Terra Antartica
2000, **7**(3), 313-322

Preliminary Depositional Environmental Analysis of CRP- 2/2A, Victoria Land Basin, Antarctica: Palaeoglaciological and Palaeoclimatic Inferences

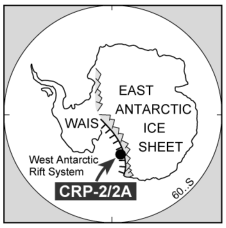
R.D. Powell[1*], L.A. Krissek[2] & J.J.M. van der Meer[3+]

[1]Department of Geology and Environmental Geosciences, Northern Illinois University, DeKalb, IL 60115 - USA
[2]Department of Geological Sciences, Ohio State University, Columbus, OH 43210 - USA
[3]Fysisch Geografisch en Bodemkundig Laboratorium, University of Amsterdam, Nieuwe Prinsengracht 1309
1018 VZ, Amsterdam - The Netherlands
[+]Present address: Department of Geology, Queen Mary and Westfield College, Mile End Road, London E1 4NS - UK

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

Received 11 October 1999; *accepted in revised form* 14 March 2000

Abstract - Cape Roberts Project drill core 2/2A was obtained from Roberts Ridge, a sea-floor high located at 77 °S, 16 km offshore from Cape Roberts in western McMurdo Sound, Antarctica. The recovered core is about 624 m long and includes strata dated as being Quaternary, Pliocene, Miocene and Oligocene in age. The core includes twelve facies commonly occurring in 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 with minor iceberg influence, outer shelf-inner shelf-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. Changes in palaeoenvironmental interpretations up the core are used to estimate relative glacial proximity to the site through time. These inferred glacial fluctuations are then compared with the global eustatic sea level and $\delta^{18}O$ curves to evaluate the potential of glacial fluctuations on Antarctica influencing these records of global change. Although the comparisons are tentative at present, the records do have similarities, but there are also some differences especially in possible number (and perhaps magnitude) of glacial fluctuations that require further evaluation.



INTRODUCTION AND REGIONAL SETTING

The Cape Roberts Project is an international co-operative drilling programme 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 tectonic and climatic history of the region for this period of time which is very poorly constrained. During the 1998 austral summer the second hole of the project, CRP-2/2A, was drilled in 178 m of water, 16 km off Cape Roberts at 77.006 °S and 163.719 °E (see Fig. 1 in the introduction). CRP-2 was cored from 5 to 57 mbsf (metres below sea floor) with a 91% core recovery. CRP-2A was a minor drilling deviation at the same site, reaching down to 624 mbsf with 95% recovery which terminated in strata older than about 35 Ma.

The drill site is located on a sea floor high, Roberts Ridge, which is a tectonic horst, thought to have been rotated perhaps during and after Miocene time (*cf.* Cape Roberts Science Team, 1998, Fig. 5). Roberts Ridge rises 500 m from the half graben to the west between it and the present coast. To the north of Roberts Ridge is a deep, sinuous sea floor trough, the Mackay Sea Valley over 900 m deep, which is thought to have been eroded by an expanded Mackay Glacier. This glacier is a major outlet of the East Antarctic Ice Sheet and feeds into Granite Harbour just north of Cape Roberts. By analogy with valleys to the south, it is likely that the Mackay system has been a valley and palaeofjord throughout at least the Miocene Epoch with the palaeo-Mackay Glacier advancing and receding within its trough (*cf.* Barrett, 1989; Barrett & Hambrey, 1992). It is also known that several times during the Cenozoic Era grounded ice expanded in the Ross Sea to a position well north of Roberts Ridge. This ice may have eroded younger strata from the top of the ridge (Cape Roberts Science Team, 1998, p. 4).

Cape Roberts Project drill hole 1 (CRP-1) was drilled on Roberts Ridge up-dip from CRP-2/2A. The recovered core was about 147 m long, with the upper 43.55 metres below sea floor dated as Quaternary and the older part of the sequence Miocene. 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

