2001

Depositional Environments for Strata Cored in CRP-3 (Cape Roberts Project), Victoria Land Basin, Antarctica: Palaeoglaciological and Palaeoclimatological Inferences

R. D. Powell
Northern Illinois University

M. G. Laird
University of Canterbury

T. R. Naish
Institute of Geological and Nuclear Sciences

Christopher R. Fielding
University of Nebraska-Lincoln, cfielding2@unl.edu

L. A. Krissek
Ohio State University, Columbus

See next page for additional authors

Authors
R. D. Powell, M. G. Laird, T. R. Naish, Christopher R. Fielding, L. A. Krissek, and J.J. M. van der Meer

Terra Antartica
2001, **8**(3), 207-216

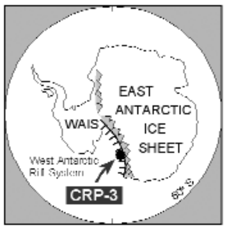
TERRA ANTARTICA

Depositional Environments for Strata Cored in CRP-3 (Cape Roberts Project), Victoria Land Basin, Antarctica: Palaeoglaciological and Palaeoclimatological Inferences

R.D. Powell[1*], M.G. Laird[2], T.R. Naish[3], C.R. Fielding[4], L.A. Krissek[5] & J.J.M. van der Meer[6]

[1]Department of Geology and Environmental Geosciences, Northern Illinois University, DeKalb, IL 60115 - USA
[2]Department of Geological Sciences, University of Canterbury, Private Bag 4800, Christchurch - New Zealand
[3]Institute of Geological and Nuclear Sciences, P.O. Box 30368, Lower Hutt - New Zealand
[4]Department of Earth Sciences, University of Queensland, Brisbane, QLD 4072 - Australia
[5]Department of Geological Sciences, Ohio State University, Columbus, OH 43210 - USA
[6]Department of Geography, Queen Mary College, University of London, London E1 4NS - UK

Received 6 February 2001; *accepted in revised form* 21 November 2001



Abstract - Cape Roberts Project drill core 3 (CRP-3) was obtained from Roberts ridge, a sea-floor high located at 77°S, 12 km offshore from Cape Roberts in western McMurdo Sound, Antarctica. The recovered core is about 939 m long and comprises strata dated as being early Oligocene (possibly latest Eocene) in age, resting unconformably on ~116 m of basement rocks consisting of Palaeozoic Beacon Supergroup sediments. The core includes ten facies commonly occurring in five major associations that are repeated in particular sequences throughout the core and which are interpreted as representing different depositional environments through time. Depositional systems inferred to be represented in the succession include: outer shelf, inner shelf, nearshore to shoreface each under iceberg influence, deltaic and/or grounding-line fan, and ice proximal-ice marginal-subglacial (mass flow/rainout diamictite/subglacial till) singly or in combination. The record is taken to represent the initial talus/alluvial fan setting of a glaciated rift margin adjacent to the block-uplifted Transantarctic Mountains. Development of a deltaic succession up-core was probably associated with the formation of palaeo-Mackay valley with temperate glaciers in its headwaters. At that stage glaciation was intense enough to support glaciers ending in the sea elsewhere along the coast, but a local glacier was fluctuating down to the sea by the time the youngest part of CRP-3 was being deposited. Changes in palaeoenvironmental interpretations in this youngest part of the core are used to estimate relative glacial proximity to the drillsite through time. These inferred glacial fluctuations are compared with the global $\delta^{18}O$ and Mg/Ca curves to evaluate the potential of glacial fluctuations on Antarctica for influencing these records of global change. Although the comparisons are tentative at present, the records do have similarities, but there are also some differences that require further evaluation.

INTRODUCTION AND REGIONAL SETTING

The Cape Roberts Project is an international co-operative drilling programme that was originally designed to recover continuous drill core from strata between about 30 and 100 Ma from western McMurdo Sound, Antarctica. The main aim of the project is to study the poorly constrained tectonic and climatic history of the region for this period of time. During the 1999 austral summer the third hole of the project, CRP-3, was drilled in 295 m of water, 12 km off Cape Roberts (Cape Roberts Science Team, 2000). CRP-3 was cored to 939 mbsf (metres below sea floor) with a 97% core recovery and terminated in strata thought to be of Devonian age sitting unconformably below strata of earliest Oligocene to latest Eocene age.

The drillsite was located on a sea floor high, Roberts ridge, which is a tectonic horst thought to have been rotated perhaps during and after Miocene time (see Cape Roberts Science Team, 2000, Figs. 7.7 and 7.8). Roberts ridge rises 500 m from the surface of the graben infill to the west between it and the present coast. To the north of Roberts ridge is a deep, sinuous, east-west trending sea floor trough, the Mackay Sea Valley. This is over 900 m deep and thought to have been eroded by an expanded Mackay Glacier. This glacier is a major outlet for the East Antarctic Ice Sheet and feeds into Granite Harbour just north of Cape Roberts. Like the Ferrar Valley 70 km to the south (*cf.* Barrett, 1989; Barrett & Hambrey, 1992), it is likely that the Mackay system has been a valley and palaeofjord since at least the mid-Oligocene times with the palaeo-Mackay Glacier advancing and receding within its trough. It is also known that several times during the Cenozoic Era

**Corresponding author* (ross@geol.niu.edu)

grounded ice expanded in the Ross Sea to a position well north of Roberts ridge (Brancolini et al., 1995; Licht et al., 1996). This ice may have eroded younger strata from the top of the ridge (Cape Roberts Science Team, 1998, p. 4).

Cape Roberts Project drillhole 1 (CRP-1) was drilled on Roberts ridge up-dip from CRP-2/2A and 3. The recovered core was about 147 m long, with the upper 43.55 mbsf dated as Quaternary and the older part of the sequence early Miocene (Roberts et al., 1998). This core includes nine facies: sandy diamict, muddy diamict, gravel/conglomerate, rubble/breccia, graded poorly sorted sand(stone), better sorted stratified sand(stone), mud(stone), clay(stone) and carbonate (Cape Roberts Science Team, 1998). Seven depositional systems were recognised on the basis of the facies: offshore shelf, ice protected/below wave-base; prodeltaic/offshore shelf; delta front/sandy shelf; ice contact and ice proximal, mass flow and submarine, fluvial efflux system; ice-contact and ice proximal, mass flow system; subglacial till/rainout diamict/debris flow diamicts singly or in combination; and a carbonate-rich shelf bank (Powell et al., 1998). The Quaternary section was interpreted to represent deposition on a polar shelf with two or three glacial fluctuations, and the Quaternary carbonate unit was thought to indicate a period of ice sheet retreat. In contrast, the early Miocene section was thought to represent deposition from polythermal glacial systems. The older early Miocene section was glacially dominated whereas the younger part was much less so.

