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Mineral particles content in recent snow at Summit (Greenland)

E. Drab^a, A. Gaudichet^a, J.L. Jaffrezo^b, J.L. Colin^{a,*}

^a *Laboratoire Interuniversitaire des Systèmes Atmosphériques, Faculté des sciences, UMR CNRS 7583, Université Paris 7 et Paris 12, 61 Av. du Général de Gaulle, 94010 Créteil, cedex, France*

^b *Laboratoire de Glaciologie et Géophysique de l'Environnement, Rue Molière, BP 96, 38402 St. Martin d'Hères, cedex, France*

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Abstract

The mineral insoluble fraction of snowpit samples collected at Summit is investigated, representing deposition from summer 1987 to summer 1991. We attempt to describe the particles which are observed in the series, with very large seasonal variations. Elemental, mineralogical and size distribution studies are carried out on four samples selected according to the chemical profile of the snowpit (two samples from spring and two from winter) using X-ray fluorescence spectrometry and analytical transmission electron microscopy. Results indicate a large predominance of the soil-derived particles originating from arid or semi-arid regions of the Northern Hemisphere. The mineralogy clearly indicates a high contribution for the muscovite-illite associated with a low kaolinite/chlorite ratio, together with the rather lack of smectite. This supports the hypothesis of an Asian source. Several other factors are consistent with this Asian source, like the recent climatology and the good timing between the Asian dust storms period and the peak of dust concentration in the ice. The mineralogy of the insoluble particles in the snow is similar between winter and spring, suggesting that the change of concentration between the seasons is more strongly linked to changes of atmospheric parameters than changes of the source regions.

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1. Introduction

It is now well recognised that ice cores in polar regions are a unique way to have access to past atmospheric aerosol content. Especially, the Greenland ice sheet is of particular interest since, far from continental areas, it reflects to a large extent the aerosol loading in the high latitudes of the Northern Hemisphere. The study of insoluble particle concentrations in central Greenland ice cores, which can cover the last 150,000 years (Dansgaard et al., 1993), is of great interest since dust embedded in the snow can be used as a tracer of the past atmospheric turbidity, and

therefore gives key information concerning paleoclimate (GRIP Members, 1993). Indeed, a strong connection between the total dust mass and climate variability (as indicated by $\delta^{18}\text{O}$ record) is reported by previous studies on Greenland ice cores (Thompson and Mosley-Thompson, 1981; Hansson, 1994; Mayewski et al., 1994; De Angelis et al., 1997). It clearly indicates an increase in the concentration of impurities during the last glacial period. Several explanations have been proposed, such as change of the emission characteristics of the dust sources, or of their extension or localisation (Thompson, 1977; Fisher, 1979; Rea, 1994). Other factors have been also suggested, like the modification of the dust atmospheric lifetime (Porter and An, 1995). Large-scale modelling is still not reproducing these glacial/interglacial changes very well (Andersen et al., 1998).

*Corresponding author.

E-mail addresses: jlj@glaciog.ujf-grenoble.fr (J.L. Jaffrezo), colin@lisa.univ-paris12.fr (J.L. Colin).

However, the interpretation of the signal recorded in the ice requires understanding of the transfer of particles from the polar atmosphere to the snow. This point was investigated previously through a 1 year field campaign at Dye 3 (Southern Greenland) during the DGASP program (Jaffrezo and Davidson, 1993), when aerosols and fresh snow events were collected simultaneously. A seasonality of aerosols inputs in the Greenland atmosphere was observed at Dye 3 (Mosher et al., 1993; Colin et al., 1997), nevertheless with timing differences compared to other arctic sites at lower altitude (Barrie and Hoff, 1985; Barrie, 1986). At Dye 3, results indicate that the timing of the dust inputs in the snow remains consistent with the variations of the concentration of mineral aerosol (Davidson et al., 1993a; Dibb and Jaffrezo, 1993) and that no fractionation is observed for major mineral elements, such as Fe and Al, during the air-to-snow transfer (Colin et al., 1997). The mineral signal in the snow is thus strongly related to the signal in the overlying atmosphere, governed by the large-scale atmospheric transport and the source fluxes.

In order to confirm these previous observations and to study further general processes involved in the overall transfer of minerals from source regions to the Greenland ice, a second program Transfer of Aerosol and Gases to Greenland Snow and Ice (TAGGSI) was undertaken at Summit on the Greenland ice sheet between 1994 and 1996 (Dibb and Jaffrezo, 1997). The main objectives were to identify the sources of the major atmospheric compounds, the influence of transport on the chemical signal and the air-to-snow transfer relationship, with attention to post-depositional processes.

The present study focuses on the determination of the mineral particle content in recent snow layers at Summit according to the seasonality of the mineral inputs. It emphasises the mineralogy of the particle content of the snow, especially for the clay material, which reflects lithology and the weathering characteristics of large dust source areas. The determination of the particle number size distribution gives additional information on the potential occurrence of local or remote sources. The discussion is achieved with the support of meteorological considerations.

