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Sequence Stratigraphic Analysis of CRP-1, Cape Roberts Project, McMurdo Sound, Antarctica

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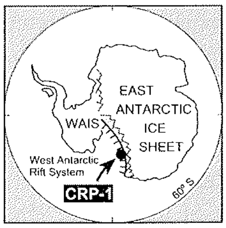
Abstract - Vertical facies associations within the CRP-1 drillcore reveal a strong cyclicity and facilitate the development of a sequence stratigraphic framework. The sedimentary record appears to be punctuated by a series of erosional sequence boundaries which are here inferred to be the product of cycles of glacial advance and retreat. This is further supported by the absence of thick (preglacial) progradational sequences within the drill core. Eight Miocene and at least two Quaternary sequences are identified on the basis of facies and textural association. The core is dominated by transgressive (local glacial retreat) and high stand (local glacial minimum) deposits, with regressive (local glacial advance) and lowstand (local glacial maximum) events being under represented.



INTRODUCTION

Published sequence stratigraphic models are most readily applied to successions accumulated in continental marginal environments (coastal and shallow marine facies). This is because the effects of relative changes in sea-level are most pronounced in these environments. To date, however, the majority of published models (*e.g.*, Emery & Myers, 1996) have been applied to sediments accumulated in temperate and tropical latitudes, and sequence stratigraphic models for polar latitude systems are not as well-established. Work published to date suggests that the stratigraphic record of glaciated, polar continental margins is complicated by the complex pattern of sediment accumulation and erosion generated by multiple glacial advance and retreat cycles, isostatic and eustatic effects. A more complete stratigraphic record appears to be preserved in periglacial or temperate marine realms (*e.g.*, Eyles, 1993; Visser, 1997), although a lack of subsurface data from presently glaciated continental margins precludes determination of where, relative to the coastline, the transition from a truncated and composite, to a complete, stratigraphic record might occur.

In the past twenty years a considerable body of information has been gathered on the Cenozoic record of the southwestern Ross Sea region of Antarctica, principally through a succession of drilling programmes (Dry Valley Drilling Project - DVDP: McGinnis, 1981; MSSTS-1: Barrett, 1986; CIROS-1: Robinson et al., 1987; Barrett, 1989; CIROS-2: Pyne et al., 1985; Barrett & Hambrey, 1992; and most recently CRP-1: Cape Roberts Science Team, 1998a-d). Until recently, however, no sequence stratigraphic analysis had been conducted on cores from these holes, and the few sequence stratigraphic models that have been put forward for the Antarctic continental margin (reviewed by Barrett, 1996) are generalised and largely conceptual.

In a recent paper, Fielding et al. (1997) have proposed a sequence stratigraphic interpretation for the CIROS-1 core (Fig. 1), and in this paper we construct a similar framework for the CRP-1 drillhole. A preliminary version

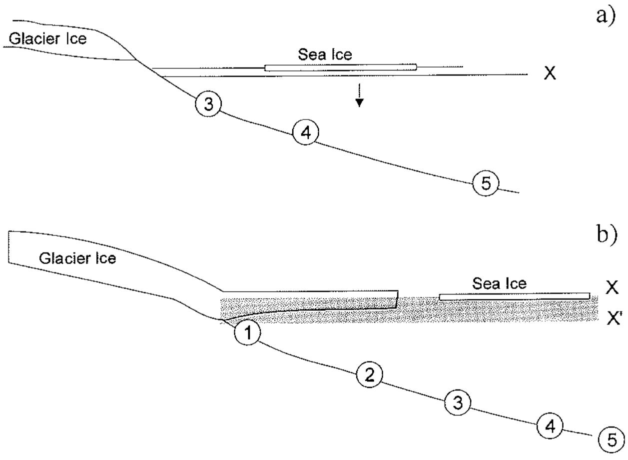


Fig. 1 - Schematic cross-sections of the Cape Roberts area during the Miocene, showing the interpreted depositional context of the lithofacies recognised (numbers in circles). The lower diagram (*b*) depicts a period of glacier advance, in which the glacier has a submarine grounding line, and the adjacent sea is semi-permanently covered by ice, thus dampening any wave activity. The upper diagram (*a*) depicts a period, of glacier retreat, such that its terminus is onland, and fluvioglacial sediments are being delivered into a shallow sea more affected by wave activity. Point X is the maximum seaward progression of a eustatically driven shore line (in the absence of ice) and Point X' the maximum seaward advance of an erosional grounding line. The potential removal and reworking of material deposited between Point X and Point X' greatly reduces the resolution of sea level reconstruction such that entire eustatic cycles may be potentially masked.

of this model was presented in the Initial Report for CRP-1 (Cape Roberts Science Team, 1998c): the present analysis is augmented by observations made during a re-examination of the archive half of the core at the Florida State University, Tallahassee, in May 1998.

CRP-1 penetrated a succession of early Quaternary age (estimated at 1.2-1.8 Ma: Cape Roberts Science Team, 1998b), unconformably overlying an interval of early Miocene age that extends to the terminal depth of the well. Core recovery in the Quaternary interval was good (70%), but several sections were lost owing to the poorly consolidated and heterogeneous nature of the strata encountered. Recovery through the Miocene section, however, was much higher (90%). We here adopt a revised position for the boundary between the Quaternary and Miocene sections from 43.55 metres below sea floor (mbsf), as published in the Initial Report, to 43.15 mbsf based on our examinations of the core (see Fielding et al., this volume).