CRP-2/2A was also drilled on Roberts ridge up-dip from CRP-3. CRP-2 was cored from 5 to 57 mbsf and CRP-2A was a minor drilling deviation at the same site, reaching down to 624 mbsf which terminated in early Oligocene strata (about 31 Ma, Wilson et al., 2000). The core was described as having twelve facies commonly occurring in associations that are repeated in particular facies sequences throughout the core and which were interpreted as representing different depositional environments through time (Cape Roberts Science Team, 1999). Depositional systems inferred to be represented in the succession included: outer shelf, inner shelf and nearshore to shoreface under iceberg influence, deltaic and/or grounding-line fan, and ice proximal-ice marginal-subglacial (mass flow/rainout diamictite/subglacial till) singly or in combination (Powell et al., 2000). The CRP-2/2A succession was interpreted in terms of deposition in glacimarine and coastal marine environments by a combination of tractional currents, fall out from suspension, sediment gravity flows and mass flows, rain-out from floating, glacial ice and deposition and redeposition in subglacial positions. By comparisons with modern glacimarine settings, this facies analysis showed that the amount of melt-water associated with the glaciers probably decreased from Oligocene time through the Miocene. In terms of comparative modern settings the data appear to agree with CRP-1 for the Miocene where the setting is thought most comparable with polythermal glaciers in the sub-Arctic (Powell et al., 1998). The trends of increasing evidence of melt-water and increasing rates of sedimentation down-core are used to infer progressively warmer temperatures and more temperate glaciation. The extreme end-member of fully temperate glaciation, as is found in Alaska, Iceland and Chile, appears to have been approached by strata lower in the core, based on proportions of preserved facies (Powell et al., 2000).

GENERAL STRATIGRAPHY AND LITHOFACIES

The Cenozoic strata cored in CRP-3 have been described lithologically and divided into 15 lithostratigraphic units and 34 subunits (Cape Roberts Science Team, 2000, Fig. 3.1, p. 59). They are thought to represent more or less continuous sediment accumulation with numerous small time breaks in the early Oligocene, possibly extending into the latest Eocene (31 to *ca.* 34 Ma; Hannah et al., this volume) (Fig. 1). Ten recurrent lithofacies are recognised within the core and are defined using lithologies or associations of lithologies, bedding contacts and bed thicknesses, texture, sedimentary structures, fabric and colour. The lithofacies scheme used for CRP-3 follows that for CRP2/2A with the exception of two facies, volcaniclastics and mudstone breccia, that do not occur in CRP-3. Although the same scheme is followed, modifications to the descriptions have been made because some characteristics are particular to CRP-3. The 10 lithofacies, which are based primarily on the visual core descriptions reported by the Cape Roberts Science Team (2000), are presented in table 1 and appendix 1, along with our palaeo-environmental interpretations. The reader is referred to photographs of each facies and particular features of note in the CRP-3 Initial Report (Cape Roberts Science Team, 2000, pp. 68-75).

FACIES SEQUENCES AND DEPOSITIONAL ENVIRONMENTS THROUGH TIME

The facies outlined above have common associations throughout the core. A combination of individual and associations of facies in vertical sequences and some particularly distinctive sedimentological or biological characteristics are used to interpret depositional environments up the core (Fig. 1; Tab. 1). This analysis is a synthesis, and attempts to keep groupings and facies sequences to a minimum; alternative interpretations may be possible in some instances and are discussed in the text below. The alternative interpretations may be resolved in

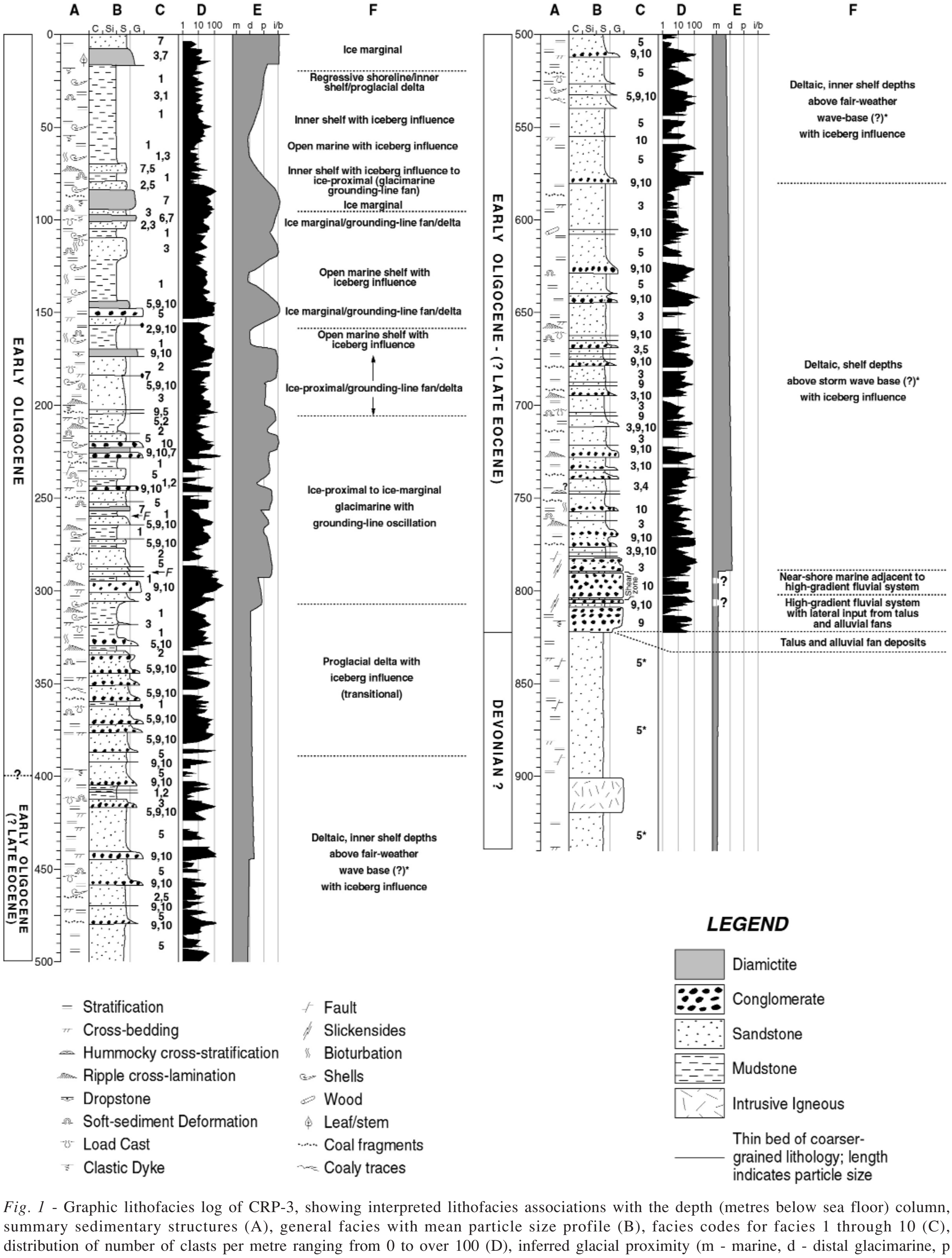


Fig. 1 - Graphic lithofacies log of CRP-3, showing interpreted lithofacies associations with the depth (metres below sea floor) column, summary sedimentary structures (A), general facies with mean particle size profile (B), facies codes for facies 1 through 10 (C), distribution of number of clasts per metre ranging from 0 to over 100 (D), inferred glacial proximity (m - marine, d - distal glacimarine, p - proximal glacimarine, i/b- ice contact/subglacial) (E), and interpreted depositional system and inferred palaeoenvironment (F). Note that facies in the LSU 2.1 (83.10 to 95.48 mbsf) interval are modified from the original log (Cape Roberts Science Team, 2000) following particle size analyses of Barrett (this volume).

future when other data, such as from palaeoecology, are also considered. The sequences are interpreted as representing particular settings which, when combined, define broad sedimentary environments and changes in environments through time. Some apparent dislocations in what could be predicted as a logical succession according to the principles of Walthers' Law, occur in parts of the core between the sequences

Tab. 1 - Summary table of facies characteristics and their interpretations of core CRP-3*.

