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Sand Grain Detrital Modes in CRP-1: Provenance Variations and Influence of Miocene Eruptions on the Marine Record in the McMurdo Sound Region

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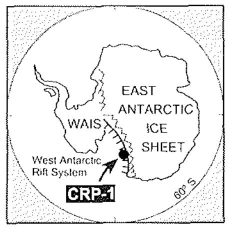

Abstract - Detrital modes for the sand-size fraction in 24 samples from the CRP-1 drillcore are described. Most samples are largely composed of quartzo-feldspathic detritus sourced dominantly from Palaeozoic granitoids and quartzose sedimentary sequences. Minor contributions from basic lamprophyre dykes, felsic dykes and possibly Kirkpatrick basalts are also identified as detrital components for the first time. The provenance also included a minor outcrop area of high-grade metamorphic rocks. Detritus derived from a Ferrar dolerite source is common throughout. It was possibly derived mainly from thick sills of the lower coastal ranges (intruding Palaeozoic and older "basement") rather than those sills intruding the stratigraphically higher Beacon sedimentary sequence, although this suggestion is not strongly constrained. Tephra particles from both magmatic and hydrovolcanic eruptions are well represented and persistent at all levels in the core, although no primary tephra layers are present. The volcanic influence is minor in most of the Quaternary samples analysed (although these are few) and most Miocene samples. Conversely, the topmost part of the Miocene sequence (above 62 metres below sea floor (mbsf)) is strongly affected by volcanism, with two major basic–intermediate eruptions represented in the detrital record (at *c.* 61 and 45 mbsf) and provisionally correlated with a volcano formerly situated near Mount Morning. A third eruption of evolved pumice is also recorded in the Miocene sequence at *c.* 116 mbsf.

INTRODUCTION

Drilling off Cape Roberts during October-November 1997 recovered about 100 m of a 148 m-thick Quaternary and Miocene sedimentary sequence. The background and objectives of the investigation, and the location, stratigraphy, lithology, and sedimentological, dating and palaeoenvironmental aspects of the recovered sequence are described elsewhere (Cape Roberts Science Team, 1998, and this volume). This paper describes:

1 - the modal petrology of the sand-grade sedimentary fraction present,
2 - variations in provenance and
3 - initial interpretation of these features, which has significance for the geological evolution of the region, particularly erosion of the Transantarctic Mountains in southern Victoria Land and the volcanic history of the region.

METHODS AND LIMITATIONS

SAMPLE SELECTION AND TREATMENT

Quantitative sand-grain counts (detrital modes) were obtained on thin sections of samples selected from the CRP-1 core. Initially, thirty nine samples were selected, with the intention of obtaining at least one modal analysis for every lithostratigraphic unit defined in the stratigraphical summary. Most samples were obtained from sand or sandstone beds, but a small proportion (7 samples) represent sand-grade or sand-rich lenses within diamicts or diamictites. Laboratory examination showed that 15 samples were too fine grained for the meaningful determination of detrital modes and they were rejected. Of the remaining 24 samples, the mean grain size varied from very fine–fine to medium–coarse sand, and 6 samples contained a significant proportion of fine-grained (<30 mm) matrix (20-33%). The combination of very variable mean grain size and significant fine matrix can cause major difficulties, not only in determining the modes but also by introducing important errors caused by a grain size dependency of the modes themselves (see below). Detrital modes, often from multiple samples, were obtained for all except one of the Miocene lithostratigraphic units but only two of the Quaternary lithostratigraphic units.

Friable samples (mainly those of Quaternary age) were impregnated in resin prior to slabbing and grinding, and all the samples were stained for alkali and plagioclase feldspars using normal wet-chemical staining methods (Houghton, 1980). The yellow stain for alkali feldspar was successfully obtained in all cases but that for plagioclase (pink) proved quite fugitive and was notably less successful. An additional problem of staining is that Na-rich plagioclase (albite) does not take up the pink stain. However, it is unlikely that plagioclase was commonly misidentified as it can nearly always be distinguished from quartz by a combination of additional distinctive optical characteristics, including relief, cleavage, alteration, inclusion trails, compositional zoning, etc.

DETRITAL MODES

Accurate determination of detrital modes is essential in any studies of provenance, palaeogeography and interpretation of former tectonic setting from sediments. In the literature, two principal point-counting methods have been used, both concentrating on the framework components of sandstones. One method counts all polymineralic crystalline grains as lithic fragments, irrespective of the grain size of the constituent minerals in those fragments. Unfortunately, this method introduces a compositional dependence on the measured detrital modes, since the proportion of coarse-grained lithic fragments must diminish in finer-grained sandstone host rocks (see discussion in Dickinson, 1970). The compositional effect can be reduced by selecting for analysis only those samples with a uniform grain size, normally medium sand grade. An alternative method, which has gained wide acceptance and was used in this study, is the Gazzi-Dickinson (G-D) method (*e.g.* Dickinson, 1970), which counts all sand-size components, including sand-size minerals in polymineralic lithic fragments. This largely eliminates the compositional effect imposed by lithic clasts, since all the detrital components are effectively reduced to sand-size "grains". The grain size effect is also reduced significantly and sediments with a wide range of grain sizes can be counted (Ingersoll et al., 1984).

A total of about 300 points was counted for each sample. This is less than the 400-500 counts used by previous workers on samples from the CIROS and MSSTS cores (Barrett et al., 1986; George, 1989). However, because the clasts are predominantly fresh and unaltered, identification of almost all grains was achieved with certainty, and the 300 counts per section yielded statistically reliable values for most parameters (*cf.* Ingersoll et al., 1984). Where inaccuracies are likely to creep in are among those parameters with counts forming less than about 5% of the total.