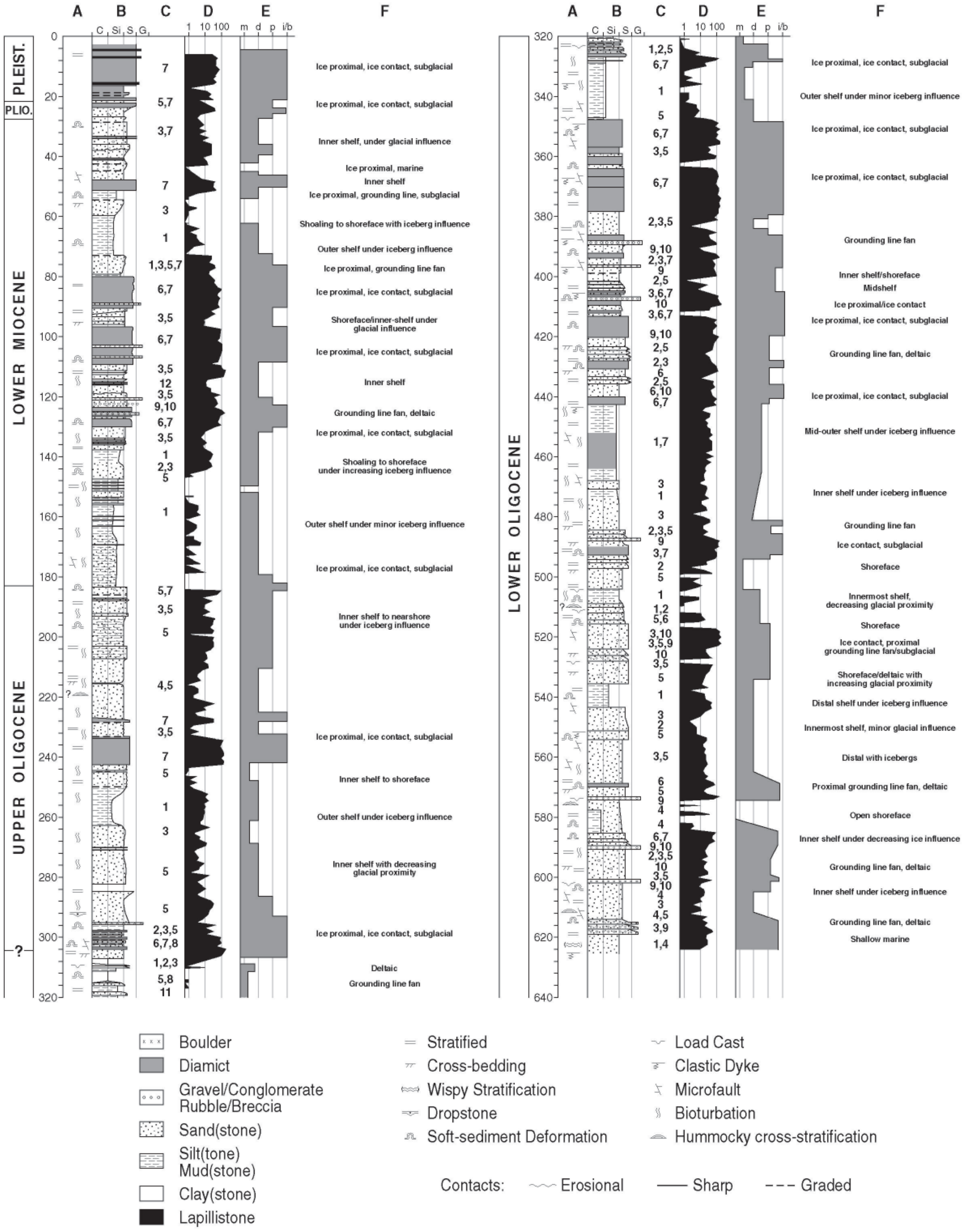


Fig. 1 - Graphic lithofacies log of CRP-2/2A, showing interpreted lithofacies associations with the depth (metres below sea floor) column, summary sedimentary structures (A), general facies with mean particle size profile (B), facies codes for facies 1 through 12 (C), distribution of number of clasts 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).

thought to indicate a period of ice sheet retreat. In contrast, the Miocene section was thought to represent polythermal glacial systems. The older Miocene section is glacially dominated whereas the younger section is much less so.

Currently, Mackay Glacier terminates in Granite Harbour as a floating glacier-tongue and recent studies have documented the style of sedimentation and facies produced under the modern interglacial conditions (Macpherson, 1987; Ward et al., 1987; Leventer et al., 1993; Powell et al., 1996; Dawber & Powell, 1997). These data are useful for interpreting parts of the drill core at Cape Roberts because this glacial system is potentially a primary source of ice to produce much of the sediment record recovered.

GENERAL STRATIGRAPHY AND LITHOFACIES

CRP-2/2A has been described lithologically and divided into 15 lithostratigraphic units and 40 subunits (Cape Roberts Science Team, 1999, Fig. 3.1, p. 51). The core is thought to represent four main time intervals: Pleistocene, Pliocene, Miocene, and Early and Late Oligocene (Fig. 1). The youngest interval of Late Oligocene age has a questionable age assignment because of dating problems due to scarcity of fossils; the time line between Early and Late Oligocene is poorly defined. Given the goals of CRP, the Miocene through Oligocene section of CRP-2/2A is the primary focus of this paper.