Facies number and name		Key sedimentological characteristics	Depositional process interpretation	Key interpretation criteria
1	**Mudstone**	- massive, often sandy - local laminae - common lonestones - locally brecciated - marine macro- and microfossils	- hemipelagic suspension settling - rainout from ice rafting - may be modified by other processes - brecciated by tectonism or glacial tectonism	- fine-grained character - isolated clasts - marine fossils
2	**Interstratified sandstone and mudstone**	- sandstones on sharp contacts - sandstones grade up, often to mudstones - massive and amalgamated beds - planar stratified - local ripple cross-lamination - some normal, local reverse grading - dispersed to abundant clasts - marine macro- and microfossils	- range of marine processes: low- to moderate-density sediment gravity flow deposition; combined wave and current action - rapid deposition and resedimentation	- sandstone/mudstone association - style of internal stratification and grading - marine fossils
3	**Poorly sorted (muddy) very fine to coarse sandstone**	- various poorly sorted sandstones - locally massive and amalgamated - locally planar laminated and bedded - normal grading, local reverse - local ripple cross-lamination - local soft-sediment deformation, boudinage - local dispersed clasts grading to matrix-supported conglomerate - marine macro- and microfossils	- medium- to high-density sediment gravity flow deposition - very fine to fine sandstones may be from settling from turbid plumes with high sediment concentrations - may be massive due to depositional processes or mixing by bioturbation, freeze/thaw, loading	- style of internal stratification and grading - degree of sorting - marine fossils
4	**Moderately to well sorted, stratified fine sandstone**	- local low angle cross-bedding and cross-lamination - locally planar, thin bedded to laminated - possible HCS - quartz rich, local coal laminae - locally with dark mudstone, bituminous - penecontemporaneous soft-sediment deformation - marine macro- and microfossils	- dilute tractional currents (within or about wave base to shoreface)	- style of internal stratification - particle size and sorting - marine fossils
5	**Moderately to well sorted, stratified or massive, fine to coarse sandstone**	- mostly medium-grained, locally fine or coarse - planar- to cross-stratified - locally massive and amalgamated - dispersed to abundant clasts - local gravelly layers at base - weak to moderate bioturbation - marine fossils	- marine currents/wave influence (perhaps shoreface) - local erosion with hiatuses - rainout from iceberg rafting	- particle size and sorting - style of internal stratification - bioturbation - marine fossils

*Notes in addition to those presented in the Initial Reports volume (Cape Roberts Science Team, 2000) regarding interpretation of these facies are presented here in the Appendix.

of interpreted facies associations. The dislocations may be real and indicate intervals of erosion, such as by a glacier, or they may represent extremely rapid switches in depositional processes, as is common in the inferred environments.

The percentage of each facies up the core was tabulated by subdividing the succession into its lithostratigraphic units (LSUs), in order to evaluate trends with time (Tab. 2). A note of caution is that the record is likely to have been deposited under very high sediment accumulation rates in most intervals (see discussion below) and given the time control on the succession, much of the record must be missing. We have no way of estimating the proportion of each facies in each time interval that has been lost. Thus the percentages used here are probably biased toward deeper water and/or more ice-distal deposits, which have a greater likelihood of being preserved.

The oldest preserved record (LSU 15.3-15.1) above the Beacon Sandstone is dominated by coarse clastic debris interpreted as terrestrial talus. This is followed immediately by conglomerate supported by a matrix dominated by mudstone (LSU 14.1), which is inferred to represent deposition on a fan-delta with sufficient marine or lacustrine influence to allow quiet water sedimentation and settling of fines. Through a transition (LSU 13.2) the succession is then dominated by sandstones with minor conglomerates (LSU 13.1-11.1) that are most likely fluvial-deltaic associations. At this time, glaciers may have been becoming established locally as a sediment source, but they were further developed elsewhere because they produced icebergs to raft lonestones to the site. Thicker mud intervals are first preserved in LSU 12.2, but are more common in the LSUs 10.1 and younger, indicating the preservation of probably more common offshore conditions. Between LSU 10.1 and 3.1 there are repeated fining-upwards intervals from conglomerate through sandstone to mudstone facies. These are interpreted as having a source from glacial meltwater discharges and deposited in shallow marine settings, mostly above wave base and most likely in a deltaic system. Local glaciers were probably entering the sea during times represented by LSU 6.1 and younger, based on the poorly sorted character of the facies and presence of diamictites. Following and including the time that LSU 2.2 accumulated, glaciers had a strong presence in the area as reflected by thick diamictite units in a commonly mud-rich, marine section. Using the models of glacimarine sedimentation (*e.g.* Dowdeswell, 1996; Powell & Alley, 1997; Dowdeswell et al., 1998) as a guide, the large amount of sorted sediment introduced by meltwater, the common deltaic systems, the rapid sediment accumulation rates and a dominance of gravelly mudstones/muddy sandstones over diamict, all point to a warm glacial system present in the area, being temperate or perhaps the very warm end of the polythermal glacier spectrum.

Following these general trends in facies, five

Tab. 2 - Percentage of facies in each lithostratigraphic unit (LSU) within CRP-3. Facies numbers correspond to their description in the text and in table 1; mbsf refers to the depth in metres below the sea floor of the lower contact of each LSU.

LSU	mbsf	1	2	3	4	5	6	7	8	9	10
1.1	16.72			15	2			83			
.2	52.00	94		2					4		
.3	70.40	94		2					4		
.4	83.10	13	21	52		7		2	5		
2.1	95.48	1	11					88			
.2	120.20	16	8	50			4	22			
3.1	144.67	96	1	1					2		
4.1	157.22		8			25		4		30	33
5.1	169.47	17	73	4			1		5		
.2	176.42			88			4	1			7
.3	184.45	3	36			27	7		4	12	12
6.1	202.18	71	18	6			5				
7.1	211.40					86			5	9	
.2	264.33	14	16	1		49		2		5	13
.3	270.51	100									
.4	293.43	4	9	2		76			3	3	3
.5	306.26	1				26				36	37
8.1	324.88	56		33		8			3		
9.1	406.00	3	4	6		76				5	6
10.1	413.56	39	40	16		5					
11.1	444.44					96				2	2
12.1	458.48					98				1	1
.2	462.91		100								
.3	539.31			1	3	87				5	4
.4	558.87					91				4	5
.5	576.28					90				5	5
.6	605.90			83		8				3	5
.7	611.03					97					3
13.1	767.70			59	11	20				4	6
.2	789.77	3		55		1				14	28
14.1	805.60										100
15.1	813.41									50	50
.2	822.87									100	
.3	823.11									100	

facies associations have been defined in upward succession (for details of interpretation see Cape Roberts Science Team (2000; pp. 187-197) and in the discussion section below):

1. monomictic breccia and conglomerate, derived from the Beacon Supergroup (823.11-822.88 mbsf) interpreted as probably being talus immediately above the unconformity due to clast composition and angularity.
2. clast-supported conglomerate and minor sandstone (822.88-789.77 mbsf) interpreted as grading upward from facies association 1 into a high gradient fluvial system capable of transporting boulders of greater than 1 m initially with a talus contribution. Up-core from about 804 mbsf, mud becomes a major matrix component and is taken to possibly represent a transition from terrestrial to marine conditions.
3. muddy sandstone with subordinate conglomerate (789.77-~580 mbsf) are interpreted as sediment gravity flow deposits mainly of debris flow and high-density turbidity current origin. They are thought to have been deposited in a deltaic setting in varying water depths but often above at least storm wave-base. Iceberg rafting over the delta probably indicates that the delta itself was fed by glacial outwash streams.
4. clean sandstone with subordinate conglomerate (~580-378.36 mbsf) which due to their better sorting, are thought to have been deposited in shallower water than facies association 3, though they are still marine, and likely to be delta-front deposits. Their cleanness may also be a function of the decreasing proximity of the glacier source or by an increase in sorting due to wave action (Barrett, this volume).
5. muddy sandstone and mudstone, with subordinate conglomerate and diamictite (378.36-0.00 mbsf) are similar to associations found in younger CRP cores and are interpreted as being of temperate glacimarine origin commonly associated with their grounding lines.

