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# INVESTIGATION OF DUST BANDS FROM BLUE ICE FIELDS IN THE LEWIS CLIFF (BEARDMORE) AREA, ANTARCTICA: A PROGRESS REPORT

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***Abstract:*** Blue ice fields in Antarctica are well known for their high areal meteorite concentrations. The exact type of accumulation model and the age of the ice is still not well known. Dust bands on blue ice fields may help to clarify some of these problems. Dust, which has been isolated from dust band samples from blue ice areas in the Lewis Cliff/Walcott Neve area (Beardmore region), Antarctica, was studied to determine petrographic characteristics and chemical compositions. One sample has an average grain size of around 0.5 mm, and is rather different from the others in its abundances of trace elements. The REE pattern and some other trace element ratios of that sample suggest it is a sediment from the local Beacon Supergroup, which has been scooped up from the ground by ice movement. The other five samples which were investigated have very small grain sizes (20 $\mu$m), and abundant glass shards. Major element data on the glass shards (and some feldspar crystals, which are also present in the dust band samples) allow the conclusion that they have originated from an alkaline volcano. The chemical composition of the glasses is highly variable, some showing basanitic composition, some showing trachytic or peralkaline K-trachytic composition. The silica *vs.* sum of alkalis plot shows that the Lewis Cliff samples are different from dust collected at the Allan Hills, but that there is a close similarity with volcanic material from The Pleiades, Northern Victoria Land. The trace element chemistry of all volcanic samples show the characteristic volcanic trace elements, like Ta, W, Sb, Th, and the REE, enriched by a considerable factor. The REE patterns exhibit a prominent negative Eu anomaly, which may be explained by mixing basanites (no Eu anomaly, but steep REE patterns) with K-trachytes and peralkaline K-trachytes (very pronounced negative Eu anomaly). The same components are obvious in major element analyses of individual glass shards, thus each dust band is a mixture of at least three different source materials (which, however, originated from the same volcano in a single eruption). The Pleiades seem to be a likely source for the volcanic debris found in the dust bands at Lewis Cliff.

## 1. Introduction

Dust bands are found in ice cores at different stations throughout Antarctica, including the Byrd Station ice core (GOW and WILLIAMSON, 1971; KYLE and JEZEK, 1978; KYLE *et al.*, 1981; PALAIS, 1985; PALAIS and LEGRAND, 1985), the Dome C ice core (KYLE *et al.*, 1981), a South Pole firn core (KING and WAGSTAFF, 1980), and the

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Vostok Station ice core (KYLE *et al.*, 1982). Usually the term tephra layers is used in conjunction with layers present in drill cores, referring to the volcanic nature of the particles comprising the dust bands. The ice cores are extremely useful for the study of climatic variations during the late Pleistocene and present times since they preserve a record of fluctuations *e.g.* variations in such stable isotopes as $^{18}O$ or $^{13}C$. Aerosol particulates in the ice cores, often associated with dust bands, and soluble components like sulfate and nitrate aerosols (PALAIS and LEGRAND, 1985), give information about trace components and impurities of the paleoatmosphere and its change through the history covered by the cores. A very important factor recorded in the dust band strata of the ice cores is the activity and the change in activity of volcanoes on the Antarctic continent. Other possible sources of ice impurities (soluble and insoluble) could be derived from marine (aerosols), continental (non-volcanic), and extraterrestrial environments.

The differentiation between different sources is rather difficult, especially when trying to identify extraterrestrial particles. Cosmic particles do not occur in layers, so the search for them is tedious. THIEL *et al.* (1987) had to use up to 4t of Antarctic shelf ice to detect usable quantities of cosmic particles. YIOU and RAISBECK (1987) found five particles of possible cosmic origin after melting several hundred kilograms of ice from Dome C and South Pole cores. A new source of extraterrestrial particles in Neogene till in the Transantarctic Mountains has recently been reported by KOEBERL *et al.* (1988).

The best investigated tephra layers are from the Byrd Station ice core. The first detailed study was performed by GOW and WILLIAMSON (1971), who distinguished between two different types of layers; ash bands (dirt bands) and dust bands (or cloudy bands). Their distinction is based on the grain size of the debris in the bands. Cloudy bands are described as lacking all visible debris and to contain mainly glassy and crystalline fragments of less than 5 $\mu$m diameter. The grain sizes in different layers are variable to some extent, thus the 5 $\mu$m limit is probably not applicable for a distinction between dust bands and "dirt bands", the better condition being the absence of visible debris (as in the case of our material). The identification of volcanic glass shards in the layers from the Byrd Station core and their analysis for major elements led KYLE *et al.* (1981) to the suggestion that they were derived from Mt. Takahe, a young volcano, situated in Marie Byrd Land about 450 km from the drill site. Similar suggestions have been made by the same authors for the material found in the cores from Dome C.

KING and WAGSTAFF (1980) suggested eruptions of the Cosequina (Nicaragua) volcano in 1835 as being responsible for large andesitic shards found in the South Pole firn core. This conclusion was questioned by KYLE *et al.* (1982) on the basis of the size of the andesitic shards, which should have settled before reaching Antarctica. Smaller particles found in the core seem to indicate, however, a correlation with volcanic events of Krakatoa (1883), Tambora (1815), and others, including Cosequina (THOMPSON and MOSLEY-THOMPSON, 1981), indicating a world-wide distribution of small volcanic particulates from violent eruptions. The non-Antatctic volcanic record in ice cores is, however, negligible compared to the Antarctic volcanism documented by tephra layers.

Besides dust bands and dirt layers in ice cores, dust bands cropping out on ice sheets have been studied by some authors. KEYS *et al.* (1977) described tephra and debris layers in the Skelton Névé and the Kempe Glacier (South Victoria Land). Most layers studied by KEYS *et al.* (1977) were very dark brown to black, with high concentrations of material and a steep angle of dip. They report most bands to consist of basanite tephra, while some bands also contain dolerite debris. From ice crystal sizes they infer an age between 1000 and 10000 years, and suggest that the source of the basanite tephras in the Skelton Névé was a volcanic vent in the nearby Royal Society-Koettlitz Glacier area. More recently, NISHIO *et al.* (1985) and KATSUSHIMA *et al.* (1984) investigated the composition and origin of dust bands (which, because of criteria different from ours, they prefer to call dirt bands) in the Yamato Mountain area and the Allan Hills area. Like MARVIN (1986), who also investigated the Allan Hills dust bands, they found that volcanic debris makes up the bulk of the material. NISHIO *et al.* (1985) found a significant difference in the composition of volcanic glass found in the Yamato area and the material found in the Allan Hills area, suggesting entirely different source volcanoes.

We report here on chemical investigations of dust isolated from dust bands from other locations in Antarctica.

## 2. Location

The dust bands we report on were taken near the Lewis Cliff (84°17′S, 161°05′E) in the Beardmore Glacier region, Antarctica. Figure 1 shows an overview of the continent, and the black open circle inland of the Ross Shelf Ice marks the Lewis Cliff/Walcott Névé area. Our field party, consisting of six members, established a camp at the northern border of the Walcott Névé, which is separated from the main Beardmore Glacier by the Queen Alexandra Range.

The main objective of our group was the search for meteorites, being part of the annual Antarctic Search for Meteorites (ANSMET) expeditions, performed with support of NSF/DPP. Part of this season's program dealt with the collection of ice samples, which were taken from the same areas where meteorites are found. The main area investigated for meteorites and dust bands has been the Lewis Cliff Ice Tongue. Figure 2 shows a map of the Lewis Cliff/Walcott Névé area, including the Lewis Cliff Ice Tongue. Samples have been taken for trace element and isotope studies and for the investigation of dust components. The black circles at or near the Lewis Cliff Ice Tongue mark the locations where dust band samples have been collected. Figure 3 shows an aerial photograph of the Lewis Cliff Ice Tongue, which is the main stranding surface for meteorites in that area (CASSIDY, 1987; CASSIDY *et al.*, 1987). Figure 4 shows the northern end of the Ice Tongue, the main sampling area for dust band samples. In this part of the Ice Tongue, which impinges into a vast moraine separating the Walcott Névé from the Law Glacier, dust bands crop out at irregular intervals, but with a higher areal density than usual. Our program included mapping of some of the dust bands (Fig. 2), and later laboratory investigations to learn their possible bearing on ice movement, stratigraphy, and age related to the meteorite concentration mechanism. Dust band data may help to infer the path length of the accumulation zones for