Twelve recurrent lithofacies are recognised within the Miocene through Oligocene section of the core and are defined using lithologies or associations of lithologies, bedding contacts and bed thicknesses, texture, sedimentary structures, fabric and colour. The 12 lithofacies, which are based primarily on the lithologic description logs (Cape Roberts Science Team, 1999), are: 1) mudstone, 2) interstratified sandstone and mudstone, 3) poorly sorted (muddy) very fine to coarse sandstone, 4) moderately to well sorted stratified fine sandstone, 5) moderately to well sorted, stratified or massive, fine to coarse sandstone, 6) stratified diamictite, 7) massive diamictite, 8) rhythmically interstratified sandstone and siltstone, 9) clast-supported conglomerate, 10) matrix-supported conglomerate, 11)☐mudstone breccia and 12) nonwelded lapillistone. The facies and their interpretations are presented in table 1 and the reader is referred to their full descriptions in the initial reports (Cape Roberts Science Team, 1999, see pp. 61-64 and 60-67 for photographs and descriptions). Terminology used here refers to lithified forms but some Miocene lithologies are unlithifed.

FACIES SEQUENCES AND DEPOSITIONAL ENVIRONMENTS THROUGH TIME

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 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 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. 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 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. Many diamictites appear to reworked glacimarine sediment based on their micromorphology, microfossil content, texture and common intraclasts. In those cases, sediment has most likely been removed, and if the diamicts are till, they may have been derived also by deforming bed from up-stream erosion.

The percentage of facies up the core were tabulated by subdividing the succession into its age segments in order to evaluate trends with time (Tab. 2). Some time periods are under-represented in the core with very thin records, especially the Pleistocene and Pliocene, and care should be taken when making inferences from those data. A further note of caution is that the record is likely to have been deposited under very high sediment accumulation rates in many intervals (see discussion below) and given the time control on the succession, much of the record must be missing. We have no way to estimate 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 preserve. For the glacially-dominated intervals of core, micromorphological texture and structures, including the large number of intraclasts, as well as the presence of microfossils, indicate that the diamictites are commonly redeposited glacimarine sediment. Consequently, we know that sediment has been reworked or locally removed, but as yet the quantities are unknown. Redeposition has occurred either proglacially or subglacially which has replaced some lost sediment, but once again, the quantities are unknown.

Given these cautions it is noteworthy that the preserved record of the Pleistocene and Pliocene is dominated by diamicts which are primarily massive in character. That may be a function of the site being a topographic high during much of these time periods, but it also follows the models of glacimarine sedimentation in that during these periods of colder glacial ice, the models predict more diamict and less sorted sediment (*e.g.* Dowdeswell et al., 1996; Powell & Alley, 1997). The models also predict decreasing sedimentation rates and hence lower accumulation rates as climate cools (*e.g.* Milliman & Syvitski, 1992; Elverhøi et al., 1995, 1998; Powell & Alley, 1996; Hallet et al., 1996), although this may not influence preservation potential in a glacimarine setting.

Tab. 1 - Summary table of facies characteristics and their interpretations of core CRP-2/2A.

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	oderately 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
6	Stratified diamictite	- clast-rich to clast-poor, sandy or muddy - a-axes locally aligned with stratification outsized clasts - stratification by: mudstone, siltstone, very fine to very coarse sandstone laminae; change in mean size in matrix sand; varying proportions of mud - commonly grade with massive diamictite - commonly interbedded with conglomerates, diamictites, sandstones and mudstones - locally strong soft-sediment deformation - locally include marine macrofossils	- amalgamated or single debris-flow deposition - rainout with currents - subglacial deposition	- particle size and sorting - style of internal stratification and grading - style of contacts - associated facies - marine fossils
7	Massive diamictite	- clast-rich to clast-poor, sandy or muddy - graded contacts with conglomerate, sandstone and mudstone - or lower contact sharp (loaded and deformed) - rarely a-axes apparent preferred sub-horizontal orientation - locally include marine macrofossils and lapilli	- subglacial deposition - amalgamated or single debris flow deposition - rainout with currents	- particle size and sorting - style of contacts - associated facies - marine fossils

Tab. 1 - Continued.