A more detailed record of glacial fluctuations also can be inferred from the interpreted sequences of facies. This record is presented in figure 1 as a curve showing relative glacial proximity to the drillsite. It is difficult to use the sequence of facies associations to infer relative sea-level changes because of the complex interaction in the inferred environments between changes in sediment source and changes in sea level, as is discussed below.

DISCUSSION AND DEPOSITIONAL MODELS

The sequence recovered in CRP-3 is dominated by facies representative of shallow marine settings, as is indicated by the sporadic occurrence of marine fossils through the core. Characteristic lithofacies complement these conclusions from fossils, such as:

- the mudstone of Facies 1, indicative of hemipelagic sedimentation,
- the interstratified sandstone and mudstone of Facies 2, indicative of either dilute marine currents, such as from wave action, or sediment gravity flows,
- the poorly sorted sandstone of Facies 3, deposited by sediment gravity flows, or settling from turbid plumes,
- the stratified, fine sandstones of Facies 4, with possible hummocky cross-stratification, indicative of wave-base settings,
- presence of lonestones of various types set with textural contrast in mudstones and sandstones and which are interpreted as having been iceberg rafted (Atkins, this volume),
- the common gradational contacts of the diamictites in Facies 6 and 7 and the interbedding of some intervals with other marine facies, indicative of proximal glacimarine redeposition and rain-out processes,
- the rhythmic sandstones and siltstones of Facies 8 that are interpreted as cyclopsams and cyclopels from highly sediment-charged, glacial streams in the sea.

From the individual facies and their associations, the shallow marine settings appear to have varied from the shoreface to wave base and beyond, but they also appear to include alluvial fan/fan delta, fluvial/deltaic and grounding-line fan settings with large fluvial discharges. Associated processes were commonly delta/fan front and prodeltaic/fan sediment gravity flow deposits, as well as cyclopels and cyclopsams in the younger part of the core. Commonly both fan and deltaic settings are associated with ice-marginal and ice-proximal environments.

The intimate association of fan sediments with debris flow diamictites and penecontemporaneous, sediment deformation in the younger part of the core are common grounding-line associations. Indeed, the volume of sediment associated with melt-water influx and rapid deposition, with consequent slumping and redistribution indicate a polythermal to temperate glacial condition. During periods when the glacier advanced into the sea the relatively flat shoreface and shelf may have relief produced by grounding line deposits in the form of morainal banks, sufficient to produce mass flow and sediment redeposition. Isolated banks may have also created restricted circulation conditions on their shoreward side during some time periods, as is indicated by some macrofossil assemblages and some of the darker Facies 1 mudstones which represent distal glacimarine and paraglacial conditions.

The CRP-3 site was initially dominated by talus and alluvial fan depositional systems (facies associations 1 and 2) in a tectonically active subsiding basin (see discussion in Cape Roberts Science Team, 2000) that can be viewed in terms of models established by Postma (1990), Prior & Bornhold (1990) and Nemec (1990). Because the palaeo-Transantarctic Mountains were in their early formational stages, relief of the area may not have been as high as that depicted in the models in the literature. However, the geometry of the systems showing talus and cone-shaped fans being established along coastal mountains and rapidly building into the sea to form an alluvial fan/delta system (Prior & Bornhold, 1990) is thought to be very appropriate for the oldest Cenozoic strata cored in CRP-3. In the initial stages of the development of palaeo-Mackay valley the system follows more that depicted by Nemec (1990). Perhaps his conical underwater delta lacking a subaerial distributary plain is an appropriate analogue for the early phase of the valley/delta system (facies association 3). His Gilbert-type delta variety is more like a later phase represented by facies association 4.

Previously, a conceptual model was constructed in order to demonstrate how the CRP-2/2A succession may have accumulated during repeated cycles of glacial advance and retreat (Powell et al., 2000, Fig. 2). In that figure, hypothetical facies associations and sequences are generated by a series of glacial advance, retreat and readvance. Much of the record of CRP-3 can also be interpreted using this model. Facies associations 3 and 4 of the record represent fluvial-deltaic outwash systems that occurred as shown in the model, but probably were forming before the very first glacial advance down the palaeo-Mackay valley. Facies association 5 represents a time when glaciers actually advanced into the sea from the valley and were the start of the glacial fluctuation cycle described by the model that last through the Miocene as recorded in CRP-2/2A and CRP-1.

CONCLUSION AND PALAEOCLIMATIC AND PALAEOGLACIAL HISTORY

The CRP-3 succession is interpreted in terms of deposition along a glaciated continental margin in early phases of rifting and mountain formation. Initial deposition was as talus at the marine margin of a faulted, uplifting coastal mountain system that was rapidly followed by building of cone shaped fans and alluvial fan to fan delta systems as they grew and also became marine (facies associations 1 and 2). Sedimentation continued to be rapid and the setting may well have been glaciated at this stage but there is no supporting evidence. However, during the next phases of valley formation in the area and the establishment of fluvial and deltaic systems, the headwaters may well have been glaciated because sediment accumulation rates were high and there are striated clasts and lonestones used as indicators of iceberg rafting. The icebergs must have originated elsewhere along the coast, but they are significant in that they show glaciation was sufficiently intense to provide a positive mass balance while maintaining a marine terminus. Given the temperate conditions, precipitation must have been very high to enable glaciers to maintain marine termini and that strongly argues for having a fully glaciated coastal mountain range at least by this stage (facies association 3) even if all of the glaciers did not reach tidewater. Such settings are common along glaciated coasts of Chile and Alaska today and valley trains feed fan deltas from valley glaciers while nearby the glaciers have tidewater termini. By the time facies association 4 was being deposited the glaciers had either retreated slightly or the palaeo-Mackay Valley had developed more fully such that the fluvial system was well developed and a distinct delta plain was established (*cf.* Nemec, 1990).

Facies association 5 is more similar to successions recovered in CRP-2/2A and CRP-1, with much more evidence of direct glacial activity. In that succession glacimarine and coastal marine environments are represented by a combination of tractional currents, fall out from suspension, sediment gravity flows and mass flows, rain-out from floating, glacial ice and deposition and redeposition in subglacial positions. By comparison with modern glacimarine settings, our facies analysis shows that the amount of melt-water associated with the glaciers probably was very large and sedimentation rates were high. The extreme end-member of fully temperate glaciation, as is found in Alaska, Iceland and Chile today, appears to have been approached. This interpretation is in agreement with that made for the lower strata in CRP-2/2A, which was made based on proportions of preserved facies and terrestrial palynological data (Powell et al., 2000). Thus, there is a trend through the entire Cape Roberts section of decreasing evidence of melt-water and rates of sedimentation up-section are used to indicate progressively cooler temperatures through Oligocene times until in the Miocene, the setting is thought more comparable with polythermal glaciers in the sub-Arctic (Powell et al., 1998).

