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Volcanic ash bands in the Frontier Mountain and Lichen Hills blue-ice fields, northern Victoria Land

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Abstract: Dust bands in the blue-ice of the Frontier Mountain meteorite trap (northern Victoria Land, Antarctica) were previously reported as upthrust basal debris. Four of them have now been sampled at Frontier Mountain and Lichen Hills. The absence of local rocks and sedimentary fragments, the ubiquitous abundant volcanic glass with no evidence for abrasion, the igneous minerals, the chemical compositions of glass and minerals and the bulk chemical compositions indicate that they are volcanic ash bands (tephra) and not glacial debris. Although hardly distinguishable in the field, the different volcanic ash bands are discriminated using mineralogical and chemical data, as well as particle size, abundance and vesicularity of glass. Chronological constraints, particle size and chemical compositions localize the source for the Frontier Mountain and Lichen Hills tephra within the recent activity of the Mount Melbourne Volcanic Province in northern Victoria Land; possible emission centres are the Pleiades (40 ± 50 ka to 3 ± 14 ka) and/or Mount Rittmann (3.97 Ma to present).

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Key words: Antarctica, blue-ice, Frontier Mountain, Lichen Hills, particle size, tephra, volcanic ash bands

Introduction

Frontier Mountain is a productive area for the collection of meteorites that have fallen on the Antarctic ice cap and been concentrated by ice dynamics (e.g. Delisle *et al.* 1986, 1989, 1993, Cassidy *et al.* 1992, Delisle 1993, Folco 1997).

Dust bands on the Frontier Mountain blue-ice field were first observed by the 1984–85 German GANOVEX IV glaciological party, and used to model the local ice flow responsible for the meteorite concentration (Delisle *et al.* 1986, 1989). The bands were assumed to be basal debris, folded and thrust upward by compressional flow against the bedrock. No chemical or mineral data were provided.

During the 1995 PNRA expedition to Frontier Mountain and nearby Lichen Hills, various dust bands, up to several kilometres long, were observed. We decided to determine their chemical and mineral data to verify whether the bands are actually basal debris, or dust deposited by windfall (e.g. aeolian dust or volcanic ash). The two different answers may help to define the mechanism responsible for meteorite concentration; for instance, indicating presence or absence of frictional processes at the ice-bedrock interface, they might support different ice dynamics.

Our approach finds its rationale in previous work that showed the common occurrence of volcanic ash layers in the Antarctic Ice Sheet (e.g. Dunbar *et al.* 1995). For instance, the Byrd ice core hosts more than 2000 volcanic ash bands, erupted between 16 000 and 30 000 yr BP (Gow & Williamson 1971) from the Mount Takahe volcano (Kyle & Jezek 1978, Kyle *et al.* 1981, Palais 1985, Palais *et al.* 1988). Volcanic ash bands were cored at Vostok (Basile *et al.* 1997) and Dome C (Kyle *et al.* 1981, Grousset *et al.* 1992, Basile *et al.* 1997). They have been also observed at the ice surface of other meteorite traps (e.g. Yamato Mountains, Nishio *et al.* 1985; Allan Hills, Marvin 1986; Lewis Cliff, Koeberl 1989).

Geological setting and samples

Frontier Mountain is a nunatak within the Transantarctic Mountains (Fig. 1), in the inland catchment of the upper Rennick Glacier, northern Victoria Land. It is a NW–SE trending, ~9 km long ridge at the edge of the Polar Plateau, projecting above the 2200 m ice level for about 600 m. Frontier Mountain is a barrier to the flow from the Polar Plateau toward Rennick Glacier. The two ice streams that surround the mountain meet at an ablation zone, caused by S–SW katabatic winds, where a blue-ice field of several tens km^2 is exposed; a shallow, E–W trending depression probably marks the boundary between the two ice streams (Folco 1997). Moraines and fist-sized stones scattered throughout are fragments of local rocks, i.e. granitoids, pegmatites and aplites belonging to the Granite Harbour Intrusive Complex (Gunn & Warren 1962), with minor thermometamorphosed schists. No igneous and sedimentary rocks belonging to the Beacon Supergroup and Ferrar Group have been here found, although they are common elsewhere in the Priestley and Rennick glaciers areas (GANOVEX III 1987).

The blue-ice field hosts tens of dark bands, some centimetres thick and metres to tens of metres apart (Fig. 2). The bands, continuous for some kilometres, have horizontal bedding;