Facies number and name		***Key sedimentological characteristics***	***Depositional process interpretation***	***Key interpretation criteria***
8	Rhythmically interstratified sandstone and siltstone	- very fine and fine sandstone sharply interstratified with mudstone - mudstone with discrete siltstone laminae - lonestones, dropstones and outsized clasts - often with Facies 2, 6 and 7	- suspension settling from turbid plumes - may include low density turbidity current deposition	- one-grain-thick lamina style of cyclopels and cyclopsams - graded style of turbidites
9	Clast- supported conglomerate	- massive, poorly sorted, locally graded - no clast orientation, some clasts angular - sharp lower contacts - gradational up into matrix supported conglomerate to sandstone	- settling from submarine jet from subglacial streams - fluvial/shallow marine deposition - may include rainout from ice-rafted debris - redeposition of conglomerate by mass flow	- clast-support style - clast features - style of contacts
10	Matrix- supported conglomerate	- massive, very poorly sorted - angular clasts quite common - gradational into clast-supported conglomerate or sandstone	- high-density mass flow deposit - hyperconcentrated flows from submarine jet of subglacial stream - very local mass flow redeposition of fluvial sediment - suspension settling and rainout	- clast-support style - clast features - particle sorting - style of contacts
11	Mudstone breccia	- massive - intraclasts of mudstone, angular to subrounded - clast-supported - within soft-sediment deformed sequences	- mass flow deposition	- clast features - clast-support style - facies sequence
12	Non-welded lapillistone	- pumiceous lapillistone - massive and laminated fine and medium sandstone with dispersed ash and lapilli - dark volcanic ash laminae	- air-fall through water - reworked by marine currents and sediment gravity flows	- particle size and composition - internal stratification

There is also a trend of a decreasing proportion of stratified to massive diamict from Oligocene through Miocene times. When stratified diamict is associated with Facies 2, 3 and 8 as commonly it is through the older part of the succession, the preferred interpretation is for the diamicts to be debrites and most likely to have been associated with submarine, ice-marginal, depositional environments. Other trends that complement the notion of decreasing amount of sorted sediment relative to the volume of meltwater associated with glaciers are trends in sandstone and conglomeratic facies. The proportion of facies 2 to facies 3 decreases with time, as does the accumulated proportion of facies 9 and 10. When the interstratified sandstone and mudstone facies represents sediment gravity flow deposition and is in higher proportion through time than other inferred sandy sediment gravity flow deposits of facies 3, it is also taken to represent a higher degree of sorting and meltwater production at the glacial source. Therefore, each of these diamict, sandstone and conglomerate trends is taken to represent a decreasing amount of meltwater associated with glacial deposition through Oligocene to Miocene time. That is not to say that the Miocene was free of meltwater, just that it had relatively lower amounts compared with Oligocene glaciers. An ultimate inference from this using glacimarine models is that glaciers were cooler in the Miocene, and by association, so were climatic conditions.

As had been inferred from CRP-1, Miocene sediments

Tab. 2 - Percentages of lithofacies through CRP-2/2A divided into time periods. Note that the Pleistocene and Pliocene epochs are not well represented in the core in terms of thickness recovered, and thus reliability of the data may be questionable.

TIME PERIOD	**BASAL DEPTH (mbsf)**	**FACIES PERCENTAGES**											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Pleistocene	21.16	0	0	0	0	0	2	92	0	2	4	0	0
Pliocene	26.79	0	0	0	0	39	4	57	0	0	0	0	0
L. Miocene	185.95	33	4	18	0	21	1	21	0	Tr	Tr	Tr	2
U. Oligocene	306.64	11	2	24	0	47	3	12	1	0	0	0	0
L. Oligocene	624.15	17	16	12	5	22	8	12	Tr	3	4	1	0
Total	624.15	19	9	16	3	26	5	17	Tr	2	2	1	Tr

are considered similar to modern polythermal glacial sequences, such as in parts of the Antarctic Peninsula, or in Svalbard today (Powell et al., 1998). Polythermal glaciers are typified by ice at the pressure melting point where it is thickest, and sub-zero ice around the margins around the snout where it terminates on land. They occur in areas where the mean annual temperature is several degrees below freezing. In Early Oligocene time climatic conditions at CRP-2/2A may have been closer to those of modern cool-temperate zones because of the apparent high fluvial discharges. In areas such as Alaska and Chile today, rainwater and meltwater combine to produce very high, glacifluvial discharges and glacier ice is at, or near the pressure melting-point throughout. One important difference from modern cool-temperate settings may be the three to four months of darkness during deposition of the CRP-2/2A sequence because of its high latitude. That also probably allowed sea-ice to form, at least during the winter months. Those conditions may have made Antarctic Oligocene glaciers partly like modern polythermal glaciers, but with large volumes of meltwater running during their melt-season, perhaps similar to parts of modern Svalbard.