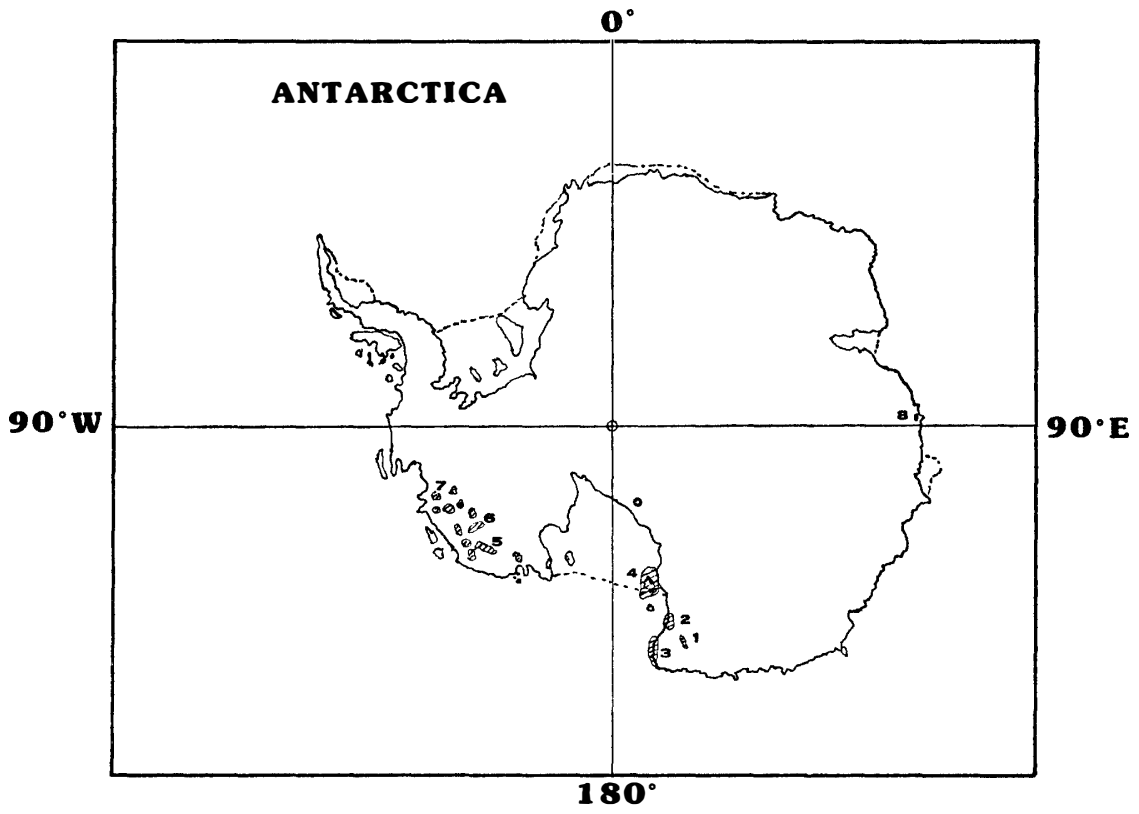


*Fig. 1. Map of Antarctica showing the location of the Lewis Cliff (black open circle) in the Beardmore Glacier area. Also shown are the locations of Late Cenozoic volcanic provinces, indicated by numbers. 1: The Pleiades, 2: Mt. Melbourne, 3: Hallet volcanic province, 4: Ross Island-McMurdo volcanic province, 5: Mt. Berlin, 6: Executive Committee Range, 7: Mt. Takahe, 8: Gaussberg. The two principal locations of Late Cenozoic volcanic provinces is in the Northern Victoria Land-McMurdo area (KYLE, 1982; GONZÁLES-FERRÁN, 1982; GOLDICH et al., 1975) and in the Marie Byrd Land area (LEMASURIER and REX, 1982; GONZÁLES-FERRÁN, 1982), both areas are possible as sources for volcanic debris at Lewis Cliff. The Gaussberg is unlikely as a source, since it is further away and has a different chemistry (COLLERSON and MCCULLOCH, 1983).*

meteorites. Most of the bands were found to run generally perpendicular to the direction of the ice flow, but deviations from that common orientation were recorded very often. In some cases we observed that dust bands striking in one direction curl back 180° and run back in the other direction. Obviously there is a direct connection to the ice flow, and it seems that a sometimes very complicated ice movement may lead to distortion and dislocation of the dust bands. The dust bands are not continuous across bare ice areas. They pinch and swell and eventually disappear after distances of 1000 m or less. This might reflect primary depositional patterns. The surface expression width of the bands is usually between 10 and 25 cm. Widths larger than 40 cm lead to problems in recognition. The density of dust per dust band (as inferred from our samples) seems to be relatively constant with small variations. If bands get too wide, the cause may be found in ice movements or shallowly dipping angles. The dip of the dust layers at each of the sites varied from 20° southward for 86–1, 32° southward for 86–3, 74° northward for 86–4, and near vertical for 86–5.

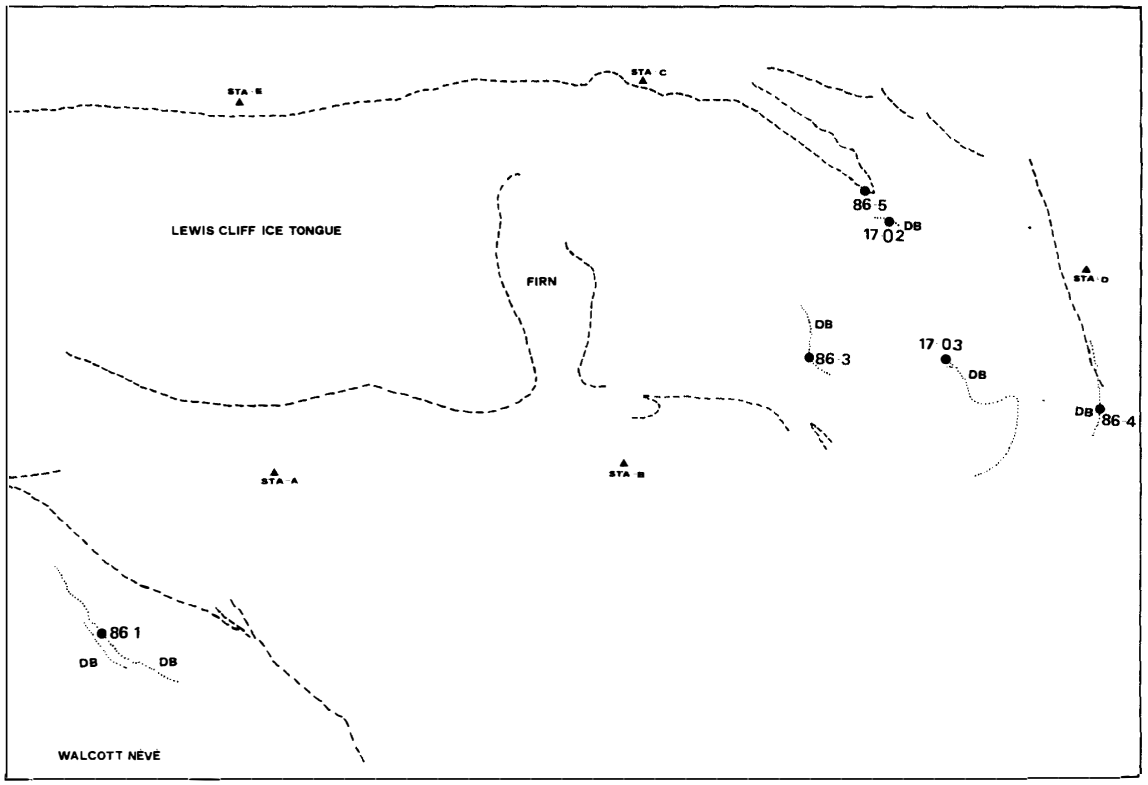


*Fig. 2. Map of the Lewis Cliff Ice Tongue area next to the Walcott Névé. The Lewis Cliff itself extends basically from the South to the North (right side of the map). This map is part of the general field map of the Ice Tongue obtained by surveying meteorite locations, ice sample locations, and other points. Stations (black triangles) have determined geographic coordinates. Dust band sample locations are marked by black dots and are numbered accordingly. Dust bands are labelled "DB" (dotted lines).*

## 3. Sampling

Ice samples from dust bands were taken with two objectives: (a) radiometric ice age determinations and (b) characterization of included dust deposits. Reliable radiometric age determinations of polar ice would be of great importance, and large blocks of ice including dust were cut out for that purpose. Age determinations on this material, mainly using uranium series dating, are to be performed by E.L. FIREMAN (FIREMAN and NORRIS, 1982; FIREMAN, 1986). The ice and dust band samples were out out of the bare ice surface using a chainsaw. Figures 5–8 show the sampling procedure in some detail. After taking out the ice blocks, they were cleaned of "sawdust" and wrapped in clean plastic bags, sealed, and kept at temperatures below 0°C during the whole transport. Smaller samples of the central dust band were used in our study.