2. Experimental procedures

2.1. Sampling location and protocols

Samples were collected during August 1991 and August 1992 in the Summit area (72°20'N, 38°45'W, elevation 3240 m) (Dibb and Jaffrezo, 1997). The accumulation rate at this location is about 23 g H₂O/cm²/year, with a mean annual temperature of -32°C. At this elevation, we observed no melting of the superficial firn layers during summer, which could generate mixing

between layers. There are also few sastrugis, which could enhance the dry deposition by aerosol filtration through the porous firn and mix the seasonal signal (Jaffrezo et al., 1995). Thus, snowpits sampled at Summit provide a sub-annual record of precipitation with only limited occurrence of post-deposition processes.

A *first snowpit* was dug during summer 1991 about 30 km from Summit, 2.5 km SSE of an atmospheric remote camp (Dibb and Jaffrezo, 1997). A sequence of 34 samples was obtained to a depth of 200 cm, sampled according to the visual stratigraphy. Each layer was sampled several times to fill up one or two ultraclean 1L wide-mouth polypropylene bottles. Three deposition annual cycles were thus recovered from 1989–1991.

A *second snowpit* was sampled during summer 1992, 2 km away from the previous location. A sequence of 40 samples was collected at a depth corresponding to three depositional annual cycles, beginning from 1989 until 1987. In all, 5 years of accumulation were recovered, with about 1 year (1989) of overlapping.

A parallel sequence was collected in this second snowpit for specific analyses of H₂O₂ (Bales, 1993).

Both snowpits were hand-dug by operators wearing full clean room clothing, and samples were collected with a Teflon corer of 250 ml. Each sample represents a 4 cm interval. In both cases, samples were packed in double clean polyethylene bags and kept frozen until analysis.

2.2. Sample filtration and analysis

The snow samples were filtered in a clean room (class 100) under laminar flow immediately after melting at room temperature, using a Nuclepore membrane with 0.4 μm porosity, with strict procedures against contamination (Colin et al., 1997). The risk of analytical biases due to the loss of some of the finest particles during the filtration is not significant, based on the evaluation of the soluble part of trace metals (Hofmann et al., 1991). Moreover, filtration has no effect on the mineralogical analyses since only the particles >0.3 μm in diameter were considered.

(a) *Global chemical analysis*: Insoluble fractions of snow samples collected on filters were analysed by X-ray fluorescence spectrometry (Siemens™ SRS 303) that provided elemental concentrations for Na, Mg, Al, and Si (with a rhodium emission tube), and for K, and Fe (using a copper emission tube), assuming thin layer conditions (Elichegaray et al., 1981).

Systematic laboratory and field blanks were made in order to evaluate any procedural contamination during sampling, filtration and analyses. The elemental concentrations of blanks were systematically measured under the detection limits, which were estimated with the usual statistical method (3σ). Detection limits were typically from 5–15 ng/filter according to the different

elements of the insoluble fraction analysed by XRF. Detection limit of soluble Na analysed by graphite furnace atomic absorption spectroscopy was $0.03 \mu\text{g/l}$.

(b) *Microscopic analysis*: Analysis of individual particles was conducted using a transmission electron microscope (JeolTM 100CX2) fitted with an X-ray energy dispersive spectrometer (TracorTM TN 5400). Four samples were selected for this analysis, distributed among the seasons, as discussed in the next section. These four filters were previously treated following a protocol described in Gaudichet et al. (1986), in which particles are directly transferred onto an electron microscopy copper grid. Operating conditions for microanalysis were as follows: grid mounted in a carbon receptacle; 35° tilt angle in the direction of the detector; accelerating voltage at 100 kV; accumulation time of 80–100 s; size of the focused beam of $0.3 \mu\text{m}$.

The microscopic observation associated with the energy dispersive X-ray analyser identifies the major elements ($Z \geq 11$) in the particle. For silicates, elemental spectra were computed according to the peak-ratio method, using Si as the reference element (Cliff and Lorimer, 1975). This treatment leads to the chemical composition of silicates in terms of oxide weight percentage, regardless of water content of particles.

The *mineralogical identification* of a single particle is the result of several criteria obtained simultaneously, which are based on morphological, crystallographic, and chemical information. Practically, in a first step, the morphological aspect allows to distinguish the non-spherical mineral particles from the spherical ones (which are generally associated to combustion processes), separating microsoots from fly ash. Diatom fragments are also distinguished from crustal dust particles. In a second step, the electron microdiffraction pattern allows to separate roughly amorphous particles (i.e. amorphous silica, volcanic glass, etc.) from crystalline particles. Among these last ones, the sheet silicates (especially clays) are distinguished by both their lamellar morphological features and their hexagonal electron diffraction pattern from other minerals, primarily feldspar. Finally, the semi-quantitative composition obtained of silicate particles is compared with the composition of reference silicates compiled in the literature (Deer et al., 1996), and leads to the determination of their mineralogical species. We have plotted the ratio $\text{K}_2\text{O}/\text{SiO}_2 + \text{Al}_2\text{O}_3$ versus the ratio $\text{SiO}_2/\text{Al}_2\text{O}_3$ for the clays previously classified as illite, smectite and kaolinite. This allows comparison with results obtained for various clay standards analysed under similar conditions (Fig. 1). According to these criteria, about 95% of the particles analysed were identified. No diagnosis was made on the remaining 5% because the particles, which were overlapping, gave mixed silicate chemical compositions, or were not related to a mineral described in the literature (Deer et al., 1996).

