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Quaternary and Miocene Glacial and Climatic History of the Cape Roberts Drillsite Region, Antarctica

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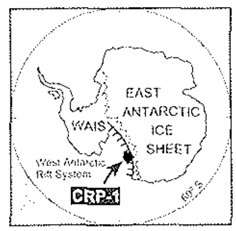

Abstract - Cape Roberts Project drillcore 1 was obtained from Roberts Ridge, a sea-floor high located at 77°S ,16 km offshore from Cape Roberts in western McMurdo Sound, Antarctica. The recovered core is about 147 m long with the upper 43.15 metres below sea floor (revised figure) being dated as Quaternary and the older part of the sequence being Miocene. The 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. These facies occur in associations that are repeated in particular sequences throughout the core, and are interpreted as representing different depositional environments through time. Seven lithofacies associations are interpreted as representing 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. The facies associations are used to infer that the Quaternary section represents deposition on a polar shelf with perhaps two or three glacial fluctuations. The Quaternary carbonate unit indicates a period of ice sheet retreat, but local glacial activity may have increased with an increase in coastal precipitation. The Miocene section represents polythermal glacial systems. The older Miocene section is glacially dominated whereas the younger section is much less so. The glacially dominated section may provide evidence for a major glacial advance that resulted in a low stand of global eustatic sea level at that time. After the low stand, eustatic sea level was gradually rising during deposition of the younger section dominated more by non-glacial processes.

INTRODUCTION AND REGIONAL SETTING

The Cape Roberts Project is an international co-operative drilling programme designed to recover continuous drillcore 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 1997 austral summer the first hole of the project. CRP-1, was drilled in 150 m of water. 16 km off Cape Roberts at 77.008°S and 163.755°E (see Fig. 1 in Introduction).

The drillsite is located on a sea floor high, Roberts Ridge, which is a tectonic horst. thought to have been rotated perhaps (luring and post-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 in excess of 900 in 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 palaeo-Mackay Glacier advancing and receding within its trough (*cf.* Barren. 1989; Barrett & Hambrey, 1992). It is also known thin perhaps 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).

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 drillcore at Cape Roberts.

GENERAL STRATIGRAPHY AND LITHOFACIES

CRP-1 has been described lithologically and divided into seven lithostratigraphic units and 18 subunits (Fig, 1; Cape Roberts Science Team, 1998, p. 19). The core represents two main time intervals: Quaternary between 15.00 and 43.15 mbsf and Miocene between 43.15 and 147.69 mbsf, the base of the core. The level of the unconformity follows that of Fielding et al. (this volume)

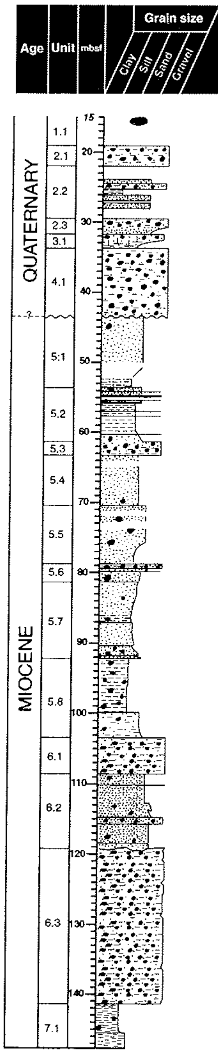

Fig. 1 - Graphic log summarising the lithology and lithostratigraphic subdivision of CRP-1 (from Cape Roberts Science Team, 1998).

Tab. 1 - Summary lithofacies descriptors with their facies codes.

Facies Code	Summary Facies Description
D1	Sandy diamicts
D2	Muddy diamicts
G, B	Gravels, Breccias
S1	Graded sands
S2	Stratified sands
M, Z, C	Muds, silts, clays
L1	Fossiliferous siliciclastics
L2	Calcareous sandy mud

rather than that of the Cape Roberts Science Team (1998) where it was placed at 43.55 mbsf. The four units (6 subunits) of Quaternary age above the 43.15 mbsf unconformity are largely unconsolidated whereas the Miocene units below are consolidated. The lithological distinction between the two ages of sediment is not especially clear because of the highly fractured nature of the core near the unconformity.

We define nine facies within CRP-1 based primarily on the lithologic description logs (Cape Roberts Science Team, 1998; Tab. 1) and they closely follow those described in the Initial Reports (Cape Roberts Science Team, 1998, see p. 31-33 and 63-68 for photographs and descriptions). We make no distinction between Quaternary and Miocene age facies in terms of their consolidation, and each facies description includes both unconsolidated and consolidated deposits.

DIAMICT FACIES (D)

Diamicts, including both Quaternary diamictons and Miocene diamictites vary between clast-rich and clast-poor types, commonly within one bed. Diamicts occur in beds less than about 20 m thick; their contacts are commonly sharp, and locally show signs of soft-sediment deformation, whereas others are graded or amalgamated. Some D units are macroscopically structureless through entire beds, whereas others have wispy lamination and show indications of internal soft-sediment deformation (*e.g.* 133-135 mbsf). The latter forms are commonly interstratified with sorted sediments that were also deformed while soft; these distinctions are discussed further under "Facies Associations". Clasts are dominated by extraformational rock types, but intraformational types also occur. Clasts rarely show preferred orientation of apparent a-axes in the vertical plane of the core, but there are local alignments, generally parallel with stratification (*e.g.* 105-107 mbsf). One interval (62.64 mbsf) of four examined show preferred alignment of apparent a-axes in the horizontal plane (Cape Roberts Science Team, 1998, p. 77). Clasts are dominated by subangular and subrounded forms and range from very angular to rounded. Some clasts show facets and striae, depending on rock type. Macro- and microfossils are components of many units.