These ice samples, to be used for chemical and pertrological investigations of the dust, were processed in the field camp after collection to avoid complicated and costly transport procedures. The ice, containing dust particles, was put in special superclean plastic bags (provided by NASA Johnson Space Center for meteorite collection) and slowly melted. The dust was allowed to settle on the bottom of the plastic bag, after which the water was decanted. The dry Antarctic environment fostered the evaporation

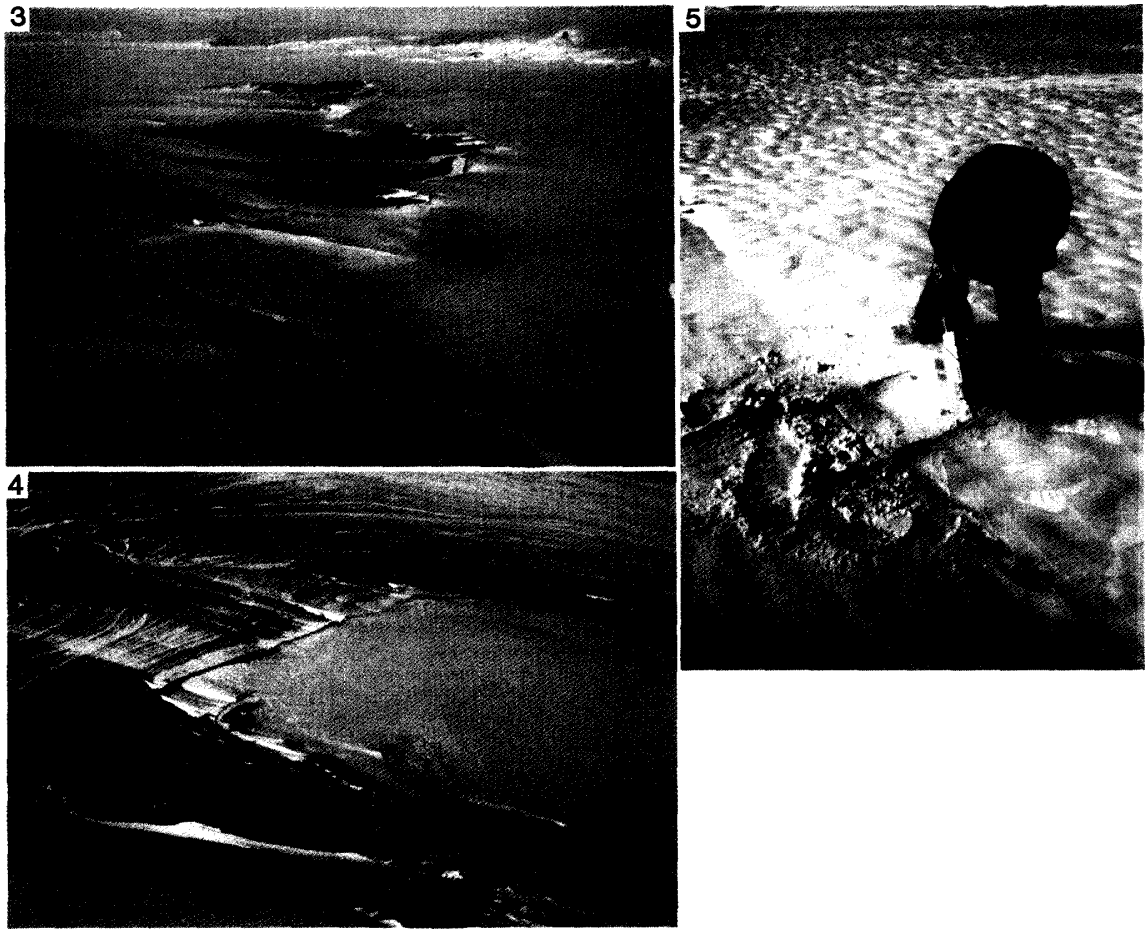


*Fig. 3. Aerial photograph of the Lewis Cliff Ice Tongue. The Lewis Cliff is crossing from the lower right corner of the picture to the upper left. The viewing direction is towards the Northeast. At the horizon the Queen Alexandra Range is visible. One of the mountains in the middle of the picture is Coalsack Bluff.*

*Fig. 4. Close-up aerial photo of the northern end of the Lewis Cliff Ice Tongue, site of sample locations 86–3, 86–4, 86–5, 17–02 and 17–03. The viewing direction is to the Northeast. At about the middle of the picture, at the western border of the Ice Tongue, there is a trailing moraine visible, intruding the Ice Tongue. At the tip of this moraine sample 86–5 was taken.*

*Fig. 5. Dust band at sample locations 86–1, next to Meteorite Moraine, just outside of the Lewis Cliff Ice Tongue. Note the sharpness of the contact, and the slight depression at the location of the dust band. A large block of ice is being cut out using a chainsaw.*

of the remaining water, and the dry dust remained on the bottom of the plastic bag, which was then sealed in two more plastic bags, and was only reopened in the laboratories in Vienna and Tokyo. Performing these operations in the field ensures that the samples are exposed to no additional, non-Antarctic contaminations. This is important, because in most cases the collected material amounted to only a few milligrams. The sampling procedure described above leads to the loss of soluble impurities in the ice, and to the probable loss of extremely small submicron sized particles, both of which are, however, not directly relevant to our study.

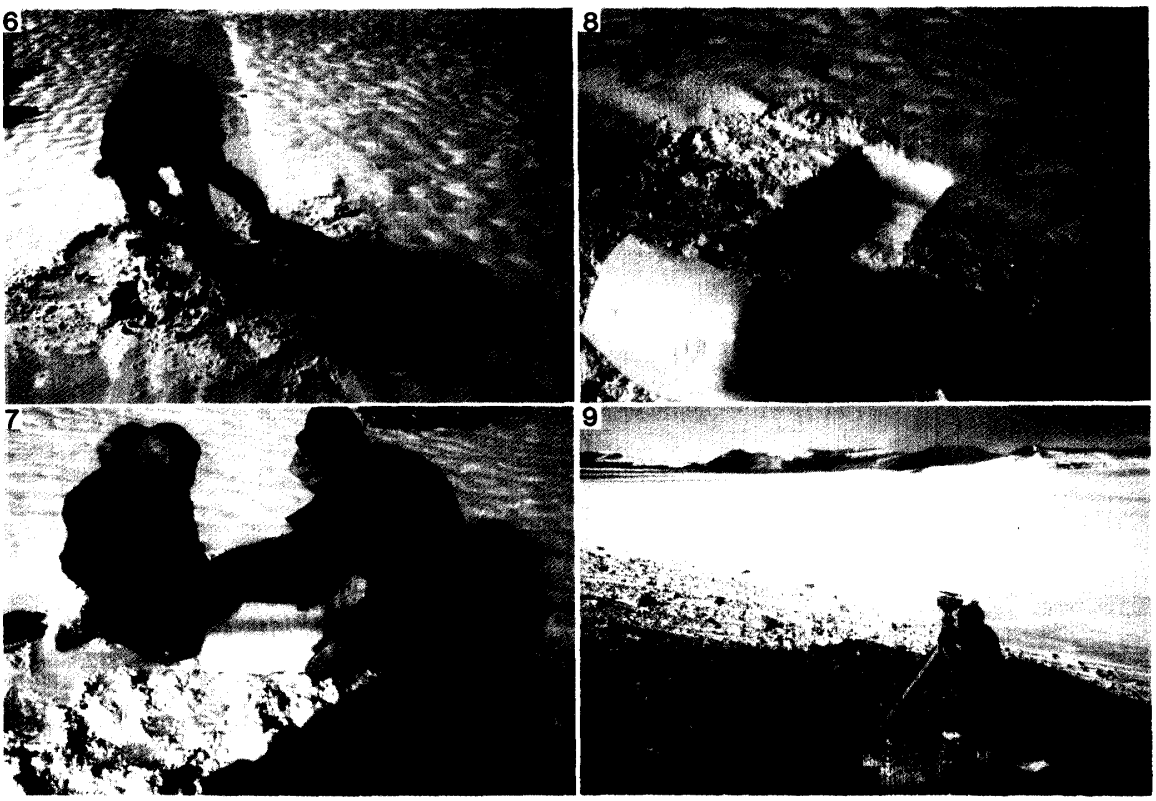


*Fig. 6. Removal of dust band-ice samples using a chainsaw.*

*Fig. 7. After the block has been cut, it is taken out. Note the narrow brown dust band and the sharpness of the contact, which is well visible on the freshly cut surface.*

*Fig. 8. The dipping angle (close to 20°) becomes visible in the remaining pit after the ice cube has been taken out. The steepness of the dipping changed from the end of the Ice Tongue, where it was very steep, to outside of the Ice Tongue (location 86-1, visible here), where it was shallow.*

*Fig. 9. The process of mapping the sample locations involved setting up a theodolite equipped with an automatic distance measuring device on a location with predetermined known geographical coordinates. Visible here is Station C at the Western rim of the Lewis Cliff Ice Tongue. The Ice Tongue is in the back of the picture, looking Northeast.*

## 4. Techniques

### *4.1. Mapping*

In the field, the sample locations were determined in conjunction with the surveying of meteorite locations and the establishment of a general field map of the Lewis Cliff Ice Tongue. Dust band lineations and trends (which may have implications on ice movement studies related to meteorite accumulation processes) have been mapped by measuring a number of points along the band. The measurements were performed using a theodolite situated on a station (usually a hill or mountain next to the Ice Tongue; see Fig. 9) with predetermined geographic coordinates. The theodolite was equipped with an infrared distance measuring device, the counter station on the point to be measured being a retro-reflector. The results of the surveying and mapping will be reported in detail elsewhere (JWS, in preparation).

### 4.2. *Analytical techniques*

Thin section mounts have been prepared for microscopic examination and measurement of grain sizes, as well as for electron microprobe studies. Major elements were determined using the computer controlled JEOL 733 electron microprobe at NIPR in Tokyo, with standard correction procedures.

Trace element concentrations in milligram and sub-milligram amounts of dust have been measured using instrumental neutron activation analysis (INAA). The methods follow procedures which have been described before (*e.g.* KOEBERL *et al.*, 1987—see also for analytical precision).