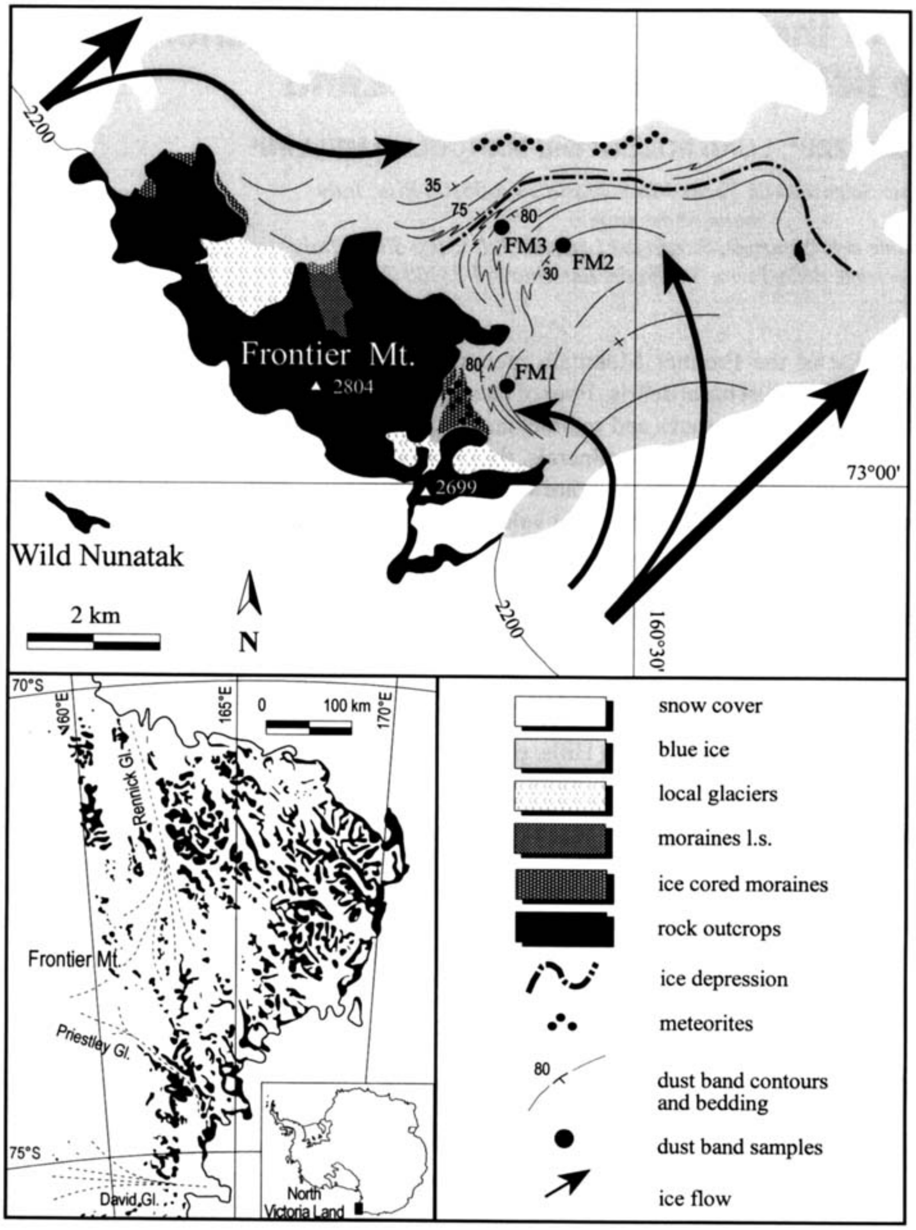

Fig. 1. Map of the Frontier Mountain blue-ice field, with sample location and schematic dust band contours.

following the ice flow, they acquire progressively steeper dips; finally, they become almost vertical, discontinuous and severely folded (namely, sheet folds with serrated hinges) at the foot of the mountain and along the depression, indicating compressive flow against shallow bedrock. In the field, the bands are indistinguishable in terms of colour, average thickness, density, size and nature of the particles.

Table I. Field setting of the Frontier Mountain (FM) and Lichen Hills (LH) volcanic ashes.

label	Latitude S	Longitude E	strike	dip
FM1	72°59'31"	160°25'46"	015°	85°E
FM2	72°58'09"	160°27'17"	020°	30°SE
FM3	72°57'55"	160°26'06"	045°	80°SE
LH1	73°13'43"	161°58'11"	–	–

Geographic co-ordinates by GPS (error ± 100 m).

Three individual bands were sampled on the ice stream entering the ablation zone from the south-west (Table I and Fig. 1). The FM1 sample was taken at the surface of the ice tongue facing Meteorite Valley, and hence from the set of bands interpreted as upthrust basal debris by Delisle *et al.* (1989). Two more samples, FM2 and FM3, come from the ice depression, a few of kilometres away from the mountain. An additional sample (LH1) was collected at Lichen Hills, about 60 km south-east of Frontier Mountain.

Mineral and glass data

Identification and mineralogical characterization of the particles were obtained combining X-ray powder diffraction with optical microscopy, microanalytical scanning electron

Table II. Mineralogical composition and particle size of the FM and LH volcanic ashes.

Sample	Particle size		Mineralogical composition						
	Full range µm	Typical range µm	Glass	Alkali feldspars	Plagioclases	Quartz	Amphiboles	Pyroxenes	Accessories
FM1	5–180	25–75	**	****	***	*	*	**	fe-ox; calcite
FM2	5–100	10–30	****	**	**		*	*	fe-ox; biotite
FM3	2–200	25–150	****	***	***		***	*	fe-ox; calcite
LH1	20–500	100–250	****	**	*		*	*	

**** = very abundant; *** = abundant; ** = common; * = rare

microscopy (SEM/EDS), and electron microprobe analyses (EMPA) of epoxy embedded and polished fragments. Selected data are reported in Tables II–V.

Particle size and morphology

Particle size ranges from 2 to 500 µm, with typical values between 10 and 250 µm (Table II). Size-sorting is moderate within individual samples, but size contrast is evident from sample to sample: particle size increases from FM2 to FM1 and FM3; distinctly larger sizes are observed in LH1. All the specimens consist exclusively of fragments of volcanic glass and minerals. The glass shards have delicate cuspate forms, well-defined vesicularity, with no evidence for abrasion due to mechanical reworking (Fig. 3); mineral fragments have fresh angular shapes.

Glass

Glass is a major component of all the samples. It is unweathered, and no smectite or evidence for palagonization was observed. FM samples show both elongated and equant glass shards. Colour is variable; FM1 mostly shows transparent brown fragments with minor dark opaque shards; their amount increases in FM3 and becomes dominant in FM2. The LH1 glass is definitely different, always colourless and markedly pumiceous. Several shards from each sample were studied by EMPA. Shards from individual samples are chemically homogeneous, as indicated by the low deviations from the average (Table III); the largest internal variation regards the Al versus Fe contents of FM1. The low total of the FM3 glass and the lack of petrographic evidence for weathering point to a moderately high volatile content, as water in unaltered glass can be as high as 2 wt% (Carmichael 1979, Hunt & Hill 1993). Based on the IUGS total alkali-silica classification scheme (Le Bas *et al.* 1986), and the alkaline/subalkaline field boundaries of Irvine & Baragar (1971) and Macdonald & Katsura (1964), shards from all the samples show alkaline character, with distinct chemical compositions in the trachytic (FM specimens) to rhyolitic (LH1 specimen) range.

Fig. 2. The Frontier Mountain dust bands, as seen on the ice field.

Minerals

Common minerals are ubiquitous feldpars, together with variable clinopyroxenes and amphiboles; from specimen to specimen, minor amounts of olivine, biotite, quartz and iron oxides may occur (Table II), along with secondary calcite.

Feldspars commonly occur as tabular anhedral individuals, always unweathered; plagioclases, commonly showing albite twinning and direct zoning, range from andesine to albite. Among the alkali feldspars, anorthoclase is the most abundant, with subordinate amounts of albite and rare sanidine (Table IV and Fig. 4). Whereas LH1 ash bears alkali feldspars (close to Ab_{67}) only, both Na-dominant alkali feldspars and plagioclases are present in the FM specimens. Feldspar compositions

Table III. WDS chemical composition of glass shards.