Two diamict subfacies are distinguished based on visually estimated modal textural size of the matrix: those being dominated by sand size particles (sandy diamicts - D1) and those by mud sizes (muddy diamicts - D2). These modal size estimates are generally borne out by particle size analysis (DeSantis & Barrett, this volume). In general D2 diamicts are more common lower in the core, below about 110 mbsf; commonly they have fewer clasts than the D1 types which are more common higher in the core (Cape Roberts Science Team, 1998, Fig. 3, p. 35). These size differences may be a function of source rock types and degree of basement weathering; however, petrological and chemical investigations of the core provide no indication of which are the controlling factors (Cape Roberts Science Team, 1998, pp. 42-49 and 79-86). The difference may be a function of syndepositional mixing of different sediment sources during transport and deposition. Diamicts commonly are a result of mixing of different sediments: for example, debrites may result from several different sorted lithofacies that are mixed during redeposition. Rainout diamicts may be from a combination of ice-rafting (either ice shelf, iceberg or sea ice) and suspension settling of marine particulate matter. Subglacial till may be a mix of subglacial fluvially sorted sediment common in temperate glaciers and erosion products from the glacial bed that could be any rock type, including young proglacial sediment that is overrun, such as glacimarine muds. If D2 diamicts are not a function of bedrock source control, then they may be a result of such mixing processes where the higher proportion of fine particles is indicative of an environment where abundant fine-grained sorted sediment is available to be mixed.

GRAVEL AND CONGLOMERATE (G) AND RUBBLE AND BRECCIA (B) FACIES

Coarse-grained facies are relatively rare in the column, the most common being intraformational rubble or breccia (B) (see Passchier et al., this volume). Gravels and conglomerates (G) commonly occur in thin to medium beds of two types: (i) poorly sorted, clast- or matrix-supported with a muddy sand matrix, or (ii) moderate to well sorted and clast-supported. Both types lack internal structures. The former occur within diamict units with graded or amalgamated contacts, and the latter occur at diamict contacts and are commonly the thickness of individual clasts. The poorly sorted gravels are interpreted as indicating little variability in depositional processes where, for example, they may be coarser debris-flow units with amalgamated contacts, or may indicate variation in two-component mixing during rainout and suspension settling processes. The better sorted gravels are probably lag deposits produced by winnowing of diamict surfaces by unidirectional or bidirectional currents.

Intraformational breccias occur primarily in Miocene strata and care must be taken to distinguish depositional breccias from post-depositional brecciation of the cores (Passchier et al., this volume). In general, these breccias are made of the same lithologies as the beds in which they are contained, and are mainly siltstone or more rarely sandstone. Intraformational conglomerates are rare, and most do not appear to have experienced a long distance of transport. The breccias generally have sharp contacts, occur in thin to medium beds, and generally lack internal structures. They are interpreted as representing very local redepositional mass-movement events.

SAND AND SANDSTONE FACIES (S)

Two broad types of sand and sandstone facies occur in the cores: one is poorly sorted, commonly normally graded and often lacks internal structures (S1), and the other is moderately to well sorted with internal stratification (S2). S1 facies embrace those sediments described in the lithologic logs as muddy medium sand, muddy medium sand with dispersed gravel, silty medium sand, muddy fine sand, muddy fine sand with dispersed gravel, silty very fine sand, clayey very fine sand, laminated muddy fine sand, and laminated silty fine sand. S1 facies occur in thin to medium beds, their contacts are often sharp or loaded, and some intervals (*e.g.* between 88 and 90 mbsf) are amalgamated into thick beds. Most commonly, S1 facies exhibit normal grading, but rare inverse grading also occurs (*e.g.* at 141.10 mbsf). Any internal stratification is weakly developed, and where evident it shows horizontal laminae and, rarely, ripple cross-lamination (*e.g.* at 92 mbsf) which are best seen in X-radiographs. Extrabasinal clasts are randomly dispersed in some beds, and intrabasinal (mainly soft mud) clasts occur most commonly near the base of some units. The presence of marine fossils verifies deposition in a submarine environment. These sands are interpreted as different types of rapidly deposited, organised and disorganised turbidite sands (Pickering et al., 1989; Howe et al., this volume). A nearby delta and glacier would have supplied a large quantity of sand for relatively rapid accumulation.

Better sorted sands of S2 facies are less common, but can be associated with those of S1 (*e.g.* at 65-70 mbsf). S2 facies occur in thin to medium beds where sharp contacts are evident, but amalgamation of strata often blurs individual sedimentation units. S2 facies include the following sediments described in the lithologic logs: moderately sorted medium to coarse sand, moderate to well sorted fine to medium sand, well sorted fine sand, and very fine sand with dispersed gravel. Internal structures are relatively common in the form of planar stratification, local low-angle cross-lamination and some cross-bedding (*e.g.* at 63-66, 102 mbsf). Marine diatoms within these units indicate a submarine environment of deposition. The absence of structures indicative of direct interaction of waves with the sea floor is taken to indicate these deposits, at least in their final depositional phase, accumulated below wave-base. However, parallel and cross-stratification indicate these were deposited by marine traction currents, perhaps even generated by waves in relatively shallow water. If sufficient sea ice was available to dampen high wave activity, as can occur in many glacimarine environments even in interglacial periods, such as today, then these deposits may well be relatively shallow marine sediments of a shoreface setting. Aeolian sands are an important component of modern shelf sands in the McMurdo Sound area today as a result of sea ice action (Barrett & Hambrey, 1992). Some of the better sorting could be attributable to mixing of such contributions at the drillsite. A paucity of marine fossils in specific intervals could be attributed to a number of reasons, but is consistent with inferences of the presence of sea ice, or rapid deposition, or both.