EFFECTS OF SAMPLE GRAIN SIZES ON DETRITAL MODES

Because of the unavoidably wide range of grain sizes encountered in the sample set, the influence of grain size on the detrital modes was monitored (Fig. 1). A correlation with grain size is particularly pronounced for quartz (Q) and total feldspar (F), which vary antithetically, but it is also noticeable for pyroxene (though much less so); the effect essentially disappears for components with abundances much less than 10% of the mode. Blatt (1992) noted that F/Q ratios may increase as grain size decreases from medium sand to coarse silt, then decrease in finer grain sizes. The CRP-1 data show that F/Q ratios diminish initially between coarse and medium sand-grade samples, but then increase through the finer grain sizes, essentially consistent with the observations of Blatt (1992; Fig. 1). Since grain size does not vary unidirectionally down-core

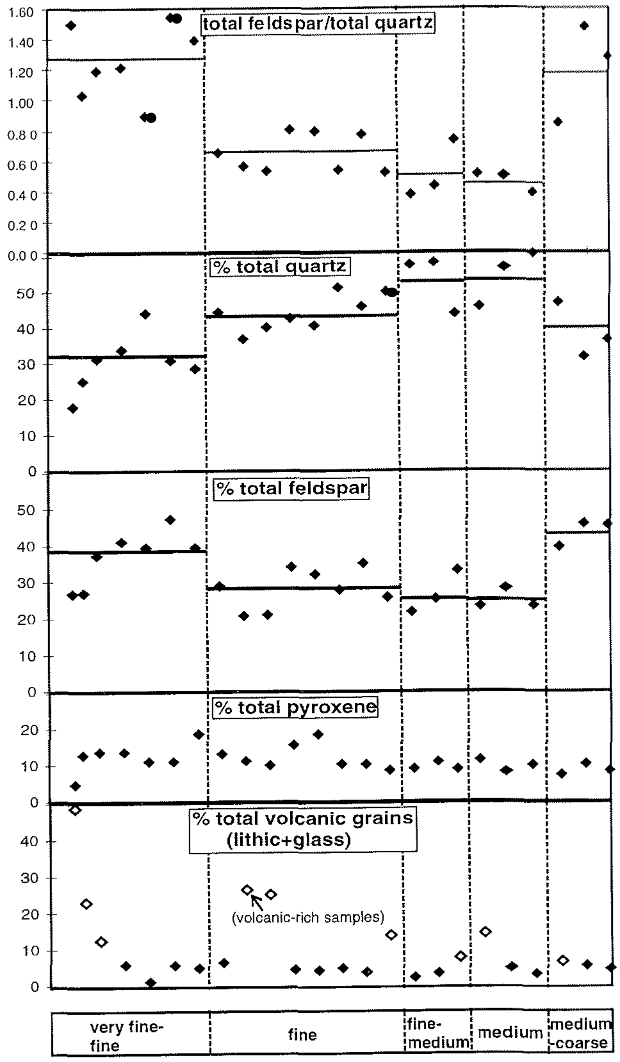

Fig. 1 - Summary diagram showing selected detrital modes and ratios sorted according to mean grain size of the samples. The data illustrate a strong dependence of abundant indices, such as quartz and feldspar, on grain size. Horizontal bars are mean values for each grain size category (Note: mean for very fine-fine sand-grade rocks excludes values for the single unusually volcanic-rich sample, which otherwise creates an artificial skew to the data). Although there is a slight grain size influence on less abundant indices such as pyroxene, it is absent in volumetrically minor detrital constituents such as volcanic grains (comprising total counts for lithic volcanic grains and glass). However, an enigmatic feature of the latter is the apparent strong correspondence between abundance of volcanic grains and grain size in volcanic-rich samples only. This suggests that in those volcanic-rich rocks, the greatest proportion of the volcanic detritus is concentrated in the finest sedimentary fraction.

(*i.e.* the incidence of fine grained samples is random), the principal effect is to increase the scatter on the modal diagrams. Because of this influence, an estimate of mean grain size is included in the table of detrital modes (Tab. 1).

GRAIN TYPES

Barrett et al. (1986) and George (1989) identified and described the principal grain types which were also encountered in the CRP-1 core. In particular, the classification of grain types of George (1989) was found

Tab. 1 - Modal analyses of sand grains in samples from CRP-1.

sample	Mean	QUARTZ			FELDSPAR						MICA	
(mbsf)	grain size	Qa	Qr	Qtot	Plag	AlkFsp	FeldspTOT	PyroxTOT[1]	AmphTOT[2]	Biot[3]	Musc	MicaTOT
24.53	F	36.63	4.94	41.56	17.28	9.88	27.16	12.35	0.82	1.65	0.41	2.06
26.63	VF-F	21.13	2.80	24.13	16.08	9.09	25.17	11.54	1.40	1.75	0.00	1.75
27.51	M-C	nd	nd	25.80	15.55	6.36	21.91	3.89	0.00	0.35	0.00	0.35
30.88	F-M	34.94	10.04	44.98	10.04	6.83	16.87	6.83	0.40	0.40	0.00	0.40
44.83	VF-F	16.67	1.06	17.73	21.63	4.96	26.60	4.61	0.35	0.00	0.00	0.00
47.23	VF-F	30.35	0.50	30.85	28.36	8.46	36.82	13.43	0.50	1.00	0.00	1.00
55.85	M-C	29.80	0.82	30.61	30.20	15.10	45.31	11.02	0.41	3.27	0.41	3.67
60.66	M	42.14	2.86	45.00	13.21	9.64	22.86	11.07	0.71	0.00	0.00	0.00
60.99	F	33.67	2.69	36.36	15.49	5.05	20.54	11.11	0.00	0.34	0.00	0.34
61.88	F	36.73	2.86	39.59	15.92	4.90	20.82	9.80	0.00	1.22	0.00	1.22
65.27	F	37.63	4.30	41.94	23.30	10.39	33.69	15.41	0.72	0.36	0.00	0.36
72.51	F	38.67	1.17	39.84	23.05	8.59	31.64	18.36	0.39	0.00	0.00	0.00
79.50	F-M	44.68	12.77	57.45	16.67	8.16	24.82	10.64	0.71	0.35	0.00	0.35
89.14	M	40.13	15.38	55.52	20.40	7.02	27.42	7.69	0.00	0.00	0.00	0.00
90.72	M	49.50	10.30	59.80	14.62	8.31	22.92	9.63	0.00	0.00	0.33	0.33
91.50	F	43.04	7.59	50.63	19.41	8.02	27.43	10.13	0.00	0.00	0.00	0.00
103.10	F	39.38	5.79	45.17	22.01	12.74	34.75	10.04	0.00	1.16	0.00	1.16
106.90	VF	31.25	1.79	33.04	22.77	17.41	40.18	13.39	1.79	0.45	0.45	0.89
109.70	VF-F	42.50	0.83	43.33	26.25	12.50	38.75	10.83	0.00	0.83	0.00	0.83
115.20	M-C	29.72	5.94	35.66	32.87	12.59	45.45	8.04	0.70	0.70	0.00	0.70
116.55	F	43.34	5.80	49.15	17.06	8.19	25.26	8.19	1.02	0.00	0.00	0.00
117.55	F-M	35.53	8.06	43.59	23.81	8.79	32.60	8.79	0.37	0.37	0.00	0.37
124.83	VF-F	28.50	1.40	29.91	32.71	13.55	46.26	10.75	0.93	0.47	0.00	0.47
138.52	VF-F	27.00	1.00	28.00	29.50	9.50	39.00	18.50	1.00	1.00	0.00	1.00

