurements of absolute concentrations lower than 1% requires an electron microprobe with polished standard and sample surfaces. Such equipment was not available for our study.

Preliminary measurements performed on about 1 000 particles from two filters containing more than $10^7$ particles $cm^{-2}$ showed that Si, Al, Fe, and K were the main constituents with relative concentrations of 65, 19, 9, and 3% (from oxide weight). Other elements like Na, Mg, Ca, and Ti were also detected but at lower concentrations.

We then decided to analyse filters containing fewer particles for the following reasons: (i) background due to surrounding particles does not interfere with the studied X-ray spectrum when particles are sparse, (ii) flat particles which are not "bright" and often stuck to the filter are easier to analyse when not shadowed by larger or thicker particles, (iii) it is difficult to be objective when choosing a few particles from all the others in order to have a representative sample for EDAX analysis. It is more suitable to analyse all the particles of each selected scanning electron microscope (SEM) view. This is possible only for filters containing less than $10^6$ particles $cm^{-2}$.

## RESULTS

Nine light loaded samples from both the Holocene and the last glacial period were filtered and 399 particles were analysed. Typical particles with their corresponding X-ray spectra are shown in Figure 2. For each detectable element the percentage of particles containing at least 2% of this element is presented in Figure 3. Silicon was detected in all the particles and Al in 88% of them. Si and Al were associated mostly with K and Fe according to the preliminary studies performed on heavily loaded filters. Na, Ca, Mg, and Ti were observed in a lower percentage of particles. A small number of the studied particles contained S and Cl as trace elements, probably of organic origin (volcanic aerosols containing S or Cl are generally water-soluble). Other elements like Cr, P, Zn, and Ni, although easily detectable by the EDAX technique, were never observed but may be present as ultratraces. These data agree with results obtained by instrumental neutron activation analysis and by particle concentration measurements (Petit and others 1981) which showed that insoluble particles were of crustal origin. Several other investigators have observed the same main trace elements when analysing individual particles from the total Antarctic aerosol (Parungo and others 1979, Shaw 1980) and insoluble microparticles from
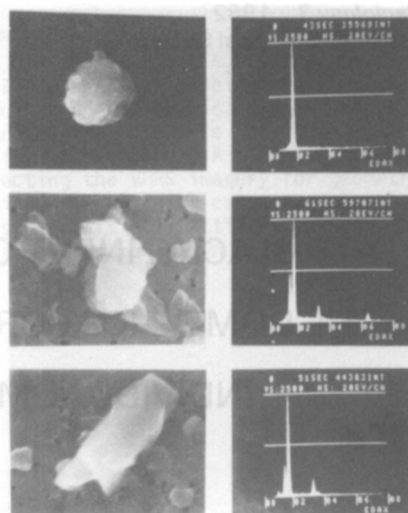


Fig.2. Microphotographs of typical particles from the Dome C ice core with their respective X-ray spectra (pore size is 0.2$\mu$m and gives the scale).
Top: particle probably quartz. Element composition from the X-ray spectrum: Si.
Middle: flat particle, probably a clay mineral (perhaps illite). Element composition from the X-ray spectrum: Al, Si, K, Fe.
Bottom: particle with a glass morphology probably a volcanic particle. Element composition from the X-ray spectrum: Na, Al, Si, K.
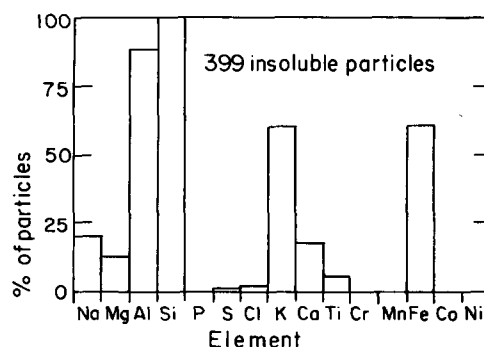


Fig.3. Frequency of elements present in the 399 particles analysed along the Dome C ice core.

Antarctic ice samples (Thompson 1977, Mosley-Thompson unpublished).

About 80% of the 399 studied particles belong to one of the nine categories presented in Table I according to their detectable components. In 52 particles (12% of the total) only Si was detected. These rather round particles (Fig.2, top) were identified as quartz. The other element groupings might be associated with a large variety of aluminosilicates which cannot be identified with certainty only from the measured elemental composition alone, so additional data concerning the particle morphology were also used.