MUD AND MUDSTONE FACIES (M, C)

These facies are generally poorly sorted and commonly have dispersed gravel as lonestones, which rarely show they have been dropped. These facies include: silty clay, clayey silt, laminated clayey silt, sandy mud, sandy mud with dispersed gravel, mud with dispersed gravel, mud with dispersed gravel, and sandy silt with dispersed gravel. These facies are subdivided here on their dominant particle size into two broad facies: a coarser facies that includes the silt/siltstone and mud/mudstone lithologies (M) and a finer facies that includes clayey fine silt/siltstone and silty clay/claystone lithologies (C). Other important characteristics of both of these facies are laminated beds, evidence of soft-sediment deformation, the presence of load casts and the inclusion of extrabasinal clasts or lonestones. Intraformational clasts also occur locally, primarily in the M facies. In general, most intervals of the M and C facies are internally structureless in visual appearance as well as in X-radiography (*e.g.* at 58.80 to 58.93 mbsf). This characteristic can be used to indicate several points about the nature of sedimentation and post-depositional processes. X-radiography shows very little evidence of bioturbation in the structureless intervals (Cape Roberts Science Team, 1998, p.74). Some sections of the cores do exhibit bioturbation (*e.g.* at 145.70 mbsf), but those sections appear to be rare. The apparent lack of bioturbation may be due either to (i) a very uniform original lithology in which there is no density contrast to selectively impede the X-rays even if it is bioturbated, or (ii) the fact that the sediment has not been bioturbated. The latter interpretation is preferred because the sediments do not show visual evidence of heavy bioturbation. Consequently, the structureless nature of the M facies is used to infer that the sediment was deposited very rapidly from suspension without significant sorting and reworking processes. Furthermore, consistent particle size distributions appear to have been introduced in suspension into the environment over the period when these intervals were deposited.

Some intervals of the fine-grained units do show stratification visually, whereas others can be seen only in X-radiographs (*e.g.* at 119.30 mbsf). The stratification occurs in a range from thin laminae to thin beds, and locally shows evidence of soft-sediment deformation. The observation of this stratification shows that it is possible to detect stratification in the fine-grained units using the X-radiographic technique in these cores and thus the apparent structureless appearance in X-radiographs of many other intervals in the core, is probably real. It also indicates either that sedimentation rates were high enough to inhibit infaunal burrowing, or that other physical and chemical environmental factors were not conducive to benthic life.

Inclusion of marine fossils in these units indicates a submarine environment of deposition. Facies M is locally associated with Facies S1, and rarely S2. Where M facies are part of upward-fining S1 facies, most commonly as thin beds, facies M are interpreted as the later stages of deposition from the gravity flows. Facies M also occurs alone as very thin beds and laminae which are interpreted as originating from dilute turbidity currents. These associations will be discussed below in more detail under "Facies Associations". Thicker beds of the M facies that are either structureless or faintly laminated, and locally have one-clast-thick horizons of lonestones (*e.g.* between 96 mbsf and 98 mbsf), are interpreted as suspension settling deposits from fluvially fed overflow plumes combined with iceberg-rafted debris. These M facies can also contain laminae of finer-grained S1 facies interpreted as distal turbidites. Particular cases of facies M occur where very fine sand or coarse silt grains form one-grain-thick layers within the mud (*e.g.* at 55.6 mbsf and 110 mbsf). They are interpreted as cyclopels (Mackiewicz et al., 1984; Cowan & Powell, 1990). They are associated with layers of one-clast-thickness, outsized lonestone layers and laminated fine to very fine sandstones (possibly cyclopsams; Mackiewicz et al., 1984; Cowan & Powell, 1990).

Facies C are far less common than facies M; they are most often structureless but are locally weakly laminated where bioturbation is limited or absent. These facies include rare lonestones and scattered sand grains, and siltstone laminae. Generally, these facies are the most highly bioturbated and are interpreted as being the most slowly deposited of all facies. Facies C commonly coarsens upwards gradationally into M facies over tens of centimetres or metres.

CARBONATE FACIES (L)

One interval within the Quaternary part of the core (lithostratigraphic Unit 3, 31.70-33.82 mbsf) is highly fossiliferous. Details of sediments in the interval are presented by Cape Roberts Science Team (1998), but in general they are mixed siliciclastic-carbonate with a 10-40% biogenic component. The siliclastic component comprises silt and fine to very fine, polymict sand and lonestones. The biogenic sandy fraction includes bioclasts/biosomes from bryozoans, foraminifera, octocorals, gastropods, bivalves, sponge spicules, barnacles and echinoids (Cape Roberts Science Team, 1998, p. 37). There are two broad carbonate facies within the sequence: (i) fossiliferous siliciclastic sediment (L1), mainly structureless poorly sorted muddy sand and sandy mud, commonly with a diamict texture, and (ii) laminated calcareous sandy mud and muddy sand or coquina (L2) occurring in thin couplets defined by variation in the bioclastic content. The facies are interpreted as having accumulated in relatively shallow (at least 50 -70 m water depth) open water over the sea-floor high of Roberts Ridge, which at the time was devoid of major siliciclastic input apart from iceberg rafting.

FACIES ASSOCIATIONS

Facies outlined above have common associations throughout the core. These associations, in combination with vertical sequences of the facies associations and some particularly distinctive sedimentological or biological characteristics, are used to interpret depositional environments up the core (Tab. 2, Fig. 2). The facies associations are discussed here, while their broad environments when placed in particular sequences in the cores, are discussed further below under "Facies Sequences". Seven associations of facies recur within the cored sequence. This analysis is a synthesis and attempts to keep associations to a minimum; alternative interpretations of the associations may be possible in some instances and will be discussed under each particular association. The alternative interpretations may be resolved in future when other data, such as from palaeoecology, are also considered. Individual lithofacies are listed in order from the dominant to least common types within the association.