## 5. Results

So far, we investigated material from six different dust bands: 86–1, 86–3, 86–4, 86–5, 17–02, and 17–03. The first four are identical with samples also taken for age determinations. The microscopic examination of the six dust samples revealed that one of the samples is different from all others: all samples except 86–5 contained abundant (and small) glass shards and some mineral fragments. Particle sizes in the samples have been determined as follows: 86–1: average diameter 25 $\mu$m (maximum 50 $\mu$m); 86–3: 20 $\mu$m (80 $\mu$m); 86–4: 2–10 $\mu$m; 86–5: 400–600 $\mu$m; 17–02: 10 $\mu$m (40 $\mu$m); and 17–03: 10–20 $\mu$m (80 $\mu$m). Thus besides showing no glass shards, only rock fragments, sample 86–5 also shows a considerably larger average particle size. The already indicates a different origin for the 86–5 dust band.

The major element compositions of individual mineral fragments (mostly feldspar) and glass shards are given in Tables 1–4 for samples 86–1, 86–3, 17–02, and 17–03. In the case of sample 86–3 (Table 2), olivine and pyroxene fragments have been measured

*Table 1. Major element data and mineral composition of selected crystal fragments (feldspar, analyses No. 1–8) and volcanic glass shards (analyses No. 9–12) in sample 86–1. All data in wt%. Errors are usually* $< \pm 5\%$.

| Analysis No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 66.63 | 48.57 | 66.80 | 67.58 | 48.09 | 68.45 | 68.98 | 49.05 | 44.05 | 58.37 | 46.36 | 58.54 |
| $TiO_2$ | .08 | .07 | .06 | .11 | .14 | .11 | .02 | .07 | 3.10 | 1.07 | 3.13 | .83 |
| $Al_2O_3$ | 18.32 | 32.01 | 19.99 | 19.03 | 33.88 | 17.21 | 19.18 | 32.17 | 11.34 | 17.38 | 17.75 | 17.79 |
| FeO | 1.91 | .01 | .53 | .52 | .69 | 1.70 | .50 | .56 | 17.75 | 6.74 | 11.51 | 6.80 |
| MnO | .00 | .00 | .00 | .04 | .04 | .03 | .00 | .00 | .29 | .21 | .10 | .32 |
| MgO | .00 | .11 | .00 | .00 | .07 | .00 | .03 | .12 | 12.21 | 1.00 | 3.68 | .75 |
| CaO | .03 | 16.20 | .79 | .62 | 16.82 | .06 | .26 | 15.70 | 6.40 | 2.82 | 9.68 | 3.04 |
| $Na_2O$ | 7.45 | 2.24 | 7.17 | 7.34 | 1.92 | 7.64 | 11.48 | 2.71 | 3.19 | 4.07 | 4.60 | 6.08 |
| $K_2O$ | 5.47 | .00 | 5.85 | 6.14 | .11 | 5.24 | .33 | .11 | .92 | 4.20 | .68 | 5.37 |
| $Cr_2O_3$ | .00 | .00 | .00 | .00 | .00 | .00 | 0.3 | .00 | .03 | .02 | .05 | .00 |
| Total | 99.94 | 99.81 | 101.19 | 101.38 | 101.76 | 100.44 | 100.81 | 100.49 | 99.28 | 95.88 | 97.54 | 99.52 |
| 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 |
| Ab 67.2 | | Ab 20.0 | | Ab 62.6 | | Ab 62.6 | | Ab 17.0 | | Ab 68.7 | | Ab 97.0 | | Ab 23.6 |
| An 0.4 | | An 80.0 | | An 3.8 | | An 2.9 | | An 82.3 | | An 0.3 | | An 1.2 | | An 75.7 |
| Or 32.4 | | Or 0.0 | | Or 33.6 | | Or 34.5 | | Or 0.7 | | Or 31.0 | | Or 1.8 | | Or 0.6 |

in addition to feldspar fragments. The feldspar compositions show several major groups and some variation between different samples. The glass composition is extremely variable between different shards, suggesting various source materials or an evolving magma composition at a single source.

Table 5 gives the results of the trace element analyses for all six dust band samples; in some cases, only a few milligrams have been available for analysis. Also reported in the table are concentrations of Na, K, and Fe. In contrast to the numbers given in Tables 1–4 for individual particles, these are the bulk contents for these three major elements. In addition, data for 32 trace elements are given. It is clearly visible that, although there are some variations, all samples except 86–5 show similar trace element abundances.

*Table 2. Major element data of mineral fragments and volcanic glass shards. Analyses No. 1–3: olivine, 4: pyroxene, 5–11: feldspar, 12: quartz, 13–17: glass. All data in wt%. Sample No. 86–3.*

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 37.81 | 38.69 | 38.83 | 51.38 | 52.82 | 62.20 | 67.63 | 67.74 |
| $TiO_2$ | .03 | .05 | .02 | .49 | .19 | .00 | .03 | .04 |
| $Al_2O_3$ | .03 | .41 | .05 | 1.90 | 29.60 | 22.42 | 19.70 | 19.21 |
| FeO | 22.68 | 25.13 | 21.24 | 12.50 | .65 | .12 | .29 | .01 |
| MnO | .51 | .34 | .41 | .95 | .00 | .01 | .00 | .04 |
| MgO | 37.26 | 34.76 | 38.32 | 9.96 | .11 | .00 | .02 | .03 |
| CaO | .34 | .40 | .31 | 19.77 | 13.11 | .47 | .43 | .34 |
| $Na_2O$ | .04 | .40 | .04 | 1.84 | 4.11 | 6.94 | 7.63 | 11.67 |
| $K_2O$ | .00 | .18 | .01 | .11 | .20 | 5.58 | 5.18 | .02 |
| $Cr_2O_3$ | .05 | .00 | .00 | .00 | .00 | .00 | .02 | .00 |
| Total | 98.75 | 100.36 | 99.23 | 98.90 | 100.79 | 97.74 | 100.93 | 99.10 |
| | Fo 74.5 | Fo 71.1 | Fo 76.3 | En 32.0 | Ab 35.8 | Ab 63.8 | Ab 67.7 | Ab 98.3 |
| | Fa 25.5 | Fa 28.9 | Fa 23.7 | Fs 22.5 | An 63.0 | An 2.4 | An 2.1 | An 1.6 |
| | | | | Wo 45.6 | Or 1.2 | Or 33.8 | Or 30.2 | Or 0.1 |

| | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 66.92 | 65.09 | 53.15 | 99.48 | 48.69 | 49.21 | 57.43 | 64.68 | 48.58 |
| $TiO_2$ | .01 | .03 | .16 | .02 | 3.06 | .63 | .44 | .23 | 4.04 |
| $Al_2O_3$ | 19.51 | 19.55 | 28.71 | .52 | 15.82 | 10.19 | 19.15 | 17.76 | 17.36 |
| FeO | .35 | .33 | .56 | .00 | 10.94 | 22.22 | 6.97 | 3.37 | 9.52 |
| MnO | .00 | .04 | .00 | .00 | .22 | .14 | .32 | .03 | .14 |
| MgO | .00 | .00 | .05 | .01 | 2.71 | 1.67 | .37 | .38 | 1.62 |
| CaO | .71 | .17 | 12.13 | .03 | 8.61 | .04 | .99 | 1.28 | 9.57 |
| $Na_2O$ | 7.80 | 7.11 | 4.45 | .04 | 4.92 | 4.37 | 5.92 | 8.37 | 5.53 |
| $K_2O$ | 4.55 | 6.89 | .32 | .18 | .86 | 4.97 | 3.00 | 3.28 | .99 |
| $Cr_2O_3$ | .03 | .00 | .00 | .04 | .00 | .01 | .00 | .00 | .02 |
| Total | 99.88 | 99.21 | 99.53 | 100.32 | 95.83 | 93.45 | 94.59 | 99.38 | 97.37 |
| | Ab 69.7 | Ab 60.6 | Ab 39.2 | | | | | | |
| | An 3.5 | An 0.8 | An 59.0 | | | | | | |
| | Or 26.8 | Or 38.7 | Or 1.8 | | | | | | |

*Table 3. Major element data and mineral composition of crystal fragments and glass shards in sample 17-02. Analyses No. 1-7: feldspar, 8-15: glass. All data in wt%.*