The array of lithofacies in the two intervals is similar. Because of the greater length of core through Miocene deposits, the lithofacies scheme for the Miocene is presented first, followed by a shorter treatment of the Quaternary succession focusing on the lithofacies unique to that interval. The facies are described in full in Cape Roberts Science Team (1998a-d) and appendices 2 and 3 of that volume contain detailed core logs and scanned core images, respectively.

FACIES ANALYSIS

MIOCENE

Six lithofacies recognised within the Miocene section are defined on the basis of lithology or associations of lithologies, bedding contacts and bed thicknesses, texture, fabric, sedimentary structures and colour (Tab. 1).

Facies 1 - Diamictite, Sandy Muddy Conglomerate

Description. Facies 1 consists of very poorly sorted mixtures of gravel, sand, silt and clay, which are generally poorly stratified to unstratified and display little internal organisation into beds. The lithology comprises a coarse clast population (granule to boulder grade), generally suspended in and supported by a matrix of mixed sand, silt and clay (Cape Roberts Science Team, 1998b, Fig. 1a & b; Cape Roberts Science Team 1998c, Fig. 1a-c). The clast and matrix proportions (and the grain-size of both components) vary considerably, typically over short vertical intervals. Some diamictite units are punctuated by discrete, fine-grained partings, which are typically up to 10 cm thick and show evidence of soft-sediment deformation and/or bioturbation. Fossil shell fragments were noted at several horizons within Facies 1, principally of the ribbed scallop *Chlamys sp.*, and marine microfossils have been recovered from samples of this and other facies.

Coarse clasts are of both intra- and extraformational rocks. Intraformational debris includes clasts of siltstone clast breccia, fine sandstone, siltstone (including one clast bearing calcareous serpulid tubes typical of Facies 6: see below) and dark grey, possibly silicified claystone, lithologies characteristic of Facies 4-6 (see below). Extraformational clasts include basic volcanic and intrusive rocks, granites of varying texture and composition, felsic porphyry, and sandstone. The largest clasts penetrated by the core are either dolerite or granite. Coarse clasts are typically very poorly sorted, and range in shape from very angular to well-rounded. Some show elaborate, angular outlines, while some dolerite clasts are almost perfectly rounded. One broken clast of dolerite was noted at *c.* 103.83 mbsf, within a cluster of clasts coated by light-coloured ?silt. Striae were noted on some smaller clasts. Directional clast fabrics (two-dimensional) were measured from certain horizons (Cape Roberts Science Team, 1998c, Fig. 5). Little evidence of stratification was noted, although some elongate clasts are inclined, suggestive of imbrication. Two intervals (133.57 - 133.81, 139.05 - 139.31 mbsf) preserve mud-lined, sand-filled sedimentary dykes, *c.* 1.5 cm wide, the upper of which appears to emanate from a mixed, fine-grained horizon immediately below that interval.

Interpretation. Macrofossils within Facies 1 indicate a marine environment less than 100 m deep, and this is consistent with microfossil assemblages found in the diamictites. The poorly sorted and, in many cases, angular nature of coarse debris suggests that a variety of processes may have played a role in delivering this sediment. Much of the gravel noted, however, probably arrived at the depositional site by falling through the water column from floating ice. Such a process can be established more confidently in a few cases where poorly defined lamination is deformed beneath coarse clasts. A broadly glacimarine origin is inferred for Facies 1, whereby sand-, silt- and clay-grade sediment was delivered from a glacier terminus some (unknown) distance from the drillsite, and mixed by physical processes in the marine environment. Coarse debris were dropped from floating ice, and changes in the abundance of such gravel have been used elsewhere (Cape Roberts Science Team, 1998d, Fig. 4) to give a first approximation as to the proximity of a glacier terminus. Some diamicts probably contain a record of ice-grounding across the drillsite (see below). Fine-grained partings may indicate hiatuses in the accumulation of glacimarine sediment, perhaps due to fluctuations in the position of a glacier terminus.

Facies 2 - Rhythmically Interlaminated Sandstone and Siltstone with Lonestones

Description. Facies 2 comprises thinly, rhythmically interbedded and interlaminated, granular to pebbly, fine- to medium-grained sandstone, and siltstone, in roughly equal proportions, with dispersed gravel of varying grade and clast shape (Cape Roberts Science Team, 1998c, Fig. 1d). Individual beds are 2 - 20 mm thick, and tabular across the width of the core. Beds are characterised by a planar stratification, which is deformed beneath some lonestones. Individual sandstone beds and laminae are moderately to well-sorted. Additionally, one thin bed of homogenised, granular to pebbly, sandstone-siltstone was

Tab. 1 - Characteristics of Miocene lithofacies recognised in CRP-1.