FACIES ASSOCIATION 1 (M; C AND M; M, C AND B)

Facies Association 1 (FA1) includes the most fine-grained of all of the units within the core. Generally, FA1 is interpreted as representing deposition in an offshore shelf environment, but similar facies are possible beyond,

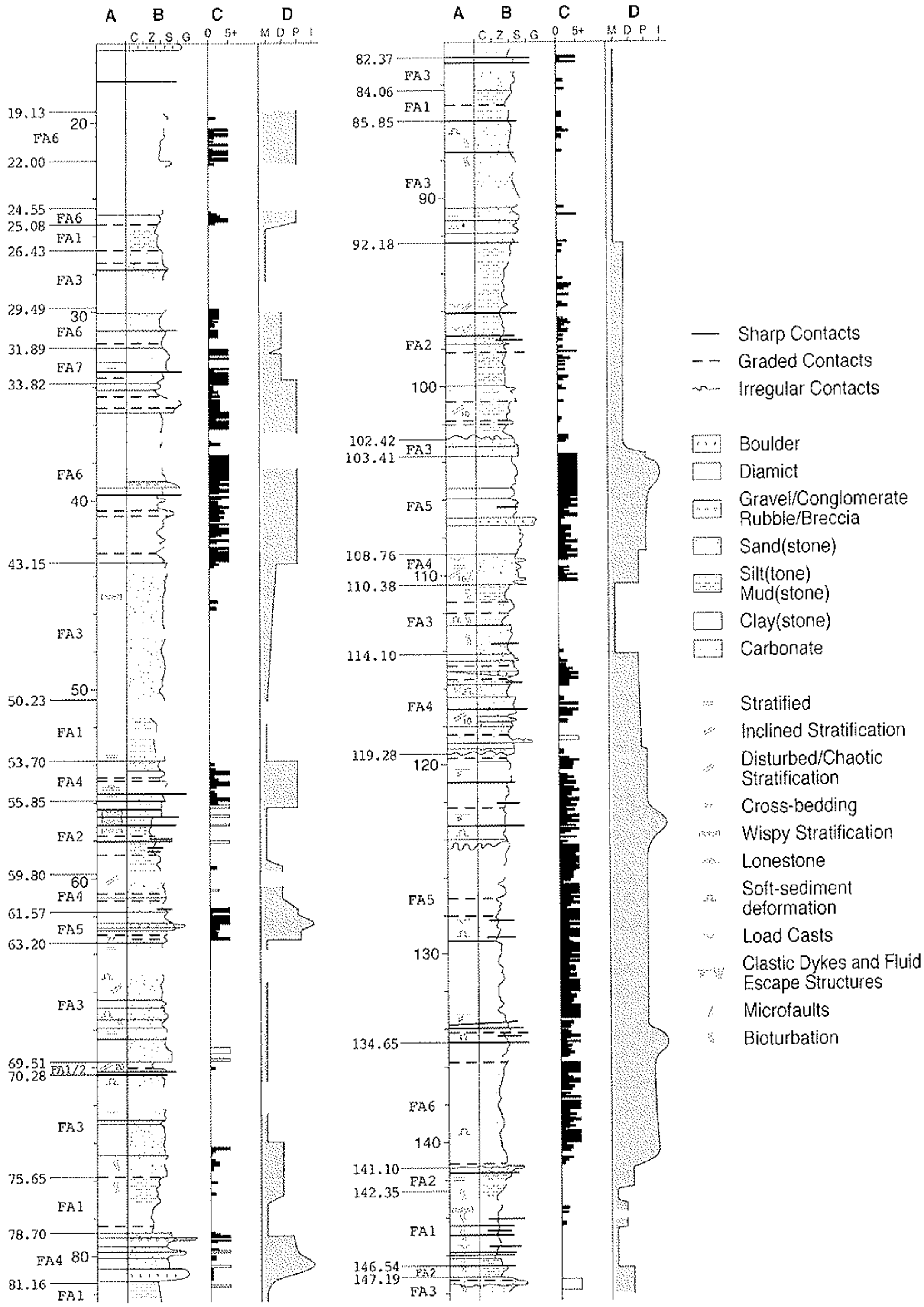

Fig. 2 - Graphic lithofacies log of CRP-1, showing interpreted lithofacies associations with the depth (mbsf) column, summary sedimentary structures (A), general facies with mean particle size profile (B), distribution of number of clasts per 10 cm ranging from 0 to over 5 (white bars are intraclasts) (C), and inferred glacial proximity (M-marine, D-distal glacimarine, P-proximal glacimarine, I-ice contact) (D). Facies association (FA) codes with major facies are: FA1 - muds; FA2 - mud with sand laminae; FA3 - mainly sand with some mud intervals; FA4 - sands inter-bedded with diamicts, gravels and muds; FA5 - diamict interstratified with sand, gravel and mud; FA6 - mainly structureless diamict; FA7 - fossil carbonate.

or locally just within, the reach of low density gravity flows from deltas. The association could also represent lateral settings away from the main depositional lobe of a delta and even of a grounding-line fan. In fact, redeposition may be a feature of those environments characterised by intraformational breccias, whereas some mud units appear to include low density turbidites. The facies association is interpreted as having been deposited below wave-base, but in sequences where glacial or paraglacial settings are inferred, such as indicated by lonestones. However, protection of the sea floor from waves by pack ice cannot be disregarded.

Tab. 2 - Description of lithofacies associations and their interpreted settings from sequences. Summary depositional environments are provided on the right.

