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Grain Size Analysis of Samples from CRP-1

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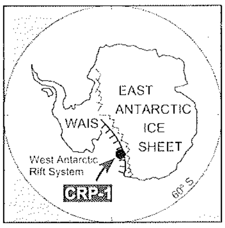
Abstract - Twenty four core samples from CRP-1, seven from Quaternary strata (20 - 43.55 metres below sea floor or mbsf) and seventeen from early Miocene strata (43.55 to 147.69 mbsf), have been analysed for their grain-size distribution using standard sieve and Sedigraph techniques. The results are in good agreement with estimates of texture made as part of the visual core description for the 1:20 core logs for CRP-1 (Cape Roberts Science Team, 1998). Interpretation of the analyses presented here takes into account the likely setting of the site in Quaternary times as it is today, with CRP-1 high on the landward flank of a well-defined submarine ridge rising several hundred metres above basins on either side. In contrast, seismic geometries for strata deposited in early Miocene times indicate a generally planar sea floor dipping gently seaward. Fossils from these strata indicate shallow water depths (<100 m), indicating the possibility that waves and tidal currents may have influenced sea floor sediments.

The sediments analysed here are considered in terms of 3 textural facies: diamict, mud (silt and clay) and sand. Most of the Quaternary section but only 30% of the early Miocene section is diamict, a poorly sorted mixture of sand and mud with scattered clasts, indicating little wave or current influence on its texture. Although not definitive, diamict textures and other features suggest that the sediment originated as basal glacial debris but has been subsequently modified by minor winnowing, consistent with the field interpretation of this facies as ice-proximal and distal glaciomarine sediment. Sediments deposited directly from glacier ice appear to be lacking. Mud facies sediments, which comprise only 10% of the Quaternary section but a third of the early Miocene section, were deposited below wave base and largely from suspension, and show features (described elsewhere in this volume) indicative of the influence of both glacial and sediment gravity flow processes. Sand facies sediments have a considerable proportion of mud, normally more than 20%, but a well-sorted fine-very fine sand fraction. In the context of the early Miocene coastal setting we interpret these sediments as shoreface sands close to wave base.



INTRODUCTION

The purpose of this paper is to quantify the grain-size distribution of samples representative of each unit of CRP-1 core, cored in 150 m of water 15 km off Cape Roberts on the south Victoria Land coast (Fig. 1), and make some inferences on their modes of deposition. To assist with this, comparisons are made with modern sea floor sediments from earlier studies in McMurdo Sound (Powell, 1981; Barrett et al., 1983; Barrett, 1989), in nearby Granite Harbour (Macpherson, 1987) and the Ross Sea (Anderson et al., 1980, 1984). The sediment in both Quaternary and early Miocene sections of the core is entirely siliciclastic, apart from the Quaternary carbonate interval from 32 to 34 mbsf. Lithology of clasts from the core (Cape Roberts Science Team, 1998) indicate that the principal source of sediment in the area of CRP-1 has been the early Palaeozoic and older granitic basement, together with the Jurassic Ferrar Dolerite in the Transantarctic Mountains, a short distance to the west. In addition, studies of the sand (Armienti et al., this volume; Smellie, this volume) show that volcanic debris, probably from centres to the south, is a significant component of early Miocene strata above 60 mbsf. Despite these variations in provenance and composition, we believe that the textures of these sediments reflect primarily depositional processes and environment.

The regional tectonic setting (Davey & Brancolini, 1995; Hamilton et al., this volume) and seismic stratigraphy (Brancolini et al., 1995; Henrys et al., this volume) suggest that the physiographic setting for early Miocene sedimentation was rather different from that for Quaternary sedimentation, which was very similar to that of today. Quaternary sediments in CRP-1 have been deposited as a drape only a few tens of metres thick on a submarine topography with considerable relief, ranging from the sea valley immediately east of Cape Roberts (500 metres below sea level or mbsl) to the crest of Roberts Ridge (less than 100 mbsl and just seaward of CRP-1) and out into Erebus Basin (900 mbsl) (Fig. 2). This topography was probably shaped by extensive erosion from thick grounded ice. The Quaternary sediments represent only the more recent fragmentary record of a complex late Neogene glacial and glacimarine history.

The early Miocene strata of CRP-1, by contrast, appear in seismic records to be planar and rising gently towards the coast. These strata are now truncated by a deep erosional trough between CRP-1 and Cape Roberts (Figs. 1 & 2). It is reasonable to assume that the strata once continued landward to the coast, as N-S profiles (*e.g.* NBP9001-94, Hamilton et al., 1997) show only shallow channelling in early Miocene strata, though still possibly from grounded ice. Macrofauna throughout the early Miocene section