The contribution of the different species was then evaluated by a statistical approach. Each particle encountered in a randomly chosen observation field was counted and identified. With this procedure, a total of 150–200 individual particles on each filter was analysed with a magnification $10\,000\times$ for spring samples and $7200\times$ for winter samples. The magnification that was selected represents the best compromise between the need to observe a reasonable number of particles per unit area and the observation quality for each particle. Thus, spring samples much more loaded than winter samples were observed under higher magnification.

The *size distribution* of selected terrigenous particles was also determined using semi-automatic image analyser (Microvision instrument, SAISAM IVP) interfaced with the microscopic observation. Since particles cover a wide range of size, we used two magnifications for each sample, but the selection of the high magnifications differs for spring and winter samples for the reason previously given. For particles smaller than $2 \mu\text{m}$, we used magnifications of $10\,000\times$ and $7200\times$ for spring and winter samples, respectively, whereas for particles larger than $2 \mu\text{m}$ we used a magnification of $2900\times$ for both winter and spring samples. For each sample, counts were integrated on the whole area of the filter, and a total of 500 particles were analysed on each filter. Practically, the contour of each particle (as small as $0.08 \mu\text{m}$ in diameter) included in the observed field is drawn. This protocol leads to the determination of an equivalent diameter based on area. These data, which are recorded and fitted using a log-normal distribution (Gomes et al., 1990), provide a mean diameter value with a standard deviation for each sample studied.

3. Results and discussion

3.1. Chemical profiles: the annual seasonality

We merged the 1991 and 1992 records into single series for each chemical species by first adjusting the depths using the insoluble aluminium profiles, as indicated in Fig. 2. The accuracy in the overlapping is also excellent for all the other insoluble elements (Si, Ti, Na, Mg, and K). Then, the concentrations for the overlapping year were recalculated by averaging the concentrations of samples of each pit, located in a same layer. In the following discussion, we will only consider this reconstructed sequence of 5 consecutive years of accumulation.

Seasonal dating of the pit sequence is performed using some specific markers, as described by Whitlow et al. (1992), and Legrand and Mayewski (1997). High concentrations of soluble sodium (Fig. 3a) are indicative of winter–spring inputs of marine air masses above