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 66.55 | 67.41 | 64.82 | 67.49 | 66.07 | 66.00 | 66.54 |
| $TiO_2$ | .07 | .03 | .11 | .02 | .07 | .12 | .01 |
| $Al_2O_3$ | 17.81 | 17.68 | 19.57 | 18.39 | 19.10 | 17.39 | 17.90 |
| FeO | 1.33 | 1.11 | .38 | .86 | 1.17 | .78 | .27 |
| MnO | .05 | .00 | .00 | .04 | .00 | .03 | .00 |
| MgO | .01 | .00 | .04 | .00 | .00 | .00 | .00 |
| CaO | .18 | .15 | 1.35 | .12 | .25 | .26 | .04 |
| $Na_2O$ | 6.87 | 8.10 | 7.26 | 7.30 | 7.64 | 5.65 | 1.73 |
| $K_2O$ | 5.09 | 4.46 | 5.30 | 6.00 | 5.33 | 6.87 | 13.13 |
| $Cr_2O_3$ | .00 | .00 | .00 | .00 | .02 | .03 | .06 |
| Total | 97.96 | 98.94 | 98.83 | 100.22 | 99.65 | 97.13 | 99.68 |
| | Ab 66.6<br>An 0.9<br>Or 32.4 | Ab 72.9<br>An 0.7<br>Or 26.4 | Ab 63.2<br>An 6.5<br>Or 30.3 | Ab 64.6<br>An 0.6<br>Or 34.9 | Ab 67.7<br>An 1.2<br>Or 31.1 | Ab 54.8<br>An 1.4<br>Or 43.8 | Ab 16.7<br>An 0.2<br>Or 83.1 |

| | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 45.09 | 44.40 | 46.59 | 46.54 | 52.65 | 60.30 | 60.27 | 45.21 |
| $TiO_2$ | 3.29 | 4.16 | 4.13 | 4.11 | 4.59 | .97 | .42 | 3.76 |
| $Al_2O_3$ | 14.59 | 14.66 | 17.08 | 15.14 | 2.79 | 16.04 | 14.76 | 17.10 |
| FeO | 13.39 | 12.65 | 11.21 | 13.67 | 23.02 | 6.77 | 7.13 | 7.89 |
| MnO | .27 | .19 | .19 | .30 | .46 | .24 | .27 | .12 |
| MgO | 4.77 | 5.09 | 3.28 | 4.88 | .17 | 1.72 | .27 | 4.45 |
| CaO | 8.42 | 10.54 | 10.65 | 10.47 | 1.08 | 3.75 | 2.64 | 12.53 |
| $Na_2O$ | 4.49 | 4.19 | 3.29 | 3.01 | 11.28 | 4.78 | 6.38 | 3.00 |
| $K_2O$ | 1.23 | 1.20 | .63 | 1.00 | .45 | 4.31 | 4.71 | .32 |
| $Cr_2O_3$ | .00 | .02 | .00 | .00 | .00 | .00 | .00 | .02 |
| Total | 95.54 | 97.10 | 97.05 | 99.12 | 96.49 | 98.88 | 96.85 | 94.40 |

## 6. Discussion

In our discussion we will mainly concentrate on comparisons with dust bands on ice sheets rather than in ice cores. The presence of glass shards in five of six dust band samples strongly supports the interpretation of a volcanic origin of the material in the bands, as previously suggested by several authors (KEYS *et al.*, 1977; GOW and WILLIAMSON, 1971; KYLE *et al.*, 1981, 1982; NISHIO *et al.*, 1985). There are some interesting differences, however, from dust bands which have been studied previously.

The size of the particles in the five dust bands of probable volcanic origin is smaller than the average size reported for other dust bands. NISHIO *et al.* (1985) found that the grain size of volcanic debris in dust bands in the Allan Hills area averaged around 100 $\mu$m and the average grain size of material from the Yamato Mountains meteorite field was 45 $\mu$m. Together with chemical and petrological data, they interpreted this result as an indication of different volcanic sources for different areas, namely the McMurdo area for the Allan Hills tephra, and the South Sandwich Islands for the Yamato tephra.

*Table 4. Major element data and mineral composition of crystal fragments and glass shards in sample 17–03. Analyses No. 1–7: feldspar, 8–12: glass. All data in wt%.*

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 68.87 | 67.11 | 79.07 | 68.01 | 68.02 | 53.20 | 66.87 | 60.74 | 57.57 | 58.93 | 60.28 | 62.29 |
| $TiO_2$ | .00 | .04 | .20 | .03 | .03 | .08 | .00 | .71 | 1.88 | .73 | .83 | .64 |
| $Al_2O_3$ | 19.59 | 17.55 | 14.28 | 20.26 | 18.59 | 29.51 | 18.52 | 14.68 | 11.21 | 13.73 | 13.90 | 14.72 |
| FeO | .10 | 1.88 | .47 | .07 | .28 | .46 | .12 | 9.42 | 17.42 | 9.84 | 10.05 | 8.90 |
| MnO | .04 | .01 | .00 | .01 | .03 | .08 | .02 | .34 | .55 | .34 | .35 | .31 |
| MgO | .01 | .00 | .21 | .01 | .00 | .07 | .00 | .29 | .37 | .64 | .31 | .06 |
| CaO | .04 | .01 | .29 | .32 | .24 | 12.85 | .06 | 2.19 | 3.41 | 4.19 | 2.43 | 1.57 |
| $Na_2O$ | 11.66 | 7.17 | 5.16 | 11.69 | 11.49 | 4.25 | 1.50 | 4.71 | 5.41 | 5.92 | 4.77 | 3.91 |
| $K_2O$ | .06 | 5.93 | 1.26 | .03 | .11 | .24 | 13.09 | 4.31 | 3.34 | 4.21 | 3.76 | 4.28 |
| $Cr_2O_3$ | .00 | .01 | .00 | .00 | .00 | .02 | .00 | .04 | .00 | .00 | .00 | .01 |
| Total | 100.37 | 99.71 | 100.94 | 100.43 | 98.79 | 100.76 | 100.18 | 97.43 | 101.16 | 98.53 | 96.68 | 96.69 |

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| Ab 99.5 | Ab 64.7 | Ab 83.9 | Ab 98.4 | Ab 98.3 | Ab 36.9 | Ab 14.8 |
| An 0.2 | An 0.1 | An 2.6 | An 1.5 | An 1.1 | An 61.7 | An 0.3 |
| Or 0.3 | Or 35.2 | Or 13.5 | Or 0.2 | Or 0.6 | Or 1.3 | Or 84.9 |

The mean grain size of deposited volcanic material decreases with increasing distance from the source volcano (WALKER, 1981; CAREY and SIGURDSSON, 1982; CORNELL *et al.*, 1983; NISHIO *et al.*, 1984). The absence of large volcanic glass shards in our samples indicates the origin from a distant volcanic source. In fact, there are no close Cenozoic volcanoes known, since our sampling site is rather far inland, distant from all known centers of recent volcanic activity (see also Fig. 1). There are, however, older volcanic centers near the Scott Glacier (Mt. Saltonstall and Mt. Early) south of the Beardmore area, which are too old to be responsible for these ash layers. Also, all Cenozoic volcanoes are located further north, thus requiring the ash either to travel against the katabatic winds, or to be erupted and deposited during a windless interval, or to be injected into the stratosphere to settle and enter the katabatic circulation upstream of the Lewis Cliff Ice Tongue. The first and last mechanisms lead to the survival of only small grain sizes, while larger grains will settle out faster. The second alternative seems to be less realistic because the katabatics blow almost constantly. The third alternative seems the most realistic, since the quantity of dust is rather high. Considering the already great distance of the Lewis Cliff site from the Antarctic coast, it seems justified to exclude any volcanic sources outside the Antarctic continent.

Another difference with previously investigated dust bands is the highly variable chemical composition of the glass shards even within one Lewis Cliff sample. NISHIO *et al.* (1985) found that in the cases of the glass from Allan Hills and Yamato dust bands, the chemical compositions are rather uniform. The average of the volcanic debris from the Allan Hills area as given by NISHIO *et al.* (1985) and reported in Table 6, compares well with some of our glass particles, *e.g.* analyses 8–11 of sample 17–02 (Table 3). There are, however, differences, like the lower $Na_2O/K_2O$ ratio in the Allan Hills particles (1.4), compared with 2–4 in the Lewis Cliff particles. Also, the FeO content is considerably higher in most of the Lewis Cliff samples. NISHIO *et al.* (1985)

*Table 5. Trace element data for six dust band samples. All data in ppm, except where noted otherwise. Numbers in parentheses are sample weights in mg.*