Sample Oxides wt% & 1σ	FM1 (n = 5)	FM2 (n = 5)	FM3 (n = 9)	LH1 (n = 4)
SiO_2	63.67 (86)	59.08 (41)	61.39 (85)	69.60 (21)
TiO_2	0.22 (3)	0.94 (9)	0.34 (7)	0.13 (2)
Al_2O_3	15.53(116)	17.45 (26)	17.27 (35)	13.85 (6)
Cr_2O_3	bdl	bdl	bdl	bdl
FeO	6.33(132)	6.92 (42)	3.50 (34)	3.22 (17)
MnO	0.33 (9)	0.24 (4)	0.14 (5)	0.06 (5)
MgO	bdl	0.99 (13)	0.31 (11)	bdl
CaO	1.03 (28)	2.82 (19)	1.44 (17)	0.42 (7)
Na_2O	6.44 (19)	5.92 (16)	6.31 (24)	5.52 (13)
K_2O	4.72 (11)	4.99 (26)	5.22 (16)	4.65 (6)
F	0.59 (22)	0.16 (10)	bdl	0.48 (33)
Cl	0.80 (3)	0.16 (1)	0.17 (4)	0.50 (2)
sum	97.66	99.69	96.09	98.42

n = number of analysed shards; bdl = below detection limit.

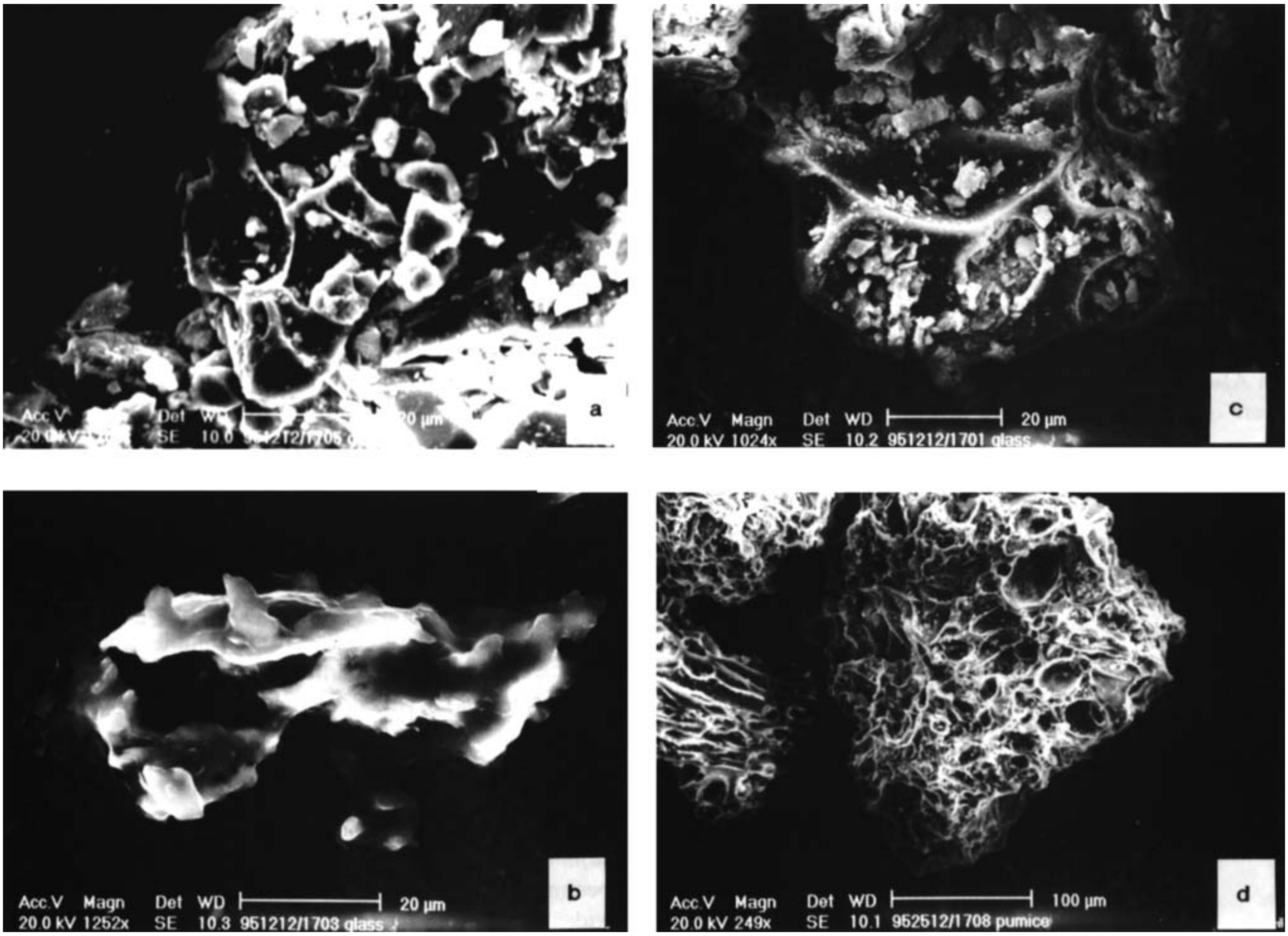

Fig. 3. Scanning electron micrographs of volcanic glass shards from Frontier Mountain and Lichen Hills tephra. **a.** FM1, **b.** FM2, **c.** FM3 and **d.** LH1.

provide an additional discriminating feature; in fact, variable ternary compositions corresponding to the anorthoclase field occur in FM2. Rare oligoclase to andesite plagioclases (analyses 5, 6 and 7 in Table IV) occur together with dominant alkali feldspars in FM1; pure albite, ternary feldspars and plagioclases are present in FM3.

Mafic minerals, normally present as euhedral [001] elongated crystals, are relatively abundant at Frontier Mountain, and rare at Lichen Hills (Tables II & V). Hedenbergitic clinopyroxenes occur in FM1, sodic amphiboles and intermediate olivine in FM2, sodic amphiboles and diopsidic clinopyroxene in FM3. The FM2 and FM3 amphiboles mostly differentiate as regards the tetrahedral Al and octahedral Ti contents, both higher in the FM3 amphibole. FM1 contains also an important amount of lithic fragments (more abundant than glass shards), with vitrophyric textures.

In conclusion, mineral and glass data indicate unambiguously that the specimens are volcanic ashes (tephra). Particle size matches that of other Antarctic ashes (e.g. Nishio *et al.* 1985, Dunbar *et al.* 1995), evidence for mechanical abrasion is absent, and mineral and lithic fragments possibly related to local rocks are absent.