A more detailed record of glacial fluctuations 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 drill-site. The facies associations are supplemented by preliminary data about sediment porosity (Cape Roberts Science Team, 1999, Fig. 2.17 and 2.18, pp. 38-39), clast fabric data (Cape Roberts Science Team, 1999, pp. 72-75) and diamict micromorphology (van der Meer, this volume). All diamictites sampled, even those close to inferred unconformities, have macrofabrics more indicative of sediment gravity flows and rainout deposits than with subglacial deposition. However, micromorphological studies indicate three convincing horizons of grounded glaciers (121.8, 122.4 and 298.8 mbsf) in the upper 300 m of core. The same study indicated ten other horizons (18.6, 45.6, 48.7, 86.1, 91.2, 129.6, 184.7, 227.7, 238.8 and 300.0 mbsf) also may be the result of grounded glaciers.

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. Under non-glacial, continental shelf conditions, sea-level change and tectonism are the major factors driving facies changes. However, glaciated shelves also experience major facies changes during glacial advance and recession that may not be related to either tectonism or sea-level change. Some broad inferences can be made about relative water-depth changes based on facies but, commonly, even that is difficult to establish given that a change in particle size could simply be a factor of glacier proximity and not of water-depth change. Facies associations can be used to evaluate relative water-depth changes in a broad way, but they must be constrained by some inferences from other data, such as diatom ecology (Cape Roberts Science Team, 1998, pp. 50-53 and 93-100). At present, a full relative water-depth curve up the core cannot be established.

DISCUSSION AND DEPOSITIONAL MODEL

The sequence recovered in CRP-2/2A 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,
- 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,
- the volcaniclastic-rich Facies 12, which includes evidence of falling through water and reworking by dilute currents and sediment gravity flows.

From the individual facies and their sequences, the shallow marine settings appear to have varied from the shoreface to wave base and beyond, but they also appear to include deltaic and/or grounding-line fan settings with large fluvial discharges and their associated delta/fan front and prodeltaic/fan sediment gravity flow deposits, as well as cyclopels and cyclopsams. The fan setting and perhaps the deltaic setting, are associated with ice-marginal and ice-proximal environments. The intimate association of the fan sediments with debris flow diamictites and major, penecontemporaneous, sediment deformation 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, especially in the older Oligocene strata. Deformation in the sequence is also associated with glacial over-riding and some diamictites are subglacial tills. Based on the marine character of the sequence, the most logical inference is for the subglacial deposition to have been from glaciers grounded in the sea. 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. Independent of the glacial and marine settings, nearby volcanic eruptions contributed volcanic ash of various composition and most of it subsequently was reworked in the marine environment.

The volcanism is a reminder of the active tectonism that may have accompanied deposition of the whole sequence, but as yet, the influence of that tectonism on facies variations is not well understood.

A conceptual model has been constructed in order to demonstrate how the CRP-2/2A succession may have accumulated during repeated cycles of glacial advance and retreat (Fig. 2). In the figure, hypothetical facies associations and sequences are generated by a series of glacial advance, retreat and readvance. The sequences emphasise glacial activity and lack variability of changes in water depth due to forcings by changes in sea level, isostasy and tectonism. A stratigraphic record constructed by repeated glacial fluctuations varies depending on timing of glacial movements during different stages of the cycles, the amount of erosion (glacial mainly) and the forcings of sea level, isostasy and tectonism, and their rates and timing relative to each glacial cycle.

CONCLUSION AND PALAEOCLIMATIC AND PALAEOGLACIAL HISTORY

The CRP-2/2A succession is 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 toward present 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 trend of increasing evidence of melt-water and rates of sedimentation down-core are used to indicate 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, as represented by strata lower in the core based on proportions of preserved facies and as is also suggested by the terrestrial palynological data (see Cape Roberts Science Team, 1999, pp. 131-137).