Depth (mbsf)	Facies Associations	Facies Sequence	Depositional Environment
end - 147.19	S1 (Sandy turbidites)	Delta front/sandy shelf, medial glacimarine	Deltaic/shelf below wave base, from medial to distal glacimarine to paraglacial/(?) nonglacial to medial glacimarine upward, showing glacial retreat then advance
147.19 - 146.54	M+C+S1 (Suspension settling deposits, low density gravity flow deposits)	Prodeltaic/offshore shelf, distal glacimarine	
146.54 - 142.35	C+M (Suspension settling deposits with rare clasts as lonestones, low density gravity flow deposits)	Offshore shelf, ice protected/below wave-base, paraglacial	
142.35 - 141.10	S1+M (Sandy turbidites, suspension settling deposits)	Prodeltaic/offshore shelf, medial glacimarine	
141.10 - 134.65	D2 (Structureless diamict - till or rainout)	Subglacial or rainout, ice contact and ice proximal	Ice contact morainal bank and pro-bank then grounding-line fan or delta
134.65 - 119.28	D2+D1+S1+M (Debris flow diamicts with thin low density gravity flow deposits, graded/amalgamated contacts, soft sediment deformation)	Ice-contact and ice proximal mass flow system	
119.28 - 114.10	S1+D1+M (Stacked debris flow diamicts, sandy turbidites, ice-rafted debris as lonestones and pavements, soft sediment deformation and fluid escape)	Ice contact and ice proximal mass flow and submarine fluvial efflux system	
114.10 - 110.38	S1+S2+M (Sandy turbidites and marine current-depo-sited sands, suspen-sion settling deposits)	Delta front/prodelta/shelf, below wave-base, non-glacial	Nearshore to offshore non-glacial delta/shelf - two cycles
110.38 - 108.76	S1+M (Stacked sandy turbidites, lonestones and dropstones, cyclopels and cyclopsams)	Ice contact and ice proximal mass flow and submarine fluvial efflux system	Grounding-line fan, then morainal bank and pro-bank and then delta
108.76 - 103.41	D1+S1 (Debris flow diamicts and (?)subglacial till)	Ice contact and ice proximal mass flow system	
103.41 - 102.42	S1+M (Stacked low density gravity flow deposits, lonestones)	Delta front/sandy shelf, glacial	
102.42 - 92.19	M+S1 (Suspension settling deposits with clasts as lonestones and in horizons, low density gravity flow deposits)	Prodeltaic/offshore shelf, medial glacimarine to paraglacial	Medial glacimarine with glacial retreat and then shoreline progradation at start of sequence above
92.19 - 85.85	S1+S2 (Gravity flow and traction deposits with rare lonestones)	Delta front/sandy shelf, paraglacial	Nearshore to off-shore paraglacial delta/shelf - two cycles
85.85 - 84.06	M (Suspension settling deposits with rare lonestones)	Offshore shelf, ice protected/below wave-base, paraglacial	
84.06 - 82.37	S1+M+S2(+B) (Gravity flow and traction deposits with rare lonestones)	Delta front/sandy shelf, paraglacial	
82.37 - 81.16	M (Suspension settling deposits with rare lonestones)	Offshore shelf, ice protected/below wave-base, paraglacial	
81.16 - 78.70	D1+S1+G+B (Debris flow diamicts and (?)subglacial till)	Ice contact and ice proximal mass flow and submarine fluvial efflux system, (?)sub-glacial, reworked lags and redeposited flows	Ice-contact grounding-line fan and morainal bank and then glacial over-riding; final stage - shallow water reworking
78.70 - 75.65	C+M (Suspension settling deposits with rare lonestones)	Offshore shelf, ice protected/below wave-base, paraglacial	Shelf progradation with glacial influence in last stages, then glacial retreat with continued shelf sedimentation in perhaps two cycles
75.65 - 70.28	S1+S2+M (Gravity flow and traction (+aeolian mix?) deposits with rare lonestones)	Delta front/sandy shelf, ice-protected/below wave-base, paraglacial	
70.28 - 69.51	M+C+B (Suspension settling deposits and very low density gravity flow deposits)	Offshore shelf (?prodelta), ice protected/below wave-base, paraglacial/(?) non-glacial	
69.51 - 63.20	S1+S2+M (Sandy turbidites and marine current-deposited (+aeolian mix?) sands)	Delta front/sandy shelf, non-glacial	
63.20 - 61.57	D1+S1+G (Debris flow diamicts, subglacial till, rare sandy turbidites)	Ice-contact and ice proximal mass flow system, some sub-glacial deposition(?)	Ice contact morainal bank and pro-bank and grounding-line fan system
61.57 - 59.80	S1+M+G (Stacked sandy turbidites, rare debris flow diamicts, lonestones)	Ice contact and ice proximal mass flow and submarine fluvial efflux system	
59.80 - 55.85	M+B+S1 (Suspension settling deposits and very low density gravity flow deposits)	Prodeltaic/offshore shelf, below wave-base, non-glacial	Offshore sedimentation in glacial retreat phase
55.85 - 53.70	S1+D1+M (Sandy turbidites, debris flow diamicts, traction sands, cyclo-pels, lonestone layers)	Ice contact and ice proximal mass flow and submarine fluvial efflux system	Ice contact grounding-line fan system

Tab. 2 - Continued.

Depth (mbsf)	Facies Associations	Facies Sequence	Depositional Environment
53.70 - 50.23	M (Suspension settling deposits)	Poorly constrained. Offshore shelf, below wave-base, non-glacial(?)	Offshore sedimentation in general coarsening-up progradation during glacial retreat phase
50.23 - 43.55	S2+S1 (Marine current-deposited sands and sandy turbidites)	Delta front/sandy shelf, below wave-base/(?) ice protected, non-glacial/(?)paraglacial	
43.55 - 33.82	D1+M+G (Diamicts with graded contacts within and with muds, lonestone horizons)	Rainout with local subglacial(?), ice contact and ice proximal	Glacial shelf deposition, (?) minor glacial fluctuation, (?) more distal upward
33.82 - 31.89	L+M+D1+S1 (Coquina, calcareous mud, diamict and sand)	Carbonate shelf	Deposition on shelf bank with some influence of iceberg rafting
31.89 - 29.49	D1+S1 (Sharp and graded contacts, diamict-diamict, diamict-sand)	Ice-contact, ice proximal mass flow, and rainout systems	Glacial shelf deposition at and near grounding-line
29.49 - 26.43	S1 (Marine current-deposited sands and sandy turbidites)	Delta front/sandy shelf, below wave-base, non-glacial(?)	Glacial shelf deposition during glacial retreat
26.43 - 25.08	M (Suspension deposited mud, ?drilling disturbed?)	Offshore shelf, ice protected/below wave-base, paraglacial	
25.08 - 24.55	D1 (Rainout diamict graded up from sandy mud below)	Rainout, ice contact and ice proximal	Glacial shelf deposition
24.55 - 22.00	No core		
22.00 - 19.13	D1 (Structureless diamict)	Rainout (?and subglacial), ice contact and ice proximal	Glacial shelf deposition, rainout/(?) subglacial

FACIES ASSOCIATION 2
(M, C AND S1; M AND S1; M, B AND S1)

Facies Association 2 is dominated by mud, but includes laminae or thin beds of facies S1. This association is interpreted as being prodeltaic, or at least offshore shelf. However, as with FA1, some units could represent lateral deposition away from a major influx rather than be farther offshore. Where the presence of glaciers is inferred, this association also could represent a pro-grounding-line fan setting. The glacimarine environment represented can vary from proximal through medial to distal. That variation is inferred from numbers of lonestones and to some degree from the proportions of sandy (S1) or silty laminae.