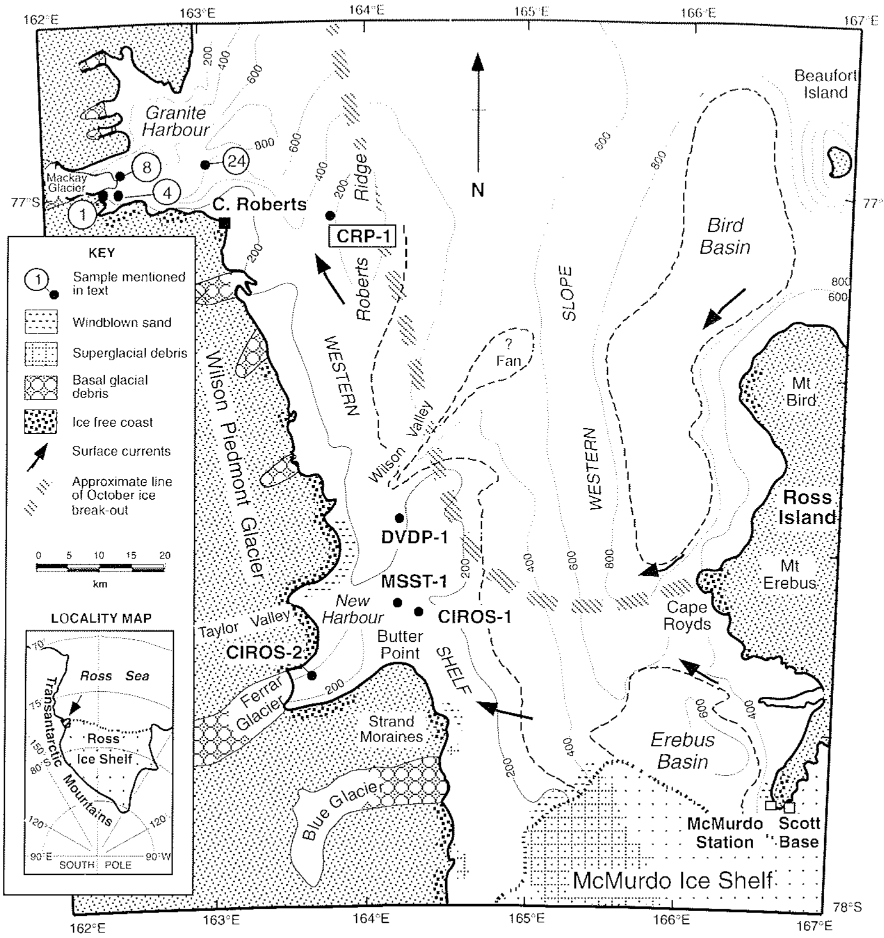


Fig. 1 - Map of McMurdo Sound showing the main bathymetric features, surface currents and likely modern sources of sea-floor sediment. The location of drillsites and of modern sediment sampling sites in Granite Harbour (numbers on map link to samples in Fig. 3) are also indicated. Modified from Barrett et al. (1983).

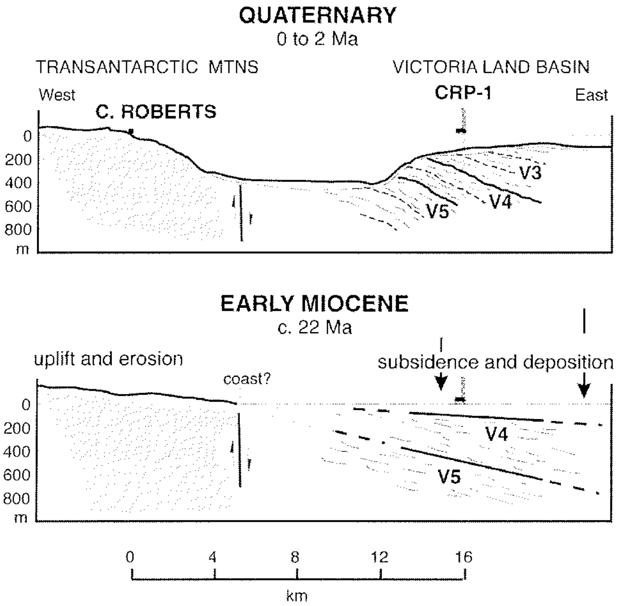


Fig. 2 - East-west profile from the coast at Cape Roberts through the CRP-1 drillsite on Roberts Ridge for *a)* Quaternary time, when a deep channel separated Roberts Ridge from the coast, and *b)* early Miocene times, when water was shallower and we infer from seismic profiles a much reduced relief offshore.

indicates a depositional water depth of less than 100 m at CRP-1 (Cape Roberts Science Team, 1998), while abundant benthic diatoms suggest that, in places, water depth was less than 50 m (Harwood et al., this volume). We assume that the early Miocene coast was near the tectonic hinge between mountains to the west and the basin to the east, and located close to the major fault 11 km west of CRP-1. This fault is the most obvious dislocation that separates the Transantarctic Mountains, which have risen 5.5 km in the last 55 million years. (Fitzgerald, 1992), from the Victoria Land Basin which at CRP-1 was sinking and accumulating hundreds of metres of sediment at least until 16 Ma (Brancolini et al., 1995; Henrys et al., this volume). For this model and for 100 m water depth at CRP-1 the sea floor gradient in early Miocene times was 1:110 (0.5°). We take this shallow offshore coastal setting into account in interpreting the texture of the early Miocene sequence.

METHODS

The samples were disaggregated in distilled water by stirring for 60 minutes in an ultrasonic bath. They were then dried and weighed, and the gravel fraction (>2 mm or

Tab. 1 - Frequency percent in each size class (limits in phi units) for grain-size analyses of samples from CRP-1.