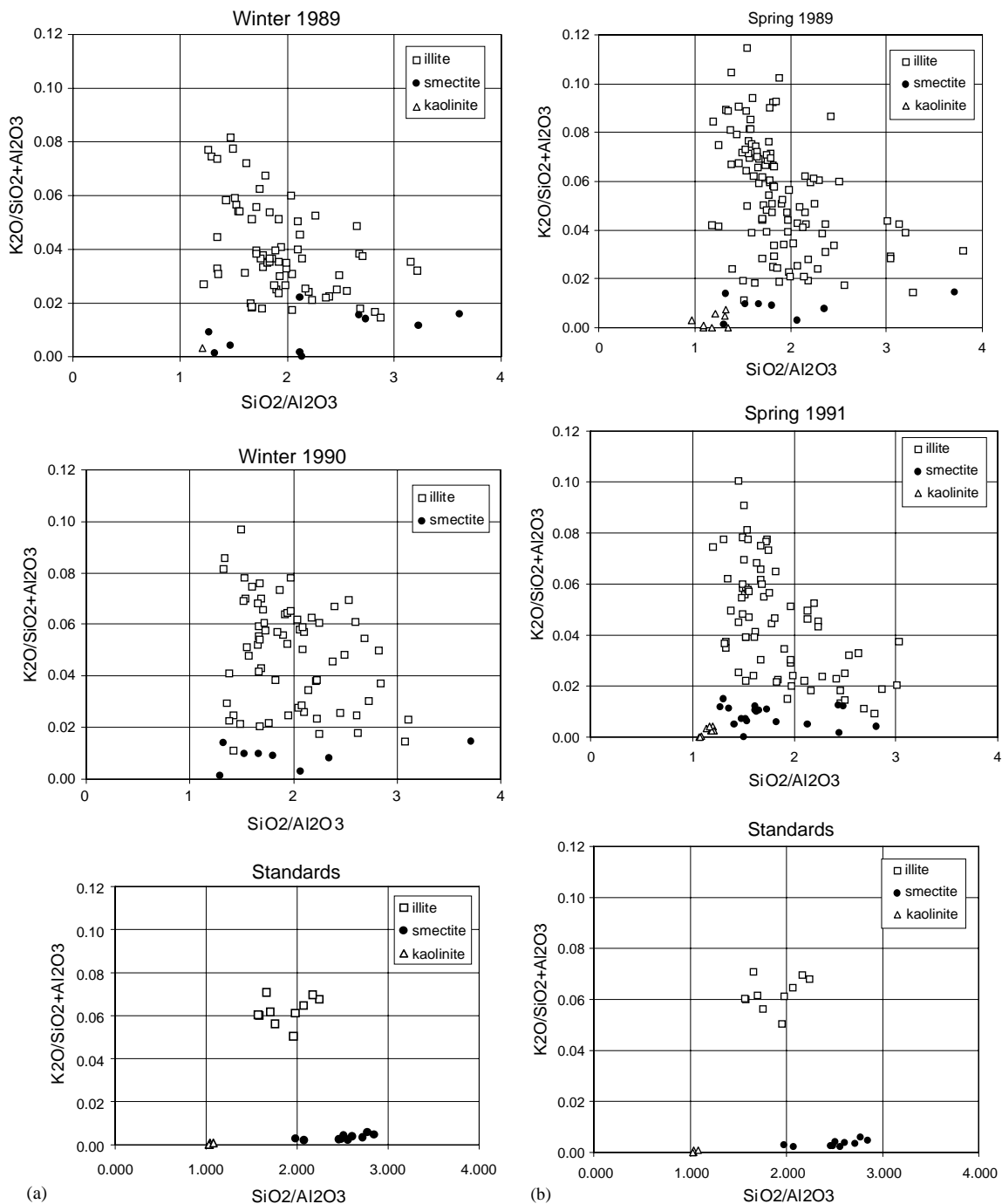


Fig. 1. $K_2O/SiO_2 + Al_2O_3$ ratio versus SiO_2/Al_2O_3 ratio to support the identification of illite, smectite and kaolinite in clays: (a) winter samples; and (b) spring samples.

Greenland due to increased cyclogenesis in the North Atlantic. High and low concentrations of hydrogen peroxide (Fig. 3b) are ascribed to the photochemistry maximum in summer and minimum in winter, respectively (Bales, 1993). The timing of the maximum

concentration for the insoluble elements is therefore located during spring, in agreement with the current hypotheses (Whitlow et al., 1992; Legrand and Mayewski, 1997), and with previous direct observations on the aerosol at Dye 3 (Mosher et al., 1993; Colin et al., 1997),

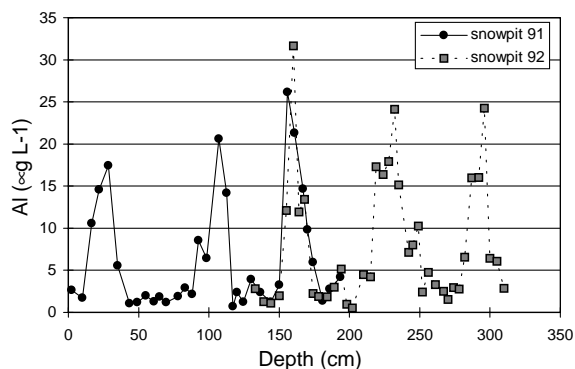


Fig. 2. Record of the insoluble aluminium concentration profiles of the two snowpits sampled at Summit during the summers of 1991 and 1992, providing a single reconstructed sequence of 5 consecutive years of accumulation.

at Summit (Wahlin, 1996), and in fresh snow events at Dye 3 (Davidson et al., 1985, 1993a; Colin et al., 1997). The concentrations of all of the insoluble elements presented here show very similar patterns, as indicated in Figs. 3c and d. They show very high correlations with that of aluminium (Table 1). The years corresponding to each spring maxima are shown in Fig. 3c, which also indicate the filters which were selected for microscopy and mineralogical analysis. These have been chosen according to the observed seasonal variations, with two samples in spring (1989 and 1991) and two samples in winter (1989 and 1990), corresponding to high and low particle loadings, respectively.

The average spring concentration of aluminium at Summit is about $15 \mu\text{g/l}$, in good agreement with values reported by Davidson et al. (1985) for fresh snow events collected at Dye 3. Our data are somewhat lower for K, Mg, and Na, most probably because the concentrations at Dye 3 are given for total (soluble plus insoluble) content of these species.

3.2. Microscopic investigation: the particle characteristics versus their quantitative annual seasonality

The 720 total particles observed in our four samples can be roughly classified into two main groups: natural particles and anthropogenic ones. It must be noted that some particles cannot be obviously individually isolated, and that we did not take into account microsoots in our counting.

3.2.1. Particles from natural origin

The largest contribution is due to clays (between 65% and 86%) (Fig. 4a). The clays have been classified as illite, chlorite, kaolinite, smectite and very sparse vermiculite. Among them illite are always the most

abundant species (Fig. 4b) even if some analyses are plotted at the border between illite and smectite standard areas (Fig. 1). At all, the relative abundance of such sheet silicates is quite similar from one sample to another.

Feldspars are also typical terrigenous particles and their contribution is variable (1–11%) in our samples. Except for 10% of them, their composition is similar between spring and winter samples, with a large proportion of K and Na-rich feldspars. The predominance of these last species indicates that those feldspars probably originated from acidic soils.