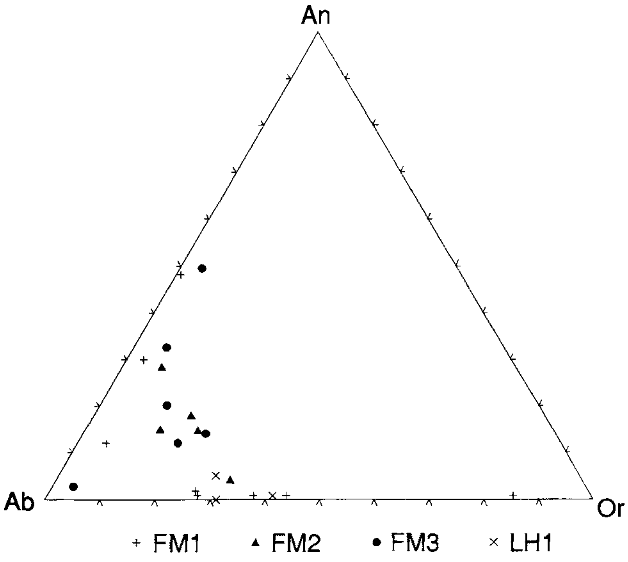

Fig. 4. Chemical compositions of feldspars from the Frontier Mountain and Lichen Hills ash bands.

Table IV. Chemical compositions of feldspars, obtained by SEM/EDS.

LH1 feldspar				FM1 feldspar							
	1	2	3 ($n = 2$)	1 ($n = 11$)	2 ($n = 2$)	3 ($n = 3$)	4 rim	4 core	5 ($n = 3$)	6	7 ($n = 2$)
Na$_2$O	8.0	7.3	6.6	8.3 (3)	6.4	1.6 (3)	8.3	7.1	9.5 (3)	7.8	5.9
K$_2$O	5.4	4.7	7.0	4.6 (5)	7.6	14.4 (8)	4.7	6.4	0.9 (3)	0.5	0.3
CaO	0.1	1.2	0.2	0.5 (2)	0.2	0.2 (1)	0.4	0.3	2.5 (2)	6.3	10.1
Si$_2$O	67.0	68.4	66.9	65.3 (6)	66.1	65.2 (3)	66.6	67.0	64.4 (6)	59.3	54.3
Al$_2$O$_3$	19.5	18.4	18.5	19.7 (3)	19.5	18.6 (1)	19.5	19.2	22.5 (8)	25.8	28.9
Fe$_2$O$_3$	0.0	0.0	0.9	0.6 (1)	0.2	0.0	0.5	0.0	0.0	0.3	0.5
Na	0.69	0.63	0.58	0.73	0.55	0.14	0.71	0.61	0.82	0.67	0.52
K	0.31	0.27	0.41	0.27	0.43	0.84	0.27	0.37	0.05	0.03	0.01
Ca	0.00	0.05	0.01	0.02	0.01	0.01	0.01	0.01	0.12	0.30	0.49
Si	2.98	3.03	2.99	2.94	2.97	2.99	2.96	2.99	2.85	2.65	2.45
Al	1.02	0.96	0.98	1.05	1.03	1.01	1.02	1.01	1.17	1.36	1.54
Fe	0.00	0.00	0.03	0.02	0.00	0.00	0.02	0.00	0.00	0.01	0.01
FM2 feldspar						FM3 feldspar					
	1 ($n = 2$)	2 ($n = 2$)	3 ($n = 2$)	4	5 ($n = 8$)	1	2 ($n = 2$)	3 ($n = 3$)	4 rim	4 core	5 ($n = 7$)
Na$_2$O	8.5	7.4	7.5	7.4	7.2 (4)	11.3	8.0	7.8 (4)	7.3	5.3	7.1 (4)
K$_2$O	2.4	5.7	3.2	3.6	1.3 (3)	0.7	3.2	2.0 (1)	4.0	0.7	1.2 (1)
CaO	3.2	0.9	3.8	2.9	5.7 (7)	0.7	2.6	4.3 (5)	2.9	10.2	6.9 (5)
Si$_2$O	62.7	65.0	62.4	66.2	61.0 (16)	65.1	63.7	62.2 (3)	65.0	55.0	58.8 (9)
Al$_2$O$_3$	23.0	20.4	22.3	19.9	24.5 (8)	21.1	22.1	23.2 (1)	20.8	28.3	25.2 (3)
Fe$_2$O$_3$	0.2	0.6	0.8	0.0	0.3 (3)	1.1	0.4	0.5 (2)	0.0	0.5	0.8 (4)
Na	0.73	0.65	0.65	0.63	0.62	0.97	0.69	0.67	0.63	0.46	0.62
K	0.14	0.32	0.18	0.20	0.07	0.04	0.18	0.12	0.22	0.04	0.06
Ca	0.15	0.04	0.18	0.14	0.27	0.03	0.12	0.20	0.14	0.49	0.33
Si	2.79	2.91	2.8	2.94	2.72	2.88	2.84	2.77	2.89	2.49	2.64
Al	1.21	1.08	1.17	1.04	1.29	1.10	1.16	1.22	1.09	1.50	1.33
Fe	0.00	0.02	0.02	0.00	0.01	0.03	0.01	0.02	0.00	0.02	0.02

n = number of analyses; standard deviation in parentheses; crystalchemical formulae recalculated to eight oxygen atoms.

Table V. Chemical compositions of mafic minerals, obtained by SEM/EDS.

FM1 augite ($n = 4$)		FM2 olivine ($n = 3$)		FM2 amphiboles			FM3 augite		FM3 amphiboles			
					ferro-hornblende	ferro-edenite				kaersutite ($n = 2$)	tschermakite	ferro-tschermakite
SiO$_2$	49.9 (6)	SiO$_2$	35.3 (5)	SiO$_2$	43.9	47.0	SiO$_2$	54.2	SiO$_2$	41.3	43.3	42.0
Al$_2$O$_3$	1.0 (3)	Al$_2$O$_3$	1.1 (1)	Al$_2$O$_3$	10.1	7.1	Al$_2$O$_3$	0.8	Al$_2$O$_3$	13.1	10.8	11.1
TiO$_2$	0.5 (3)	FeO	41.3 (8)	TiO$_2$	2.1	1.1	TiO$_2$	0.0	TiO$_2$	6.2	4.6	4.2
FeO	27.8 (8)	MgO	20.0 (4)	FeO	21.3	18.5	FeO	0.9	FeO	13.0	6.2	20.1
MnO	1.5 (9)	MnO	1.7 (1)	MnO	0.6	0.7	MgO	17.7	MgO	12.0	11.8	8.3
CaO	16.9 (8)	CaO	0.6 (1)	MgO	7.7	9.9	CaO	25.5	CaO	11.3	22.1	10.2
Na$_2$O	2.5 (5)			CaO	11.2	10.8	Na$_2$O	0.9	Na$_2$O	2.6	1.0	2.7
				Na$_2$O	1.7	3.2			K$_2$O	0.5	0.2	1.4
				K$_2$O	1.4	1.7						
Si	2.01	Si	1.02	Si	6.65	7.01	Si	1.97	Si	6.00	6.24	6.28
Al^{VI}	0.05	Al	0.03	Al^{IV}	1.35	0.99	Al^{IV}	0.03	Al^{IV}	2.00	1.76	1.72
Ti	0.01	Fe^{2+}	1.00	Al^{VI}	0.43	0.27	Ti	0.00	Al^{VI}	0.23	0.06	0.24
Fe^{2+}	0.93	Mg	0.86	Ti	0.23	0.09	Fe^{2+}	0.03	Ti	0.66	0.50	0.45
Mn	0.05	Mn	0.03	Fe^{2+}	2.64	2.33	Mg	0.96	Fe^{2+}	1.58	0.74	2.55
Ca	0.72	Ca	0.01	Mn	0.06	0.09	Ca	0.98	Mg	2.58	2.51	1.86
Na	0.19			Mg	1.73	2.16	Na	0.06	Ca	1.70	2.00	1.64
				Ca	1.73	1.71			Na	0.73	0.26	0.57
				Na	0.49	0.90			K	0.09	0.02	0.18
				K	0.25	0.36						