sample	Mean	LITHIC							GLASS				
(mbsf)	grain size	Qp	Ls	LvMVGbasic	LvMVGevol	LvOther	Lm	LithicTOT	Brown	Clear	GlassTOT	Other[4]	(Matrix%)[5]
24.53	F	0.00	5.35	4.12	0.00	1.65	0.82	11.93	0.82	1.23	2.06	2.06	19.00
26.63	VF-F	0.35	8.39	6.29	0.00	1.75	0.00	16.78	11.89	2.45	14.34	4.90	4.67
27.51	M-C	0.00	43.82	3.53	0.00	0.00	0.00	47.35	0.35	0.00	0.35	0.35	5.67
30.88	F-M	1.20	20.88	1.61	0.00	3.21	1.20	28.11	0.40	0.00	0.40	2.01	17.00
44.83	VF-F	0.00	0.35	21.28	1.77	1.77	0.00	25.18	20.57	4.96	25.53	0.00	6.00
47.23	VF-F	0.00	1.00	6.47	1.00	1.49	0.00	9.95	2.99	1.99	4.98	2.49	33.00
55.85	M-C	1.22	0.00	0.82	0.00	2.04	0.00	4.08	2.45	2.45	4.90	0.00	18.33
60.66	M	0.00	0.00	3.21	1.79	3.93	0.00	8.93	8.21	1.43	9.64	1.79	6.67
60.99	F	0.00	0.00	9.09	2.02	3.03	0.67	14.81	12.79	2.69	15.49	1.35	1.00
61.88	F	0.00	0.00	6.12	3.67	2.04	0.41	12.24	13.47	2.04	15.51	0.82	18.33
65.27	F	0.00	0.36	1.43	0.00	1.79	0.00	3.58	2.87	0.36	3.23	1.08	7.00
72.51	F	0.00	0.39	1.56	0.00	3.91	0.00	5.86	1.56	1.17	2.73	1.17	14.67
79.50	F-M	0.00	0.00	0.71	1.77	1.77	0.00	4.26	0.71	0.35	1.06	0.71	6.00
89.14	M	0.00	0.67	2.68	1.34	3.68	0.00	8.36	0.67	0.33	1.00	0.00	0.33
90.72	M	0.00	0.00	1.99	0.66	3.99	0.00	6.64	0.33	0.33	0.66	0.00	0.00
91.50	F	0.00	0.00	2.95	0.00	2.53	0.00	5.49	0.42	1.69	2.11	4.22	21.00
103.10	F	0.00	0.00	1.54	0.39	3.47	0.00	5.41	0.77	1.16	1.93	1.54	13.67
106.90	VF	0.45	1.79	1.34	0.00	2.23	0.00	5.80	3.57	0.89	4.46	0.45	25.33
109.70	VF-F	0.00	1.25	0.00	0.00	2.50	0.00	3.75	0.42	0.83	1.25	1.25	20.00
115.20	M-C	0.00	0.00	3.50	0.70	3.15	0.70	8.04	0.35	0.35	0.70	0.70	9.21
116.55	F	0.34	0.34	2.05	0.00	1.37	0.00	4.10	0.34	11.60	11.95	0.34	5.18
117.55	F-M	0.37	2.56	2.56	0.37	2.93	0.00	8.79	0.73	3.66	4.40	1.10	9.00
124.83	VF-F	0.00	1.87	0.47	0.47	2.34	0.00	5.14	2.80	1.87	4.67	1.87	28.67
138.52	VF-F	0.00	0.50	0.00	0.00	4.50	0.50	5.50	2.50	2.50	5.00	2.00	33.33

Note: [1]includes Ti-augite, deep green cpx, opx, pigeonite; [2]includes rare sodic amphibole; [3]mainly brown, rare green; [4]includes garnet, epidote, opaque oxide, ?aenigmatite, ?glauconite, olivine, zircon, sphene, bioclastic debris (siliceous and carbonate); [5]calculated as % of the total count, excluded from other values in the table.