The history of growth and decay of the Antarctic ice sheet and its links with 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 Wilson et al., this volume) a comparison can be made of the inferred glacial history from CRP-2/2A with the global eustatic sea level curve (Haq et al., 1987) and the oxygen isotope records from the deep sea (*e.g.* Abreu & Anderson, 1998). The sea level curves could be interpreted as representing forcing other than glaciers but the glacial inference is used here so a direct comparison can be made between the three data sets. Since Haq et al. (1987) established their sea level curve the time scales used have been modified, but recalibrations for the curve over the time period of CRP-2/2A differ (*e.g.* Pekar & Miller (1996) (which is used here) *cf.* Abreu & Anderson (1998)). The oldest reliably dated interval in CRP-2/2A core is Early Oligocene between about 624 - 306 mbsf and the succession is about 30.9 - 24.2 My old, although dating is problematic (Wilson et al., this volume). This period represents a time when glaciers came near to or over the site 12 times, locally represented by successions 30 m thick or more (Fig. 1). Global eustatic sea level curve shows three low stand phases, whereas the δ^{18}O curve shows five possible glacial pulses. Within this Early Oligocene interval, the section between 420 - 306 mbsf is poorly controlled by dating but is currently assigned an Early Oligocene age. The poor dating control results from the interval being dominated by glacial activity very near and over the site for much of the time, that is, a period of one or more major glacial advances. The Late Oligocene interval from about 24.2 - 23.8 My ago, between about 306 - 186 mbsf, represents a period when glaciers were mainly distal from the site, although glaciers may have advanced near to the site on five occasions and may have been at the site during first and last of those periods. Over this time global eustatic sea level was rising and the δ^{18}O record could represent a period of one glacial advance. The Early Miocene has been divided into three time segments based on quite tight dating (Wilson et al., this volume). The oldest of the three intervals between about 186 - 130 mbsf, represents a period between about 23.8 - 23.7 My ago. It is another period when glaciers were mainly distal from the site at the same that there was inferred to be rising eustatic sea level and the δ^{18}O record indicates a glacial advance. Between 130 and 52 mbsf another Early Miocene interval is currently thought to be from about 21.5 to 20.5 My old, and it contains thick diamictite sequences. It is interpreted here as representing a period when there were three glacial advances to or over the site. The Haq curve shows one fluctuation in eustatic sea level through this period and a small glacial event during the same period. The youngest Miocene interval is from 52 to 27 mbsf and represents 18.8 - 18.2 My ago. Glaciers were at or over the site at the start of this period and then retreated with one minor advance that came near to the site. At this time eustatic sea level is shown to be rising and the δ^{18}O curve indicates a minor glacial advance followed by a retreat. Although these are tentative comparisons at present, there does appear to be similarities in the records, but also some significant differences, especially in possible number (and perhaps magnitude) of glacial fluctuations 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. Palaeoevironmental interpretations are best done with as much diverse data as possible. As many