n = number of grains; standard deviation in parentheses; crystalchemical formulae recalculated based on six, twenty three and four oxygens for pyroxenes, amphiboles and olivine, respectively.

Furthermore, the different glass and mineral abundancies, the different particle sizes, the chemical data from glasses and minerals all sharply differentiate the four volcanic ash bands.

Bulk compositions

Chemical data for major and trace elements for the bulk FM1, FM3 and LH1 samples (Table VI) were gathered by X-ray fluorescence (XRF). As the limited amount of material prevented XRF for FM2, major elements (Table VI) were obtained by performing wide (5 mm^2) window analyses of epoxy-embedded and polished ashes in the SEM/EDS; this procedure was verified to produce reliable data, by comparison of XRF and simulated XRF data from the FM1 and FM3 specimens.

Major elements

The FM3, FM2, FM1 and LH1 ashes show intermediate to acid compositions with alkaline character, corresponding to trachyandesitic, trachytic and rhyolitic compositions, respectively. The Na_2O/K_2O ratios for the FM and LH samples range from 1.2 to 1.4, indicating a weak sodic character that relates to the presence of Na-rich plagioclases and anorthoclase in all samples, kaersutite in FM3, and of augite with Na_2O = 2.5 wt% in FM1 (Tables IV & V). Since the glass shards provide an analogous compositional pattern (Table III), we conclude that this chemical signature reflects the parent magma compositions, in spite of the mechanical sorting occurred during atmospheric transport.

Table VI. Bulk chemical compositions of the volcanic ashes (FM1, FM3 and LH1 by XRF; FM2 by SEM-EDS).

	FM1	FM2	FM3	LH1
SiO_2	63.96	58.4	54.27	69.18
TiO_2	0.48	1.1	1.55	0.19
Al_2O_3	15.45	18.2	15.48	12.88
Fe_2O_3	5.33	7.8	8.32	4.10
MnO	0.15	0.0	0.17	0.10
MgO	1.32	0.6	2.96	0.09
CaO	1.72	3.6	5.00	0.50
Na_2O	6.24	5.9	4.04	6.15
K_2O	4.15	4.1	3.26	4.32
P2O5	0.11	0.0	0.38	0.01
LOI	1.09	–	4.57	2.48
S	105	–	529	52
Cl	1309	–	622	3794
V	32	–	100	0
Cr	27	–	66	5
Co	10	–	21	6
Ni	20	–	39	9
Cu	17	–	40	56
Zn	170	–	120	269
Rb	299	–	127	315
Sr	96	–	581	5
Y	64	–	33	151
Zr	955	–	468	1316
Nb	322	–	132	442
Ba	157	–	779	–
La	203	–	99	169
Ce	295	–	154	293

The differences between the bulk and glass compositions in FM3 reflect the high amount of amphibole in the bulk specimens (Table II). The exceptionally high LOI value of 4.57 (Table VI) in FM3 is consistent with this major amphibole occurrence; in particular, this LOI value indicates important fluid pressure in the parent magma; in part, water is now contained within amphibole, in part likely dissolved within the glass.

Trace elements

The three analysed samples show distinct trace element contents (Table VI). For instance, Sr and Ba increase by approximately one order of magnitude from LH1 to FM1 and from FM1 to FM3; their values are negatively related with Rb, Y, Nb and Zr. Taking Zr as differentiation index, a fairly good positive correlation (Fig. 5) exists between this element and Rb, Y and Nb. The elements possibly connected with the gas content in the magma further discriminate the different ash bands; the S/Cl ratio changes by almost two orders of magnitude from LH1 to FM1 and FM3 (0.014, 0.08 and 0.85, respectively).

Source of the Frontier Mountain and Lichen Hills tephra

Particle size, chemical compositions and geochronological estimates constrain the source of the Frontier Mountain and Lichen Hills volcanic ashes.

Because volcanic ashes undergo either stratospheric or tropospheric transport, their source may be either remote or proximal, respectively. However, analysis of particle size distributions allows the distinction between the two transport mechanisms (Lisitzin 1996) and limits the distance from the source. Stratospheric ash fallout consists of mechanically sorted fine dust, with a median diameter below 1 μm and rare particles larger than 3–5 μm; in turn, sizes ranging from 10–50 μm are dominant in tropospheric ash fallout. As the particles size of the FM and LH ashes typically is some to

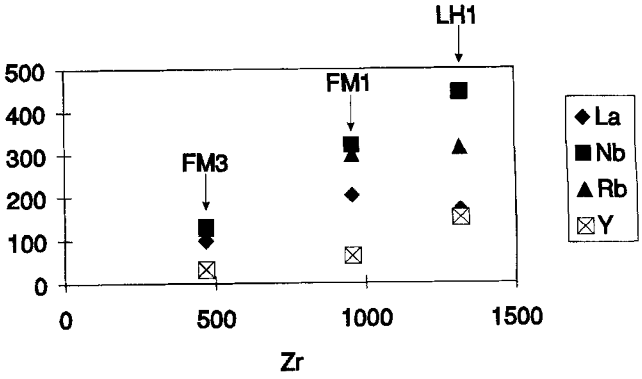

Fig. 5. Variation diagram of minor elements vs Zr content, assumed as index of fractionation.

several tens μm (Table II), deposition occurred after tropospheric transport.

