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

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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 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 δ18O 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
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 mbf 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 mbf and CRP-2A was a minor drilling deviation at the same site, reaching down to 624 mbf 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 diamict/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 future when other data, such as from palaeoecology,
Depositional Environments for Strata Cored in CRP-3

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).

LEGEND
- Diamicrite
- Conglomerate
- Sandstone
- Mudstone
- Intrusive Igneous
- Thin bed of coarser-grained lithology; length indicates particle size

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 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 limestones to the site. Thicker mud intervals are first preserved in LSU 6.1 and younger, based on the poorly sorted character of the diamictite units in a commonly mud-rich, marine setting, 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 diamicites. Following and including the time that LSU 2.2 accumulated, glaciers had a strong presence in the area as reflected by thick diamicite units in a commonly mud-rich, marine section. Using the models of glaciomarine 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 diamic, 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 facies associations have been defined in upward
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.

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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, thou, they are still marine, and likely to be delta-fan 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 limestones 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 deltaic and prodeltaic sediment gravity flow deposits, as well as cyclopelagic and cycloplasms 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 diamicrines 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 straited clasts and limestones 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-Antartic (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, synchronicity 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. Palaeoenvironmental 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 palaeoeological data is needed, as well as a more thorough evaluation of diamicton 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. JIInvdM was supported by the Antarctic Programme of the Netherlands Organisation for Scientific Research (NWO) and he acknowledges supportive collaboration with Antarctica New Zealand.

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**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 "limestones". 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 "nestes" or "clusters", often monolithologic, within mudstones (droplets). 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 limestones as well as contributing sand and more silt particles (cf. Cai et al., 1994). These deposits accumulated below the wave base or 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 be complex (e.g. Pratsoun & Steel, 1999), there is continuing debate over the precise process and flow type to deposit these types of sediment (e.g. Kneller & Branney, 1995; Shimmugum, 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 sandstones may include very rapidly deposited units 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; Pink-Bjorklund & Ronnert, 1999). Icebergs are the most likely source of most limestones, although clasts within turbidites are known (Postma et al., 1988).

**Facies 4 - Moderately- to Well-Sorted Stratified Fine- to Coarse-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). 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 limestones; 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). Hydroplana of muddy debris flows commonly leads to a lack of bottom erosion and long run-out distances (Mohrig et al., 1996; 1999; Pratsoun et al., 2000), which may be responsible for both the contact characteristics in some CRP and diamictite sequences as well as the occurrence of thin, isolated diamictite beds within stratified intervals. Some units, especially those that grade into and out of massive diamictitic deposits, may result from direct rain-out of ice-rafter 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; Drainack et al., 1999).

**Facies 7 - Massive Diamictite:** Although massive diamictite is the most likely depositional facies, the current data from the core show that none of those thus far evaluated are subaerial. 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 interbedded by sequences that also contain evidence of sub-aerial deposition. Such deposits are common in grounding-line depositional systems (e.g. Powell & Mohla, 1989; Lonne, 1995; McCabe & O'Caugh, 1995; Hunter et al., 1996).

**Facies 8 - Rhythmically Interstratified Sandstone and Siltstone:** Elsewhere, this facies is intimately associated with marine sequences (e.g. Cowan & Cochonat, 1997, 1998, 1999; Hambley & McKeever, 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 cyclopa and cyclopaol deposits. They are commonly associated with Facies 2 and arc 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 into sandstone through matrix-supported conglomerate into the class-supported conglomerate. The course, 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; Nemecek & 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 includes at a 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 quartzite sandstone. The interval is capped by 6 cm of matrix-supported, small pebble conglomerate of the same composition. Above an unconformity with 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 73- 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. Nemeck & Steel, 1984; Postma, 1980; Prior & Bornhold, 1990; Nemeck, 1990; Kneller & Branney, 1995; Shimmugum, 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).