Class Limits Depth (mbsf)	-1.00	-0.50	0.00	0.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50	7.00	7.50	8.00	9.00	10.00	REST
20.55 - 1	8.6	1.2	1.1	1.2	2.4	3.8	5.4	6.0	8.3	7.2	10.1	3.3	2.4	2.1	2.4	2.4	2.9	2.1	1.8	3.6	2.8	18.5
25.76 - 2	0.9	0.4	0.9	1.3	1.8	2.4	4.0	5.5	8.2	8.2	13.0	7.8	4.4	3.1	2.3	0.8	2.3	2.5	0.9	4.6	2.7	22.1
27.61 - 3	0.1	0.1	0.1	0.1	0.5	1.5	3.7	5.7	10.5	14.0	18.5	6.5	5.8	2.6	1.5	1.7	1.9	1.7	1.6	3.6	4.1	14.2
29.77 - 4	10.0	2.5	2.2	3.0	3.9	4.2	4.7	5.6	8.2	7.1	9.0	4.9	4.0	2.4	1.3	1.7	1.7	2.4	1.6	2.3	3.2	14.4
35.41 - 5	1.1	0.6	0.6	0.2	1.0	2.1	3.4	4.6	7.2	7.4	13.1	6.3	5.0	3.7	3.1	3.0	2.3	2.9	2.4	4.6	3.5	21.7
37.58 - 6	0.0	0.5	0.5	0.6	1.1	1.6	3.4	5.0	8.5	7.9	11.5	8.5	6.0	2.9	0.5	4.0	4.1	.9	1.8	6.0	4.3	20.4
37.58 - 6b	0.0	0.5	0.5	0.6	1.1	1.6	3.4	5.0	8.5	7.9	11.7	7.5	5.0	4.2	3.2	3.2	2.9	3.4	2.0	4.3	4.1	19.5
41.48 - 7	5.9	0.6	0.7	1.0	1.4	1.9	5.5	5.1	8.6	8.4	11.4	7.7	5.0	4.6	4.1	3.5	3.1	2.5	2.0	3.5	2.5	11.0
43.81 - 8	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.4	7.2	25.5	24.8	6.2	10.1	4.5	4.0	3.6	3.0	2.2	1.4	2.2	1.0	3.7
51.48 - 9	0.0	0.2	0.0	0.0	0.0	0.1	0.2	0.2	0.5	1.5	10.3	7.0	8.3	7.1	5.3	6.5	5.8	6.5	5.4	8.0	6.1	21.0
54.14 - 10	0.1	0.0	0.1	0.2	0.2	0.1	0.2	0.3	0.5	0.5	7.8	10.5	9.0	7.2	7.0	5.6	6.0	7.2	4.7	6.2	6.8	19.6
63.38 - 11	0.0	0.0	0.2	0.0	0.0	0.1	1.0	12.9	43.4	17.3	7.6	2.1	0.4	5.2	0.2	0.0	0.6	0.8	0.2	0.3	0.5	7.6
72.90 - 12	0.0	0.0	0.0	0.1	0.1	0.1	0.3	2.3	29.4	31.6	17.0	5.5	1.5	0.7	0.3	0.5	0.3	0.5	0.4	0.5	0.5	8.5
74.60 - 13	0.3	0.2	0.1	0.1	0.2	0.3	0.5	0.7	2.2	9.9	21.8	12.2	8.8	4.6	2.4	1.8	2.0	2.0	1.3	2.5	3.1	23.1
79.15 - 14	1.2	0.5	0.5	0.7	1.2	2.3	5.0	4.8	14.1	9.7	9.0	6.8	3.7	4.9	4.8	3.7	2.8	3.1	2.6	4.8	3.3	10.6
84.38 - 15	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.2	0.7	2.3	8.3	10.7	6.5	7.8	8.5	7.4	6.9	6.5	4.8	5.8	3.7	19.4
89.72 - 16	7.8	1.4	1.9	2.5	5.6	13.8	23.4	15.2	18.8	5.8	1.5	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.8
99.50 - 17	0.0	0.0	0.0	0.0	0.0	0.1	0.6	0.5	1.8	1.5	8.3	4.5	2.0	3.6	7.1	6.3	6.0	9.6	4.6	7.3	6.8	29.5
99.50 - 17b	0.0	0.0	0.0	0.0	0.0	0.1	0.7	0.5	1.8	1.6	3.3	5.1	3.4	0.0	5.6	6.1	7.3	6.9	6.9	8.3	5.4	37.0
105.52 - 18	1.1	0.7	0.5	1.3	1.0	1.9	3.7	8.6	12.7	10.0	11.9	6.9	5.3	3.8	2.8	1.9	2.9	2.2	0.9	3.2	0.8	16.1
108.78 - 19	0.1	0.1	0.1	0.1	0.1	0.2	0.7	1.8	6.0	7.5	9.3	6.8	2.9	3.7	2.3	2.3	3.8	4.4	3.7	7.6	7.2	29.4
123.83 - 21	1.9	0.4	1.0	0.9	10.1	1.8	2.8	4.2	7.3	7.6	13.3	7.1	8.1	5.8	4.1	1.4	3.0	4.9	2.3	2.4	3.1	15.7
123.83 - 21b	1.9	0.4	1.0	0.9	1.1	1.8	2.8	4.2	7.2	7.6	9.9	7.3	8.5	6.7	4.4	3.4	4.5	4.1	1.6	3.8	2.5	14.6
134.71 - 23	2.7	0.7	0.6	1.0	1.3	1.9	2.9	4.2	6.9	8.1	13.9	6.9	4.7	4.0	3.4	2.9	2.3	2.7	1.6	2.5	2.3	22.4
134.71 - 23b	2.7	0.7	0.6	1.0	1.3	1.9	2.9	4.2	6.9	8.1	11.2	6.9	6.0	4.8	4.2	2.5	3.5	3.5	2.0	4.1	2.4	18.7
144.53 - 24	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.0	6.7	6.5	4.2	6.6	10.1	7.6	5.5	9.2	8.2	34.8
146.51 - 25	10.6	0.1	0.2	0.2	0.3	0.4	0.7	1.2	2.7	5.3	10.0	6.2	2.8	1.3	4.7	4.4	5.5	5.5	4.7	7.0	5.0	21.3

Analyst: Laura De Santis.

Tab. 2 - Statistics for grain-size analyses of samples from CRP-1.