Facies	Lithology	Geometry, Contacts, Structures	Fossils	Interpretation
1	Diamictite to muddy/ sandy conglomerate, variable texture and fabric but mainly very poorly sorted, variable clast content of pebbles to boulders, shape varies from very angular to well-rounded (most subangular - subrounded)	Sharp-bounded units <22 m thick, some with fining-upward tops, mainly unstratified, but with local wispy lamination, soft-sediment deformation and siltstone partings, local inclined clasts (?imbrication), some coated clasts, one sedimentary dyke	Scattered shells of ribbed scallops (*Chlamys sp.*)	Glacimarine, sand and mud deposited from aqueous currents and suspension fallout, gravel from floating ice, some probable subglacial deposits
2	Rhythmically interlaminated and thinly interbedded fine-grained sandstone and siltstone, scattered clasts up to cobble grade	?Sharp-bounded unit 0.66 m thick, planar lamination, deformed lamination beneath some clasts	None observed	Subaqueous current deposits, possibly proximal glacimarine with ice-rafted dropstones
3	Sandstone, generally fine- to medium-grained, clean and relatively well-sorted, minor granules and pebbles, rare siltstone partings	Amalgamated, mainly sharp-bounded beds and units, intervals <4 m thick, some normal grading, also alternating medium-fine laminae, well-stratified with abundant planar/flat stratification, local low-angle cross-bedding and ripple cross-lamination, and rare high-angle cross-bedding	None observed	Deposition from dilute, subaqueous currents
4	Sandstone, generally fine- to medium-grained, variable mud content, rare granules and pebbles, minor siltstone laminae and partings	Amalgamated, mainly sharp-bounded beds <2 m+ thick, intervals <8 m thick, normal and reverse grading or no upward grain-size trend, floating mud clasts, local silt clast layers mainly at bed bases, vague flat stratification (ripple cross-lamination in X-ray images), load casts	Minor bioturbation, calcareous serpulid tubes	Rapid deposition from submarine currents, probably density currents, including traction carpet deposits at base of some beds
5	Siltstone, coarse-grained to sandy in places, rare granules and pebbles	Intervals <5 m thick, some coarsening-upward, Flat lamination, load casts, siltstone clasts, soft-sediment deformation	Bioturbation, calcareous serpulid tubes	Submarine deposition from ?density currents and from suspension
6	Siltstone, fine-grained, rare granules and pebbles	Intervals <6 m thick, generally at base of coarsening-upward sequences, primary lamination, disturbed in places by bioturbation	Bioturbation, calcareous serpulid tubes	Submarine deposition from suspension

noted within the interval 55.34 – 55.89 mbsf. The top of this interval is marked by a >0.13 m, possibly rounded dolerite cobble.

Interpretation. The alternation of coarse and fine laminae is suggestive of a subaqueous environment affected regularly by alternating high and low energy conditions. The presence of lonestones with deformation of lamination beneath them suggests the introduction of coarse debris from floating ice. This distinctive, rhythmically bedded facies is similar to deposits termed "cyclopsams" by Mackiewicz et al. (1984) and Cowan & Powell (1990), and interpreted by those authors as the deposits of turbid plumes issued from efflux points in grounded ice. Cowan & Powell (1990) further showed that the rhythmic bedding style of cyclopsams and their finer-grained equivalents (cyclopels) can be related to tidal processes. The role of tidal processes cannot be established in the present case, but a setting relatively close to a source of glacier ice is suggested by the abundance of apparently ice-rafted debris.

Facies 3 - Stratified, Moderately- to Well-Sorted Sandstones

Description. This facies consists of generally fine- to medium-grained, moderately- to well-sorted sandstones of quartzofeldspathic composition, which are organised into grain-size-differentiated laminae and beds (Cape Roberts Science Team, 1998c, Fig. 1e). Sandstones are arranged in stacked, amalgamated units up to 5 m thick, such that individual beds are difficult to define. Where individual beds can be recognised, they typically fine upward and some show extraformational gravel at the bed base. Internal stratification is well-developed in this facies, most commonly flat stratification and low-angle cross-stratification, with less abundant ripple cross-lamination and rare high-angle cross-bedding. Soft-sediment deformation structures were noted locally. Lonestones are absent from this facies.

Interpretation. From the presence of rare shell debris, together with its intimate association with other fossiliferous lithologies, Facies 3 may be interpreted as the product of sediment deposition in a marine setting. The abundance of physical sedimentary structures and the persistent grain-size sorting in this facies points towards deposition from dilute, tractional currents, of varying strength. In the absence of any unequivocal wave-generated or combined-flow structures, the low-angle cross-bedding noted may be interpreted as truncated cross-bedding, suggesting in turn that sands were mostly laid down under physical conditions close to or within the plane bed stability field. Accordingly, Facies 3 is interpreted as reflecting a shallow submarine environment into which coarse sediments were introduced by dilute, tractional currents.