| | 86-1 (27.24) | 86-3 (0.86) | 86-4 (11.42) | 17-02 (129.89) | 17-03 (1.31) | 86-5 (263.04) |
|---|---|---|---|---|---|---|
| Na (wt%) | 3.33 | 3.52 | 5.0 | 5.44 | 5.60 | 2.54 |
| K (wt%) | 2.02 | 2.05 | 2.76 | 5.11 | 3.17 | 2.89 |
| Sc | 6.51 | 8.64 | 1.6 | 1.39 | 7.05 | 11.8 |
| Cr | 12.3 | 111 | 12.5 | 14.0 | 21.6 | 57.2 |
| Mn | 1730 | 1710 | 2060 | 1980 | 1750 | 567 |
| Fe (wt%) | 6.82 | 5.42 | 6.64 | 8.38 | 4.83 | 2.73 |
| Co | 14.2 | 20.2 | 5.8 | 12.1 | 14.8 | 13.8 |
| Ni | <150 | <300 | 120 | <300 | <300 | 50 |
| Ga | <5 | 60 | <10 | 49 | <20 | 60 |
| As | 6.7 | 0.31 | 5.5 | 4.7 | 7.6 | 2.0 |
| Br | <2 | <3 | 8 | <1 | 5.8 | <1 |
| Rb | 110 | 98 | 124 | 135 | 114 | 85 |
| Sr | <180 | <300 | <250 | <300 | <300 | 127 |
| Zr | 1190 | 1030 | 1160 | 1450 | <500 | 370 |
| Sb | 11.0 | 8.0 | 11.1 | 0.5 | 7.5 | 0.52 |
| Cs | 1.29 | 4.5 | 4.42 | 2.42 | 2.41 | 6.10 |
| Ba | 167 | 680 | 150 | 210 | 1090 | 373 |
| La | 83.1 | 44.0 | 92.7 | 113 | 71.0 | 19.2 |
| Ce | 145 | 87.3 | 235 | 246 | 150 | 43 |
| Nd | 47.0 | 35 | 83.6 | 103 | 70 | 18.4 |
| Sm | 10.5 | 8.26 | 16.2 | 20.9 | 13.1 | 4.03 |
| Eu | 1.80 | 1.38 | 2.80 | 3.19 | 2.52 | 0.79 |
| Gd | 15.4 | 7.9 | n.d. | 22.2 | 10.5 | 3.48 |
| Tb | 2.44 | 1.48 | 2.35 | 4.2 | 1.65 | 0.67 |
| Dy | 11.4 | 9.1 | 14.5 | 25.5 | 9.5 | 4.12 |
| Tm | 0.97 | 0.82 | n.d. | 2.1 | 0.92 | 0.4 |
| Yb | 5.95 | 6.0 | 9.05 | 13.0 | 6.0 | 3.00 |
| Lu | 0.89 | 0.84 | 1.27 | 1.60 | 0.78 | 0.48 |
| Hf | 25.3 | 9.0 | 39.5 | 27.5 | 14.4 | 5.80 |
| Ta | 8.2 | 3.8 | 11.7 | 15.2 | 4.5 | 0.70 |
| W | 30 | <30 | 67 | 30 | 15 | 1.8 |
| Au | 0.014 | 0.030 | 0.060 | 0.078 | <0.03 | 0.0087 |
| Hg | <1.4 | 6 | 1.5 | <0.3 | 2 | <0.2 |
| Th | 36.9 | 7.4 | 24.1 | 21.2 | 8.88 | 9.12 |
| U | | | | 13 | 13 | 1.4 |
| La/Lu | 93.8 | 52.4 | 72.7 | 88.3 | 90.9 | 40.0 |
| $(La/Lu)_{CN}$ | 9.23 | 5.16 | 7.16 | 6.95 | 8.92 | 3.94 |

compared their average Allan Hills ash to trachybasalts from the Ross Island volcanic province and found good agreement. For the glass particles in the Lewis Cliff area (as mentioned above) the similarities to some basanites seem to be greater than to trachybasalts (see Table 6). This applies, however, only to the high Ca/Mg glasses. Some other glasses seem to be more similar to peralkaline K-trachyte reported from The Pleiades volcanoes (KYLE and RANKIN, 1976; KYLE, 1982), examples being analysis 16 in sample 86-3 (Table 2) *vs.* the data given for the peralkaline K-trachyte in Table 6. Some other glass particles (*e.g.* analysis #14 in 17-02, Table 3) show similarities

*Table 6. Analytical data for comparison rocks from different Cenozoic volcanic provinces in Antarctica. All data in wt%, from* KYLE *et al. (1981),* NISHIO *et al. (1985),* KYLE *and* RANKIN *(1976), and* GOLDICH *et al. (1975).*

| | Peralkaline trachyte Mt. Takahe | Peralkaline K-trachyte The Pleiades | K-trachyte The Pleiades | Basanite The Pleiades | Trachyte Ross Island | Trachybasalt Ross Island | Allan Hills dust, ave. |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 61.22 | 64.36 | 59.98 | 44.26 | 58.1 | 44.6 | 44.23 |
| $Al_2O_3$ | 14.11 | 16.85 | 17.67 | 14.82 | 15.9 | 16.9 | 16.29 |
| $Fe_2O_3$ | — | 2.34 | 5.57 | 4.01 | 2.72 | 11.8 | — |
| FeO | 8.79* | 1.52 | 0.98 | 8.70 | 5.06 | 0.06 | 10.19* |
| MnO | — | 0.15 | 0.17 | 0.20 | 0.23 | 0.22 | 0.22 |
| MgO | 0.06 | 0.08 | 0.75 | 7.21 | 0.90 | 3.78 | 4.06 |
| CaO | 1.21 | 0.93 | 2.47 | 10.98 | 2.40 | 9.44 | 9.91 |
| $Na_2O$ | 6.58 | 8.26 | 7.09 | 3.80 | 5.28 | 5.37 | 4.29 |
| $K_2O$ | 4.40 | 5.24 | 4.74 | 1.74 | 4.98 | 2.01 | 2.95 |
| $TiO_2$ | 0.52 | 0.14 | 0.70 | 3.66 | 1.00 | 3.46 | 3.76 |

* All Fe as FeO.

with K-trachyte (Table 6). If average values are calculated (omitting #12 in 17–02), the similarity to Allan Hills ash becomes more pronounced, except for $SiO_2$. However, calculation of averages for the Lewis Cliff ash does not seem justified, since there are rather large chemical intrasample variations, pointing to at least three different components as parent material for four of the volcanic dust band samples. This diagram can be used to distinguish between alkaline and non-alkaline compositions, and it is immediately obvious that all Lewis Cliff samples plot in the alkaline region of the diagram. For comparison we have also included data for the Allan Hills and the Yamato volcanic debris. The Yamato debris plots in the non-alkaline part of the diagram, while the Allan Hills debris (indicated by the shaded area) also falls in the alkaline region, but does not show a spread similar to the Lewis Cliff debris. Interestingly enough, there is no overlap between the Lewis Cliff and the Allan Hills debris in the diagram, indicating a different source volcano, although of the same general type. Data from The Pleiades volcanoes (KYLE, 1982) show almost exactly the same distribution as the Lewis Cliff volcanic debris. Similar data from Ross Island (not included in the diagram, but see NISHIO *et al.*, 1985) show a different distribution and are more similar to the Allan Hills ash. On the other hand, some volcanic material from Marie Byrd Land shows a distribution similar to The Pleiades (*cf.* GONZÁLES-FERRÁN and VERGARA, 1972). A distinction between the two provinces on the basis of the $Na_2O+K_2O$ *vs.* $SiO_2$ diagram therefore is not easy to establish (Fig. 10).

The trace element data given in Table 5 reveal some interesting aspects. Trace elements are very useful for further conclusions about the nature and origin of Antarctic dust bands, as suggested by FUKUOKA *et al.* (1985). Only very recently data on trace elements have been reported in the literature (FUKUOKA *et al.*, 1987). The general trends observed by them agree with ours, but their REE patterns (for Allan Hills and Yamato) are quite different. The composition given in Table 5 has to be regarded as an average bulk composition of each sample. One of the most interesting results is the immediate confirmation of the volcanic nature of samples 86–1, 86–3, 86–4, 17–02,

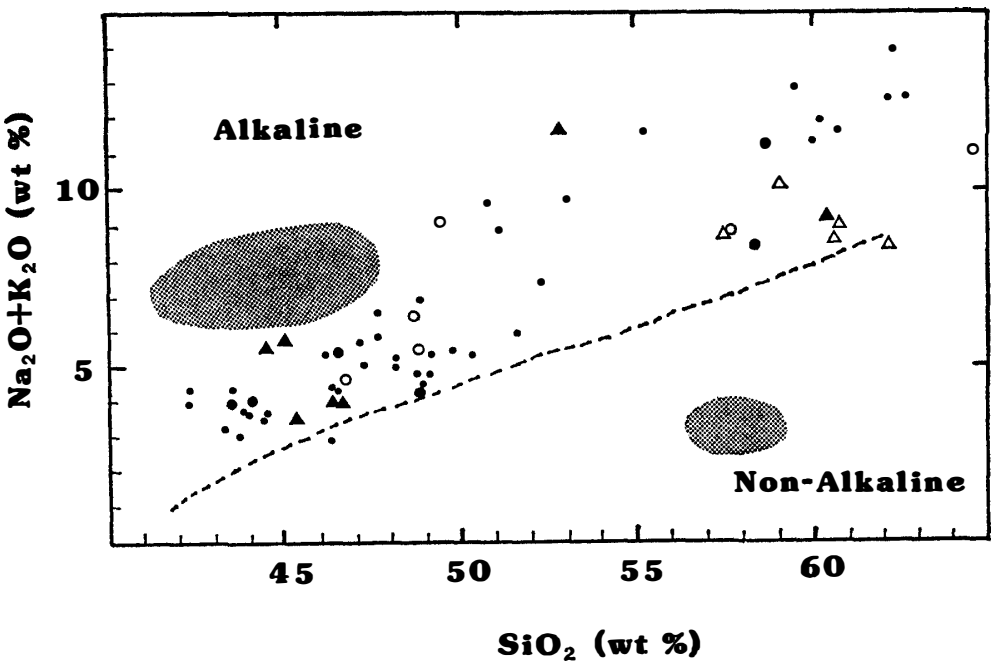


*Fig. 10.* *$SiO_2$ vs. $Na_2O+K_2O$ diagram, allowing the distinction of volcanic rocks in alkaline and non-alkaline varieties (divided by the broken line; GONZÁLES-FERRÁN, 1982). The samples are indicated as follows: large black dots: 86–1; open circles: 86–3; full triangles: 17–02, and open triangles: 17–03. The small black dots mark volcanic rocks from The Pleiades, Northern Victoria Land (KYLE, 1982), and the shaded areas mark the Yamato ash found in dust bands there (in the non-alkaline part), and the Allan Hills ash, respectively (NISHIO et al., 1985). All Lewis Cliff samples show a close relationship with material from The Pleiades, and are distinct from the Allan Hills dust bands.*

and 17–03. All have high concentrations of typical "volcanic" trace elements like As, Sb, the REE, Hf, Ta, W, and Th, as well as some volatiles (Br, Ga, Au). All these elements are characteristic of volcanic glasses (*e.g.* obsidians) and can be used as tracers of volcanic processes. In most cases, trace element abundances do not vary considerably between the five volcanic samples. There are a few exceptions, when one or two, or even three elements behave differently, without disturbing the overall picture. An example is the high Ba content of sample 86–3, which also shows a rather low Th abundance and a high Cr content. This sample has the lowest weight of all samples analyzed and uneven distribution of trace elements in single particles may cause differences to other samples. The high Co and Cr may also result from some ultramafic contamination.