Depth	Lithology			Percentiles						Folk measures							
(mbsf)	(from CRP core logging manual)	1	5	16	25	50	75	84	95	Mean	Sdev	Skew	Gravel	Sand	Silt	Clay	Total
20.55 - 1	Clast-rich muddy diamicton	-7.4	-2.9	1.2	2.1	3.7	8.0	10.8	16.0	5.2	5.3	0.4	8.6	46.8	19.6	25.0	100.0
25.76 - 2	Sandy mud w/dispersed clasts	-0.8	0.9	2.4	3.0	4.2	8.9	12.0	17.6	6.2	4.9	0.6	0.9	45.8	24.0	29.4	100.1
27.61 - 3	Muddy sand w/dispersed clasts	1.1	1.9	2.7	3.1	3.9	7.1	9.6	12.8	5.4	3.4	0.7	0.1	54.7	23.2	22.0	100.0
29.77 - 4	Clast-rich sandy diamicton	-4.9	-2.4	0.2	1.4	3.4	6.7	9.4	15.4	4.4	5.0	0.3	10.0	50.2	20.0	19.8	100.0
35.41 - 5	Clast-poor muddy diamicton	-1.1	1.4	2.7	3.3	4.7	9.0	12.1	18.7	6.5	5.0	0.6	1.1	40.4	28.8	29.7	100.0
37.58 - 6	Sandy mud	0.0	1.6	2.7	3.3	4.6	9.0	12.0	19.8	6.4	5.1	0.6	0.0	40.5	28.8	30.7	100.0
37.58 - 6b	Sandy mud	0.0	1.6	2.7	3.3	4.7	8.6	11.0	15.7	6.1	4.2	0.5	0.0	40.7	31.5	27.8	100.0
41.48 - 7	Clast-rich muddy diamicton	-9.1	-1.9	1.9	2.7	4.0	6.5	8.3	12.8	4.7	3.8	0.3	5.9	44.4	32.5	17.1	99.9
43.81 - 8	Muddy sandstone	2.6	2.9	3.2	3.4	3.8	5.1	6.1	8.8	4.4	1.6	0.6	0.0	58.2	35.0	6.9	100.1
51.48 - 9	Clayey siltstone w/sand	2.8	3.7	4.2	4.8	6.7	9.3	11.1	15.1	7.4	3.5	0.4	0.0	13.1	51.9	35.0	100.0
54.14 - 10	Clayey siltstone w/sand & clasts	2.1	3.7	4.3	4.8	6.5	9.2	10.7	14.0	7.2	3.2	0.4	0.1	10.0	57.3	32.6	100.0
63.38 - 11	Sandstone w/mud	1.9	2.3	2.5	2.7	2.9	3.3	4.4	19.0	3.3	3.0	0.8	0.0	82.3	9.4	8.3	100.0
72.90 - 12	Sandstone w/mud	2.2	2.6	2.8	2.9	3.3	3.8	4.3	20.8	3.5	3.1	0.6	0.0	80.9	9.5	9.6	100.0
74.60 - 13	Sandy mudst w/dispersed clasts	1.2	3.0	3.5	3.8	4.6	9.4	12.6	19.0	6.9	4.7	0.8	0.3	35.8	35.1	28.7	99.9
79.15 - 14	Clast-poor muddy diamictite	-1.2	1.2	2.5	2.8	4.1	6.9	8.5	12.2	5.0	3.2	0.5	1.2	47.9	32.3	18.6	100.0
84.38 - 15	Clayey siltstone w/sand	2.9	3.6	4.2	4.7	6.3	8.6	11.1	16.9	7.2	3.7	0.5	0.0	11.9	59.3	28.8	100.0
89.72 - 16	Sandstone w/abundant clasts	-6.0	-2.2	0.7	1.2	1.9	2.6	2.8	3.4	1.8	1.4	-0.3	7.8	89.9	1.0	1.3	100.0
99.50 - 17	Mudstone w/abundant clasts	2.3	3.5	4.4	5.7	7.4	10.8	12.6	16.4	8.1	4.0	0.3	0.0	12.9	43.6	43.5	100.0
99.50 - 17b	Mudstone w/abundant clasts	2.2	3.6	4.9	6.2	8.1	12.3	14.4	18.7	9.1	4.7	0.4	0.0	8.0	41.4	50.6	100.0
105.52 - 18	Clast-poor sandy diamictite	-1.1	1.1	2.4	2.8	3.9	6.7	10.2	51.1	5.5	9.5	0.8	1.1	52.2	26.8	20.0	100.1
108.78 - 19	Sandy mudst w/dispersed clasts	1.8	2.7	3.5	4.0	7.2	10.6	12.2	15.3	7.6	4.1	0.2	0.1	25.9	29.8	44.2	100.0
123.83 - 21	Clast-poor muddy diamictite	-2.5	0.9	2.7	3.3	4.5	7.3	9.9	15.4	5.7	4.0	0.5	1.9	40.4	36.7	21.1	100.1
123.83 - 21b	Clast-poor muddy diamictite	-2.5	0.9	2.7	3.3	4.7	7.2	9.4	15.9	5.6	4.0	0.4	1.9	36.9	40.6	20.7	100.1
124.52 - 22	Clast-poor muddy diamictite	-1.3	1.0	2.8	3.3	4.5	8.1	10.8	16.2	6.0	4.3	0.6	1.3	39.9	33.3	25.5	100.0
134.71 - 23	Clast-poor muddy diamictite	-3.1	0.5	2.6	3.2	4.4	8.8	13.0	21.5	6.7	5.8	0.6	2.7	41.5	28.6	27.2	100.0
134.71 - 23b	Clast-poor muddy diamictite	-3.1	0.5	2.6	3.2	4.6	8.1	11.3	19.2	6.2	5.0	0.5	2.7	38.8	33.2	25.3	100.0
144.53 - 24b	Silty claystone	4.6	4.9	5.8	6.5	8.2	11.3	12.9	16.0	9.0	3.5	0.4	0.0	0.7	47.1	52.1	99.9
146.51 - 25	Clayey siltstone w/sand	-	-	2.9	3.7	6.4	9.2	11.3	15.4	6.9	12.0	-0.3	10.6	21.2	34.9	33.4	100.1

Note: Mean - Folk graphic mean; Sdev - Folk graphic standard deviation; Skew - Folk graphic skewness. Analyst: Laura De Santis.