Silica particles include crystalline silica (quartz) and amorphous silica, this last type including diatoms fragments. The variability of silica from one sample to another could be influenced by the variable contribution of diatom fragments. A very few number of diatom fragments with typical morphology (<1%) were clearly observed in all samples. These microorganisms could have either a marine or a continental origin. Different diatom species were observed by Gayley and Ram (1988) in an ice core from Crete (Central Greenland), with both marine and terrigenous sources. Unfortunately, the specimens from our samples were too fragmented to determine the species accurately and to identify their sources.

We also observed the presence of a few particles with a glassy aspect. They are amorphous, as confirmed by the lack of an electron microdiffraction pattern, and are enriched in silicon. This is consistent with volcanic glasses inputs. Furthermore, their permanent large size (diameter > $5 \mu\text{m}$) suggests a rapid transport or a source close to Greenland. These volcanic glasses arise more likely from resuspension of old deposits from Icelandic or other volcanic eruptions (De Angelis and Legrand, 1994; Palais et al., 1991). They are associated with a small number of mineral fiber species identified as palygorskite, which probably represents volcanic alteration products (Grousset et al., 1983).

Overall, the relative abundance of main species shows a very large contribution of silicate particles, especially clays, which is consistent with a predominant soil-derived dust source for both seasons studied (Fig. 4a). This large contribution of silicates was already observed in the aerosol collected at Dye 3 (Central Greenland) during springs of 1982 and 1983, and studied by scanning electron microscopy associated to a microchemical analysis (Davidson et al., 1985). These authors detected crustal elements like Si, K, Fe, Ca, and Al in most particles. It is, however, the first time that such analysis is performed on samples from another season.

3.2.2. Anthropogenic particles

This group includes mainly combustion particles, fly ash, and aggregated microsoots (Fig. 4a). Fly ash particles are emitted by coal or fuel power plants and

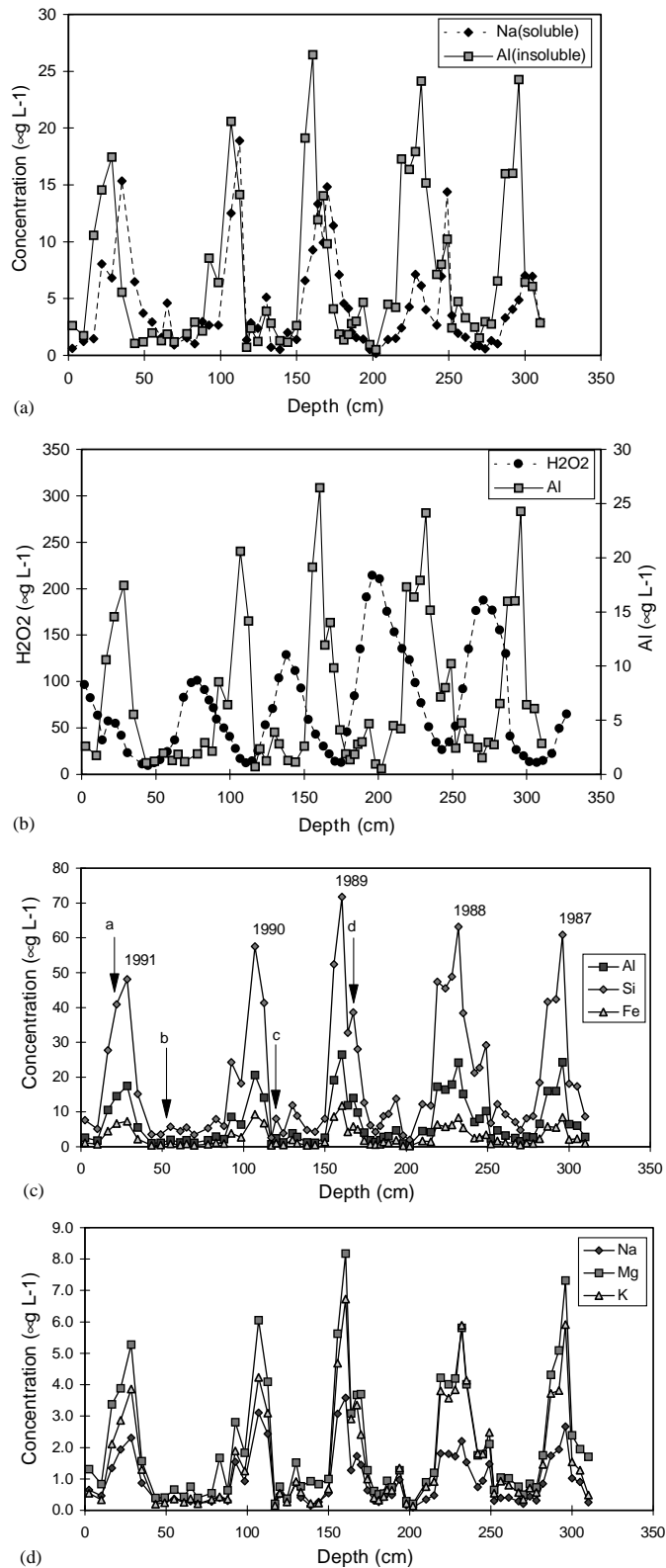


Fig. 3. (a) Concentrations of insoluble aluminium and of soluble Na in the snowpit at Summit; (b) concentration of insoluble aluminium and of H₂O₂ in the snowpit at Summit; (c) and (d) elemental concentration of insoluble Si, Al, Fe, Mg, K and Na in the snowpit at Summit with the years of the spring peaks. Samples selected for microscopy analysis are indicated as: (a) spring 91; (b) winter 90; (c) winter 89; and (d) spring 89.