The trace element composition of sample 86–5 is grossly different from the other five samples. This is already visible in the different $Na_2O/K_2O$ ratio (from Table 5), which clusters around 1.9 for the bulk of the volcanic glasses (similar to most lavas from The Pleiades; KYLE, 1982), but which is close to 1 for sample 86–5. The volcanogenic elements mentioned above do not show any enrichment, and the REE abundances are closer to average crustal abundances (*e.g.* TAYLOR and MCLENNAN, 1985). Figure 11 shows a plot of the chondrite-normalized REE abundances for all six samples. The difference between the volcanic samples and the 86–5 sample is obvious. The absolute

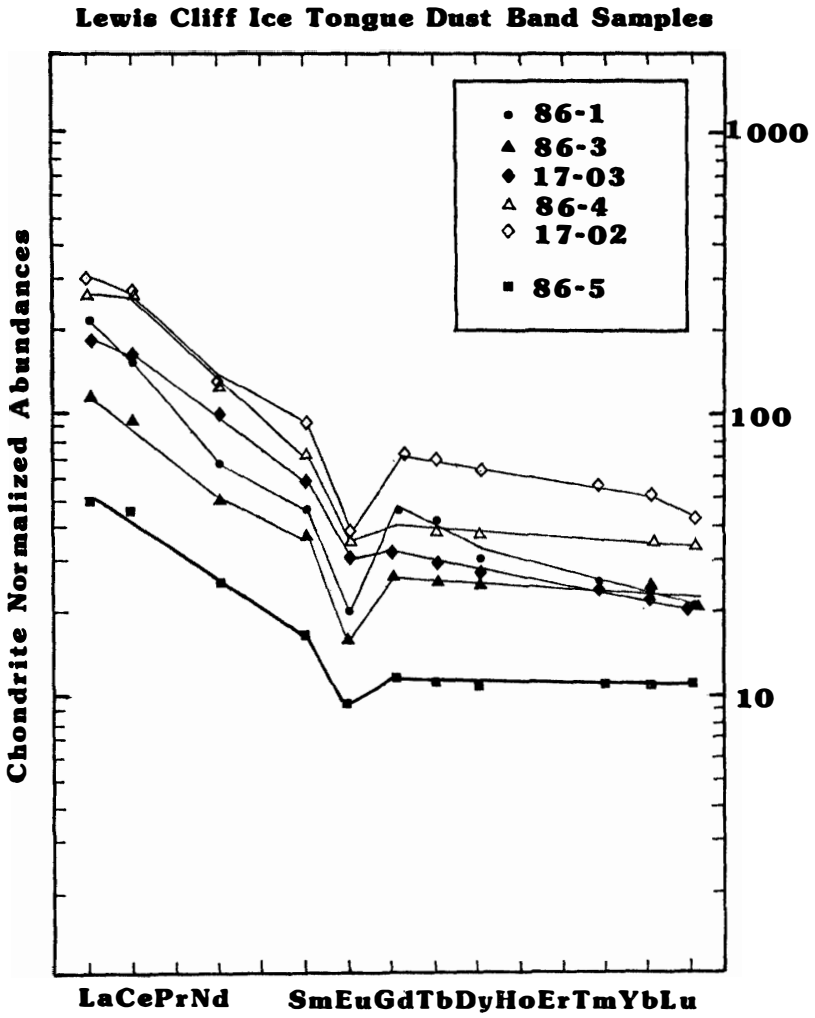


*Fig. 11. Chondrite normalized rare earth element patterns for all six dust band samples. The lower pattern (quadrangles and solid thick line) is sample 86–5, which shows a different pattern than the volcanic glasses in the upper part of the diagram. The pattern for 86–5 looks similar to sedimentary material (steep LREE, but flat HREE pattern, pronounced, but not extreme negative Eu anomaly; lower absolute abundances—almost identical to PAAS—*TAYLOR *and* MCLENNAN, *1985).*

abundances of the REE, the steeper LREE pattern, but flat HREE pattern, the presence of a modest Eu anomaly (compared to large Eu anomalies in the volcanic samples), and some trace element ratios (*e.g.* Th/Sm, La/Sc, Sc/Hf, etc.) are suggestive of a sedimentary material if all these criteria are found together (compare TAYLOR and MCLENNAN, 1985).

Since this sample was collected from a dust band closely associated with a moraine intruding into the northwestern end of the Lewis Cliff Ice Tongue (Fig. 4) we suggest that the debris in this band consists of local material from the Beacon Supergroup, and probably relates to shear zones in the ice sheet. Since there are no trace element data available for the local Beacon sandstone, we cannot make any final conclusion about

the provenance of the material in dust band sample 86–5, but there is a good similarity with sediments.

The interpretation of the trace element data of the volcanic material is also hampered by the scarcity of trace element data for different Cenozoic volcanic provinces in Antarctica. KYLE and RANKIN (1976) published a thorough study of REE and some other trace elements in different rocks from the McMurdo volcanic province, including The Pleiades in Northern Victoria Land. It is interesting to note that the peralkaline K-trachyte, which we already mentioned in the major element section as being close to some glass shards, also has bearings on the trace element chemistry. It is the only sample in KYLE and RANKIN's (1976) study which shows a marked (almost extreme) Eu depletion. It has a steep LREE, but a rather flat HREE pattern, while the dust band samples show a medium steepness in the LREE part, and also some inclination (steeper than 86–5, for example) in the HREE part. On the other hand, basanites have a steeper slope in the HREE part, but no negative Eu anomaly. The negative Eu anomaly of the peralkaline K-trachyte from The Pleiades is much too pronounced to compare with the Lewis Cliff samples directly. A mixture of basanitic, feldspathic, and peralkaline K-trachytic components would, however, more easily explain the REE and trace element chemistry. The REE pattern may also be reproduced in a different way. Some obsidians from Bouvetøya island in the Southern Atlantic show almost exactly the same REE patterns (PRESTVIK, 1982), but Sc contents are lower, and Hf contents are higher than in the Lewis Cliff samples. The same applies for the peralkaline K-trachyte. Here the Rb, Cs, Th, and REE contents are higher than in the Lewis Cliff volcanic debris, but Ba and Sr are lower. The reverse is true for basanites and K-trachytes from the same source volcano. Again, a mixture of these rocks as principal components would seem to lead to a trace element chemistry like the one observed for the Lewis Cliff volcanic debris.

## 7. Conclusions

We have investigated the petrographic characteristics, grain sizes, and chemical compositions of dust components from six different dust bands from the Lewis Cliff area. Five of these six samples are very similar, having average grain sizes close to 20 $\mu$m diameter. One of the samples, 86–5, has a grossly different grain size and contains debris easily visible without a microscope. Bases on the trace element composition and the fact that this sample was collected from a band closely associated with a moraine, we conclude that 86–5 contains Beacon Supergroup debris, probably local sandstones.

The presence of glassy shards in the other five samples led to the suspicion of a volcanic origin for those bands. Major element data allow the conclusion that the source has been an alkaline volcano. In the $Na_2O+K_2O/SiO_2$ diagram, the glassy shards from the Lewis Cliff dust bands plot in the same region as the material from The Pleiades or Marie Byrd Land volcanic provinces, although other major elements (*e.g.* Ca/Mg) seem to favor The Pleiades over the Marie Byrd Land volcanoes (see Table 6). The major element data for the individual glass shards indicate that the dust bands are composed of at least three different parent materials, which are all consistent with an alkaline volcanic source. This result is supported by the trace element distributions, especially

by the REE patterns. If the components suggested by major element analyses are taken to model the trace element abundances, they agree very well. Thus major and trace element data support the conclusion that the Lewis Cliff dust band samples are comprised of peralkaline K-trachyte, K-trachyte, and basanite (plus feldspar).

Only an admixture of peralkaline K-trachyte explains the presence of the pronounced negative Eu anomaly in all five dust band samples, since the other components (basanites, K-trachyte; or other materials inferred for sites like the Allan Hills or Yamato) generally do not show a pronounced negative Eu anomaly. Volcanic rocks from the Ross Island/McMurdo volcanic province are different in major and trace element chemistry (KYLE and RANKIN, 1976) and are thus more unlikely as a parent for the Lewis Cliff dust bands. It is unclear if selected volatilization of alkalis is possible, and if this would change the picture.