The history of growth and decay of the East Antarctic Ice Sheet and its links with eustatic sea level change were two of the questions that the Cape Roberts Project was designed to address. Lithofacies analysis of the core can address these questions, at least in part, at this early stage of data analysis and synthesis. If the sequence of interpreted depositional environments is placed in chronological control from various dating methods (see Hannah et al., this volume) a comparison can be made of the inferred glacial history from CRP-3 with the broad trends in the global eustatic sea level curve (Haq et al., 1987), the oxygen isotope records from the deep sea (*e.g.* Zachos et al., 2001) and the derived Mg/Ca curve for inferred ice volume changes (Lear et al., 2000). When making these comparisons the question must be asked as to whether all of the glacial fluctuations recorded in the CRP core represent major changes in volume of the full East Antarctic Ice Sheet or simply those of one of its outlets or even a locally fed glacier. That is, should we expect a concomitant change in eustatic changes in global sea level or changes in chemistries of the far-field proxy records that correspond with the inferred glacial fluctuations in the CRP-3 record?

Undoubtedly some of the recorded glacial fluctuations do coincide with major changes in ice sheet volume and with the consequent global changes, as has been demonstrated for three sequences in CRP-2/2A (Naish et al., 2001). However, given what we know of both modern and Pleistocene behaviour of glaciers under the same regimes as we infer for CRP-3, synchroneity with major ice sheet volume changes is not necessarily the condition for each glacial fluctuation recorded in the CRP-3 cores. For example, many coastal marine-ending glaciers responded to the Little Ice Age with significant advances and retreats, some by more than 70 km (Powell, 1990b); and that occurred without a significant change in eustasy. The record of large changes in the Laurentide Ice Sheet as reflected by iceberg-rafting events in the Heinrich layers of the North Atlantic also appear to have occurred without significant changes in the position of the rest of the ice sheet margin and sea level, although they are detected in deep-marine proxy records (as recently summarized by Bond et al., 1999). Therefore, caution must be used in assigning major changes in the East Antarctic Ice Sheet from a local record of glacial fluctuations close to one outlet glacier.

Coarsening and fining facies trends that are commonly used to help define stratigraphic sequences and relative sea level changes on many low latitude continental shelves can also be generated by relative changes in glacier proximity to a site on glaciated continental margins. In such settings located at rifted margins, it can be possible to have a monotonic increase in relative sea level from tectonic subsidence to create accommodation space for a superimposed sedimentary record produced by repeated glacial advances and retreats. Those conditions are likely to have been the situation for at least some of the CRP glacial fluctuations, where the repetition of glacial pulses and sediments could have occurred without the need to create accommodation space by eustasy.

With this discussion in mind a brief, preliminary comparison of global proxy records is made here; the $\delta^{18}O$ and Mg/Ca records are considered most reliable for the comparison. Given the poor dating control thus far on the lower part of CRP-3 and also lack of evidence of glacial fluctuations below facies association 5, the discussion here can only address the record represented in facies association 5. That interval in the core appears to lie within the time range of 31.4 to 31.7 Ma, with some extrapolation from known data points (Hannah et al., this volume). Over that interval of time the $\delta^{18}O$ record has about three small scale, short term fluctuations (and even more smaller scale ones) (Zachos et al., 1996; 2001). Over the same interval of time the broad trend of ice sheet volume inferred from Mg/Ca ratios shows a decreasing trend, but short term fluctuations are as yet unresolved. Comparatively, the glacial proximity curve of CRP-3 shows at least four glacial fluctuations and several even smaller-scale oscillations. Furthermore, placing this CRP-3 record in perspective with the entire CRP record, as noted above, there is decreasing evidence of melt-water and rates of sedimentation up-section, which are used to indicate progressively cooler temperatures through Oligocene times and into the Miocene. This trend appears to be the inverse of that inferred from the global oxygen isotope record which has lower isotopic values (less ice/warmer water) in early Miocene and late Oligocene than for early Oligocene (*cf.* Zachos et al., 2001). However, CRP appears to have been glaciated for progressively smaller intervals of time from Oligocene through Miocene time, which does support the suggestions of Lear et al. (2000) and Zachos et al. (2001) that Antarctic ice sheets were probably smaller in volume or more ephemeral during the Miocene compared with the Oligocene. Although these are tentative comparisons at present due to poor dating resolution, there appear to be some similarities and also important differences that require further investigation.

FUTURE WORK

This paper should be treated as a preliminary interpretation, given the recognised limitations of facies analysis in a single core, where 3-D relationships cannot be determined. More reliable, closely spaced seismic reflection surveys are required along this coast at appropriate (medium to high) resolution and in dip and strike orientations. Those surveys would help map out sediment packages defined in cores and describe their geometries and architecture. Palaeoevironmental interpretations are best done with as much diverse data as possible. As many data-sets on the core are still being accumulated, a more reliable interpretation must await results from these studies. In the future, it is hoped that the trends in relative water depth and glacial fluctuations can be refined. These records must be integrated with other trends in variables such as magnetic susceptibility, mineralogy (bulk, sand, clays), clast- and sand-grain composition and detailed clast variability. A more comprehensive integration of palaeoecological data is needed, as well as a more thorough evaluation of diamictite fabrics, micromorphology, over-consolidation events, and relationship between *in situ* brecciation and glacial over-riding. Perhaps major erosion events can then be recognised and linked to true sequence boundaries that are in turn related to sea-level changes. Only then will it be possible to test the glacial fluctuation record against the global eustatic record.

ACKNOWLEDGEMENTS - We wish to thank the drillers and core recovery staff for providing the best quality core possible. We thank the Antarctic Support Associates support staff for their great assistance in laboratory and equipment support, as well as the staff at Scott Base. The project chief scientist, Peter Barrett is acknowledged for his work in establishing and steering the project, and with the scientific steering committee, for ensuring a successful outcome to the final seasons drilling. Peter Webb is thanked for organising the U.S. scientific component. We thank other participating project scientists for stimulating discussions and interactions, as well as for the help they provided. The authors wish to thank Grant Young, Anders Elverhøi, and Peter Barrett for constructive reviews of the manuscript. This aspect of the sedimentological part of the project was supported by NSF grants to RDP (OPP-9527481) and LAK (OPP-9527482). MGL thanks Antarctica New Zealand for its support. JJMvdM was supported by the Antarctic Programme of the Netherlands Organisation for Scientific Research (NWO) and he acknowledges supportive collaboration with Antarctica New Zealand.

REFERENCES

Atkins C.B., 2001. Glacial influence from clast features in Oligocene and Miocene strata cored in CRP-2/2A and CRP-3, Victoria Land Basin, Antarctica. This volume.

Barrett P.J. (ed)., 1989. Antarctic Cenozoic history from the CIROS-1 drillhole, McMudro Sound. *DSIR Bull*., 245, Science Information Publishing Centre, Wellington, 254 p.