FACIES ASSOCIATION 3 (S1; S1 AND S2; S2 AND S1; S1 AND M; S1, S2 AND M; S1, M, S2 AND B)

FA3 is dominated by sandy facies, but also may include some fine-grained beds. The most common form of beds are interpreted as sandy turbidites which can be generated on deltas, grounding-line fans and on storm-dominated shelves. Those sequences dominated by S2 sands may most appropriately be described as sandy shelf deposits which typically include an aeolian contribution, as occurs today by sea-ice dispersal, to help produce the better sorting. These processes appear to have occurred under both a non-glacial as well as a variety of glacial regimes including proximal to medial glacimarine and occasionally paraglacial environments, as indicated by lonestone abundances.

FACIES ASSOCIATION 4 (S1 AND M; S1, M AND G; S1, D1 AND M; S1, D1 G, AND B)

FA4, like FA3, is dominated by sandy facies, but also includes interbeds of diamicts and gravels, as well as mud. Mud is often laminated and, locally, the mud intervals include facies interpreted as cyclopsams and cyclopels that are produced from fluvial discharges in glacimarine settings experiencing very rapid deposition (Mackiewicz et al, 1984; Cowan & Powell, 1990). This association is interpreted as representing ice-contact and ice-proximal settings, with mass-flows associated with a submarine fluvial efflux system. That all or part of these intervals may be deltaic cannot be excluded, as these processes may occur at deltas. However, because FA4 is commonly associated with FA5, and cyclopels are commonly produced from submarine discharges, an ice-contact grounding-line setting is currently the preferred interpretation.

FACIES ASSOCIATION 5 (D1 AND S1; D1, S1 AND G; D2, D1, S1 AND M)

The dominant facies of FA5 are diamicts, but often they are interbedded with sand, gravel and mud. Commonly, the sand component has dispersed clasts, and includes graded S1 beds. Soft-sediment deformation is common within the diamicts as well as involving sorted interbeds. Locally, clasts have preferred orientation and are aligned with deformed contacts. Fluid escape and sediment-injection structures also occur. These features, soft-sediment deformation, presence and geometry of clast orientation, combine to indicate that these types of diamictites probably were deposited originally on a slope by debris flows. This deposition was likely to have been very rapid (metres per year) because the sediments had a high water content when they experienced soft-sediment deformation. They were probably stacked in pulses and interstratified with minor sorted sediment pulses, following which the pile experienced minor creep down-slope to further deform the mass. Apparent amalgamated contacts (*e.g.* at 122.20 mbsf), and other contacts that are sharp but show soft-sediment deformation between a diamict and another unit (*e.g.* at 124.10 mbsf), further support this interpretation. FA5 may have some interbeds of diamicts that are either rainout or subglacial deposits, but distinctions require further analyses of the diamicts.

FACIES ASSOCIATION 6 (D1; D1 AND S1; D1, M AND G; D2)

FA6 like FA5, is dominated by diamicts, but locally has subordinate mud and gravel. Commonly, the diamicts are visually structureless, but local soft-sediment deformation, amalgamated contacts and interstratification of sorted strata may be indicative of flowage. Where it is truly structureless, FA6 could be either a subglacial or rainout deposit, whereas where the diamict is structureless but it grades into or out of M and G, it is likely to be rainout. In general, this association is taken to represent subglacial, mass flow or rainout deposition, or it may be a combination of the three; a problem to be resolved with future analyses. The setting is ice-contact or ice proximal.

FACIES ASSOCIATION 7 (L, M, D1 AND S1)

This facies association occurs as one unit within the core and is dominated by fossil carbonate. It includes fossiliferous sand or packstone, interpreted as a coquina which is interbedded with siliciclastic units with varying amounts of fossiliferous debris. The siliciclastic units include mud, graded sand and diamict. This association is interpreted as representing a shelf bank on which an epibenthic community was established while some iceberg rafting still occurred. However, the site was beyond the influence of major glacial siliciclastic input for much of the time. Local redepositional events occurred on the bank, and perhaps local iceberg grounding contributed some of the siliciclastic sediment and caused local redeposition.

FACIES SEQUENCES AND DEPOSITONAL ENVIRONMENTS THROUGH TIME

The facies associations described above occur within the core in sequences as shown in table 2 and figure 2. 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 extemely rapid switches in depositional processes as is common in the inferred environments. Alternatively, they may represent an artifact of over-simplification in interpretations of the associations.

When the facies sequences are examined, two broad characteristics are seen. The first is that the style of Quaternary sedimentation appears to be different from that of the Miocene. That is, the Quaternary facies are more like modern polar glacier deposits, whereas Miocene sediments are inferred to be more similar to modern polythermal glacial sequences, such as in parts of the Antarctic Peninsula or in Svalbard today. 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. Those distinctions will be discussed below where conceptual models are presented. The other broad distinction is within deposits of Miocene age where the oldest part of the section (below about 100 mbsf) is dominated by diamicts, whereas younger parts of the Miocene are dominated by sorted deposits. Although minor glacial advances appear to have occurred during the younger part of the Miocene, most of that interval is interpreted as having been a phase of glacial recession. As discussed above under "diamict facies", diamicts below about 110 mbsf are also finer-grained than younger diamicts; this may be a function of the increased volume of sorted sediment available for mixing in the diamicts under polythermal conditions.