Based on the data discussed above we tentatively suggest The Pleiades in Northern Victoria Land as a likely source for the volcanic debris in the Lewis Cliff Ice Tongue samples. We are not able, however, to exclude volcanoes from the Marie Byrd Land Cenozoic volcanic province, which are located at about the same distance from the Lewis Cliff area as The Pleiades (Fig. 1), as sources. The different components of the Lewis Cliff dust bands (which show a larger chemical variation than Allan Hills or Yamato samples, thus averages of major elements are difficult to compare) seem to have originated from one source – most probably a vast eruption – or a series of eruptions narrowly spaced in time-of one volcano. The alternative of different volcanoes going off at different sites and being deposited together seems rather unlikely. The components may be produced by the evolving composition of a magma chamber.

Further investigations, including trace element studies of different volcanic provinces, precise age determinations of ice and dust, and analysis of material from other dust bands, as well as mapping them, will be needed to establish more definite conclusions about the relationship between meteorites, ice movement (WHILLANS and CASSIDY, 1983), and dust bands. Dust bands, after determination of their age and origin, are useful for the study of ice dynamics and path lengths of meteorite accumulation zones.

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## References

CAREY, S. N. and SIGURDSSON, H. (1982): Influence of particle aggregation on deposition of distal tephra from the May 18, 1980, eruption of Mount St. Helens volcano. J. Geophys. Res., **87**, 7061–7072.

CASSIDY, W.A. (1987): The Antarctic search for meteorites during field season 1986–1987. Antarct. J. U.S., **22** (5) (in press).

CASSIDY, W.A., SCHUTT, J.W., KOEBERL, C., YANAI, K., LINDNER, L. and MARDON, A. (1987): The meteorite concentration at the Lewis Cliff, Antarctica, Ice Tongue. Meteoritics, **22**, 353.

COLLERSON, K.D. and MCCULLOCH, M.T. (1983): Nd and Sr isotope geochemistry of leucite-bearing lavas from Gaussberg, East Antarctica. Antarctic Earth Science, ed. by R.L. OLIVER *et al.*

Cambridge, Cambridge Univ. Press, 676–680.

CORNELL, W., CAREY, S.N. and SIGURDSSON, H. (1983): Computer simulation of transport and deposition of the Campanian Y-5 ash. J. Volcanol. Geotherm. Res., **17**, 89–109.

FIREMAN, E.L. (1986): Uranium series dating of Allan Hills ice. Proc. Lunar Planet. Sci. Conf., 16th, Pt 2, D539–D544 (J. Geophys, Res., **91** Suppl.).

FIREMAN, E.L. and NORRIS, T.L. (1982): Ages and composition of gas trapped in Allan Hills and Byrd core ice. Earth Planet. Sci. Lett., **60**, 339–350.

FUKUOKA, T., ARAI, F. and NISHIO, F. (1985): Identification of tephra layers in the meteorite ice field based on trace element compositions and refractive indices of glass (abstract). Mem. Natl Inst. Polar Res., Spec. Issue, **39**, 250.

FUKUOKA, T., ARAI, F. and NISHIO, F. (1987): Correlation of tephra layers in Antarctic ice by trace element abundances and refractive indices of glass shards. Kazan (Bull. Volcanol. Soc. Jpn., Ser. 2), **32**, 103–118.

GOLDICH, S.S., TREVES, S.B., SUHR, N.H. and STUCKLESS, J.S. (1975): Geochemistry of the Cenozoic volcanic rocks of Ross Island and vicinity, Antarctica. J. Geol., **83**, 415–435.

GONZÁLES-FERRÁN, O. (1982): The Antarctic Cenozoic volcanic provinces and their implications in plate tectonic processes. Antarctic Geoscience, ed. by C. CRADDOCK. Madison, Univ. of Wisconsin Press, 687–694.

GONZÁLES-FERRÁN, O. and VERGARA, M. (1972): Post-miocene volcanic petrographic provinces of West Antarctica and their relation to the Southern Andes of South America. Antarctic Geology and Geophysics, ed. by R.J. ADIE. Oslo, Universitetsforlaget, 187–195.

GOW, A.J. and WILLIAMSON, T. (1971): Volcanic ash in the Antarctic ice sheet and its possible climatic implications. Earth Planet. Sci. Lett., **13**, 210–218.

KATSUSHIMA, T., NISHIO, F., OHMAE, H., ISHIKAWA, M. and TAKAHASHI, S. (1984): Composition of dirt layers in the bare ice areas near the Yamato Mountains in Queen Maud Land and the Allan Hills in Victoria Land, Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **34**, 174–187.

KEYS, J.R., ANDERTON, P.W. and KYLE, P.R. (1977): Tephra and debris layers in the Skelton Névé and Kempe Glacier, South Victoria Land, Antarctica. N.Z. J. Geol. Geophys., **20**, 971–1002.

KING, E.A. and WAGSTAFF, J. (1980): Search for cometary dust in the Antarctic ice. Antarct. J. U.S., **15**(5), 78–79.

KOEBERL, C., KLUGER, F. and KIESL, W. (1987): Rare earth element determinations at ultratrace abundance levels in geologic materials. J. Radioanal. Nucl. Chem., **112**, 481–487.

KOEBERL, C., HAGEN, E. and FAURE, G. (1988): Chemical composition and morphology of meteorite ablation spherules in Neogene till in the Dominion Range, Transantarctic Mountains. Lunar and Planetary Science XIX. Houston, Lunar Planet. Inst., 625–626.

KYLE, P.R. (1982): Volcanic geology of The Pleiades, Northern Victoria Land, Antarctica. Antarctic Geoscience, ed. by CRADDOCK. Madison, Univ. Wisconsin Press, 747–754.

KYLE, P.R. and JEZEK, P.A. (1978): Compositions of three tephra layers from the Byrd Station ice core, Antarctica. J. Volcanol. Geotherm. Res., **4**, 225–232.

KYLE, P.R. and RANKIN, P.C. (1976): Rare earth element geochemistry of Late Cenozoic alkaline lavas of the McMurdo volcanic group, Antarctica. Geochim. Cosmochim. Acta, **40**, 1497–1507.

KYLE, P.R., JEZEK, P.A., MOSLEY-THOMPSON, E. and THOMPSON, L.G. (1981): Tephra layers in the Byrd Station ice core and the Dome C ice core, Antarctica, and their climatic importance. J. Volcanol. Geotherm. Res., **11**, 29–39.

KYLE, P.R., PALAIS, J.M. and DELMAS, R. (1982): The volcanic record of Antarctic ice cores; Preliminary results and potential for future investigations. Ann. Glaciol., **3**, 172–177.

LEMASURIER, W.E. and REX, D.C. (1982): Volcanic record of Cenozoic glacial history in Marie Byrd Land and Western Ellsworth Land; Revised chronology and evaluation of tectonic factors. Antarctic Geoscience, ed. by C. CRADDOCK. Madison, Univ. Wisconsin Press, 725–734.

MARVIN, U.B. (1986): Components of dust bands in ice from Cul de Sac, Allan Hills region, Antarctica. Meteoritics, **21**, 442–443.

NISHIO, F., KATSUSHIMA, T., OHMAE, H., ISHIKAWA, M. and TAKAHASHI, S. (1984): Dirt layers and atmospheric transportation of volcanic glass in the bare ice areas near the Yamato Mountains in

Queen Maud Land and the Allan Hills in Victoria Land, Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **34**, 160–173.

NISHIO, F., KATSUSHIMA, T. and OHMAE, H. (1985): Volcanic ash layers in bare ice areas near the Yamato Mountains, Dronning Maud Land and the Allan Hills, Victoria Land, Antarctica. Ann. Glaciol., **7**, 34–41.

PALAIS, J.M. (1985): Particle morphology, composition and associated ice chemistry of tephra layers in the Byrd ice core; Evidence for hydrovolcanic eruptions. Ann. Glaciol., **7**, 42–48.

PALAIS, J.M. and LEGRAND, M. (1985): Soluble impurities in the Byrd Station ice core, Antarctica; Their origin and sources. J. Geophys. Res., **90**, 1143–1154.

PRESTVIK, T. (1982): Trace element geochemistry of volcanic rocks from Bouvetøya, South Atlantic. Antarctic Geoscience, ed. by C. CRADDOCK. Madison, Univ. Wisconsin Press, 771–774.

TAYLOR, S.R. and MCLENNAN, S.M. (1985): The Continental Crust; Its Composition and Evolution. Oxford, Blackwell Scientific Publ., 312 p.

THIEL, K., PETERS, J., GRAF, W. and REINWARTH, O. (1987): Does there exist an accumulation mechanism for cosmic dust in Antarctic shelf ice? Meteoritics, **22**, 515–516.

THOMPSON, L.G. and MOSLEY-THOMPSON, E. (1981): Temporal variability of microparticle properties in polar ice sheets. J. Volcanol. Geotherm. Res., **11**, 11–27.

WALKER, G.P.L. (1981): Generation and dispersal of fine ash and dust in volcanic eruptions. J. Volcanol. Geotherm. Res., **11**, 81–92.

WHILLANS, I.M. and CASSIDY, W.A. (1983): Catch a falling star; Meteorites and old ice. Science, **222**, 55–57.

YIOU, F. and RAISBECK, G. M. (1987): Cosmic spherules from Antarctic ice core. Meteoritics, **22**, 539–540.

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