Barrett P.J. & Hambrey M.J., 1992. Plio-Pleistocene sedimentation in Ferrar Fiord, Antarctica. *Sedimentology*, **39**, 109-123.

Barrett P.J., 2001. Grain-size analysis of samples from Cape Roberts Core CRP-3, Victoria Land Basin, Antarctica, with inferences about depositional setting and environment. This volume.

Blair T.C. & McPherson J.G., 1994. Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages. *J. Sedimentary Research*, **A64**, 450-489.

Bond G.C., Showers, W., Elliot M., Evans M., Lotti R. Hajdas I., Bonani G. & Johnson S., 1999. The North Atlantic's 1-2 kyr climate rhythm: Relation to Heinrich Events, Dansgaard/Oeschger Cycles and the Little Ice Age. In Clark, P.U., Webb, R.S & Keigwin, L.D. (eds) *Mechanisms of Global Climate Change at Millennial Time Scales*, American Geophysical Union, Geophysical Monograph Series, **112**, 35-58.

Brancolini G., Cooper A.K. & Coren F., 1995. Seismic facies and glacial history in western Ross Sea (Antarctica). In: Cooper A.K. & Barker P.F & Brancolini G. (eds.), *Geologic and Seismic Stratigraphy of the Antarctic Margin,* American Geophysical Union, Antarctic Research Series, **68**, 209-233.

Cai J., Powell R.D., Cowan E.A. & Carlson P.R., 1997. Lithofacies and seismic reflection interpretations of temperate glacimarine sedimentation in Tarr Inlet, Glacier Bay, Alaska. *Marine Geology*, **145**, 5-37.

Cape Roberts Science Team, 1998. Initial report on CRP-1, Cape Roberts Drilling Project, Antarctica. *Terra Antartica*, **5**, 1-187.

Cape Roberts Science Team, 1999. Initial report on CRP-2/2A, Cape Roberts Drilling Project, Antarctica. *Terra Antartica*, **6**, 1-173.

Cape Roberts Science Team, 2000. Initial report on CRP-3, Cape Roberts Drilling Project, Antarctica. *Terra Antartica*, **7**, 1-209.

Cowan E.A., Cai J., Powell R.D., Clark J.D & Pitcher J.N., 1997. Temperate glacimarine varves from disenchantment Bay, Alaska. *Journal Sedimentary Research*, **67**, 536-549.

Cowan E.A., Cai J., Powell R.D., Seramur K.C. & Spurgeon V.L., 1998. Modern tidal rhythmites deposited in deep water. *Geo-marine Letters*, **18**, 40-48.

Cowan E.A., Cai J., Powell R.D. & Seramur K.C., 1999. Tidal and meltwater controls on cyclic rhythmic sedimentation in an Alaskan fjord. *Sedimentology*, **46**, 1109-1126.

Cowan E.A. & Powell R.D., 1990. Suspended sediment transport and deposition of cyclically interlaminated sediment in a temperate glacial fjord, Alaska, U.S.A. In: Dowdeswell J.A. & Scourse J.D. (eds.), *Glacimarine Environments: Processes and Sediments.* Geological Society London, Spec. Pub., **53**, 75-89.

Domack E.W., Jacobson E.A., Shipp S., & Anderson J.B., 1999. Late Pleistocene/Holocene fluctuation of the West Antarctic Ice Sheet in the Ross Sea: Part 2- sedimentologic and stratigraphic signature. *Geological Society America Bulletin,* **111**, 1517-1536.

Dowdeswell J.A., Kenyon N.H., Elverhøi A., Laberg J.S., Hollender F.-J., Mienert J. & Siegert M.J., 1996. Large-scale sedimentation on the glacier-influenced polar North Atlantic margins: Long-range side-scan sonar evidence. *Geophysical Research Letters*, **23**, 3535-3538.

Dowdeswell J.A., Elverhøi A. & Spielhagen R., 1998. Glacimarine sedimentary processes and facies on the Polar North Atlantic Margins. *Quaternary Science Reviews*, **17**, 243-272.

Dowdeswell J.A., Whittington R.J., Jennings A.E., Andrews J.T., Mackensen A. & Marienfeld P., 2000. An origin for laminated glacimarine sediment through sea-ice build-up and suppressed iceberg rafting. *Sedimentology*, **47**, 557-576.

Dowdeswell J.A., Whittington R.J., & Marienfeld P., 1994. The origin of massive diamicton facies by iceberg rafting and scouring. *Sedimentology*, **41**, 21-35.

Hambrey M.J., Barrett P.J., Ehrmann W.U., Larsen B., 1992, Cenozoic sedimentary processes on the Antarctic continental shelf: the record from deep drilling. *Zeitschrift Geomorphology*, **86**, 77-103.

Hambrey M.J. & McKelvey B., 2000. Neogene fjordal sedimentation on the western margin of the Lambert Graben, East Antarctica. *Sedimentology*, **47**, 577-608.

Hannah M.J., Wrenn J.H. & Wilson G.J., 2001. Preliminary report on early Oligocene and ?latest Eocene marine palynomorphs from CRP-3 drillhole, Victoria Land Basin, Antarctica. This volume.