Facies 4 - Poorly Stratified, Poorly Sorted Sandstones

Description. Facies 4 comprises relatively muddy, poorly sorted and poorly stratified sandstones with rare, thin silt laminae, which form sharp-based and in many cases fining-upward beds up to 2 m thick. Amalgamated intervals of Facies 4 sandstones vary up to 8 m thick. These sandstones are typically dark olive grey in colour in contrast to the lighter grey colour of Facies 3 (Cape Roberts Science Team, 1998c, Fig. 1f & g). Many beds are normally graded, some with a siltstone clast breccia/conglomerate horizon at or near the base, while a few beds (*e.g.*, 141.24 - 141.82 mbsf) display inverse grading with a coarse fraction "floating" near the top of the bed. Other beds contain floating siltstone clasts suspended within apparently massive or poorly stratified sandstone. Some beds noted displayed a texture and colour intermediate between Facies 3 and 4.

Sedimentary structures are sparsely developed within Facies 4. Some beds show load-casted bases, and vague flat stratification is widespread, but few other structures were noted on the surface of the core. Biogenic structures are rare within this facies: serpulid tubes and unidentified shell debris were recorded in a few places, and indeterminate bioturbation noted at a number of horizons.

Interpretation. A marine environment of deposition is indicated by the fossil evidence. The sharp-based, often graded and poorly stratified nature of Facies 4 is suggestive of deposition from at least partly or temporarily turbulent sediment gravity flows (density-modified grain flows or turbidity flows). Clast-rich horizons near the base of some beds are interpreted as traction carpet deposits, while floating intraformational clasts may reflect the role of buoyancy in some flows. Inverse grading is also considered an indicator of higher flow viscosity among the spectrum of sediment gravity flows (Nemec & Steel, 1984; Nemec, 1990). Howe et al. (this volume) interpret several Facies 4 beds from CRP-1 as the deposits of muddy debris flows, sandy debris flows and turbidites based on macroscopic core-logging, x-radiography, textural and microstructural evidence. Accordingly, Facies 4 is interpreted as the product of periodic sediment gravity flows across the submarine surface. No direct evidence of formative water depth is evident from the sediments themselves, but the fossil assemblage in this and associated facies is suggestive of depths no greater than 100 m.

Facies 5 - Coarse-Grained Siltstones

Description. Facies 5 comprises coarse-grained or sandy siltstones that are intimately associated with Facies 4, in many cases forming the upward-fining, upper part of Facies 4 beds (Cape Roberts Science Team, 1998c, Fig. 1g & h). Other occurrences are associated with coarsening-upward sequences up to a few metres thick (*e.g.*, 76 - 79 mbsf). Flat stratification is evident in a few cases, as is load casting and indeterminate soft-sediment deformation, and floating siltstone clasts were noted at a few horizons (*e.g.*, 59 - 60 mbsf). Both serpulids and bioturbation were noted as in Facies 4.

Interpretation. The intimate association and similarity of Facies 4 and 5 indicates a genetic link between the two. Accordingly, Facies 5 is intepreted as reflecting the waning-flow and/or distal portions of the density currents responsible for Facies 4 (see also Howe et al., this volume).

Facies 6 - Fine-Grained Siltstones

Description. Facies 6 consists of intervals of fine-grained siltstone up to 6 m thick, which are in places laminated and in others either apparently massive or bioturbated. Coarse, extraformational clasts occur rarely within this facies (Cape Roberts Science Team, 1998c, Fig. 1i). Serpulid tubes were noted at a few horizons.

Interpretation. The fine-grained siltstones of Facies 6 are interpreted to have formed by fallout of fine sediment from suspension in the (marine) water column. Rare, coarse clasts are likely to have dropped from floating ice.

QUATERNARY

Description. For the most part, the lithofacies recognised within the Quaternary part of the core (Tab. 2) are identical to those from the Miocene section (see above), although they are less strongly lithified. The principal difference lies in the occurrence of a bioclastic carbonate interval (31 - 34 mbsf: Facies B3, B4 in Tab. 2, and see Cape Roberts Science Team, 1998b), composed of skeletal packstones and wackestones, and carbonate-poor muds, typically thinly-interbedded. Although bryozoans are the dominant skeletal contributor to the carbonate, a wide variety of marine invertebrates have been noted (including, in a preliminary listing, 35 mollusc taxa). The top, bottom and middle of the carbonate-rich interval are characterised by concentrations of coarse, extraformational debris.

Interpretation. Clastic facies noted in the Quaternary interval are interpreted in the same way as those of the Miocene section (see above). The carbonate-rich deposits, referred to as a "bryomol" facies, have been interpreted (Cape Roberts Science Team, 1998b) as the deposits of a relatively offshore, quiet, intermittently current-washed marine environment. As such, they are broadly similar to the fine-grained clastic facies (6), but perhaps reflect differences in water temperature and clarity, etc. The broader implication of this unit is that it must record a period of time when sea was warmer (and hence conducive to a wider variety of marine invertebrate life) than at present. The presence of coarse, extraformational debris, interpreted as ice-rafted in origin, nonetheless indicates that the environment was polar marine, beyond the ice margin.

OVERALL FACIES INTERPRETATION

The facies assemblage indicates that both the Quaternary and Miocene sections in CRP-1 accumulated in mainly shallow marine environments of deposition, at

Tab. 2 - Characteristics of lithofacies recognised within the Quaternary section of CRP-1.