-1 phi) separated. A 20 gram split was wet-sieved into sand and mud fractions, the sand fraction (0.063-2 mm) dry-sieved and the mud fraction analysed by Sedigraph 5100. Because wet sieving invariably retains some coarse silt, dry sieving was extended to catch 4.5 and 5.0 phi fractions. The weights retained were then merged with the Sedigraph results. The analyses are reported in table 1 for each sample as frequency percent at 0.5 phi intervals for the range -1 to 10 phi (2 to 1/1 024 mm), and the percent finer than 10 phi. Summary statistics (percentiles, Folk mean, etc. and proportions of gravel, sand, silt and clay) are given in table 2. The grain-size data are also presented as histograms against the lithological log in figure 3.

Four samples, one from the Quaternary and three from

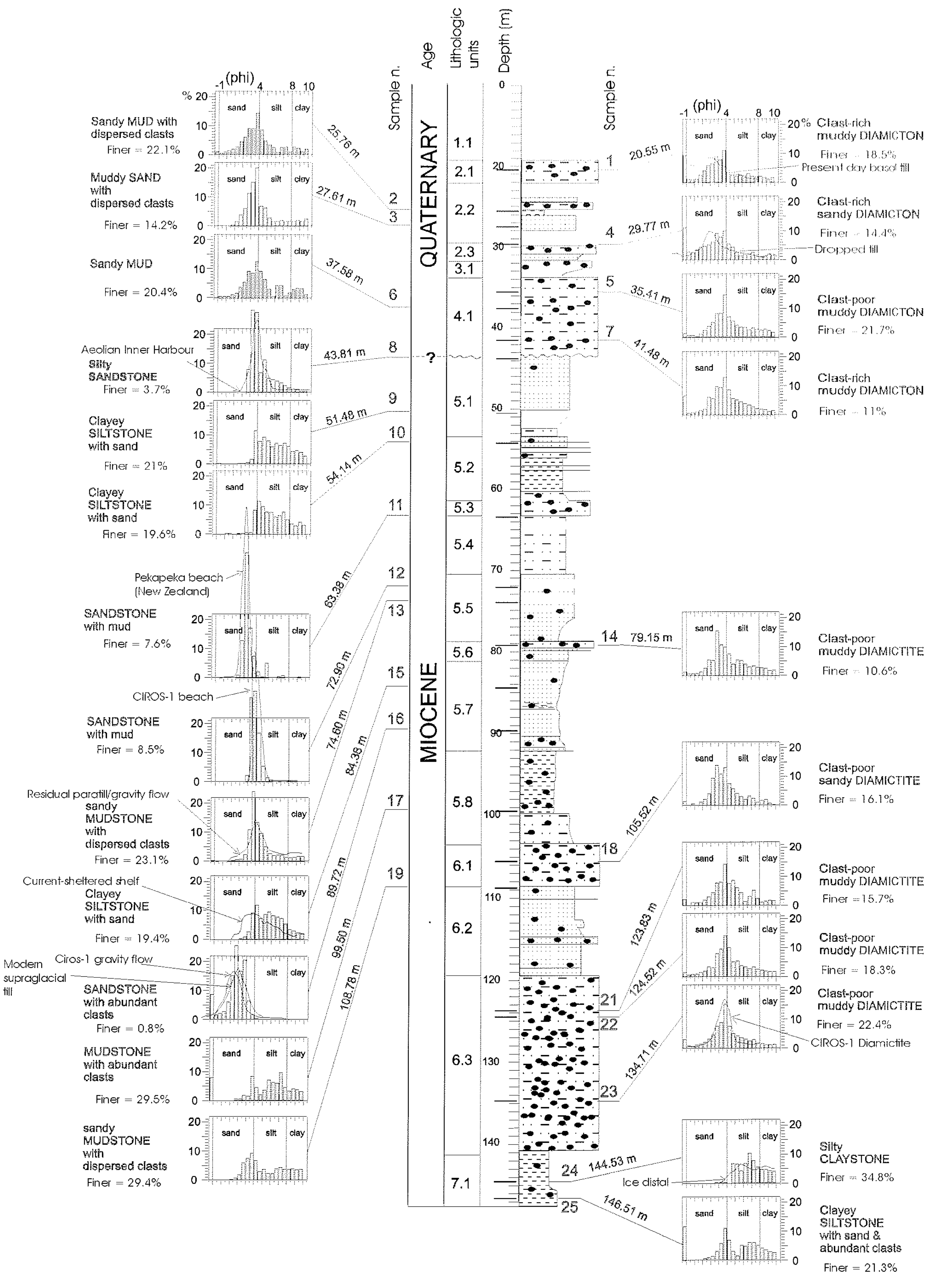


Fig. 3 - Lithological log for CRP-1, with histograms showing the size-frequency distribution of the samples reported here. Samples are indicated by their depth in metres and by sample number. Analytical data are given in table 1. Curves from modern and CIROS-1 facies analogues (Robinson, 1979; Macpherson, 1987; Barrett et al., 1983; Barrett 1989) have been superimposed over some histograms for comparison (see text for discussion).

the early Miocene core, were analysed in duplicate to check on the precision of the procedure. Differences range from 0.3 to 1.0 phi in mean size and from 0.2 to 4.9 in percent sand (Tab. 2). Around 3/4 of the samples contain gravel in proportions ranging up to 10%. However, because of the small sample size, the proportion of gravel cannot be reliably estimated. Grain-size statistics in table 2 and the sand-silt-clay plot in figure 4 are therefore calculated on a gravel-free basis.