Haq B.U., Hardenbol J. & Vail P.R., 1987. Chronology of

fluctuating sea levels since the Triassic. *Science*, **235**, 1156-1166.
Hein F.J., 1984. Deep-sea and fluvial braided channel conglomerates: a comparison of two case studies. In Koster, E.H. & Steel, R.J. (eds), *Sedimentology of Gravels and Conglomerates. Canadian Society Petroleum Geologists Memoir*, **10**, 33-49.
Johnson H.D. & Baldwin C.T., 1996. Shallow clastic seas. In: Reading, H.G. (ed*), Sedimentary Environments: Process, Facies and Stratigraphy*, Blackwell Science, London, 232-280.
Hunter L.E., Powell R.D. & Smith G.W., 1996. Facies architecture and grounding-line fan processes of morainal banks during the deglaciation of coastal Maine. *Geological Society America Bulletin*, **108**, 1022-1038.
Kneller B.C & Branney M.J., 1995. Sustained high density turbidity currents and the deposition of thick massive sands. *Sedimentology*, **42**, 607-616.
Lear C.H., Elderfield, H. & Wilson, P.A., 2000. Cenozoic deep-sea temperatures and the global ice volumes from Mg/Ca in benthic foraminiferal calcite. *Science*, **287**, 269-272.
Licht K.J., Jennings A.E., Andrews J.T. & Williams K.M., 1996. Chronology of late Wisconsin ice retreat from the western Ross Sea, Antarctica. *Geology*, **24**, 223-226.
Lønne I., 1995. Sedimentary facies and depositional architecture of ice-contact glaciomarine systems. *Sedimentary Geology*, **98**, 13-43.
McCabe A.M. & Ó Cofaigh C., 1995. Late Pleistocene morainal bank facies at greystones, eastern Ireland: an example of sedimentation during ice-marginal re-equilibration in an isostatically depressed basin. *Sedimentology*, **42**, 647-664.
Mohrig D., Whipple K.X., Honoz M. Ellis C. & Parker G., 1998. Hydroplaning of subaqueous debris flows. *Gelological Society America Bulletin*, **110**, 387-394.
Mohrig D., Elverhøi A. & Parker G., 1999. Experiments on the relative mobility of muddy subaqueous debris flows and their capacity to remobilize antecedent deposits. *Marine Geology*, **154**, 117-129.
Mulder T. & Cochonat P., 1996. Classification of offshore mass movements. *J. Sedimentary Research*, **66**, 43-57.
Naish T.R., Woolfe K.J., Barrett P.J., Wilson G.S. Atkins C., Bohaty S.M., Bücker C.J., Claps M., Davey F.J., Dunbar G.B., Dunn A.G., Fielding C.R., Florindo F., Hannah M.J., Harwood D.M., Henrys S.A., Krissek L.A., Lavelle M., van der Meer J., Mcintosh W.C., Niessen F., Passchier S., Powell R.D., Roberts A.P., Sagnotti L., Scherer R.P., Strong C.P., Talarico F., Verosub K.L., Villa G., Watkins D.K. Webb P.-N. & Wonik T., 2001. Orbitally induced oscillations in the East Antarctic ice sheet at the Oligocene/Miocene boundary. *Nature*, **413**, 719-723.
Nemec W., 1990. Aspects of sediment movement on steep delta slopes. In: Colella A. & Prior D.B. (eds.), *Coarse-grained Deltas*, International Association of Sedimentologists, Special Publication, **10**, 29-74.
Nemec W. & Steel R.J., 1984. Alluvial and coastal conglomerates: their significant features and some comments on gravelly mass-flow deposits. In Koster, E.H. & Steel, R.J. (eds.), *Sedimentology of Gravels and Conglomerates*. Canadian Society Petroleum Geologists Memoir, **10**, 33-49.
Pickering K.T., Hiscott R.N. & Hein F.J., 1989. *Deep Marine Environments*, Unwin Hyman, London, 416 pp.
Plink-Bjorklund P. & Ronnert L., 1999. Depositional processes and internal architecture of Late Weichselian ice-margin submarine fan and delta settings. *Sedimentology*, **46**, 215-234.
Postma G., 1990. Depositional architecture and facies of river and fan delta systems: a synthesis. In: Colella A. & Prior D.B. (eds.), *Coarse-grained Deltas*, International Association of Sedimentologists, Special Publication, **10**, 13-27.
Postma G., Nemec W. & Kleinspehn K.L., 1988. Large floating clasts in turbidites: a mechanism for their emplacement. *Sedimentary Geology*, **58**, 47-61.
Prior D.B. & Bornhold B.D., 1990. The underwater development of Holocene fan deltas. In: Colella A. & Prior D.B. (eds.), *Coarse-grained Deltas*, International Association of Sedimentologists, Special Publication, **10**, 75-90.
Powell R.D. & Molnia B.F., 1989. Glacimarine sedimentary processes, facies, and morphology on the south-southeast Alaska shelf and fjords. *Marine Geology*, **85**, 359-390.
Powell R.D., 1990a. Grounding-line fans and their growth to ice-contact deltas. In: Dowdeswell J.A. & Scourse J.D. (eds.), *Glacimarine Environments: Processes and Sediments*. Geological Society London, Special Publication, **53**, 53-73.
Powell R.D., 1990b. Advance of tidewater fronts of temperate glaciers. In: Milner A.M. & Wood J.D., (eds.), Proceedings of the Second Glacier Bay Science Symposium, U.S. National Park Service, Anchorage, 67-73.
Powell R.D. & Alley R.B., 1997. Grounding-line systems: Process, glaciological inferences and the stratigraphic record. In: Barker P.F. & Cooper A.C. (eds.), *Geology and Seismic Stratigraphy of the Antarctic Margin, 2, Antarctic Research Series, AGU, Washington, DC*., 169-187.
Powell R.D., Hambrey M.J. & Krissek L.A., 1998. Quaternary and Miocene glacial and climatic history of the Cape Roberts drillsite region, Antarctica. *Terra Antartica*, **5**, 341-351.
Powell R.D. Krissek L.A. & van der Meer J.J.M., 2000. Depositional environments of Cape Roberts 2/2A drill core, Antarctica: Palaeoglaciological and palaeoclimatic inferences. *Terra Antartica*, **7**, 313-322.
Pratson L.F., Imran J., Parker G., Syvitski J.P.M. & Hutton E., 2000. Debris flow versus turbidity current: a modeling comparison of their dynamics and deposits. In: Bouma A.H. & Stone C.G. (eds.), Fine-grained turbidite systems. *AAPG Memoir*, 72/*SEPM Special Publication*, **68**, 57-72.
Roberts A.P., Wilson G.S. Florindo F., Sagnotti L., Verosub K.L. & Harwood D.L., 1998. Magnetostratigraphy of Lower Miocene strata from the CRP-1 core, McMurdo Sound, Antarctica. *Terra Antartica*, **5**, 703-713.
Shanmugam G., 1996. High-density turbidity currents: are they sandy debris flows? *J. Sedimentary Research*, **66**, 2-10.
Stow D.A.V., 1979. Distinguishing between fine-grained turbidites and contourites on the Nova Scotian deep water margin. *Sedimentology*, **26**, 371-387.
Vorren T.O., Hald M., Edvardsen M. & Lind-Hansen O.W., 1983. Glacigenic sediments and sedimentary environments on continental shelves: general principles with a case study from the Norwegian shelf. In: Ehlers J. (ed.), *Glacial Deposits in North-West Europe*. Balkema, Rotterdam, 61-73.
Zachos J.C., Pagani M., Sloan L., Thomas E. & Billups K., 2001. Trends, rhythms and aberrations in global climate 65 Ma to present. *Science*, **292**, 686-693.
Zachos J.C., Quinn T.M. & Salamy K.A., 1996. High-resolution deep-sea foraminiferal stable isotope records of the Eocene-Oligocene climate transition. *Palaeoceanography*, **11**, 256-266.

APPENDIX

This Appendix contains notes on facies descriptions and interpretations used in this paper that are additional to the descriptions in the Initial Reports volume (Cape Roberts Science Team, 2000).

One feature of the strata that transcends the facies categories, is that of "lonestones". These are isolated clasts with a much larger (~100 times) mean diameter than the mean particle size of the host sediment in which they sit, and are found scattered throughout the cores with varying abundance, in the entire spectrum of mudstone and sandstone facies. Locally they deform strata, showing evidence of having been dropped, or they occur in "nests" or "clusters", often monolithologic, within mudstones (dropstones). Their exotic nature may also be defined solely by them being out-sized, indicating significant hydraulic non-equivalence (Atkins, this volume; Cape Roberts Science Team, 2000; pp. 93-95).

Facies 1 - Mudstone: Beds above about 332 mbsf are up to 10 to 15 m thick whereas below that depth, mudstone is rare and thin (between 362.7 to 364.0, 404.9 to 412.0, 458.8 to 459.8. 710.6 to 710.8 and 781.1 to 787.7 mbsf), generally being less than 1 m thick. Marine macrofossils and their fragments are sparsely scattered (fewer than one fragment per metre) through mudstone facies. These sediments also had contributions from distal or dilute sediment gravity flows in the form of very fine sand and silt laminae and from icebergs contributing lonestones as well as contributing sand and more silt particles (*cf.* Cai et al., 1997). These deposits accumulated below wave base on the shelf or deeper parts of a sea valley.

