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Facies Analysis and Sequence Stratigraphy of CRP-2/2A, Victoria Land Basin, Antarctica

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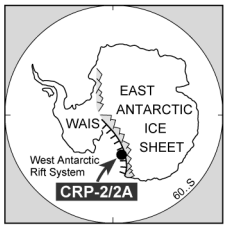

Abstract - The Oligocene to Quaternary succession encountered in CRP-2/2A is divided into twelve recurrent lithofacies (some of which have been subdivided further), reflecting a range of marine, glacimarine and possibly subglacial environments of sediment accumulation. A cyclical vertical arrangement of lithofacies was noted throughout the core, and is used as the basis for a sequence stratigraphic analysis. Twenty-four sequences are recognised, each of which begins with a Sequence Boundary (Glacial Surface of Erosion), and each is interpreted to record a cycle of glacial advance and retreat with associated changes in relative sea-level. During at least some of these cycles, ice is interpreted to have extended as far as and seaward of the drill-site. A recent reinterpretation of seismic reflection data by Henrys et al. (this volume) permits the first correlation between seismic reflection records and the stratigraphic surfaces identified herein. All but one of the reflectors recognised correspond to sequence boundaries, and most reflectors correspond to the base of thin, truncated and amalgamated sequences. Additionally, three thick and relatively complete sequences (9 to 11) are identified individually by seismic reflectors. The major surfaces of omission in CRP-2/2A, identified from a variety of evidence, correspond to changes in cross-sectional geometry in the seismic records, and in the case of the unconformity at 307 mbsf can be interpreted as recording the onset of a phase of active tectonic subsidence associated with half-graben development, bounded by periods of more uniform, slower, possibly thermal subsidence. Possible controls on cyclicity are discussed, and include long-term eustatic cycles, Milankovitch frequency cycles, and more local climatic and/or tectonic events. The analysis allows the recognition and separation of tectonic from climatic (?glacio-eustatic) controls on the Cainozoic stratigraphy of the McMurdo Sound region.

INTRODUCTION

This paper provides details of a sequence stratigraphic framework for CRP-2/2A, and the lithofacies scheme on which it is based. The facies scheme is similar to, but somewhat modified from, that presented in the Initial Report for CRP-2/2A (Cape Roberts Science Team, 1999) including subdivision of certain facies, and incorporates a considerably greater variety of lithofacies than was encountered in CRP-1 (Cape Roberts Science Team, 1998). The sequence stratigraphic model is based on similar criteria to that proposed for CRP-1 (Cape Roberts Science Team, 1998). The subdivision of the succession into sequences is unchanged from Cape Roberts Science Team (1999), but more details on the internal facies composition of sequences and variability between sequences is provided. Additionally, the possible origins of the highly cyclical lithostratigraphy penetrated in CRP-2/2A are discussed, and a correlation with the latest reinterpretation of seismic reflection data made.

Twelve lithofacies are recognised within the Quaternary to Oligocene (?Eocene) section of CRP-2/2A and are defined using lithologies or associations of lithologies, bedding contacts and bed thicknesses, texture, sedimentary structures, fabric, contained fossils (macroinvertebrates, microfossils and trace fossils), and colour. Terminology used here refers to lithified forms but some Miocene and younger facies are unlithified.

FACIES ANALYSIS

FACIES 1 - MUDSTONE

Description

Facies 1 (Cape Roberts Science Team, 1999, Fig. 3.2a) consists of sandy mudstone and mudstone. Some mudstones are apparently massive, while others show various degrees of lamination and bedding, expressed by colour changes and by inclusion of siltstone and very fine sandstone laminae. Mudstones locally pass vertically into sandstone over tens of centimetres. Most intervals of Facies 1 contain dispersed extraformational clasts, the distribution and composition of which are detailed by Talarico et al. (this volume). Sandstone laminae and more rarely beds up to 5

cm thick are locally interbedded within Facies 1.