Association A - Quaternary section (Units 1 and 3)

Facies	Lithology	Geometry, Contacts, Structures	Fossils	Interpretation
A1	Diamicton to muddy/sandy gravel (conglomerate), varying texture and fabric but mainly very poorly sorted, matrix muddy to sandy, variable clast content, clasts < boulder grade, subangular - subrounded	Composite intervals <8 m+, contacts gradational or sharp, some irregular unit bases, apparently unstratified	Scattered shell debris and Miliolid forams in some units	Glacimarine, fine fraction deposited from aqueous currents and suspension fallout, coarse clasts introduced mainly from floating ice, some probable subglacial deposits
A2	Gravel, moderately to well sorted, clast-supported, occurs at unit boundaries	Single clast thickness layer (3 cm), contacts sharp	None observed	Lag deposit, winnowed by current and/or wave activity
A3	Sand, fine- to medium-grained, variable but generally low mud content	Simple beds <1.5 m thick, sharp-bounded, normal or reverse grading in some beds	Scattered shell debris and Miliolid forams in some units	Rapid deposition from submarine currents, possibly density currents
A4	Mud and sand/mud mixtures, rare granule/pebble clasts	Intervals <1.3 m thick, associated with Facies 3 above	None observed	Mainly fallout from suspension, distal equivalent of 3 above

Association B - Quaternary section (Unit 2)

Facies	Lithology	Geometry, Contacts, Structures	Fossils	Interpretation
B1 (As 3 above)	Sand, fine- to medium-grained, variable but generally low mud content	Simple bed <0.2 m thick, sharp-bounded	Scattered shell debris and Miliolid forams	Rapid deposition from submarine currents, possibly density currents
B2 (As 4 above)	Mud and sand/mud mixtures	Intervals <1.8 m thick, sharp-bounded, normal and reverse grading, associated with Facies 1 above	None observed	Mainly fallout from suspension; distal equivalent of 1 above
B3	Calcareous muddy diamicton to calcareous silt with dispersed pebbles (Bryomol)	Composite intervals <1.0 m thick, sharp-bounded, crude flat stratification defined by changes in fossil and/or clay content	Abundant calcareous macrofossils (bryozoans, bivalves, gastropods, echinoid spines, octocorals, ostracods, serpulids, brachiopods), and forams	Outer, open shelf (no permanent ice cover), little if any agitation, particulate surface, mainly epifauna, minimal transportation, minor ice-rafted debris
B4	Shell hash (coquina)	Single, 2 cm thick unit, sharp-bounded, some alignment of fossils	Abundant intact valves of bivalves	Accumulation of shells in biostrome, *in situ*, during time of minimal sediment supply

times under the influence of floating ice and probably offshore from glacier termini. The most clearly ice-proximal sediments are the diamictites of Facies 1, and attempts are made in Cape Roberts Science Team (1998d) to assess the proximity of glacier ice based on the density of clasts per unit length of core. No unequivocal evidence of subglacial deposition was noted within the diamictites during initial core examinations, although the recognition of directional clast fabrics was used (Cape Roberts Science Team, 1998c, Fig. 5) to suggest that basal tills may locally be preserved, and the sedimentary dykes noted above could have formed during a period of loading by ice and/or diamict over the region. Furthermore, the over-compacted nature of some intervals indicated by physical property measurements (Cape Roberts Science Team, 1998a, Fig. 16) is suggestive of repeated loading of the sediment mass, perhaps by glacial over-riding. Subsequent, micromorphological analysis of diamict samples by van der Meer & Hiemstra (this volume) has identified a series of horizons containing a record of subglacial shearing, studies of breccia fabric by Passchier et al. (this volume) have also revealed evidence of subglacial shear, and diagenetic analyses by Baker & Fielding (this volume) have revealed that fractures pervasive through the Miocene section of the core were lined or filled by carbonate microconcretions formed under the influence of meteoric water, again suggesting exposure of the sediment surface to glacier ice. The brecciation of core associated with these fractures is, to some extent, concentrated immediately below and above the abrupt facies changes interpreted below as sequence boundaries.

The rhythmically interbedded Facies 2 may also record proximal glaciomarine environments, by analogy with the "cyclopsams" of Mackiewicz et al. (1984) and Cowan & Powell (1990). Of the other two coarse-grained facies, Facies 3 is interpreted to have formed in shallower water than Facies 4 and by somewhat different physical processes, based on its better sorting, generally coarser grain-size and more stratified nature. Given the above-mentioned attributes, the dilute water currents held responsible for Facies 3 may have been associated with outflows from glaciofluvial deltas. The lack of lonestones from this facies suggests that it formed during periods of minimal glacial influence. Facies 4 and 5, which are closely associated with Facies 3, show evidence of deposition from more sediment-charged, sediment gravity flows, and may reflect either or both of a change in water character (salinity, density, temperature, etc.) and a change in water depth. Facies 6 is interpreted to represent the most distal or deepest-water environment recorded in the core or both.

The Quaternary carbonate-rich deposits, which are also interpreted to represent relatively quiet, offshore environments, were estimated to have formed in water depths of *c.* 100-150 m.