Abbreviations: VF - very fine sand; F - fine sand; M - medium sand; C - coarse sand. Qa - angular quartz; Qr - rounded quartz. Plag - plagioclase; AlkFsp - alkali feldspar. Pyrox - pyroxene; Amph - amphibole. Biot - biotite; Musc - muscovite. Qp - polycrystalline quartz. Ls - sedimentary lithic grains. Lv - volcanic lithic grains. MVG - McMurdo Volcanic Group. evol - evolved. Lm - metamorphic (tectonite) lithic grains. mbsf - metres below sea floor.

to be most accurate and was used here. A summary of CRP-1 grain types and petrographical characteristics is also included in Cape Roberts Science Team (1998). No attempt was made to count separately the different types of plagioclase feldspars and pyroxenes. The petrographical characteristics of these mineral groups are often ambiguous or hard to determine during routine modal determinations. However, there is substantial provenance information locked up in such data (*e.g.* the distinction between pale green or colourless clinopyroxene can give a very accurate estimate of the relative proportions of contributions from Ferrar and McMurdo Volcanic Group sources; *cf.* Gamble et al., 1986; Armienti et al., this volume; Polozek & Ehrmann, this volume).

In addition to categories identified by George (1989), separate counts were made of brown (basic) *versus* colourless (evolved) glass, and lathy-textured (basic) *versus* green-clinopyroxene-bearing (evolved) lithic volcanic fragments (Tab. 1). These are important for the compositional evolution of the McMurdo Volcanic Group provenance, although the total counts of these components were often too low (<5 %) for their variations to be statistically significant.

RESULTS OF THE DETRITAL MODES

PETROGRAPHY

The rocks are quartzofeldspathic sandstones with no grain types exclusive to any sample or group of samples. Quartz and feldspar together typically comprise >70 % of the mode (Fig. 2) and they are accompanied by conspicuous numbers of pyroxene grains, which are the next most common mineral grain type (mainly Ca-rich clinopyroxene of "Ferrar-type"; see Cape Roberts Science Team, 1998, and Armienti et al., this volume). Pyroxene abundances typically range between 8 and 11%, with extreme values of *c.* 4 and 18%, and there is a local peak in pyroxene modes in samples at 65 and 72 mbsf. Lithic grains form the only other volumetrically important constituents and range between 2 and nearly 50% of the mode. They are strongly dominated by volcanic types (fine-grained basic and evolved lavas and fresh glass) but also include minor myrmekite (finely intergrown feldspar and vermicular quartz) and quartz-plagioclase-alkali feldspar "mosaic" types derived from other igneous sources. There is a wide range of accessory framework minerals, including ubiquitous amphibole (hornblende with a variety of colours probably indicative of varying composition (*cf.* Polozek & Ehrmann, this volume) and rare blue (sodic) amphibole), brown (rarely green) biotite, and opaque oxide, and trace amounts of muscovite, (?)aenigmatite, epidote, sphene, garnet, zircon. Siliceous and carbonate bioclastic debris is abundant in a few samples, and small numbers of siliceous bioclastic fragments are practically always present. Minor detrital carbonate, monazite, forsterite and apatite have also been identified by Armienti et al. (this volume) and Polozek & Ehrmann (this volume).

There are four prominent peaks in the modes for volcanic grains (Fig. 2). The two most prominent occur at *c.* 45 and 61 mbsf, with other subsidiary peaks at 26 and 116 mbsf. The two peaks at 45 and 61 mbsf are dominated by abundant volcanic lithic grains (Lv) and glass with basic–intermediate compositions, although evolved Lv grains and glass are also present. Ehrmann (this volume) also showed abundance peaks of basic volcanic-derived smectite at 45 and 59 mbsf. In the sand-grade samples, the two peaks are separated by samples with conspicuously lower abundances of volcanic grains, representing a lower influx of volcanic debris, although the overall abundance of volcanic grains is higher than in samples above 45 mbsf and below 62 mbsf. The distribution of the volcanic-rich samples has been used to identify a distinctive petrofacies (P2; see below). The subsidiary peak at 116 mbsf is distinguished by a high modal abundance of colourless pumice lapilli. It is not accompanied by an enhanced count for volcanic lithic grains or smectite. The glassy lapilli occur in a well-defined layer; samples above and below (at 115 and 125 mbsf) show very low counts for volcanic constituents. There is another peak for volcanic grains at 26 mbsf. However, there is no corresponding peak for smectite in the clay fraction (Ehrmann, this volume) and the peak for the sand-grade samples is probably an artificial effect caused by the very fine grain size of the sample counted (*cf.* Fig. 1). Two coarser-grained samples within