can be identified according to their typical morphology linked to their chemical signature (Ramsden and Shibaoka, 1982). They account for <5% of the total particles encountered. The microsots have a systematic

carbon signal without other typical element, such as S alone for automobile exhausts, or K, for biomass burning. Their numerical contribution is difficult to evaluate because the microsot particles are always aggregated and difficult to count individually.

Metallic oxides (iron or titanium) could also be considered as tracers of anthropogenic activities (Van Malderen et al., 1996). Their contribution does not exceed 8% in our samples.

Table 1
Correlation coefficients for the insoluble concentrations of Al and the insoluble concentrations of Si, Fe, K, Mg and Na in the two snowpits, collected at Summit during the summers of 1991 and 1992 (number of samples: 70)

	Al	Si	Fe	K	Mg	Na
Al	1.000	0.996	0.9549	0.9867	0.9488	0.9068

3.3. Possible origin of soil-derived particles

The silicates commonly act as ice nuclei in the formation of snow crystals within supercooled clouds.

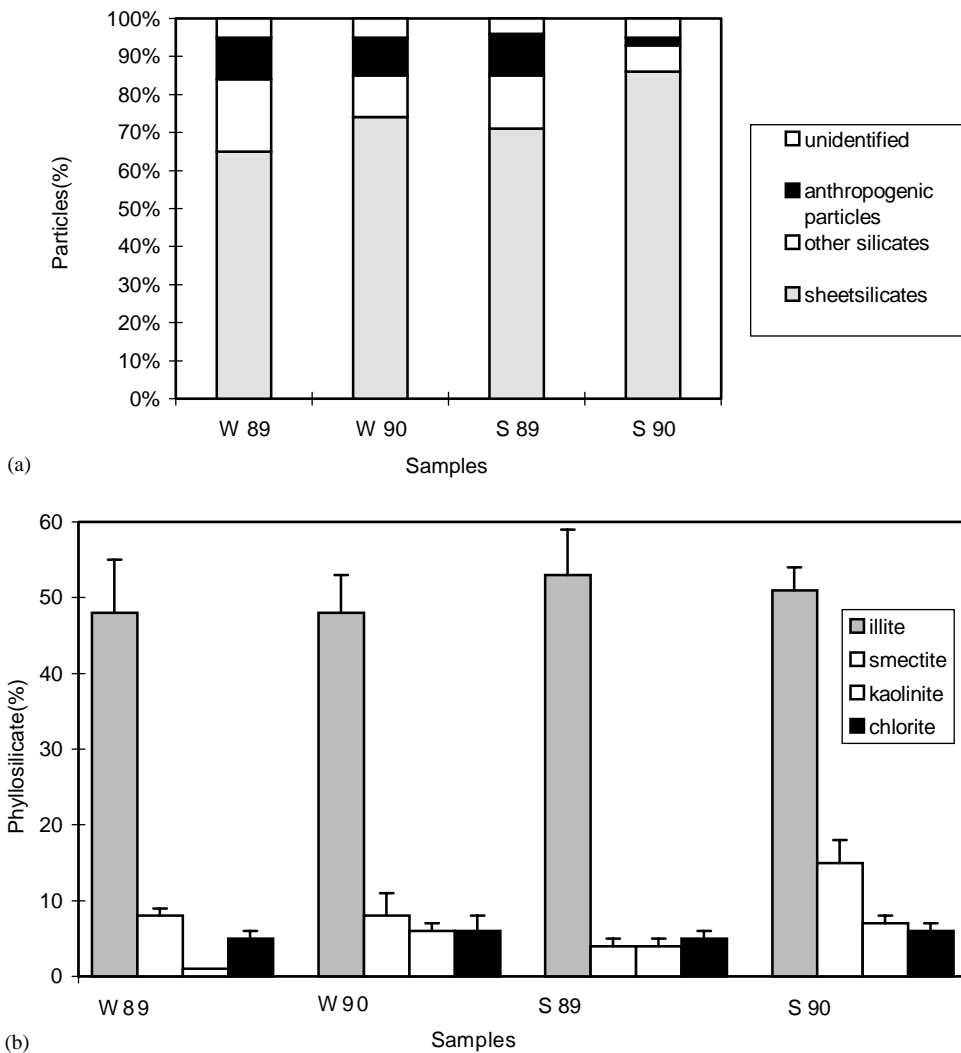


Fig. 4. (a) Relative abundance of the different particle species corresponding to winter and spring samples; (b) relative abundance of the main clay species corresponding to winter and spring samples. The upper error bars give the proportion of species identified with a risk of confusion with another phyllosilicate.