Most samples are poorly sorted mixtures of sand, silt and clay. Samples from both Quaternary and early Miocene strata cluster in the "sandy mud" field in the centre of figure 4, indicating a lack of sorting, by strong currents or waves, and consistent with deposition from melting glacier ice. This group of samples forms a diamict textural facies. Beneath this, another large group of samples forms what we will term the mud textural facies (mud in this sense comprising silt and clay). Two subgroups are identified, a silt-dominated group A, and a clay-rich sandy group B. Samples of (muddy) sand, minimally sorted by wave or current processes, form a third textural facies. Each is discussed further below.

LITHOFACIES DESCRIPTION AND INTERPRETATION

DIAMICT FACIES

The diamict facies in CRP-1 forms around 70% of the Quaternary core but only 30% of the early Miocene sequence. Samples are generally very poorly sorted with a high proportion of mud (40 to 61%) and well developed mode in the fine to very fine sand size range (Fig. 3). The occurrence of striated clasts in the diamicts (Cape Roberts Science Team, 1998) shows that at least the larger clasts have been transported by basal glacier ice. However, their grain-size distributions appear rather different from those commonly observed in basal tills deposited from grounded ice (lodgement or deformation tills). Such basal tills do not have a such a well-defined mode, and instead approximate to a broad rectangular size distribution (*e.g.* Anderson et al., 1980; Powell, 1981; Barrett et al., 1983). In the case of basal debris from local outlet glaciers, such as the Mackay, there is a broad sand mode presumably from the erosion of Beacon sandstone and crystalline basement (Macpherson, 1987, sample 83-64, with curve superimposed on CRP-1 sample 1), but the mode is much broader.

Extremely poorly sorted muddy sediment with a moderately well developed sand mode has been observed over large areas of the Ross Sea today by Anderson et al. (1984). It has been explained, with the help of flume experiments by Singer & Anderson (1984), as a consequence of weak currents and strong bioturbation of sediment previously deposited by floating glacier ice, and has been termed residual glacial marine sediment. However, similar textures can also be achieved from the release of sediment by melting from basal glacial ice just seaward of the grounding line of a tidewater (*i.e.* marine-terminating) glacier, and sorting by weak currents as the sediment settles through the water column (*e.g.* Boulton, 1990; Powell, 1984, 1990).

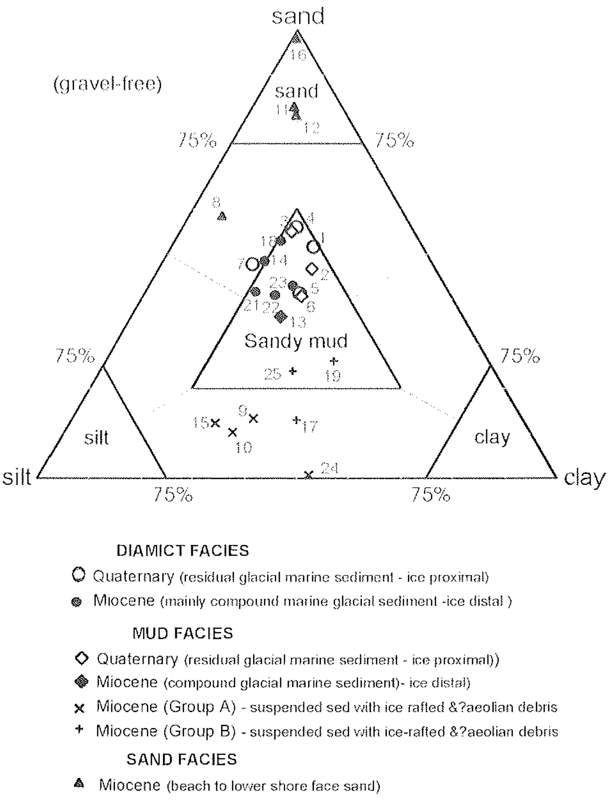


Fig. 4 - Diagram showing proportions of sand, silt and clay for samples from CRP-1 on a gravel-free basis, grouped by age and sediment type (classification of Hambrey et al., 1997, and following Anderson et al., 1980, 1984). Mud facies samples may also have been redeposited by sediment gravity flows.

CRP-1 Quaternary samples 1 (at 20.55 mbsf), 4 (at 29.77mbsf) and 7 (at 41.48 mbsf) are clast-rich diamicts with coarse-skewed histograms on account of having gravel contents from 6 to 10% (including some indurated sedimentary granules), although the samples still contain 40 to 50% mud (Fig. 3). Anderson et al. (1984) described similar samples as residual glacial marine sediments. The lithofacies from where these samples have been taken are described as generally structureless, compact, massive, and locally fossiliferous, but with no burrowing recognised (Cape Roberts Science Team, 1998). Lack of stratification suggests little or no current influence. This combination of observations suggests deposition of these samples took place by release of basal sediment into the water column just seaward of the grounding line of a tidewater glacier.