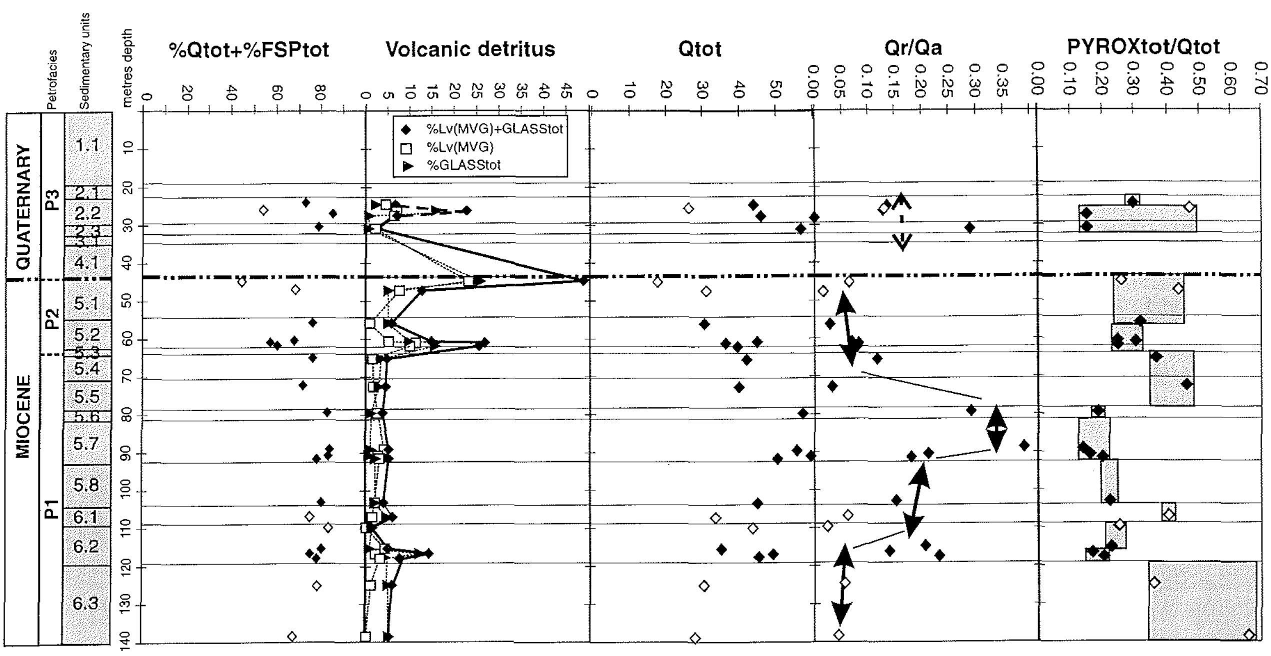

Fig. 2 - Summary diagram showing selected sand-grade detrital modes for CRP-1 samples, illustrating variations of major compositional features with depth in the sequence. See text for description. Note that the use of ratios normalised against quartz (*e.g.* pyroxene/quartz) screens out the diluting effect of major influxes of volcanic detritus on measured modal abundances. Abbreviations: Qtot - total quartz (%); FSPtot - total feldspar (%); Qr - rounded quartz; Qa - angular quartz; PYROXtot - total pyroxene (%); %Lv(MVG) - % total volcanic lithic grains (McMurdo Volcanic Group). Very fine sand samples indicated by open diamond symbols, to illustrate possible influence of grain size variation.

the same depositional unit show no enhanced volcanic influx, and the proportion of glass in heavy mineral extracts is also very low (Polozek & Ehrmann, this volume).

In practically all samples, the proportion of volcanic lithic grains with basic–intermediate compositions exceeds those with evolved compositions. Conversely, the ratio of brown/colourless glass is much more variable. Although basic–intermediate composition (brown) glass is dominant, the proportion of evolved (colourless) glass is generally much higher than indicated by the counts for lithic grains. Given the much higher total counts for glass in most samples, variation in ratios of the glass types is likely to be a more reliable indication of the proportions of the compositional types in the volcanic provenance. The proportion of evolved glass grains is highest in the sample with the colourless pumice lapilli layer at 116 mbsf, but it is also consistently high in samples between 90 and 120 mbsf.

PETROFACIES

The data can be divided into three main detrital assemblages or petrofacies (Fig. 3). One assemblage (petrofacies P1) is characterised by high Q+F (quartz + feldspar) concentrations (averaging about 78%) and low concentrations of lithic clasts (average about 6.5%; Tab. 1). The second assemblage (P2) has relatively low and more variable concentrations of Q+F (about 65%, range: 44-76%) and a very wide range of greater lithic clast contents (average about 22%; range 8-52%). The third assemblage (P3) is also lithic clast-rich, distinguished by very high contents of sedimentary clasts (Ls), which diminishes the proportion of Q+F present. There are modal data for only four samples from just 2 lithostratigraphic units in P3 and it is uncertain how representative of the Quaternary section they are. The lithic clasts in the Quaternary samples are entirely formed of reworked contemporaneous sediment. P3 is otherwise very similar to P1 when the modal abundances in P3 are recalculated to exclude Ls (Fig. 3). As the sedimentary clasts have no provenance significance, there is a strong case for their exclusion from consideration here, although the distinction of three petrofacies is retained for descriptive purposes. Moreover, the distribution of the petrofacies groups is not random and shows a clear stratigraphical control. P1 is confined to the Miocene section below 62 mbsf, P2 occurs between 62 mbsf and the Miocene/Quaternary unconformity at 43 mbsf, and P3 is entirely Quaternary.

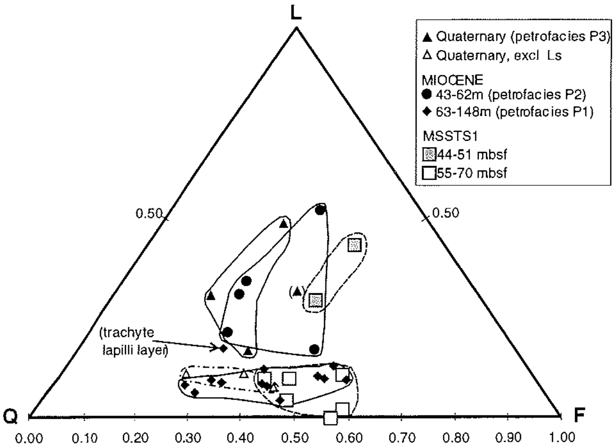

Fig. 3 - QFL triangular diagram for CRP-1 sand-grade samples showing modal characteristics of the three CRP-1 petrofacies identified. Note that petrofacies P3 can only be distinguished from petrofacies P1 by the abundance of sedimentary lithic grains in P3. These grains are intraformational and have no provenance significance, as is demonstrated by recalculating the proportions of QFL in P3 (minus Ls) and replotting in this diagram; a complete overlap with P1 is achieved. Bracketted sample (for 26 mbsf) in P3 is very fine grained and lithic volcanic-rich atypical of the petrofacies. Samples from the MSSTS-1 sequence are also shown, for comparison. Together with similar variations in rounded quartz/angular quartz (Qr/Qa) ratios in the MSSTS-1 samples (diagram not shown), it is suggested that there may be a stratigraphical correlation between the these parts of the CRP-1 and MSSTS-1 sequences on the basis of the detrital modes. Data for MSSTS-1 calculated from Barrett et al. (1986). Abbreviations: Q - quartz; F - feldspar; L - lithic grains; Ls - sedimentary lithic grains; mbsf - metres below sea floor.