Kumai and Francis (1962) indicate that all snow crystal nuclei collected in Greenland were constituted at 85% of clay minerals. Mason and Maybank (1958) also found that kaolinite was an effective ice nuclei. This mineral composition could be related to that at the source, even if, during long-range transport, the size distribution shifts towards fine particles. For example, Glaccum and Prospero (1980) indicate a mass median diameter of 6 μm for Saharan aerosol at 500 km from the African coast, and 2 μm at 5000 km (Miami, Barbados). However, despite the enrichment in the fine fraction with increased distance from the source, these authors did not observe any modification in the relative proportion of the clay particles. For all these reasons, the clay species of the particles embedded in snow layers should be rather directly related to that in the dust source.

The main arid and semi-arid areas in Asia (Chinese, Arabian, Persian) and in the North American continent are mostly located around 40°N, while the Africa Sahara desert lies at a latitude around 25°N. Deserts are characterised by general trends in the mineralogy, which reflect local lithology, the dependency on the climate and on weathering. As few maps of the mineral distributions for the arid regions are available, we used a first approach by comparing our results with the mineralogical profiles of aerosols from desert regions and also with profiles from the oceanic sediments. The mineralogy of Pacific sediments is indicative of different mineral sources: Asian sources for the Western Pacific, and North American sources for the Eastern Pacific (Uematsu et al., 1983). From the mineralogical study of aeolian dust reaching the North Pacific Ocean, Merrill et al. (1994) conclude that there are mineral signatures that are characteristic of large continental source areas: an illite-rich assemblage from central Asia, a mixed mineralogy assemblage from North America and Japan and a Kaolinite-dominated assemblage from low latitudes.

Overall, at a global scale, the repartition of the different clay species seems a relevant tool to assess the origin of soil-derived particles in the atmosphere (Caqueneau et al., 1998). Thus, the relative abundance of the main clay species in our samples are reported in Fig. 4b, and will be checked systematically against those obtained by Biscaye et al. (1997) in samples from the last glacial period in the GISP2 ice core at Summit.

A large predominance of the illite species (48% to 53%) clearly appears in Fig. 4b. These mineral species have been identified in tropical Pacific air dust. Some samples collected on the Enewetak Atoll show a strong contribution of illite, close to 47% (Gaudichet and Buat-Ménard, 1982; Buat-Ménard et al., 1983). Using air mass back-trajectories, these authors clearly associated the large predominance of illite with the air masses coming from Asia. The predominance of illite was also found in dust plumes from Sahara (Glaccum and

Prospero, 1980). However, not a single 10-day air mass backtrajectory was reported by Kahl et al. (1997) as coming from North African region to Summit in a climatology covering the last 40 years. It makes the assumption of a Saharan origin very unlikely. The clay mineralogy for the GISP2 samples is very similar to our results, showing a large predominance of illite (Biscaye et al., 1997).

Despite the high variability of smectite in our snow samples, its contribution remains low (<15%). This species is produced by the weathering of basic rocks (Chamley, 1989). Andesitic and basaltic rocks are dominant in arid regions of Western United States (Leinen et al., 1994) which explains the large contribution of smectite in the upper layer of the soil from the American continent (Reheis et al., 1995; Eghbal and Southard, 1993). In the underlying sediments of the margin of the Pacific Ocean, Leinen et al. (1994) found a greater contribution of smectite in the East part, under the influence of American dust inputs, than in the West part, which mostly receives Asian inputs. This interpretation in terms of aeolian inputs should be made with caution, because of the possibility of the authigenic formation of these minerals in the deep-sea sediments. The GISP2 samples indicate a very low smectite contribution, near zero (Biscaye et al., 1997).

The kaolinite and chlorite contributions do not exceed separately 10%. The kaolinite/chlorite ratio could be useful to distinguish between low-latitude desertic sources like Sahara, rich in kaolinite, as indicated by the studies of air samples near the African coast (Chester and Johnson, 1971; Glaccum and Prospero, 1980), and higher-latitude areas in Asia, rich in chlorite (Chizhikova et al., 1989; Eden et al., 1994). In our samples, this ratio is 0.3, 1.0, 0.8, 1.2 for winter 1989, winter 1990, spring 1989, and spring 1991, respectively. These values are in the same range of those presented by Gaudichet and Buat-Ménard (1982) for air samples originated from China (0.7). Biscaye et al. (1997) also observed low values of this ratio in the GISP2 samples.

Summarizing, a large contribution of illite with a low contribution of smectite, and low kaolinite/chlorite ratio were observed in our samples of recent snow for both seasons. These significant mineralogical results are consistent with an Asian source. These mineralogical characteristics are not pointing out directly to a precise dust source, but they are similar to the mineralogy of the GISP2 samples, which confirms Asian source using isotopic measurements (Biscaye et al., 1997).

3.4. Size distribution of the soil-derived particles

We measured the particle number size distribution in the four samples to test the possible influence of larger particles on high-concentration peaks in spring. Counts were focused on the soil-derived particles. We found

very similar size distributions for winter and spring samples (Fig. 5), with a monomodal population centred on the same median effective diameter (Table 2). The lack of differences in the size distribution between the seasons is also reported by Steffensen (1997), who considered the volume size distribution of recent snow samples near Summit.