Many mudstones are bioturbated, the apparent intensity of bioturbation varying considerably from place to place (recognition being dependent to some extent on incorporation of different grain-sized material within burrows). Individual ichnofossils referrable to *Planolites* and *?Helminthopsis* are abundant above 307 mbsf, but only locally between 307 and 443 mbsf, while *Planolites, Zoophycos* and *Teichichnus* were abundantly distributed below 443 mbsf. Calcareous invertebrate macrofossils are also abundant through the core in this facies: bivalves, serpulids and gastropods are common above 307 mbsf, only serpulids and rare bivalve fragments between 307 and 443 mbsf, abundant bivalves between 443 and 468 mbsf, and rare, dispersed shell fragments below 468 mbsf. Carbonate cementation in the form of blebs, concretions or discrete cemented layers, is common, particularly in proximity to calcareous macrofossils. Yellow staining (presumably sulphate minerals such as jarosite, after pyrite) is present locally. Dispersed organic material and coaly fragments are locally abundant.

This facies commonly preserves soft-sediment deformation structures in discrete intervals. In particular, this facies (together with Facies 2) shows abundant convolute bedding and soft-sediment folding, sedimentary intrusions (sills and dykes, with fills of mud, sand or diamictite, in many cases showing a layered, composite fill) and load structures. Many of these structures are visible through incorporation of fine-grained sand, which suggests the occurrence of at least some bedded sand in the original sediment of many intervals. Additionally, evidence of brittle failure in the form of open or mineralised fractures, microfaults (high-angle or more concordant with bedding, normal or reverse displacement) and locally, brecciation, is widespread. Some brittle fractures and veins can be seen to cross-cut soft-sediment features.

Interpretation

Facies 1 mudstones represent the lowest-energy conditions within the CRP-2/2A succession. A marine environment of deposition is indicated by the abundance of marine body and trace fossils found throughout the core. Trace fossil taxa are indicative of the *Cruziana* and *Zoophycos* ichnofacies. Muds are interpreted to have been deposited largely from suspension in offshore environments distal to sources of coarser sediment, such that only occasional, high-energy current events were able to deliver sand. The abundance of body and trace fossils suggests that the sea floor and the shallow subsurface were generally oxygenated, allowing epifaunal and infaunal organisms to thrive, although some occurrences of dark grey, sulphurous, apparently non-bioturbated siltstones suggests local or temporary development of anoxic bottom conditions. Dispersed clasts up to cobble grade in this context suggest a component of sediment supply from floating ice, and some of the mud and dispersed sand within Facies 1 mudrocks may also have been derived from the same source. Unstable sea-floor conditions are indicated by the common soft-sediment structures. This instability may have been imparted by seismic disturbances, cyclic wave loading, ice loading, or some combination of these processes.

FACIES 2 – INTERLAMINATED AND THINLY INTERBEDDED SANDSTONE AND MUDSTONE

Description

Very fine- and fine- to locally medium-grained sandstone and mudstone are commonly interlaminated or interbedded; these lithologies comprise Facies 2 (see Cape Roberts Science Team, 1999, Fig. 3.2b & c). The relative proportions of the two lithologies vary considerably, even over short vertical intervals. Sandstone beds are mostly sharp-bounded and tabular in geometry across the width of the core. Sandstones and siltstones are locally strongly cemented by carbonates and other minerals. Clasts of extraformational lithologies are scattered throughout this facies in low concentrations. Marine macrofossils are found locally, as are coaly fragments of interpreted land plant origin. Three variants are recognised within Facies 2, and described here separately.

Facies 2A, which occurs between 307 and 326 mbsf, comprises interlaminated and thinly interbedded very fine- and fine-grained sandstone, and mudstone, with thicker beds (<50 cm) of typically medium-grained sandstone interspersed in an irregular fashion (Cape Roberts Science Team, 1999, Fig. 3.2b). This sub-facies is evidently unbioturbated. The siltstones and very fine- to fine-grained sandstones are typically thinly and rhythmically interlaminated, with individual beds up to 2 cm thick. The thin sandstone beds are well structured, showing flat lamination, ripple cross-lamination and lenticular bedding, together with soft-sediment deformation structures such as convolute bedding, dish-and-pillar, clastic intrusions, load casts and microfaults. Many of these beds are normally graded. The thicker, coarser sandstone beds are either massive or in a few cases are flat laminated. This sub-facies is closely associated with Facies 11 (Intraformational Clast Breccia).