COMPOSITIONAL TRENDS

Within the broad division into petrofacies, the detrital modes also show compositional trends related to stratigraphy. P1 shows a prominent trend of Q increasing up-core, reaching peak values about 80-90 mbsf before diminishing in the two stratigraphically highest samples (Fig. 2). P2 shows generally low Q modes that aparently diminish up-core but this trend shows a clear grain size control. P3 has generally high Q contents comparable with the many samples in P1. Similar variations are also shown on a plot of rounded to angular quartz grains (Qr/Qa), with high contents of rounded quartz correlating with high total quartz counts (Fig. 2).

Although total abundances of pyroxene are very variable and show no systematic down-core trends, ratios of total pyroxene/total quartz show well-marked variations that reflect stratigraphical position (Fig. 2). The ratios decrease up-core to a minimum at *c.* 78 mbsf, then rise to high values at 72-65 mbsf. Values are also high in samples in P2 (but generally lower than in P1 samples immediately below at 72-65 mbsf). Pyroxene/quartz ratios are quite diverse in the Quaternary samples.

DISCUSSION

PROVENANCE

The abundance of sedimentary lithic clasts, used to distinguish petrofacies P3, but also present in sparse amounts in samples from the other petrofacies, is due to intraformational reworking and it has no provenance significance. Modal abundances were therefore recalculated to exclude the proportion of these clasts in order to focus on provenance characteristics and significant variations. All three petrofacies share many modal characteristics that suggest a provenance dominantly composed of coarse-grained plutonic rocks, presumably granitoids of the Cambro-Ordovician Granite Harbour Intrusive Complex. This is suggested by the overwhelmingly quartzo-feldspathic compositions of the samples, and the relatively high proportion of alkali feldspar (mainly orthoclase) in the feldspar population, presence of hornblende, biotite, zircon, myrmekite (also present in Ferrar dolerite intrusions) and polycrystalline quartz (practically all with ≤3 crystal units per grain; *cf.* Basu et al., 1975). Clasts in CRP-1 are also dominated by Granite Harbour Intrusive Complex granitoids (Talarico & Sandroni, this volume). Some altered, fine-grained alkali feldspar-rich volcanic grains may represent fine-grained felsic dykes of the Granite Harbour Intrusive Complex (*cf.* Gunn & Warren, 1962) rather than sourced in the Devonian Gallipolli Volcanics (restricted to northern Victoria Land) or unknown Granite Harbour Intrusive Complex volcanic units as previously postulated (Cape Roberts Science Team, 1998). This suggestion is supported by an Ordovician $^{40}Ar/^{39}Ar$ isotopic age obtained on one of the volcanic grains by McIntosh (pers. comm.). An alternative source might be recycled felsic volcanic clasts from basal Beacon Supergroup conglomerate (*cf.* Gunn & Warren, 1962). Very rare igneous grains with prisms of brown amphibole are texturally and mineralogically similar to Ordovician lamprophyre dykes in southern Victoria Land (*cf.* Wu & Berg, 1992).

The paucity of polycrystalline quartz and metamorphic (tectonite) rock fragments suggests that metamorphic basement forms only a very minor part of the provenance. The metamorphic grade of that basement is unclear from the sand grains themselves. However, the basement metamorphic grade varies from as low as greenschist facies to incipient granulite facies (Allibone, 1992), so it is unsurprising that the detrital material is so undiagnostic. No low-grade phyllitic fragments were observed other than one grain tentatively identified by the Cape Roberts Science Team (1998), but the presence of a (single) clast of tremolite-bearing tectonite, together with at least some of the biotite, hornblende, garnet and detrital carbonate suggest a predominant high-grade metamorphic terrane, probably corresponding to the Upper Proterozoic Koettlitz Group (*cf.* Findlay et al., 1984; Laird, 1991; Allibone, 1992). Similar conclusions were reached by Talarico & Sandroni (this volume) based on the proportion and lithologies of metamorphic rocks in the clast population.

Rounded quartz grains, or fragments of rounded quartz grains, including rare examples with narrow quartz overgrowths, are likely to have been derived exclusively from quartzose sandstones in the Beacon Supergroup (Devonian–Triassic) (Barrett et al., 1986; George, 1989). Although angular quartz grains are common in Permian parts of the Beacon sequence (Korsch, 1974), the proportion of rounded to angular quartz grains in CRP-1 samples is a fairly accurate reflection of the relative input from Beacon sources *versus* "basement" (essentially granitoids), although the modal counts of rounded grains will underestimate the true volume of Beacon-derived detritus. From figure 2, it is evident that there is a strong interdependence between high proportions of rounded quartz and high counts for total quartz. This suggests that variations in the latter are strongly controlled by detrital inputs sourced in Beacon sandstones, and that the contribution from Beacon sources has fluctuated quite markedly with time.

There are few local sources known for pyroxene grains. Pigeonite is probably restricted entirely to the Ferrar dolerites, but orthopyroxene and the dominant ubiquitous and generally abundant abraded Ca-rich clinopyroxene with distinctive optical characteristics (the "Ferrar type" described by the Cape Roberts Science Team, 1998) may be derived either from Ferrar dolerites or mafic intrusive bodies within the South Victoria Land basement. A dominant Ferrar dolerite source is most likely, however (and is assumed here), as mafic basement intrusions are volumetrically minor and restricted to outcrops relatively far to the south (Skelton Glacier) and north (Terra Nova Bay) of the Cape Roberts drillsite (Simpson & Aslund, 1996). Clasts in CRP-1 core are also dominantly granitoids, and clinopyroxene is rarely present (Talarico & Sandroni, this volume). Based on the proportion of total pyroxene to total quartz (Fig. 2), the contribution from Ferrar dolerites was very variable in the CRP-1 sequence, mainly quite low but with a few well-defined peaks, particularly in lithostratigraphic Units 6.3, 6.1, 5.5 and 5.4. Some of the variation may be due to a weak dependence on grain size. Petrofacies P2 (Units 5.1 to 5.3) also had a high input of pyroxene, but the high proportion of volcanic-derived grains also present in P2 suggests an additional source reflecting an enhanced input of volcanic pyroxene. This is confirmed by electron probe micro-analysis of the pyroxene grains (Armienti et al., this volume).