Based on the present-day subsea topography of the western Ross Sea and inspection of seismic reflection data (Barrett et al., 1995; Brancolini et al., 1995; Bartek et al., 1996; Cape Roberts Science Team, 1998a), it is considered likely that the submarine surface was irregular with significant slopes in places (a ramp, rather than shelf geometry) during most of the time represented by the cored section. Some periods of progradation are evident from clinoforms in the seismic records, and some channelling has also been noted (Cape Roberts Science Team, 1998a, Fig. 5). A flat shelf with a distinct shelf break, such as occurs on most continental margins, is not apparent from seismic data in the study area. Accordingly, schematic illustrations of the interpreted depositional environment of Facies 1 - 6 during times of 1) relative ice advance and 2) relative ice retreat shown in figure 1 depict a ramp setting.

SEQUENCE STRATIGRAPHIC INTERPRETATION

The vertical stacking of lithofacies in CRP-1 is strongly cyclical, with abrupt changes in grain-size at several horizons, and progressive fining-upward and (less common) coarsening-upward intervals of several metres thickness. Vertical facies trends form the basis for the sequence stratigraphic interpretation presented in figure 2, which in turn provides a framework within which to interpret the stratigraphic record of CRP-1.

A number of abrupt upward increases in sediment calibre occur through the cored Miocene and Quaternary sections; most but not all are at the base of diamictite intervals (Fig. 2). If the interpretation of diamictites as glacimarine deposits is accepted, then this together with the abrupt grain-size increase suggests a significant facies dislocation at the base of diamictite bodies. It is suggested that these abrupt contacts are sequence boundaries, recording a drop in relative sea-level associated with a cycle of glacier advance and retreat across the area. Furthermore, the core records clear fining-upward trends at the top of almost all diamictite units, which can be interpreted in terms of a progressive rise in relative sea-level following a glacial advance cycle. The core can thus be divided into sequences, the basal boundary of each of which lies at the base of a diamictite (or another coarse-grained facies in two cases) which then fines upward into sandstones and siltstones. The upper parts of some sequences show a degree of coarsening-upward, and the topmost parts of a few sequences show accumulations of discrete, sharp-bounded Facies 3-5 beds, reflecting progradation on a minor scale. Significantly, however, no evidence of substantial progradation (large-scale coarsening-upward sequences) is recorded within the core.

Figure 2 illustrates the division of the cored succession into sequences. Even though successive sequences may

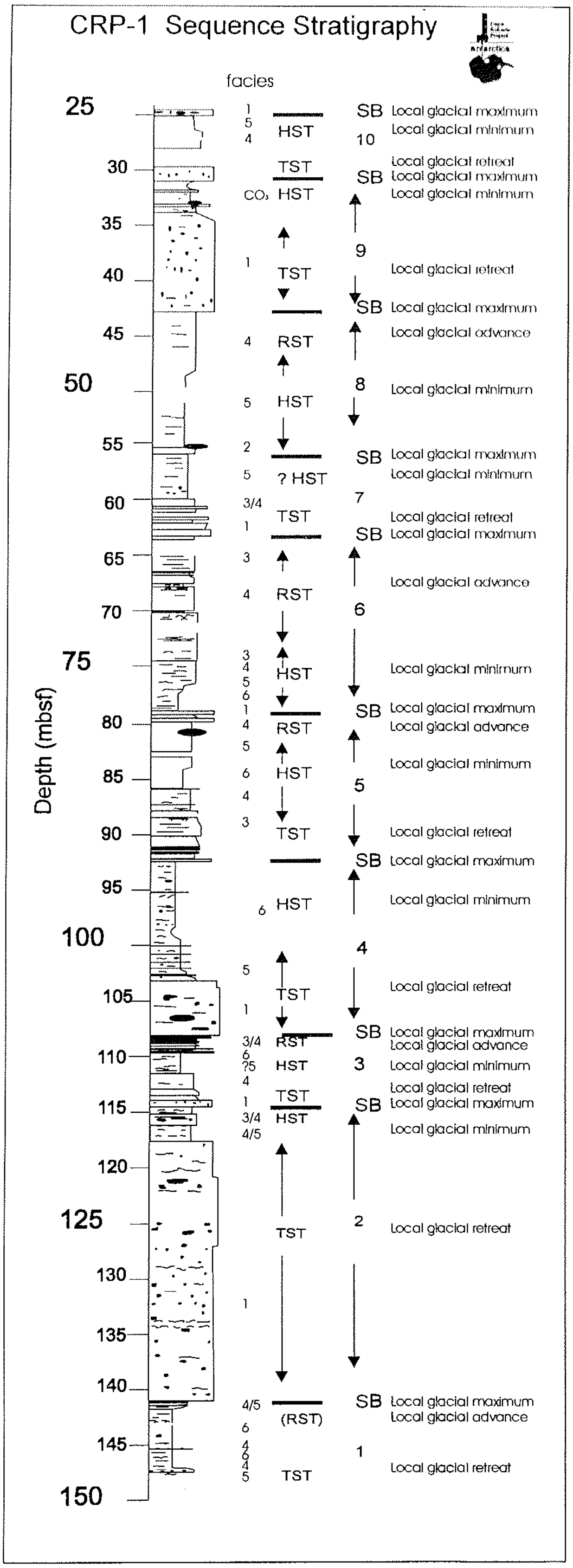


Fig. 2 - Graphic sedimentological log of the CRP-1 core, showing the distribution of Facies 1-6, and the division of the succession into sequences based on the recognition of sequences boundaries at abrupt facies dislocations. SB - Sequence Boundary, TST - Transgressive Systems Tract, HST - Highstand Systems Tract, RST - Regressive Systems tract.