In the case of tropospheric transport, particle size also provides information on the distance from the eruptive centre, with size decreasing with distance (Lisitzin 1996). The relation size versus distance has been obtained based on tephra from various volcanoes including the South Sandwich Islands (Antarctica). In spite of some dispersion accounting for variable wind regimes and strength of the outburst, this relation indicates an upper limit of 1000 km for all our FM and LH samples. A proximal source is also supported by the moderate size-sorting and the presence of individual fragments of dense, mafic minerals in the FM and LH samples (Table II), indicative of short-range transport (Juvigne & Porter 1985, Lisitzin 1996).

Therefore, the source for the FM and LH ash bands should be sought within the Antarctic volcanic region, more specifically within a circle containing the volcanic areas of the McMurdo Volcanic Group (Western Ross embayment) or the Scott and Balleny islands. All these sites (Late Cenozoic–Holocene) were active during the building of the ice sheet that today covers the Antarctic continent (LeMasurier & Thomson 1990).

Consistent with the above argument, the alkaline character of our ashes matches the great majority of Antarctic and subantarctic volcanoes, including those of the McMurdo Volcanic Group, and the Scott and Balleny islands (LeMasurier & Thomson 1990). However, the overall composition of the FM and LH ash bands further limits their source within the McMurdo Volcanic Group volcanic area (Fig. 6) and excludes provenance from the Scott and Balleny Islands, the former with products ranging from phonolites to nepheline-mugearites, the latter from basanites to nepheline-hawaiites (LeMasurier & Thomson 1990).

A further attempt to constrain the source within the McMurdo Volcanic Group can be made by combining chronological and geochemical criteria. The first requires attention to volcanic centres active during the formation of the ice now "crops out" at FM and LH. The second is based on the comparison between glass compositions from the ash bands with the geochemical trends of others from volcanic suites described in the literature.

Contrary to the large chronological data set existing for Antarctic volcanoes (e.g. LeMasurier & Thomson 1990), the precise age of the ice at the surface FM and LH is not known. Nevertheless, the age of the ice in the blue-ice surfaces of the Antarctic plateau should be close to the terrestrial ages of the meteorites they expose. This is suggested by the meteorite concentration mechanism (e.g. Cassidy *et al.* 1992) involving

i) fall of the meteorite,

ii) burying and embodying in the ice by successive snow falls,

iii) transport within the ice, and

iv) release onto the surface of the blue ice fields by ablation.

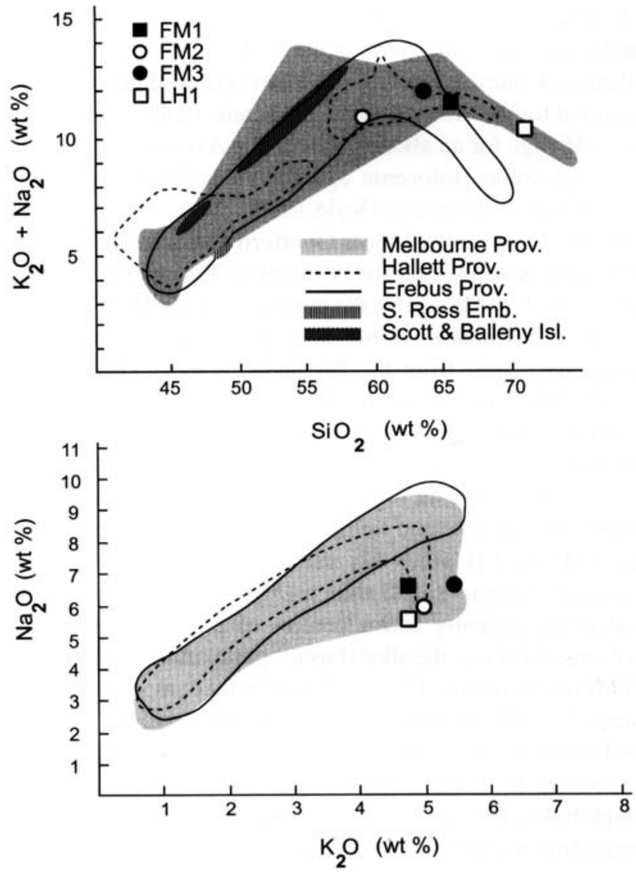

Fig. 6. Total alkali vs silica, and K_2O vs Na_2O diagrams for the Frontier Mountain and Lichen Hills ash bands. Compositional fields for Mount Melbourne (from LeMasurier & Thomson 1990 and Armienti & Tripodo 1991), Hallet, Erebus, southernmost Ross Embayment, Scott Island and Balleny Island volcanic provinces (from LeMasurier & Thomson 1990).

In general, the terrestrial ages for Antarctic meteorites, obtained by means of cosmogenic nuclides systematics, are younger than 500 ka (e.g. Nishiizumi *et al.* 1989, Welten *et al.* 1997) and, in particular, those of the Frontier Mountain meteorites are younger than 300 ka (Wieler *et al.* 1998). Likewise, ice as old as 300 ka has been identified in another meteorite concentration site of Victoria Land, the Allan Hills blue ice field (Fireman 1987). Therefore, only volcanic centres active within the last hundreds of thousands years are the possible candidates.

Amongst the volcanic provinces of the McMurdo Volcanic Group (i.e. the Hallet, Mount Melbourne, Mount Erebus and southernmost Ross Embayment provinces; LeMasurier & Thomson 1990), glass composition is consistent with a source within the Mount Melbourne Volcanic Province (Fig. 6).

According to Kyle (1990), the Mount Melbourne Volcanic Province can be divided into the volcanic fields of Malta Plateau, The Pleiades, Mount Overlord and Mount Melbourne. Chronological data are 18 to 6 Ma for Malta Plateau (Schmidt-Thomé *et al.* 1990), 40 ± 50 ka to 3 ± 14 ka for The Pleiades

(Armstrong 1978), and Pliocene to present for Mount Melbourne volcanic field (Kyle 1990). Ages of 14.5 Ma (Parasite Cone), 8.3 to 7 Ma (Mount Overlord products) are reported for the Mount Overlord volcanic field, together with a 7.5 Ma age for an alkali basalt of the Aviator Glacier area, and a possible Holocenic age for an isolated vent in the Cosmonaut Glacier area (Kyle 1990). More recently a new volcanic centre in the Mount Overlord volcanic field, Mount Rittmann, was described by Armienti & Tripodo (1991), who reported a 3.97 Ma age for the products lying at the base of the volcano. Evidence for recent volcanic activity of Mount Rittmann comes from the fumarolic activity (Bonaccorso *et al.* 1991) and from the K–Ar ages on phonolitic and trachytic lavas yielding 240 ± 200, 170 ± 20 and 70 ± 20 ka, respectively (G. Vita, personal communication 1998).