Some particles (Fig.2, middle) had a plate-like aspect, quite different from the round quartz particles, suggesting a clay mineral. These particles (≈30% in number) contained the same elements as illite clay: Si, Al, K, and Fe (Millot 1964). Illite clay represents in mass 50 to 60% of the dust clouds of desert origin (Glaccum and Prospero 1980) and 30 to 50% of the deep-sea sediments assumed to be partly of eolian origin (Griffin and others 1968). Illite clay was also found in polar snow (Windom 1969) and in the South Pole atmosphere (Kumai 1976)

28

TABLE I. FREQUENCY AND NUMBER (IN PARENTHESES) OF PARTICLES OF THE FIRST NINE GROUPINGS OF ELEMENTS IN TWO CLIMATIC PERIODS

| Element groupings | Climatic periods | | Test* |
|---|---|---|---|
| | Holocene | Glacial | |
| Si+Al+K+Fe | 30.8(29) | 25.5(78) | - |
| Si | 5.3(5) | 15.4(47) | + |
| Si+Al+K | 6.4(6) | 9.5(29) | - |
| Si+Al+Fe | 4.3(4) | 9.5(29) | - |
| Si+Al | 4.3(4) | 7.2(22) | - |
| Si+Al+K+Fe+Mg | 6.4(6) | 5.6(17) | - |
| Si+Al+Na | <3(2) | 4.9(15) | - |
| Si+Al+Na+K | 12.8(12) | <3(3) | + |
| Si+Al+Na+K+Fe | 9.6(9) | <3(2) | + |
| Sub-total | 81.9(77) | 79.3(242) | |
| Others | 18.1(17) | 20.7(63) | |
| Total | 100(94) | 100(305) | |

* Test on the difference: + positive, - negative (95% accuracy).

where it was present in 35% of 93 samples of mineral particles during the summer season.

The Si+Al and Si+Al+Fe groupings could correspond to kaolinite, but in the Dome C particles the Si/Al ratio was always close to 3 or 4 which is quite different from the ratio generally observed in kaolinite of close to 1. This agrees with some of the conclusions of Prospero and Merrill (1980) concerning the origin of continental dust. Using the same analytical procedure described in this paper, these authors compared Dome C insoluble particles with atmospheric dust collected in Broom, Western Australia. Australian samples contained iron-rich kaolinite particles with a Si/Al ratio close to 1, significantly different from the Si/Al ratio of Dome C particles. They concluded that the western part of the Australian desert does not contribute to the continental input over the Dome C region.

But on the other hand, the Si+Al+Na grouping probably corresponds to albite (sodium feldspar) and includes 16 particles. Albite was found in eolian dust deposited in New Zealand snow-fields and in deep-sea sediments from the south-eastern Pacific Ocean. It was concluded that this eolian dust originated from eastern Australia where soils contain a high proportion of albite (Windom 1969). The existence of the Si+Al+Na grouping in dust from the Dome C core could therefore mean that part of the Australian desert also contributes to the continental input over Antarctica, as is probably true for other deserts from the southern hemisphere (Shaw 1979).

The bottom photograph of Figure 2 shows a particle with a broken edge (conchoidal) and a morphology close to that of a volcanic glass shard. Except that their calcium content was always below our detection limits, this particle and 26 others studied (7% in

number) are qualitatively close in composition (Si+Al+Na+K and Si+Al+Na+K+Fe groupings) to a large glass shard previously found at 726 m depth in Dome C core and attributed to Marie Byrd Land volcanoes (Kyle and others in press). Furthermore, there were 14 other particles (3% in number) containing Si+Al+Na+K+Fe as well as a small proportion of Ca. Although all these particles are presumably of volcanic origin, we can deduce their geographic origin (local or not) from neither their composition nor their size distribution (accurate comparison between particles emitted by different volcanoes requires microprobe analysis of polished particles). Furthermore the size of the Dome C volcanic-like particles is close to other particles of continental origin (smaller than 10 μm) which travel over great distances and may therefore have been emitted by volcanoes from other southern hemisphere continents. Particles large enough to be undoubtedly of local origin (e.g. the glass shard close to 100μm studied by Kyle and others (in press)) were found neither by SEM observation nor by Coulter counter or light scattering measurements. There seem to be very few such large particles in the core. It appears from considerations of size distribution that they do not explain the high crustal input observed for the last glacial age.

We conclude that microparticles present in the Dome C core are mainly wind-blown dust (detritic) from terrestrial origin. The volcanic contribution typically represented by glass shards remains low even if we assume that particles with a qualitative composition close to feldspar are volcanic. In particular, the high crustal input observed during the glacial stage does not seem due to enhanced volcanic activity.