It is of interest that there is an antithetic relationship between relative inputs of Ferrar and Beacon sources (Fig. 2, *cf.* plots of Qr/Qa and pyroxene/quartz ratios). This is enigmatic since published maps suggest that, over broad areas, the proportion of Ferrar dolerite sills in Beacon outcrops is roughly equal to the Beacon sedimentary rocks themselves (Gunn & Warren, 1962) and contributions from the Ferrar–Beacon combined outcrop should vary sympathetically. Ferrar dolerite also forms two very thick sills (about 300 m each) intruding the pre-Beacon "basement" (the so-called basement and peneplain sills of Gunn & Warren, 1962) and one interpretation of the modal data would be that it is these sills, rather than those stratigraphically higher, that may have provided much of the Ferrar detritus in the CRP-1 samples. However, this suggestion is not very strongly constrained since the volumetric relationship is not well proven. The proportion of sills in Beacon strata and basement is highly variable in detail. For example, in places, the "basement" sill (which is also the "peneplain" sill in other places) expands to *c.* 1 000 m thick (by amalgamation with other sills) while diminishing almost to zero elsewhere. Similarly, sills in the Beacon Supergroup are highly variable in thickness and continuity, locally swelling to 1 500 m thick (information provided by I. Turnbull). Moreover, the boundaries of the catchment area for sediments deposited at Cape Roberts during Miocene times are unclear.

In a few samples, the presence of rare grains of altered fine-grained basalt with textures somewhat similar to the texturally distinctive Kirkpatrick Basalts (Jurassic) suggest the possibility of a contribution from that source. The scarcity of these grains indicates that Kirkpatrick Basalt outcrops were not very extensive areally during the period represented in the CRP-1 core, and may have been similar to those preserved today. Less plausibly, these grains may also have been recycled from the Beacon Supergroup, or from basement dykes.

The presence of volcanic lithic grains and glass throughout the CRP-1 sequence is a clear indication of a volcanic provenance contributing detritus during the entire period represented. The petrographical characteristics of the lithic grains and the occurrence of fresh glass (often unabraded), coloured pyroxenes, sodic amphibole and (?)aenigmatite leave little doubt that the volcanic provenance was alkaline and a source in the McMurdo Volcanic Group is probable (*cf.* Barrett et al., 1986; George, 1989; Cape Roberts Science Team, 1998; *cf.* Armienti et al., this volume; Polozek & Ehrmann, this volume).

VOLCANISM

The presence, in all samples, of volcanic glass and lithic grains with both basic–intermediate and evolved compositions indicates a derivation from a compositionally varied (alkaline) volcanic provenance. Detrital input was probably by a combination of direct airfall (*cf.* Cape Roberts Science Team, 1998) and sedimentary reworking. The volcanic flux into McMurdo Sound would have been particularly high in periods immediately following proximal eruptions, when tephra blanketed the region and would have been subject to rapid redistribution. Most of the sandstone beds were emplaced as sedimentary mass flows and no primary tephra fall layers have been discovered in CRP-1.

The glass fragments of all compositions are entirely fresh, mainly little-abraded and preserve relatively fragile grain shapes, suggesting that much of the volcanism was essentially coeval with deposition. From variations in the ratios of volcanic lithic grains and glass types, eruptions were dominantly basic–intermediate in composition, except for the period represented by samples between 90 and 120 mbsf, when eruptions of evolved magmas may have been relatively more voluminous and/or more frequent. The abundance of opaque lithic grains, mainly representing highly oxidised glass, together with a small proportion of red glass fragments, are indicative of frequent Strombolian (low energy) eruptions of basic–intermediate magmas. Moreover, a small proportion of the colourless glass is pumiceous and may have been sourced in highly explosive (Plinian?) evolved magmatic eruptions. There was a significant magmatic eruption preserved at 116 mbsf, and comprising evolved pumice lapilli, isotopically dated by $^{40}Ar/^{39}Ar$ as 18.4 ± 1.2 Ma (McIntosh, this volume). However, the dominant (non-oxidised) glass fragments of all compositions have blocky shapes and are non- or poorly-vesicular, which suggests that many eruptions were hydrovolcanic. The extremely low proportion of non-volcanic lithic fragments in all the samples (excluding intraformational sedimentary clasts) is unusual for products of explosive eruptions involving groundwater, which may suggest that the magmatic interaction was with surface water (lacustrine, shallow marine or meltwater formed during subglacial eruptions). Although it is difficult to substantiate this interpretation in the case of sedimentary samples derived from redeposited tephra, it is probably a reasonable inference for first-cycle sediments.

The Cape Roberts Science Team (1998) suggested that the apparent lack of covariation between volcanic lithic and glass modal counts, and in particular a roughly constant (low) proportion of lithic clasts compared with a highly fluctuating glass content, indicated a likely derivation of only the glass by direct airfall; the lithic clasts were presumed to have been input by normal erosion and sedimentation (ice transport is another possibility, but was not considered). The generally poor covariation in glass and lithic grain abundances in all three petrofacies may be consistent with separate inputs of those two detrital components, consistent with independent origins within different and probably unrelated eruptions. However, the modal counts for glass and lithics are very low (especially in P1 and P3) and the variations may not be significant statistically.

$^{40}Ar/^{39}Ar$ isotopic dating of the CRP-1 core (McIntosh, this volume) suggests that the major influxes of volcanic debris (dated at *c.* 18 Ma) are essentially coincident with eruptions at a volcano which was formerly situated close to Mount Morning, about 120 km south of the CRP-1 drillsite (*cf.* Cape Roberts Science Team, 1998). However, the dominant basic–intermediate compositions of the two peak volcanic influxes within petrofacies P2 (at *c.* 61 and 45 mbsf) conflict with the evolved (trachyte) compositions of volcanic products known from that locality (Wright & Kyle, 1990). Thus, either the source for the volcanic detritus in petrofacies P2 was from another, as yet unknown centre(s), or else the detritus indicates that the palaeo-Mount Morning volcano was compositionally more varied than is evident in present-day outcrops. A more distal source for the evolved pumice at *c.* 116 mbsf is also possible. A source in northern Victoria Land is difficult to substantiate since it would require a mechanism to transport the debris, such as palaeo-winds or drift ice patterns, which are currently unknown.