Chronological data therefore rule out a provenance from Malta Plateau volcanic field, whereas glass composition of the FM and LH ashes fits the geochemical trends of the basanite–trachyte–peralkaline trachyte suite of The Pleiades and of the recently active centres of the Mount Overlord volcanic field, e.g. the alkali basalt–peralkaline trachyte suite of Mount Rittmann (Fig. 7). The mineral composition of the ashes (Table II) is consistent with this interpretation. Volcanic rocks from The Pleiades (Kyle 1986) and from Mount Rittmann (Armienti & Tripodo 1991) typically bear Na- and Ca-amphiboles, clinopyroxenes of the diopside–hedenbergite series (often sodic), anorthoclase and oligoclase–labradorite plagioclase.

Finally, we are aware that the attribution of the FM and LH ashes to a well-defined volcanic centre within a volcanic province is tentative, considering that knowledge of Antarctic volcanoes may be still incomplete, because many may be buried beneath the present ice level. Nevertheless, on the basis of the existing evidence, we conclude that the FM and LH ash layers were likely erupted within the Mount Melbourne Volcanic Province, possibly from the recently active volcanoes of the Mount Overlord volcanic field, such as Mount Rittmann and/or The Pleiades.

Conclusions

a) Mineral and chemical data indicate the volcanic origin of the four dust bands sampled at Frontier Mountain and Lichen Hills. The previous interpretation (i.e. they represent basal debris; Delisle *et al.* 1989) was biased by the absence of quantitative mineral and chemical data, and should be abandoned. In terms of glaciodynamical conditions, our finding demonstrates that the dark bands at the Frontier Mountain ice field do not correspond to any important frictional event at the ice–bedrock interface. Any future modelling of the meteorite trap should take this aspect into account.

b) Although practically indistinguishable in the field, the ash bands are readily discriminated in the laboratory by their particle size and vesicularity, by the bulk composition and the relative abundance and composition of glass and minerals. It is hoped that these features will serve to track individual volcanic ash pulses at the regional scale, especially when supported by geochronological data.

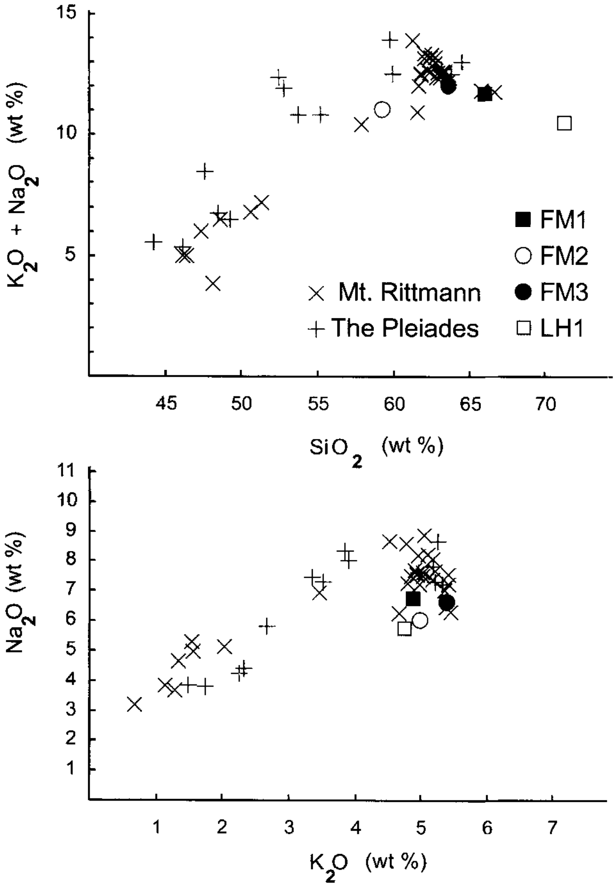

Fig. 7. Total alkali vs silica, and K_2O vs Na_2O diagrams for the Frontier Mountain and Lichen Hills ash bands, compared with data from Mount Rittmann (from Armienti & Tripodo 1991) and The Pleiades (from LeMasurier & Thomson 1990).

c) Calculated crater distance, inferred age, mineralogical and geochemical data relate the Frontier Mountain and Lichen Hills tephra to source volcanoes within the Mount Melbourne Volcanic Province, possibly to the recently active centres of The Pleiades (40 ± 50 ka to 3 ± 14 ka; Armstrong 1978) and/or of the Mount Overlord volcanic field, such as Mount Rittmann (3.97 Ma to present; Armienti & Tripodo 1991, Bonaccorso *et al.* 1991, G. Vita personal communication 1998).

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References

ARMIENTI, P. & TRIPODO, A. 1991. Petrography and chemistry of lavas and comagmatic xenoliths of Mt. Rittmann, a volcano discovered during the IV Italian Expedition in northern Victoria Land (Antarctica). *Memorie della Società Geologica Italiana*, **46**, 427–451.

ARMSTRONG, R.L. 1978. K–Ar dating: late Cenozoic McMurdo volcanic group and Dry Valley glacial history, Victoria Land, Antarctica. *New Zealand Journal of Geology and Geophysics*, **21**, 685–698.

BASILE, I., GROUSSET, F.E., REVEL, M., PETIT, J.R., BISCAYE, P.E. & BARKOV, N.I. 1997. Patagonian origin of glacial dust deposited in East Antarctica (Vostok and Dome C) during glacial stages 2, 4 and 6. *Earth Planetary Science Letters*, **146**, 573–589.

BONACCORSO, A., MIONE, M., PERTUSATI, P.C., PRIVITERA, E. & RICCI, C.A. 1991. Fumarolic activity at Mt. Rittmann volcano (Northern Victoria Land, Antarctica). *Memorie della Società Geologica Italiana*, **46**, 453–456.

CARMICHAEL, I.S.E. 1979. Glass and glassy rocks. *In* YODER JR, H.S., *ed. The evolution of the igneous rocks. Fiftieth anniversary perspective*. Princeton, NJ: Princeton University Press, 233–244.

CASSIDY, W., HARVEY, R., SHUTT, J., DELISLE, G. & YANAI, K. 1992. The meteorite collection sites of Antarctica. *Meteoritics*, **27**, 490–525.

DELISLE, G. 1993. Global change. Antarctic meteorite traps and the East Antarctic Ice Sheet. *Journal of Glaciology*, **39**, 397–408.

DELISLE, G., FRANCHI, I., ROSSI, A. & WIELER, R. 1993. Meteorite finds by EUROMET near Frontier Mountain, northern Victoria Land, Antarctica. *Meteoritics*, **28**, 126–129.