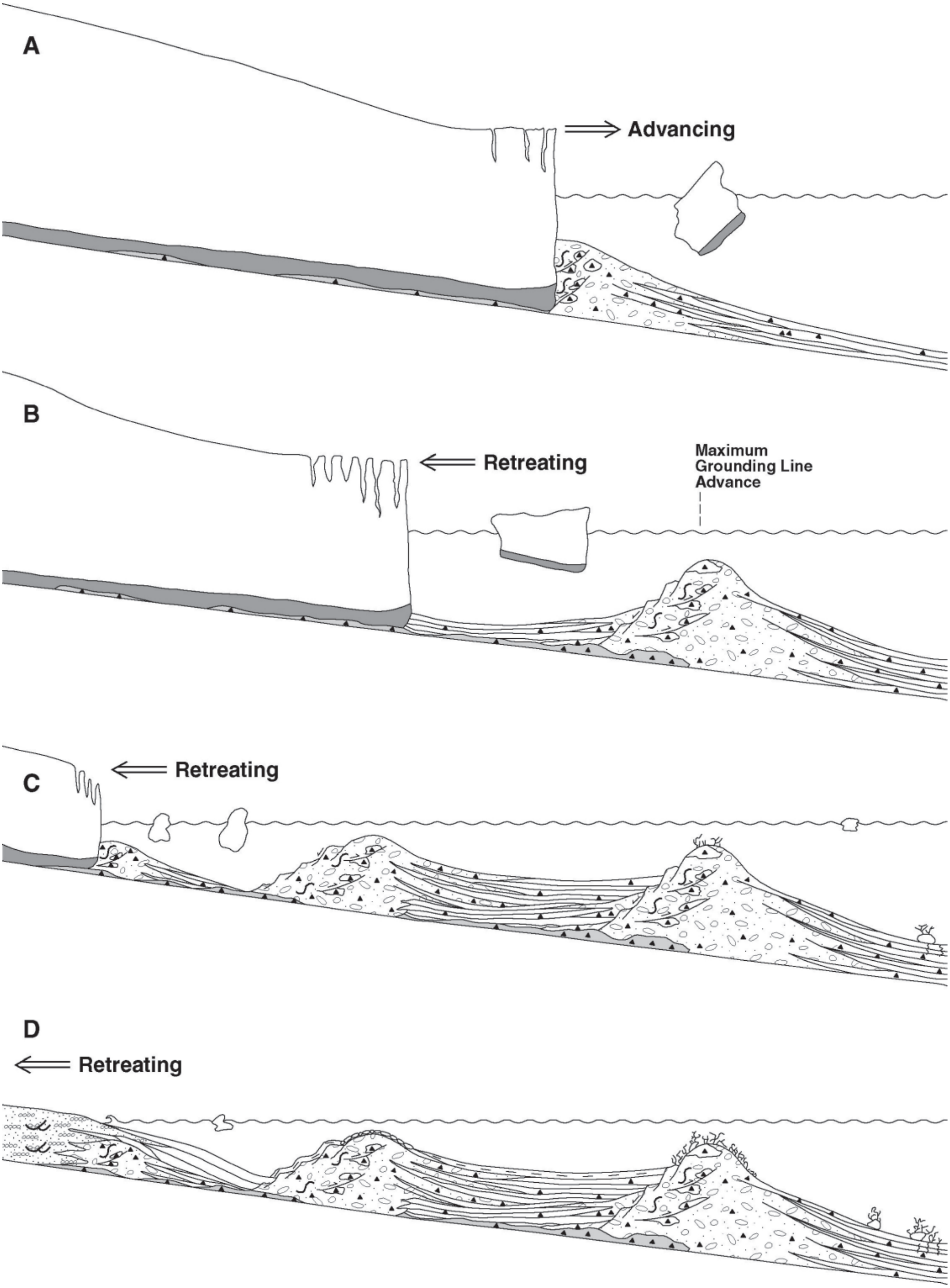


Fig. 2 - An hypothetical glacial advance, retreat and readvance sequence that depicts how facies associations and sequences are thought to have been generated to produce the CRP-2/2A succession. Scale varies in order to allow pertinent features to be shown: vertical scale is *ca.* 15 000 and the horizontal scale varies between morainal banks (*ca.* 140 000) and non-bank areas (≥ *ca.* 40 000). The facies sequences are constructed to emphasise variations relative to glacial activity, so water depth does not vary; that is, effects of sea level, isostasy and tectonics are not considered. However, a particular preserved stratigraphic record will vary depending on relative lengths of time a glacier spends within different stages of its advance and retreat modes, the amount of erosion (glacial mainly) and the other variables not considered in relative water depth changes, and their rates and timing relative to the glacial advance and retreat cycle.