Diamicts in the Quaternary deposits of CRP-1 have some similarity to the diamicts of both basal and englacial origin from the modern Mackay Glacier in Granite Harbour (curve superimposed on the histogram of sample 1, Fig. 3), and also to dropped till from beneath the Mackay Glacier Tongue (facies A2 of Macpherson, 1987, see curve superimposed on the histogram of sample 4, Fig. 3). However the modern Granite Harbour samples have a coarser mode (about 2 phi) than the Quaternary CRP-1 diamicts (about 3 to 4 phi, Fig. 3), possibly on account of a difference source.

The CRP-1 samples include a number of clast-poor diamicts (sample 5 in the Quaternary and samples 14, 18, 21-23 in the Miocene strata). These diamicts have a symmetric grain-size histogram, unlike the skewed pattern of their clast-rich equivalents described above from the Quaternary section, and show a well-defined mode in the very fine sand size. Such sediments are termed compound glacial-marine sediments by Anderson et al. (1984), and are considered to be less glacially influenced than residual glacial-marine sediments. Their texture is similar to that of the diamictites from the lower section (late Eocene-early Oligocene) of CIROS-1 (see curve superimposed on histogram of sample 23, Fig. 3), which are interpreted to have been deposited from floating ice in a distal marine glacial setting (Hambrey et al., 1989). Other features recognised by the Cape Roberts Science Team (1998) in the clast-poor diamicts of CRP-1 included medium-scale bedding and bioturbation, with local concentration of granules and coarse sand, laminae and thin deformed beds at some levels. This lithofacies was considered by them to represent shallow marine sedimentation influenced by a fluctuating balance between gravity flow input and iceberg rafting. Thus both textural and sedimentological data suggest deposition of the clast-poor diamicts from CRP-1 in a more ice distal setting than the clast-rich diamicts discussed earlier.

From the preliminary analysis of the Cape Roberts Science Team (1998), and from our grain-size analyses, there appear to be no unequivocal subglacially deposited diamictites, although micromorphologic study of diamicts from early Miocene strata in CRP-1 shows features that could have formed only during periods of ice grounding (van der Meer & Hiemstra, this volume). Also, brecciated intervals up to 6 m thick occur in early Miocene strata down to a depth of 86 mbsf, and may also be a result of sub-glacial loading (Passchier et al., this volume). Furthermore, Fielding et al. (this volume) conclude from sequence stratigraphic analysis that glacier ice extended and grounded over the CRP-1 site on a number of occasions in early Miocene times. Although texture is not a definitive criterion for recognising subglacial deposition, the textures of diamictites that we have analysed all suggest some (mostly slight) wave or current influence - perhaps the strata cored in CRP-1 were deposited largely during periods of glacial recession, as suggested by Fielding et al. (this volume).

Mud Facies

Mud facies form just 10% of the Quaternary section, but 34% of the early Miocene section in CRP-1 (Cape Roberts Science Team, 1998). They are considered to have been deposited entirely below wave base but in a relatively shallow water coastal setting as the biota indicate. The two Quaternary samples 2 and 6 are very sandy, and contain dispersed clasts, like the muddy sand sample 3. They are considered to have a similar origin: residual glacial-marine sediment from winnowing of basal glacial debris as it settles through the water column. The prominent sand mode at 3.5 to 4.0 phi indicates a possible aeolian-derived very fine sand component.

The early Miocene samples cluster in two groups (Fig. 4): i) a silt-dominated group (A) with virtually no clasts, comprising sample 9 (51.48 mbsf), 10 (54.14 mbsf), 15 (84.38 mbsf) and 24 (144.53 mbsf), the latter being an unusually fine-grained sample, and ii) a clay-rich sandy group (B) with clasts up to 10%, comprising samples 17 (99.50 mbsf), 19 (108.78 mbsf) and 25 (146.51 mbsf). Group A has over 50% silt and most of the rest is clay, but a well-sorted very fine sand mode forms around 15% of the sample. Group B has a far more obvious bimodal distribution, with the same very fine sand, but a significant coarse silt deficiency and a fine silt-coarse clay mode. This bimodal distribution is also reflected by different colour (and presumably mineral composition) in the various fine fractions (finer than 4 phi). A light grey colour characterises the silt sizes, and a dark grey colour the finer sizes. The origins of the very fine sand mode are of some interest in such fine-grained sediment, especially when samples were taken in beds of uniform texture so that such a mode could not simply represent a well-sorted but thin layer of sand. In some samples, *e.g.* 9, 15 and 17, the mode has the size and very good sorting of wind-blown sand, but in other samples, and especially in Group B, the same mode is more poorly sorted. Similar sediment is accumulating on the floor of Granite Harbour today where current velocities are only a few centimetres per second (Macpherson, 1987; see curve superimposed on sample 15 histogram, Fig. 3). Our preferred view is that the mode is the result of sediment blown by the wind onto sea or glacier ice that subsequently calved, transported and deposited the sand offshore, to settle out with the mud transported in suspension.

Both Groups A and B samples belong to fine-grained lithofacies in which alternating laminations of siltstone and mudstone, locally rhythmic, have been recognised at various levels in early Miocene strata. Sharp-based, fining-upward laminated beds have been interpreted as the product of sediment gravity flows, with some of them turbidites (Howe et al., this volume). Rhythmic laminations, locally deformed by dropstones, resemble those forming in modern tidewater glacier settings, suggesting that they are analogous to tidal rhythmites (or "cyclopels", Mackiewicz et al., 1984), which today form close to an ice front in an environment affected by tidal flux. These fine alternations in lithology are particularly evident in the lower part of Unit 7.1, where some clayey siltstone laminae have a significant sand component (21% in sample 25 at 146.51 mbsf).