A more detailed record of glacial fluctuations can be inferred from the interpreted facies associations. This record is presented in figure 2 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, 1998, Fig. 16, p. 17), clast fabric data (as described above under diamict facies) and diamict micromorphology (van der Meer & Hiemstra, this volume). Low sediment porosities at about 63-64 mbsf and below about 103 mbsf are taken as an indication of over-consolidation and interpreted as representing glacial over-riding at those levels. The diamict with a preferred clast fabric at 62.64 mbsf is interpreted as a subglacial till. Micromorphological studies thus far have identified three levels of subglacial till at 78.94, 123.20, 134.45 mbsf, whereas those at 63.0 and 105.93 mbsf are less certain and may not be subglacial (van der Meer & Hiemstra, this volume).

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 for CRP-1 cannot be established, but some data are available to use in conjunction with facies associations to constrain water depth at specific intervals in the core. Two intervals in the core are thought to have been deposited in shallow water, based on benthic diatoms (at about 59.5-60.0 and 78.62 mbsf). In addition, the Quaternary carbonate sequence is thought to have formed in water greater than about 70 mbsl, based on the macrofossil assemblage (Taviani & Claps, this volume). Some diatoms in the Quaternary section are also described as being of fresh or brackish water origin. Although facies are not well preserved in this interval, they are interpreted as being marine, and thus the diatoms are taken as having a sea-ice origin at present, until more thorough evaluations can be made.

DISCUSSION

The difference between Quaternary and Miocene facies is ascribed to palaeo-glaciological conditions. Studies of modern glacimarine systems indicate that polar glaciers with internally cold-ice do not appear to produce significant subglacial conduit flow (Powell & Alley, 1997). However, polythermal glaciers and temperate glaciers produce significant volumes of sediment from subglacial, submarine and terrestrial ice-marginal, streams (*e.g.* Bennett et al., in press). That distinction produces facies sequences which are dominated by diamicts on polar continental shelves, compared with sequences that have higher proportions of sorted sediment on shelves associated with polythermal or temperate glaciers. That is not to say that polar shelves do not have sorted sediment, but it occurs in relatively lower abundance than on other shelves. Likewise, the proportion of sorted sediment appears to be less for polythermal than temperate glacial shelves. Note that when saying 'sorted sediment' here, we included low-density gravity-flow deposits because, when they occur as thick rapidly deposited sequences or in shallow water, they most often originate from sorted sediment sources. However, debris-flow diamicts are unsorted and can originate from unsorted sediment or from mixing of a sorted sequence during its failure.

These differences in environmental characteristics are the basis for our inference that the Quaternary section represents deposition under polar conditions, whereas the Miocene section is more likely to have been deposited by polythermal glaciers. Miocene strata are dominated by sorted sediment, most commonly of low-density sediment gravity flow deposits (FA3 and FA4) with subordinate bergstone mud deposits (FA2); stratified and deformed diamicts occur in FA4 and FA5 sequences. Many of these sequences are interpreted as originating from very active deltas or grounding-line fans which are virtually absent in true polar settings. Even the thick diamict interval from 119.28 to 141.60 mbsf has many interbeds of sorted sediment (mainly turbidites) showing evidence of very rapid deposition and a high water content, and repeated intervals of penecontemperaneous redeposition of the apparently unstable sequence. Although core recovery is poorer for the Quaternary record, deposits are dominated by structureless diamicts (characterised by FA6) with little evidence of rapid deposition and with subordinate sorted sediment, more typical of polar continental shelf sequences (*cf.* Powell & Alley, 1997). Conceptual models were established using this differentiation and the facies associations described in this paper (Fig. 3). The figure depicts four different palaeo-environmental settings; two each for the Quaternary and Miocene. In each time period two extreme conditions are depicted, one of glacial retreat and one in which the glaciers are more advanced. In general, the glacial recession model for the Miocene is more appropriate for younger strata, whereas the model for a more advanced glacial setting is more appropriate for the oldest part of the core. The recession model for the Quaternary is set at the time when the carbonate interval was accumulating on Roberts Ridge, whereas the glacial model shows Roberts Ridge acting as a pinning point for the grounding line, partway through a glacial advance or recession.

Glacial sources are shown to be primarily from the palaeo-Transantarctic Mountains with palaeo-Mackay Valley being a conduit for the ice. During the Quaternary it is known that the West Antarctic Ice Sheet expanded through the area from south of McMurdo Sound, but also had a contribution from the East Antarctic Ice Sheet through the Transantarctic Mountains. Although provenance studies are not as clear for a southern source (Cape Roberts Science Team, 1998), a major contribution of ice from a southern source is depicted. Roberts Ridge is taken to be a significant bathymetric form in the Quaternary, but was less significant in the Miocene, with the drill-site more likely being on a sloping sea floor. Specific types of environments depicted are inferred from the lithofacies associations in the cores and combined with established conceptual models of the different environments (*e.g.* Powell, 1981; Elverhøi et al., 1983; Barrett, 1989; Hambrey et al., 1991, 1992; Barrett & Hambrey, 1992; Laberg & Vorren, 1996; Powell et al., 1996; Powell & Alley, 1997; Bennett et al., in press).

Relatively high sedimentations rates are typical of the polythermal glacial setting (*cf.* Hallet et al., 1996), where they can be as high as 5 to 10 cm a^{-1} of glacimarine sedimentation near to the glacier to 0.5 to 1 mm a^{-1} about 20 km away from it (Elverhøi et al., 1980, 1983). Even allowing for consolidation of the sequence, such sedimentation rates could mean that the Miocene part of the core accumulated in a matter of tens of thousands of years (several hundreds of thousands of years at a maximum) if no erosional gaps are present. Some contacts appear to be unconformities, however, and these represent important periods of time loss, as is confirmed by some facies dislocations up the core and sequence stratigraphic analysis (Cape Roberts Science Team, 1998, pp. 72-73 and 127-129; Fielding et al., this volume). However, many intervals may not have such gaps - the problem is finding them. This has important implications in terms of dating the core and inferring net accumulation rates through the time represented by the core. Given different dating controls from palaeontology, especially diatoms (Cape Roberts Science Team, 1998; Bohaty et al., this volume), Ar-Ar dates on clasts (McIntosh, this volume), Rb-Sr dates on carbonates (Lavelle, this volume) and palaeomagnetic reversal stratigraphy (Cape Roberts Science Team, 1998; Roberts et al., this volume), the total time represented by the Miocene interval of the core appears to be quite short