CORRELATION WITH OTHER BOREHOLES IN MCMURDO SOUND

Overlaps in age occur between CRP-1, MSSTS-1 and CIROS-1 drillcores, the latter obtained at two sites situated about 70 km to the south of CRP-1. Despite the presence of Quaternary strata in all three drillcores, detrital modes of the Quaternary strata in CRP-1 are essentially undiagnostic and no correlation is possible based solely on modal criteria. An important overlap between CRP-1 and CIROS-1 may also occur with the basal part of CRP-1, but that is also a section with no clear diagnostic detrital modes in CRP-1. Conversely, a tentative revision of the age of the early Miocene part (*c.* 40-70 mbsf) of MSSTS-1 by Hambrey & Barrett (1993; but see also Harwood et al., this volume) suggests the possibility of overlap with the upper part of the Miocene section in CRP-1, in a section that contains several distinctive and potentially diagnostic modal characteristics.

In the CRP-1 and MSSTS-1 drillcores, there is clear evidence for a sudden and dramatic upward transition from volcanic-poor to volcanic-rich petrofacies, which overlap significantly in QFL space (Fig. 3). The transition occurs at *c.* 62 mbsf in CRP-1 and between 51 and 55 mbsf in MSSTS-1. The consistent displacement of the MSSTS-1 modes to slightly more felsic compositions compared with CRP-1 (Fig. 3) may simply reflect differences between operators determining detrital modes in the two investigations (*cf.* Barrett et al., 1986 and this paper). Also, the prominent peak in Qr/Qa ratios observed in CRP-1 modes (lithostratigraphic Units 5.6 and 5.7; Fig. 2), reflecting a major increase in Beacon-derived sand grains, is also apparently reproduced in the MSSTS-1 data, with the corresponding peak located at 62-63 mbsf (data calculated from Barrett et al., 1986). Conversely, the peak influx of Ferrar detritus observed in CRP-1 (lithostratigraphic Units 5.4 and 5.5) is absent in MSSTS-1. However, fluctuations in the input of Ferrar detritus may be expected to be controlled by differences in the proportions of the major outcrop units in the catchment areas feeding debris to the two sites (*i.e.* a local control). Although interpretation of the detrital modes enables the tentative correlation outlined here, it requires substantiation by better dating, particularly of the MSSTS-1 core.

CONCLUSIONS

As a result of this investigation into the modal abundances of sand grade detritus in samples from the CRP-1 drillcore, three major petrofacies (P1-P3) are identified mainly using the relative abundance of volcanic grains. Four major provenance types were identified and can be correlated with outcrops exposed today in the Transantarctic Mountains, mainly between Ferrar and Mackay glaciers. The relative proportions of the outcrop types were broadly alike between Miocene and Quaternary times, with influxes of volcanic detritus mainly from a southern source. This argues for a generally stable tectonic hinterland throughout the depositional period.

Plutonic and metamorphic basement, Palaeozoic sedimentary formations - All of the samples are dominated by quartzo-feldspathic grains derived fom a provenance largely composed of basement granitoid plutons (Cambro-Ordovician Granite Harbour Intrusives) and quartzose sandstones (Devonian–Triassic Beacon Supergroup). Fluctuations in the abundance of quartz grains were largely determined by influxes of Beacon-derived grains. An additional minor detrital input derived from Lower Palaeozoic lamprophyres and felsic dykes is also identified for the first time. Detritus possibly derived from a mainly high-grade metamorphic basement terrane (possibly the Upper Proterozoic Koettlitz Group) also forms a minor proportion of the modes, indicating a small metamorphic outcrop in the provenance.

Jurassic Ferrar Dolerite formation - Grains derived from Ferrar dolerites (mainly comprising petrographically distinctive clinopyroxene) are a volumetrically important and ubiquitous component of the modes for all samples. The fluctuating modal values are antithetic to the abundance of quartz (itself determined by a Beacon source), suggesting that coastal outcrops of Ferrar dolerite sills (*i.e.* intruding the local basement) may have been an important source of Ferrar-type grains. A very few grains are similar to lavas of the texturally and mineralogically distinctive Jurassic Kirkpatrick Basalt formation, and are tentatively identified as a detrital component for the first time in this study.

Cenozoic alkaline volcanism - Volcanic-derived grains (lithic and glass) are present throughout the CRP-1 sequence and are interpreted as mainly representing products of tephra eruptions coeval with sedimentation, although no primary tephra layers are present in CRP-1. The tephra particles were deposited mainly by normal sedimentation processes (largely sediment gravity flows for the samples analysed). The abundant oxidised (sub-opaque) glass and scarce red glass fragments were likely to have been derived from subaerial eruptions of Strombolian type; less common evolved pumices probably represent much more highly explosive magmatic eruptions possibly of Plinian type. Conversely, the characteristics of the (unoxidised) glass indicate abundant hydrovolcanic eruptions. Basic-intermediate compositions predominate but evolved compositions are particularly important in the 90-120 mbsf interval. Three major volcanic influxes of tephra from three separate eruptions are identified. The oldest (at *c.* 116 mbsf) is represented by a layer rich in evolved pumice. By contrast, two eruptions at 45 and 61 mbsf are represented by a sudden and very high influx of basic-intermediate composition detritus and intervening samples are also enriched in volcanic grains, indicating a volcanically active period corresponding to lithostratigraphic Units 5.3-5.1 (petrofacies P2). These two eruptions, at least, are correlated with a possible source volcano in the Mount Morning area, although they apparently differ compositionally from those documented from the Mount Morning sequence.

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