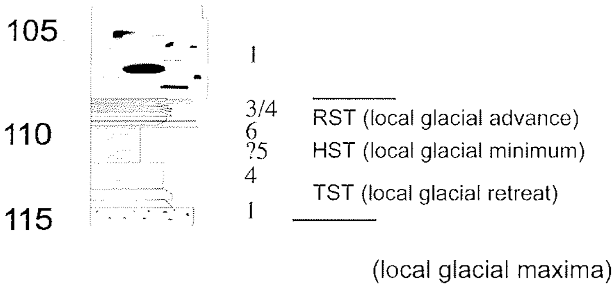


Fig. 3 - Idealised sequence stratigraphic motif for the Miocene interval in CRP-1. The motif is based on Cycle 3. While the motif is described in classical sequence stratigraphic terms it should be noted that it is generally not possible to differentiate between true eustatic signals and local glacial advance/retreat cycles.

preserve slightly different combinations of facies, there is nonetheless a consistency in the facies composition of sequences as described above such that an idealised sequence or motif can be deduced (Fig. 3). Thus, diamictite units (Facies 1) or their positional equivalents (Facies 2/3) are interpreted as late lowstand (LST) to early transgressive systems tract (TST) deposits, sandstones of Facies 3 and 4 as recording transgressive systems tracts, and the fine-grained facies (5 and 6) the highstand systems tract (HST). Some minor regressive systems tract (RST) deposits may be preserved below sequence boundaries (SB). A significant implication of this interpretation is that few if any lowstand systems tract deposits are recorded at this locality, but that such facies might logically be expected to be preserved elsewhere (perhaps in areas where clinoforms have been recorded on seismic surveys). The base of all sequences recognised coincides with an abrupt change in core physical properties (Cape Roberts Science Team, 1998a, Fig. 16), and many also coincide with palaeoecological changes interpreted from investigations of microfossils (Cape Roberts Science Team, 1998b, Fig. 13 and Cape Roberts Science Team, 1998c, Fig. 15).

The base of Sequence 1 was not cored: the dominantly fine-grained facies intersected are interpreted to mostly record a TST, with sandstones at the top of the preserved sequence perhaps recording an incipient RST much of which was eroded by a later glacial advance-retreat cycle. The base of Sequence 2 (141.43 mbsf, the base of a thick diamictite unit: Fig. 2) is also recognised as a significant stratigraphic break from palaeomagnetic data, and corresponds to a seismic reflector (Cape Roberts Science Team, 1998a, Figs. 16 & 19). The composite nature of this thick diamictite body may indicate a record of more than one cycle of glacial advance and retreat, a conclusion also drawn by van der Meer & Hiemstra (this volume) from micromorphological investigations. The uppermost part of Sequence 2 is composed of sandstones and siltstones attributed to a TST. Sequence 3 (illustrated in Fig. 3) has a thin diamictite at its base (115.82 mbsf), overlain by a fining-upward interval (TST) passing into fine-grained Facies 5 and 6 sediments (HST), in turn overlain by a crudely coarsening-upward succession of Facies 3 and 4 sandstones which is interpreted as an RST. Sequence 4 has a substantial diamictite at its base (108.73 mbsf), overlain by a well-defined fining-upward interval (TST) passing into Facies 6 siltstones (HST). These siltstones are abruptly truncated by the base of Sequence 5 at 92.22 mbsf, which is marked by well-washed, medium-grained sandstones of Facies 3. The sandstones (TST) progressively fine upward into Facies 5 and 6 siltstones (HST), with some coarser, lonestone-bearing deposits above possibly recording an RST. The base of Sequence 6 (79.33 mbsf) is marked by a thin diamictite, which passes up abruptly into fine-grained siltstones (HST). The overlying coarsening-upward sequence into Facies 3 and 4 sandstones is interpreted as a well-developed RST. The base of Sequence 7 (63.13 mbsf) is marked by a composite of thin diamictite beds, overlain by a well-defined fining-upward succession (TST - ?HST). The siltstones are abruptly truncated by Facies 2 (rhythmically interbedded sandstone-siltstone) at 55.89 mbsf, marking the base of Sequence 8. Abruptly overlying the short interval of Facies 2 deposits lies a thick siltstone section (HST), which coarsens upward into sandstones of Facies 4 (RST).

The base of Sequence 9 (43.15 mbsf) coincides with the Miocene-Quaternary boundary (Cape Roberts Science Team, 1998a-d, and see Fielding et al., this volume) and an angular unconformity recognised from seismic reflection records (Cape Roberts Science Team, 1998a, Fig. 5). Much of the sequence is occupied by a thick diamicton (TST), which fines upward into a carbonate- and mud-rich interval (HST). Sequence 10 also has a diamicton at its base (30.90 mbsf) and fines upward into fine-grained HST deposits. Although further Quaternary sequences are probably recorded in the core, no attempt has been made to interpret the core above 25 mbsf owing to the poor core recovery.