DELISLE, G., HÖFLE, H. & THIERBACHER, R. 1986. Discovery of meteorites on a blue-ice field near Frontier Mountain, North Victoria Land, Antarctica. *In* ANNEXSTAD, J., SCHULTZ, L. & WANKE, H., *eds. Workshop on Antarctic meteorites, Lunar and Planetary Institute, Houston*, **LPI-TR 86-01**, 30–33.

DELISLE, G., SHULTZ, L., SPETTEL, B., WEBER, H.W., WLOTZKA, F., HÖFLE, H., THIERBACHER, R., VOGT, S., HERPERS, U., BONANI, G., SUTER, M. & WOLFI, W. 1989. Meteorite finds near the Frontier Mountain Range in North Victoria Land. *Geologisches Jahrbuch*, **E38**, 483–513.

DUNBAR, N.W., KYLE, P.R., MCINTOSH, W.C. & ESSER, R.P. 1995. Geochemical composition and stratigraphy of tephra layers in Antarctic blue ice: insights into glacial tephrochronology. *In Abstract volume VII International Symposium on Earth Sciences, September 1995. Siena: Dipartmento di Scienze della Terra*, 115.

FIREMAN, E.L. 1987. Uranium-series date ice, 100,000 to 350,000 years old, arranged sequentially at Allan Hills. *Antarctic Journal of United States*, **22**(5), 74–77.

FOLCO, L. 1997. *Pyroxene thermometry in chondritic meteorites*. Ph.D. thesis, Open University, 188 pp. [Unpublished]

GANOVEX III. 1987. Geological map of North Victoria Land, Antarctica, 1:500 000 – explanatory notes – German Antarctic north Victoria Land expedition 1982/83. *Geologisches Jahrbuch*, **2**, 7–79.

GOW, A.J. & WILLIAMSON, T. 1971. Volcanic ash in the Antarctic ice sheet and its possible climatic implications. *Earth and Planetary Science Letters*, **13**, 210–213.

GROUSSET, F.E., BISCAYE, P.E., REVEL, M., PETIT, J.R., PYE, K., JOUSSAME, S. & JOUZEL, J. 1992. Antarctic (Dome C) ice-core dust at 18 k.y. B.P.: isotopic constraints on origins. *Earth and Planetary Science Letters*, **111**, 1750–1782.

GUNN, B.M. & WARREN, G. 1962. Geology of Victoria Land between Mawson and Mulock glaciers, Antarctica. *Bulletin of the New Zealand Geological Survey*, **71**, 1–157.

HUNT, J.B. & HILL, P.G. 1993. Tephra geochemistry: a discussion of some persistent analytical problems. *The Holocene*, **3**, 271–278.

IRVINE, T.N. & BARAGAR, W.R.A. 1971. A guide to the chemical classification of the common volcanic rocks. *Canadian Journal of Earth Sciences*, **8**, 523–548

JUVIGNE, E. & PORTER, S.C. 1985. Mineralogical variations within two widespread Holocene tephra layers from Cascade Range Volcanoes, USA. *Geographie Physique et Quatérnaire*, **39**, 7–12

KOEBERL, C. 1989. Iridium enrichment in volcanic dust from blue-ice fields, Antarctica, and possible relevance to the K/T boundary event. *Earth and Planetary Science Letters*, **92**, 317–322.

KYLE, P.R. 1986. Mineral chemistry of Late Cenozoic McMurdo Volcanic Group rocks from The Pleiades, northern Victoria Land. *Antarctic Research Series*, **46**, 305–337.

KYLE, P.R. 1990. McMurdo Volcanic Group–Western Ross Embayment. *Antarctic Research Series*, **48**, 19–145.

KYLE, P.R. & JEZEK, P.A. 1978. Composition of three tephra layers from the Byrd station ice core, Antarctica. *Journal of Volcanology and Geothermal Research*, **4**, 225–232.

KYLE, P.R., JEZEK, P.A., MOSLEY-THOMPSON, E. & THOMPSON, L.G. 1981. Tephra layers in the Byrd station ice core and the Dome C ice core, Antarctica, and their climatic importance. *Journal of Volcanology and Geothermal Research*, **11**, 29–39.

LE BAS, M.J., LE MAITRE, R.W., STRECKEISEN, A. & ZANETTIN, B. 1986. A chemical classification of volcanic rocks based on the total alkali-silica diagram. *Journal of Petrology*, **27**, 745–750.

LEMASURIER, W.E. & THOMSON, J.W. 1990. Volcanoes of the Antarctic Plate and Southern Oceans. *Antarctic Research Series*, **48**, 1–487.

LISITZIN, A. 1996. Volcanogenic sedimentation. *In* KENNET, J.P., *ed. Oceanic sedimentation: lithology and geochemistry*. Washington, DC: American Geophysical Union, 322–335.

MACDONALD, G.A. & KATSURA, T. 1964. Chemical composition of Hawaiian lavas. *Journal of Petrology*, **5**, 82–133

MARVIN, U. 1986. Components of dust bands in ice from cul de sac, Allan Hills region, Antarctica. *Meteoritics*, **21**, 442–443.

NISHIIZUMI, K., ELMORE, D. & KUBIK, P.W. 1989. Update on terrestrial ages of Antarctic meteorites. *Earth and Planetary Science Letters*, **93**, 299–313.

NISHIO, F., KATSUSHIMA, T. & OHMAE, H. 1985. Volcanic ash layers in bare ice areas near the Yamato Mountains, Dronning Maud Land and the Allan Hills, Victoria Land, Antarctica. *Annals of Glaciology*, **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. *Annals of Glaciology*, **7**, 42–48.

PALAIS, J.M., KYLE, P.R., MCINTOSH, W.C. & SEWARD, D. 1988. Magmatic and phreatomagmatic volcanic activity at Mt. Takahe, West Antarctica, based on tephra layers in the Byrd ice core and field observations at Mt. Takahe. *Journal of Volcanology and Geothermal Research*, **35**, 295–317.

SCHMIDT-THOMÉ, M., MÜLLER, P. & TESSENSOHN, F. 1990. McMurdo Volcanic Group – Western Ross embayment: Malta Plateau. *Antarctic Research Series*, **48**, 53–59.

WELTEN, K.C., ALDERLIESTEN, C., VAN DER BORG, K., LINDNER, L., LOEKEN, T. & SCHULTZ, L. 1997. Lewis Cliff 86360: An Antarctic L-chondrites with a terrestrial age of 2.35 million years. *Meteoritics and Planetary Science*, **32**, 775–780.

WIELER, R., WELTEN, K.C., NISHIIZUMI, K. & CAFFEE, M.W. 1998. Exposure ages and terrestrial ages of H chondrites from Frontier Mountain, north Victoria Land. *Antarctic Meteorites*, **23**, 170–172.