A truly ice distal depositional environment can be inferred for sample 24 at 144.53 mbsf, which has its finest mode concentrated in the fine silt and clay fractions (Figs. 3 & 4), and represents the upper 4 m of Unit 7.1. This interval is a uniform claystone, with very rare lonestones and indistinct fine lamination. This unit has been interpreted as having been deposited in quiet water by settling of the fine fraction from suspension, with little reworking by currents or gravity flows, and only episodic glacial influence. A similar grain-size distribution is shown by sediments sampled in the modern ice-distal open basin of Granite Harbour, where the sedimentation rate is 1-2 mm/year (Macpherson, 1987; see curve superimposed on sample 24 histogram, Fig. 3). This similarity should be kept in mind when considering the very low sedimentation rates suggested as an explanation for the frequent palaeomagnetic polarity changes in Unit 7.1 (Roberts et al., this volume).

Sand Facies

Sand forms 20% of the Quaternary section but 36% of the early Miocene section, and has been undersampled in this study. The only sand sample from the Quaternary section (27.71 mbsf) is extremely muddy (45%), and interpreted as residual glacial marine sediment that has been a little more winnowed than most.

Of the four sand samples from the early Miocene section, three have both a well-developed fine to very fine sand mode and a significant proportion of mud (18-42%). This is a feature of modern aeolian sediment blown onto the sea ice surface of Granite Harbour and settling to the sea floor as the ice breaks up (Macpherson, 1987; see curve superimposed on histogram of sample 8, Fig. 3). However, the extreme sorting is also a feature of temperate near-shore or beach sand (see curve superimposed on sample 11 histogram, Fig. 3), and uncharacteristic of the more poorly sorted beach sand today found in McMurdo Sound, where sea ice cover reduces sorting by wave action (Barrett et al., 1983). The same high degree of sorting is also found in laminated fine sand in late Oligocene strata cored in the CIROS-1 drillhole, 70 km to the south (Barrett, 1989) (see curve superimposed on sample 12 histogram, Fig. 3), interpreted as beach or shoreface sands in a sea ice-free setting. Well-sorted sand has also been described from banks and shallow inner shelf areas (less than 300 m deep) of the Ross Sea, as well as the outer shelf edge (Anderson et al., 1984), where they are attributed to deep currents. However, the sands lack a mud fraction and do not show the same extreme sorting of the sand mode. Other features of the Miocene CRP-1 sands are the scattered small pebbles, indicating that coastal ice was still calving during deposition. When we take into account the likely coastal setting and gentle sea floor topography of the time, as we have argued in the introduction above, we conclude that these samples are a mixture of beach-derived sand and mud from suspension deposited close to wave base. The gradual increase in sand content upcore (from example from 36% at 74.60 mbsf to 81% at 72.90 mbsf) could well represent an increase in wave influence resulting from a falling relative sea level, as documented by Dunbar et al. (1997).

Sample 16 (89.72 mbsf) is a moderately sorted medium-grained sand with around 10% gravel and only 2% mud. The grain-size distribution of the gravel-free portion is similar to two different types of deposits (see curves superimposed on histogram of sample 16 in Fig. 3). One is the debris on the surface of Mackay Glacier today, where mixtures of sand and gravel blown out onto the ice are washed down-glacier in summer meltwater streams. Similar mixtures of sand and gravel also form today on the surface, within and beneath temperate glaciers. The other is the sharp-based and graded sand beds in unit 19-22 of the CIROS-1 drillhole (Barrett, 1989), interpreted as the coarse portion of river-sourced, sediment gravity flows (Hambrey et al., 1989; Claps et al., 1998). The latter fits better with the sedimentological features of CRP-1 Unit 5.7, from which sample 16 was taken (sharp-based, medium-bedded, poorly sorted, siltstone and silty very fine sandstone lacking in bioturbation), as well as the variability in clast shape from angular to rounded (Cape Roberts Science Team, 1998, p. 71).

CONCLUSIONS

Grain-size analysis of 24 samples from CRP-1 shows that estimates in the 1:20 core logs (Cape Roberts Science Team, 1998) provide both a consistent and reasonably accurate description of sediment texture. A consideration of the drillsite location and water depth, the seismic data across it, and fossil-based estimates of past water depth, indicate that in early Miocene times the sea floor at CRP-1 was <100 m deep and sloped at a low angle (<0.5°) from the nearby coast. This is a rather different setting compared with that for the site in Quaternary times, when sediment accumulated on a submarine ridge rising several hundred metres above the surrounding sea floor.

Diamict facies sediment at CRP-1 comprise 70% of Quaternary strata but only 30% of early Miocene strata. They typically have a high mud content (40 to 61%) and variable gravel content (up to 10%). However, they are characterised by a narrow fine sand mode, in contrast to broad mode for basal glacial debris in the region today. Although the debris carries striated stones, which are plainly of basal glacial origin, this feature suggests that such sediment has experienced. Although not definitive, textures typical of deposition directly from basal ice have not been recognised.

Mud facies sediment, representing a minor part of the Quaternary strata, but forming a third of the early Miocene sequence, has a texture that indicates sedimentation from suspension. However, features recorded in visual core descriptions (Cape Roberts Science Team, 1998) suggest much redeposition by sediment gravity flows below wave-base, with significant contributions from floating ice. Some samples contain well-sorted fine to very fine sand that could represent an aeolian component.

Sand facies sediment is also a minor component of early Quaternary strata but makes up a third of the early Miocene sequence. It has well-sorted fine to very fine sand mode, which is interpreted as a mixing of beach-derived sand and sediment from suspension close to wave base. This suggests that trends of varying sand content may reflect changes in wave influence as a consequence of varying relative sea level, although glacial advances might have achieved a similar effect. Further work is needed to confirm and exploit these trends.

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