Facies 2B comprises thinly interbedded and interlaminated very fine- to fine-grained sandstone and mudstone, in sharp-bounded beds up to 15 cm thick but generally < 2 cm. A variety of interlamination structures are present, including pinstripe (linsen) lamination, lenticular bedding and ripple cross-lamination, together with various soft-sediment structures as listed above. Facies 2B is different from Facies 2A in that it does not contain thicker, coarser-grained sandstone beds, and in that the finer-grained sandstone beds are typically ungraded. Sparse bioturbation was noted in this sub-facies.

Facies 2C is similar to Facies 2B, but is generally more intensely bioturbated with well-preserved and identifiable burrows, contains abundant and well-developed carbonate cementation in the form of patches, layers and small circular nodules, and in addition to the sedimentary structures noted above also shows low-angle cross-bedding, possible small-scale hummocky cross-stratification, and symmetrical, wave-formed ripple structures (Cape Roberts Science Team, 1999, Fig. 3.2c).

In this sub-facies, the thicker sandstone beds are often intensely bioturbated.

Interpretation

Facies 2 represents subaqueous depositional conditions, with levels of sand supply somewhat greater than for Facies 1. The thinly interbedded nature of the facies suggests conditions where fine sediment settled out of suspension for much of the time, punctuated by discrete depositional events in which sand was deposited rapidly from decelerating flows. Facies 2A cannot be assigned a specific water depth, and may have formed in a variety of water depths. The close association with intraformational clast breccias of Facies 11 is suggestive of an unstable, sloping sea-floor environment (see discussion below). Facies 2B, from its lack of bioturbation and massive/graded sandstone beds, is suggestive of coarse sediment deposition from turbidity flows in relatively deep, perhaps anoxic, waters (at least tens of metres). Facies 2C, although lithologically similar to Facies 2B, contains evidence of sediment working by both dilute water currents and by waves, in some cases by fair-weather waves. This implies a quite shallow depositional setting, which from the abundance of bioturbation may also have been protected (an embayment or lagoon, for example). The rare coarse extraformational debris in Facies 2 are interpreted to have been dropped from floating ice, and then reworked by marine currents and waves.

FACIES 3 – POORLY SORTED, MUDDY, VERY FINE- TO COARSE-GRAINED SANDSTONE

Description

Varieties of poorly sorted, mud-rich, fine- to coarse-grained sandstones generally lacking in internal sedimentary structure characterise Facies 3 (Cape Roberts Science Team, 1999, Fig. 3.2d). Facies 3 occurs as sharp-bounded beds up to 0.65 m thick, some of the thicker beds containing thin mudstone partings. Thin mudstone intervals separate many beds of Facies 3. Sedimentary structure is poorly developed, with many beds showing no current-generated structures, and others flat lamination or ripple cross-lamination only near the top of beds. Some beds are normally graded, and a few show local reverse grading. Several beds contain intraformational siltstone clasts "floating" within the muddy sand matrix, while in a few cases concentrations of such clasts occur either at the base or at the top of beds. Coarse to very coarse sand and extraformational clasts are dispersed through some beds, and locally, where clasts are abundant in the medium to coarse sandstones, they may be sufficiently concentrated to form matrix-supported conglomerate or they may exhibit coarse tail fining-upward trends. Soft-sediment deformation structures were noted only locally. Facies 3 is weakly to non-bioturbated and marine macrofossils were observed locally (generally as transported debris). Facies 3 is interbedded with Facies 1 where significant intervals of siltstone occur, and grades into Facies 2A where a more clearly interbedded character is evident. Facies 3 also grades into Facies 4, such that some intervals and beds display a character transitional between the two (as was also noted in CRP-1: Fielding et al., 1998). Facies 3 is common in the core down to c. 350 mbsf, but virtually absent below this level.