Facies 2 - Interstratified Sandstone and Mudstone: Marine macrofossils are sparse. Bioturbation and marine macrofossils indicate a submarine environment of deposition for this facies. That being the case, the trend of normal grading, including parallel laminated and ripple cross-laminated sandstones passing up to massive to laminated mudstones, is characteristic of a range of current types from low to moderate density turbidity currents (e.g., summarized in Chapters 2 and 3 of Pickering et al., 1989) to that of combined wave and current action (*e.g.*, summarized in Johnson & Baldwin, 1996). Common soft-sediment deformation and clastic dykes imply the succession's pore-water pressure was at times high and that sediments were rapidly deposited. This facies may be interpreted as turbidites when occurring in association with Facies 1, 3, 8, 9 and 10 or in shelfal conditions above wave base when in association with Facies 4 and 5.

Facies 3 - Poorly Sorted (Muddy) Very Fine to Coarse-grained Sandstone: Those units exhibiting grading trends in both sand and gravel sizes may be indicative of medium- to high-density sediment gravity flow deposits (*cf.* Pickering et al., 1989). Although geometries may help (e.g. Pratson et al., 2000), there is continuing debate over the precise process and flow type to deposit these types of sediment (e.g. Kneller & Branney, 1995; Shanmugam, 1996; Mulder & Cochonat, 1996); a "sediment gravity flow" assignment will suffice for our purposes. Alternatively, these may represent waning stages of traction flows. Some of the thicker massive beds of very fine to fine sandstone may include very rapidly sedimented deposits from fluvial discharges on deltas or grounding-line fans, where they form highly sediment-charged plumes of suspended sediment as they enter sea (e.g. Powell, 1990a; Plink-Bjorklund & Ronnert, 1999). Icebergs are the most likely source of most lonestones, although clasts within turbidites are known (Postma et al., 1988).

Facies 4 - Moderately- to Well-Sorted Stratified Fine-grained Sandstone: The delicate laminae preserved in this facies are indicative of dilute tractional currents with quiescent periods represented by mudstone. Its association with other marine facies, the low-angle discordances, and the presence of possible HCS implies a marine setting within or about storm wave base (*cf.* Johnson & Baldwin, 1996).

Facies 5 - Moderately Sorted Stratified or Massive Fine- to Coarse-grained Sandstone: Marine currents are the most likely depositional mechanism for this facies, perhaps on a shoreface to about storm wave base, with local hiatuses marked by gravelly layers (*cf.* Johnson & Baldwin, 1996). Coarse-tail graded units may also originate from sediment gravity flows or may represent waning flow stages of traction currents (*cf.* Pickering et al., 1989; Kneller & Branney, 1995; Mulder & Cochonat, 1996). The facies may appear massive because of uniformity of grain size. That the environment was under the influence of icebergs is indicated by the presence of lonestones; some of the massive beds perhaps may be from iceberg turbation (*cf.* Vorren et al., 1983; Dowdeswell et al., 1994).

Facies 6 - Stratified Diamictite: The poorly sorted character and presence of outsized clasts in some areas allow alternative interpretations of this facies. The diamictic character may originate from debris flow deposition combined with ice-rafting that also introduces clasts (*cf.* Pickering et al., 1989). Hydroplaning of muddy debris flows commonly leads to a lack of bottom erosion and long run-out distances (Mohrig et al., 1998; 1999; Pratson et al., 2000), which may be responsible for both the contact characteristics in some CRP-3 diamictite sequences and for the occurrence of thin, isolated diamictite beds within stratified intervals. Some units, especially those that grade into and out of massive diamictites, may result from direct rain-out of ice-rafted debris that is acted on by currents to produce lamination of the matrix. Alternatively, subglacial tills can exhibit these types of structures (e.g. Hambrey et al., 1992; Dowdeswell et al., 1994; 2000; Domack et al., 1999).

Facies 7 - Massive Diamictite: Although massive diamictite is the most likely facies to be of subglacial origin, current data from the core show that none of those thus far evaluated are subglacial. Beds that show gradations into other types of facies are more attributable to rain-out processes from floating ice (*cf.* Dowdeswell et al., 1994) or amalgamated debris flow deposits (*cf.* Pickering et al., 1989; Mulder & Cochonat, 1996). Some of the intervals contain marine macrofossils and this facies is commonly bounded by sequences that also contain evidence of submarine deposition. Such deposits are common in grounding-line depositional systems (e.g. Powell & Molnia, 1989; Lønne, 1995; McCabe & Ó Cafaigh, 1995; Hunter et al., 1996).

Facies 8 - Rhythmically Interstratified Sandstone and Siltstone: Elsewhere, this facies is intimately associated with marine sequences (e.g. Cowan & Powell, 1990; Cowan et al., 1997, 1998, 1999; Hambrey & McKelvey, 2000). Its rhythmicity in sandstone-mudstone and mudstone-siltstone couplets is indicative of very highly turbid overflow plumes originating from fluvial discharges into the sea that produce cyclopsam and cyclopel deposits. They are commonly associated with Facies 2 and are unique from fine-grained, low-density turbidites (*cf.* Stow, 1979). They have a close association with diamictites, commonly in intervals overlying them.

Facies 9 - Clast-Supported Conglomerate: Individual beds range up to 4 m thick, but they are commonly 1 to 2 m thick. Units of this facies typically have sharp lower contacts and commonly grade upward into matrix-supported conglomerate by decreasing clast proportions. Locally, however, the facies grades up from sandstone through matrix-supported conglomerate into the clast-supported conglomerate. The coarse, poorly stratified nature and presence of subangular to subrounded clasts suggests that these deposits were deposited by or were redeposited from fluvial discharges. However, this facies may have been deposited in a submarine setting due to its common association with marine sequences above and below. More specifically, the sediment may have been transported in suspension in turbulent subglacial conduit discharges (*cf.* Powell, 1990a). Alternatively, it could represent high density, gravity-driven, mass flows or redeposited conglomerates (e.g. Hein, 1984; Nemec & Steel, 1984), especially where it grades into matrix supported types. Iceberg rafting could have contributed the angular clasts (*e.g.* Powell, 1990a). Unique variations of this facies occur within CRP-3. At one horizon, immediately above the major unconformity with the basement Beacon Supergroup is a 23-cm-thick interval of monomictic, clast-supported breccia, consisting of unsorted angular clasts (up to 6 cm) of Beacon quartzitic sandstone. The interval is capped by 6 cm of matrix-supported, small pebble conglomerate of the same composition. Above an unconformity on that matrix-supported conglomerate is another unique variety of clast-supported, boulder and cobble conglomerate. It consists mainly of well-rounded dolerite boulders (up to 1 m) in a 33-m-thick unit, which over the lowest 85 cm shows a coarse-tail coarsening trend. Some smaller clasts of Beacon Supergroup sandstone also occur, especially toward the base. These lower-most facies of the core occur in two lithofacies associations (see below) that are interpreted as talus overlain by alluvial fan deposits (*cf.* Blair & McPherson, 1994).

Facies 10 - Matrix-Supported Conglomerate: The dispersed nature of clasts in a sandy matrix and trends in grading indicate that this facies was deposited from high-density mass flows and may have been redeposited from a mixing of fluvial or shallow-marine facies close to source (*cf.* Nemec & Steel, 1984; Postma, 1990, Prior & Bornhold, 1990; Nemec, 1990; Kneller & Branney, 1995; Shanmugam, 1996; Mulder & Cochonat, 1996). Alternatively, it may represent the waning flow stage of traction currents or locally, higher in the core, they may have been deposited from suspension after transport in turbulent subglacial conduit discharges (Powell, 1990a).