The values of our mean effective diameters, ranging between 0.2 and 0.3 μm are in good agreement with the few data coming from microparticle size analyses of crustal particles incorporated in snow samples dated from the 17th century (Ram and Gayley, 1983), or from Holocene, 444 years BP (Ram and Gayley, 1994). These data indicate diameters ranging between 0.17 and 0.23 μm at Crete (Ram and Gayley, 1983), and 0.09 and 0.12 μm at Dye 3 (Ram and Gayley, 1994). The lack of coarse mode confirms that the concentration peak is not linked to an input of larger particles during spring. It also shows that the same long-range transport seems to occur during both spring and winter, as previously assumed by meteorological studies (Davidson et al., 1993b; Kahl et al., 1997) or mass size distribution studies (Hillamo et al., 1993; Jaffrezo et al., 1993).

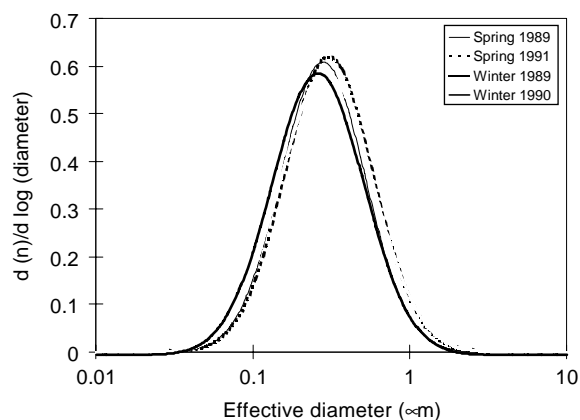


Fig. 5. Number size distribution of terrigenous particles for winter and spring samples.

Table 2

Number median effective diameters of the winter and spring samples

Samples	Number median effective diameter (μm)	Standart geometric deviation
Winter 1989	0.29	1.98
Winter 1990	0.26	1.96
Spring 1989	0.21	1.96
Spring 1991	0.30	1.90

3.5. Meteorological considerations

The climatology performed by Kahl et al. (1997) confirms that East Asian regions are involved in the atmospheric inputs at Summit. It shows that the contribution of air masses originating from Asian areas amounts to 34% in spring and 58% in winter, according to statistics on daily 10-day air mass back-trajectories for the last 44 years. The timing of the Asian dust storms is also in agreement with the crustal peak recorded in the ice. The strength of the Asian sources, strongly correlated to meteorological parameters, increases in spring, as described by Middleton (1991). The major synoptic pattern is the winter position of the Central Asian High, which is located over western Mongolia, generating stable conditions from October until April. In spring, the intensification of the zonal circulation brings cyclones, which progress rapidly from West to the East of Mongolia, creating stronger winds and intense dust storms. The maximum stream activity (April and May) occurs in the southern Gobi region. Then, as depressions bring rainfalls during June, July, and August, the dust emission decreases. The dust storm frequency remains low throughout the winter months when the ground is frozen and sometimes covered by snow. The dust emitted by the Asian storms could be injected up to 5–8 km above sea level (Merrill et al., 1989; Iwasaka et al., 1983). Several authors (Duce et al., 1980; Uematsu et al., 1983) report that this seasonality of the dust inputs coming from Asian deserts can be observed at North Pacific sites. However, the transport of particulate matter to high-altitude sites in Greenland is different due to altitude and local meteorological processes prevailing above the ice sheet. Mosher et al. (1993) suggested that the long-range transport of crustal material to the ice sheet surface depends on both the strength of the distant sources and the local meteorology. Above the ice sheet, the existence of stable conditions and especially that of the temperature inversion layer prevents the deposition of aerosol onto the surface of the ice sheet. This inversion level seems to weaken in spring at polar sunrise. Indeed, Dibb and Jaffrezo (1993) and Dibb et al. (1992) show that the vertical mixing is more efficient during the spring season and could generate high concentrations of chemical species in the atmosphere above the ice sheet. It appears that the seasonality of the crustal input seems to depend on the timing of the dust storm in Asia and/or the variability of atmospheric conditions prevailing above the ice sheet.

4. Conclusion

The study of mineral particles content in recent snow at Summit (Central Greenland) emphasises a strong

annual seasonality characterised by the highest concentrations during springtime. However, we did not observe any parallel change in mineralogical and geochemical characteristics of the particles. No change is observed either for the size distribution of particles which remain quite similar whatever the season. Consequently, we consider that the highly dust-loaded spring layers cannot be attributed to a drastic seasonal change of dust origins. In spring samples, the insoluble matter appears to be mainly terrigenous and deposited after a long-range transport. According to the predominance in the dust contents of the illite, the low-ratio kaolinite/chlorite and the low smectite proportion, Asian deserts seem to be the best candidate for the origin of that dusts. This study extends for modern conditions the results obtained by Biscaye et al. (1997) for the dust origin during the LGM.

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