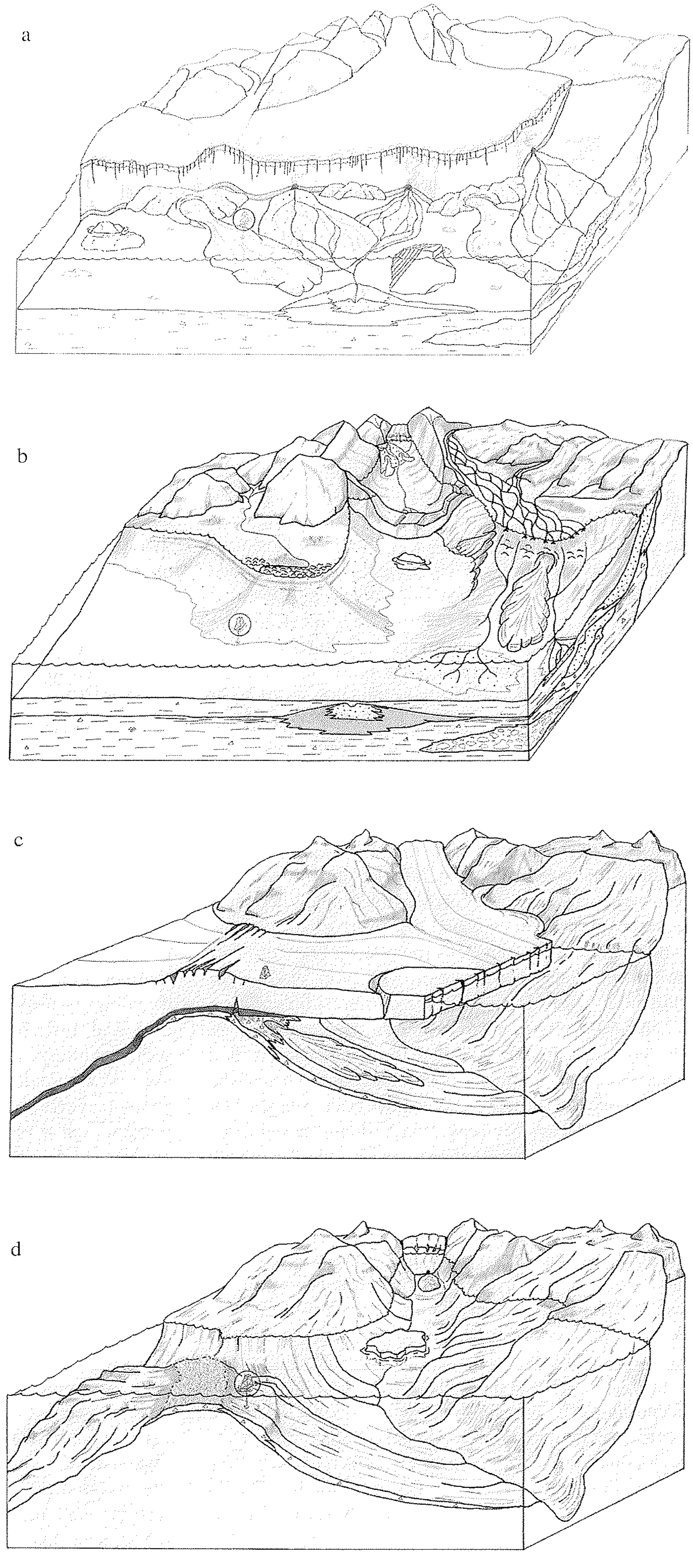

Fig. 3 - Perspective illustrations of the Cape Roberts area viewed from offshore. The illustrations are not to scale in order to allow marine environments to be emphasised. The drilling rig is encircled.

a) Miocene glacial advance as polythermal glaciers expand out from the palaeo-Transantarctic mountains (lower than today). The glaciers extend toward the drill site and occasionally beyond. For much of the time at the site, sediment rapidly accumulates, especially close to the grounding line of a glacial tidewater cliff, where deposits include morainal bank systems, grounding-line fan systems and iceberg-zone facies associations.

b) Miocene ice in recession, with most ice gone apart from remnants of valley glaciers with tidewater cliffs. Most sediment is delivered to the coast by rivers and distributed by waves and currents. Only a small proportion of the sediment is iceberg-rafted debris.

c) Phase of Quaternary glaciers while in expanded positions in the Ross Sea. The grounding line is shown pinned on Roberts Ridge and an ice shelf is fed from the south and from an ice sheet behind the mountains. Subglacial till is deposited on the ridge, rainout diamict is deposited just beyond the grounding line and debris flows move diamicts down-slope towards Mackay Sea Valley.

d) Full glacial recession phase in the Quaternary with glaciers back into the fjords and only rare icebergs cross the drill-site. A carbonate-rich epibenthic community is established on Roberts Ridge (from Cape Roberts Science Team, 1998).

and, at a maximum, it represents an interval of between about 17.5 and 22.1 Ma. The sea-level curve of Abreu & Anderson (1998) indicates a rapid drop in global eustatic sea level at about 21.5 Ma which, although core dating is still being resolved, appears to coincide with major diamict production in the core. If the current core dating is confirmed with more analysis, then this correlation would indicate that a glacial advance in Antarctica drove the lowering of sea level at that time. Furthermore, if all of the glacially dominated Miocene deposits in the core are near-synchronous, then the younger Miocene deposits dominated by sorted sediments, may have accumulated at a time when global eustatic sea-level was gradually rising. That being the case, local glacial fluctuations also would have occurred at the core site during the global sea-level rise to account for local diamict intervals. The age of the Quaternary carbonate unit is not finally constrained, but it does appear to represent warmer water without sea ice (Scherer pers comm.). It most likely represents a period of ice sheet recession, but the warmer conditions could have stimulated local glaciers, by increasing coastal precipitation, which allowed continued iceberg rafting over the site.

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 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 diamict 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.

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