If the diamictite units or their positional equivalents are interpreted as recording a cycle of glacial advance and retreat, then the question arises as to whether the diamictites record only the glacial retreat or both advance and retreat. The observation that sequence boundaries are preceded by very little if any evidence of progradation argues against the latter, suggesting rather that much of the record of glacial advance has been removed by erosion. Since there is no evidence in the core for wave activity or other high-energy physical processes, nor evidence for subaerial exposure of surfaces, it is suggested that in each cycle the advance of grounded ice across the area of the drillsite was responsible for the removal of progradational deposits. This idea is supported by the presence of common intraformational clasts within the core. Channel features of the order of 10's of m deep and up to 1 km wide noted on seismic reflection lines (*e.g.*, Cape Roberts Science Team, 1998a, Fig. 5) may record the passage of grounded glaciers across the sea floor at certain times. If subglacial sediments are incorporated within Facies 1 diamictites, however, it is possible that at least some record of glacial advance is also preserved within the core.

DISCUSSION AND CONCLUSIONS

The sequence stratigraphic model presented here attempts to account for cyclical vertical arrangements of lithofacies within the core by invoking cycles of relative sea-level change associated with advance and retreat of glaciers across the area of the drillsite. It is acknowledged that on glaciated continental margins the record of relative sea-level change will be complicated by a variety of factors. Nonetheless, this analysis shows clearly that the stratigraphy of CRP-1 is strongly cyclical, and suggests that a record of glacial advance-retreat cycles may be preserved quite close to the continental margin itself. In this respect, CRP-1 differs significantly from the stratigraphy of CIROS-1 and CIROS-2 (Pyne et al., 1985; Barrett, 1989; Barrett & Hambrey, 1992), which are more proximal to their principal source of sediment (particularly glacially-derived sediment). In a sequence stratigraphic reappraisal of the CIROS-1 core, Fielding et al. (1997) defined a series of sequence boundaries, but were unable to subdivide the succession coherently into systems tracts.

At least ten sequences are recognised in the Miocene and Quaternary sections of CRP-1. The nature, thickness and internal facies composition of these sequences is similar in both cases, suggesting that, whatever differences there may have been in the palaeogeography, the factors that controlled sediment supply and dispersal into McMurdo Sound operated through both periods recorded by the cored succession.

The sequences recorded in CRP-1 show characteristics that are different from sequences developed on non-glaciated continental margins. In the latter, the progradational record (highstand systems tract) is well-represented, and often accounts for a substantial proportion of the sequence thickness (Emery & Myers, 1996), whereas in CRP-1 this section is evidently truncated by erosion. Furthermore, sequences in non-glaciated shallow marine environments typically show a transgressive record that is truncated by shoreface erosion, whereas CRP-1 shows transgressive deposits that are uninterrupted by significant erosion. This is interpreted to reflect the inability of waves and associated currents to effectively mobilise sediment on the sea floor in the presence of floating ice. If correct, this analysis suggests that in settings proximal to the continental edge, such as the Cape Roberts drilling site, deposits recording progradation and advance of glaciers are likely to have been removed by erosion, and that significant periods of time may therefore be recorded in the sequence boundaries recognised at the base of diamictite and other lithofacies. This pattern is consistent with that found in some other sequence stratigraphic studies of glacimarine successions (*e.g.*, Deynoux, 1991; Visser, 1997), and also mirrors the sequence architecture found in Plio-Pleistocene successions of the Wanganui Basin, New Zealand, a temperate but non-glaciated margin (Abbott & Carter, 1994; Naish & Kamp, 1997).

The presence of several cycles or "sequences" within both the Miocene and Quaternary sections suggests a condensed succession representing several discrete intervals, each bounded by hiatuses, consistent with the location of CRP-1 close to the western margin of the West Antarctic Rift and close to a glaciated continental margin. Given the total thickness of the cored Miocene section and palaeontological data, an estimate of 21 m/m.y. sediment accumulation was made in Cape Roberts Science Team (1998c), which is slow within the context of extensional sedimentary basins. More recently, Lavelle (this volume) has estimated Miocene accumulation rates to lie in the range 15-64 m/m.y., and for the Quaternary 9-28 m/m.y., based on Sr isotopic dates from carbonate shell material. Since short-term sediment accumulation rates in glacially-influenced depositional systems can be very high (metres per year: *e.g.*, Powell & Molnia, 1989), it is likely that substantial amounts of time are recorded by hiatal surfaces within the core, and/or that fine-grained sediments such as Facies 6 record periods of very slow sediment accumulation. It may also suggest that the long-term sediment supply to the McMurdo Sound area through the Early Miocene was low.

The present uncertainties in the absolute dating of the CRP-1 core render any interpretation of possible causal mechanisms for facies cyclicity premature. It is possible that the sequences recognised in this study were driven by orbital fluctuations, for example the 100 k.y. eccentricity cycle, but resolution of this problem must await further data.

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