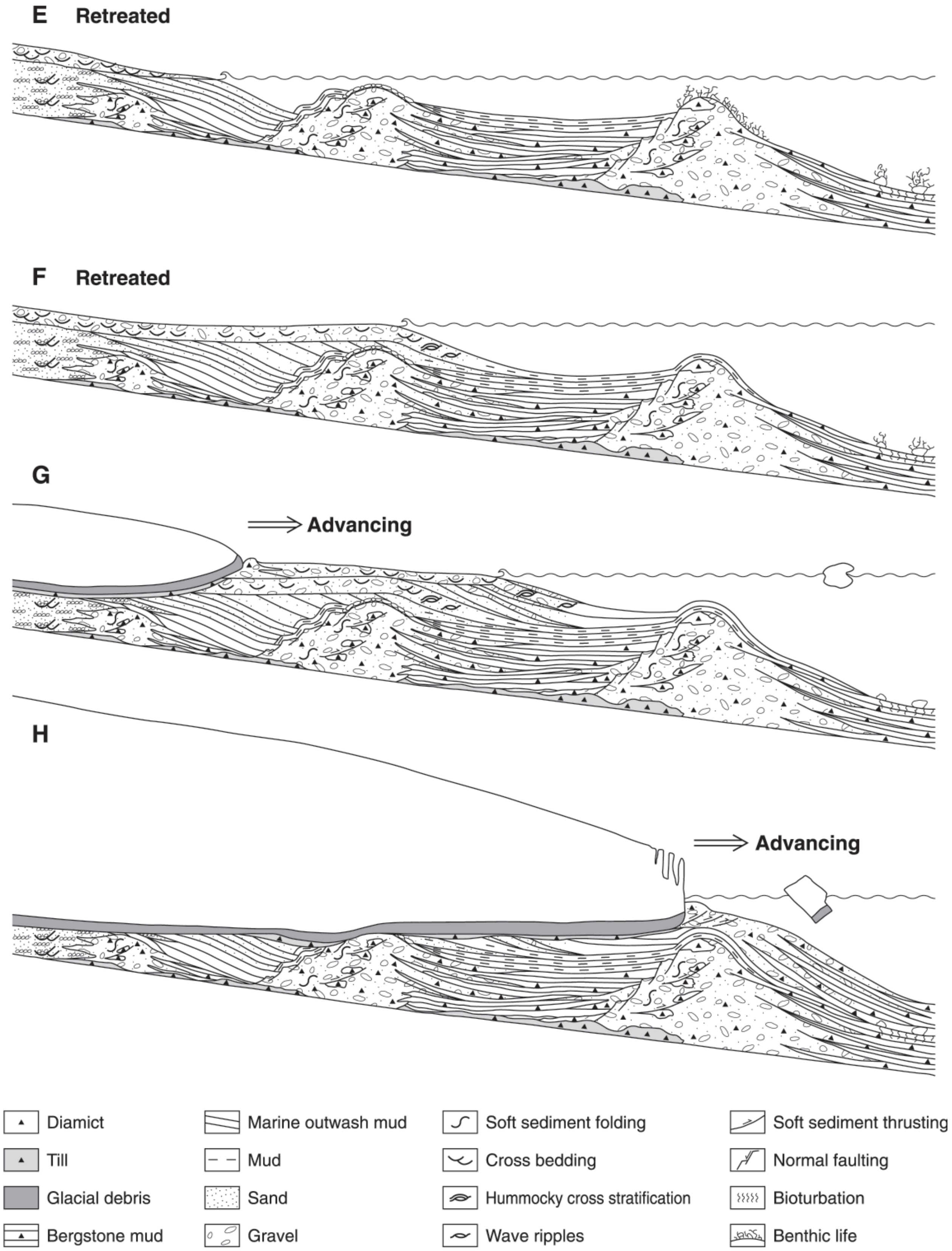


Fig. 2 - continued.

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 are 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 the project, and with the scientific steering committee, for ensuring a successful outcome to the second season's 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 various help they provided. This aspect of the sedimentological part of the project was supported by NSF grants to RDP (OPP-9527481) and LAK (OPP-9527482). 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

Abreu V.S. & Anderson J.B., 1998. Glacial eustasy during the Cenozoic: sequence stratigraphic implications. *American Assoc. Petrol. Geol. Bull.*, **82**,1385-1400.

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

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

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

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

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

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. Geol. Soc. London, Spec. Pub.*, **53**, 75-89.

Dawber M. & Powell R.D., 1997. Epifaunal distributions at marine-ending glaciers: influences of ice dynamics and sedimentation. In: Ricci C.A. (ed.), *The Antarctic Region: Geological Evolution and Processes*. Terra Antartica Publication, Siena, 875-884.

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.

Elverhøi A., Svendsen J.I., Solheim A., Andersen E.S., Milliman J., Mangerud J. & Hooke R.LeB., 1995. Late Quaternary sediment yield from high arctic Svalbard area. *Journal of Geology*, **103**, 1-17.

Elverhøi A., Hooke R.LeB. & Solheim A., 1998. Late Cenozoic erosion and sediment yield from the Svalbard-Barents Sea regoin: Implications for understanding erosion of glacierized basins. *Quaternary Science Reviews*, **17**, 209-241.

Hallet B., Hunter L. & Bogen B., 1996. Rates of erosion and sediment evacuation by glaciers: A review of field data and their implications. *Global and Planetary Change*, **12**, 213-235.

Haq. B.U., Hardenbol J. & Vail P.R., 1987. Chronology of fluctuating sea levels since the Triassic. *Science*, **235**, 1156-1166.

Leventer A.R., Dunbar R.B. & DeMaster D.J., 1993. Diatom evidence for late Holocene climatic events in Granite Harbor, Antarctica. *Paleoceanography*, **8**, 373-386.

Mackiewicz N.E., Powell R.D., Carlson P.R., & Molnia B.F., 1984. Interlaminated ice-proximal glacimarine sediments in Muir Inlet, Alaska. *Marine Geology*, **57**, 113-147.

Macpherson A. 1987. The Mackay Glacier/Granite Harbour System - a study in nearshore glacial marine sedimentation. Unpublished Ph.D. thesis, Victoria University of Wellington Library, Wellington, 173p.

Milliman J.D. & Syvitski J.P.M.., 1992. Geomorphic/tectonic control of sediment disharge to the ocean: The importance of mountainous rivers. *Journal of Geology*, **100**, 525-544.

Pekar, S. & Miller, K.G., 1996. New Jersey Oligocene "Icehouse" sequences (ODP Leg 150X) correlated with global ^{18}O and Exxon eustatic records. *Geology*, **24**, 567-570.

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., Dawber M., McInnes J.N. & Pyne A.R., 1996. Observations of the grounding-line area at a floating glacier terminus. *Annals of Glaciology*, **22**, 217-223.

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**(3), 341-351.

Ward B.L., Barrett P.J. & Vella P.P., 1987. Distribution and ecology of benthic foraminifera in McMurdo Sound, Antarctica. *Palaeogeography, Palaeoclimatology and Palaeoecology*, **58**, 139-153.