CHANGES IN PARTICLE COMPOSITION WITH CLIMATE

The results were then separated according to whether they corresponded to ice deposited before (periods 3 and 4) or after (period 1) the isotopic transition (Table I). Within each group, data from the different depths were combined. The number of particles in each time period was large enough for the use of statistical methods (94 particles from three different depths for the Holocene period, 305 particles from six different depths for the last glacial age). For each elemental grouping we used the binomial distribution to check if the difference in the percentage of particles for the two climatic periods was significant. We checked if random sampling from an initial population containing all particles could give (with 95% accuracy) the scores obtained for each grouping. The Si (probably quartz) and Si+Al+Na+K+(Fe) (probably volcanic glass) groupings were found to be statistically different for the two periods.

From the glacial to the Holocene period, particles identified as quartz decreased from 15 to 5% whereas the proportion of particles of composition similar to glass shard increased from <2 to 22%.

These results do not take the particle-size or volume distribution (useful for mass or flux calculations) into account. The particle-size distribution for each element grouping during the two considered climatic periods was not studied by SEM because the sample size was statistically insufficient. However, this was done by Coulter counter measurements for the particle number on samples from each climatic period (Petit and others 1981) and a shift in the microparticle volume distribution toward larger sizes was observed during the glacial age and associated with increasing past wind strength. Such a shift should also exist for the different element groupings but qualitatively SEM observations did not allow the testing of this fact between the two studied climatic periods. If this hypothesis is true, the shift could slightly reduce the increase observed during the Holocene period for the glass-shard grouping and

29

enhance the corresponding decrease of quartz content. As shown above, our data suggest that local or global volcanic input was not a major component of dust flux over Antarctica during the past 30 ka. The increase in the percentage of volcanic-like particles observed during the Holocene period is largely balanced by the decrease in the total number of particles by a factor of 7 to 10 shown by Coulter counter measurements (Petit and others 1981, Thompson and others 1981).

On the other hand, the change in the percentage of quartz particles is enhanced if the decrease in the total particle number is considered. A decrease in percentage of quartz particles (in number) from 15 to 5% corresponds to a decrease of the total number of quartz particles by a factor of 20 to 30 (even higher for the total mass of quartz particles if the suggested shift of the volume distribution towards a smaller size during the Holocene period is taken into account). Note that this obvious change remains significant (at 95% accuracy) even after subtracting from the total input the maximum volcanic contribution assuming that the Si+Al+Na+K+(Fe) groupings are considered to be of volcanic origin.

Quartz is a mineral of continental detritic origin and eolian quartz particles are generally taken as an indicator of aerosol of continental origin (Clayton and other 1972, Glaccum and Prospero 1980). Because of their aerodynamic properties, round particles of quartz are removed by settling faster than other minerals (flat clay particles) from dust clouds moving thousands of kilometres away from their source (Glaccum and Prospero 1980). The decrease in quartz input observed over Antarctica during the Holocene period may be interpreted as a consequence of reduced wind velocity and smaller areas of aridity. This agrees with the conclusions of other investigators studying deep-sea cores from tropical latitudes who observed changes in eolian quartz content which were attributed to enhanced trade-wind strength during glacial stages (Bowles 1975, Parkin and Padgham 1975, Venkatarathnam and Biscaye 1977).

Furthermore, transport of large quantities of dust during the glacial era was observed over many continental regions and tropical oceans (Flint 1971, Parmenter and Folger 1974, Parkin and Padgham 1975, Sarnthein 1978). Jackson and others (1973) suggested that the accretion rate of aerosol dust in the periglacial area of the northern hemisphere was 100 times higher during the Pleistocene than during the more recent period. For similar periods, Venkatarathnam and Biscaye (1977) observed an increase by a factor of 3 in the quartz accumulation rate for two deep-sea sediment cores drilled in the tropical part of the Indian Ocean.

The greater change we observed for the Dome C core may be linked to more efficient transport of dust polewards during the glacial age due to more vigorous atmospheric meridional circulation.

CONCLUSION

The study of the composition and morphology of microparticles in the Dome C ice core indicates that the volcanic contribution is not a dominant component of the non-soluble aerosol over Antarctica, neither under present climate conditions nor during the last part of the previous ice age. The increase by a factor of 20 to 30 in concentration of quartz particles observed during cold climatic conditions is probably linked with a much higher continental dust flux.

This conclusion supports the interpretation of microparticles and trace element measurements in the Dome C (Petit and others 1981) and other polar ice cores (Cragin and others 1977).

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