Interpretation

Marine body fossils, and close association with Facies 1 and 2, confirm a submarine environment of deposition for Facies 3. The mud-rich and unstratified nature of Facies 3 is suggestive of sediment deposition from sandy sediment gravity flows. The exact nature of these flows is not clear, the principal alternatives being turbidity flows or density-modified grain flows (or the "sandy debris flows" of Shanmugam, 1996). The occurrence of sedimentary structures in the upper parts of beds is suggestive of turbidity flows, perhaps high density flows which transformed into low density flows as they decelerated and deposited their sediment load. "Floating" siltstone clasts, on the other hand, could be interpreted as reflecting the role of buoyancy in flows, consistent with the more viscous flow types such as debris flow (Shanmugam, 1996, but see Postma et al., 1988, Nemec, 1990 for alternative views). The sediment gravity flows that deposited Facies 3 (and the sands of Facies 2A) flowed across a sloping submarine surface which for the most part was not amenable to benthic life. Local bioturbated intervals are suggestive of more hospitable bottom conditions. Macrofossil debris found in Facies 3 probably represents elements of shallow water benthic faunas, transported and redeposited in deeper water. Coarse debris scattered throughout Facies 3 is interpreted in the same way as for Facies 1 and 2, ie. as ice-rafted debris that was reworked by marine processes. No direct evidence of glacial conditions can be inferred from Facies 3, although the sediment gravity flows could have been initiated as turbid plumes emanating from the snouts of tidewater glaciers.

FACIES 4 – MODERATELY TO WELL-SORTED, CLEAN, STRATIFIED FINE-GRAINED SANDSTONE

Description

Facies 4 consists of clean (*i.e.* mud-poor), moderately to well-sorted, fine-grained sandstones which exhibit well-developed bedding structures. Sandstones occur as discrete beds up to c. 1 m in thickness, or as amalgamated intervals up to several metres in thickness. In the latter, individual beds are difficult to discern but thin siltstone partings attest to the composite nature of these sections. The principal physical sedimentary structures are flat lamination or bedding, low-angle cross-bedding (some of which displays a convex-upward, curved and multiply-truncated bedding style: Cape Roberts Science Team, 1999, Fig. 3.2e), high-angle cross-bedding and ripple cross-lamination. Compositionally, these sandstones are rich in quartz and feldspar, and locally contain coal grains dispersed along

laminae or constituting distinct laminae. Very fine, medium and coarse sand, is also interspersed locally, and some beds contain rare extraformational granules and pebbles. Some intervals exhibit soft-sediment deformation structures. Facies 4 sandstone is locally weakly bioturbated, mainly in mudstone partings, and contains scattered marine macrofossils (some in apparent growth position). Carbonate cementation is locally abundant, increasing in intensity downhole. Facies 4 is best-developed below *c*. 350 mbsf, and is rare above this level.

Interpretation

The abundance of bedding structures together with the clean, moderately to well-sorted texture indicates deposition from dilute subaqueous tractional currents with background sedimentation (suspension settling) represented by siltstone partings. Their association with other marine facies, presence of marine body fossils, and the presence of bedsets that display a convex-upward, curved and multiply-truncated bedding style interpreted as hummocky cross-stratification, suggest a marine setting within or about wave base (less than a few tens of metres water depth). Close association with the more mud-rich sandstones of Facies 3 in some sections suggests a genetic link between the two. Clearly, the sediment gravity flows that gave rise to Facies 3 operated in similar water depths to the more dilute tractional currents (locally with wave influence). The differences between the two facies may be explained by changes in the mechanism by which sand was introduced into the marine basin, perhaps reflecting differences in the temperature of outflowing waters (*e.g.*, colder and hence denser waters from subglacial streams producing sediment gravity flows, while warmer, less dense glaciofluvial outflows gave rise to normal shallow marine currents). Such a mechanism could also explain the interbedding of the two sandstone types.

FACIES 5 – MODERATELY SORTED, CLEAN, STRATIFIED OR MASSIVE MEDIUM- TO COARSE-GRAINED SANDSTONE

Description

Facies 5 consists of moderately sorted, medium- to coarse-grained sandstone that is similar in most respects except grain-size to Facies 4, with which it is interbedded (Cape Roberts Science Team, 1999, Fig. 3.2c & f). Beds are commonly flat- or cross-stratified but some appear massive. Ripple cross-lamination and hummocky cross-stratification are apparently absent. The sandstones contain dispersed very coarse sand and extraformational gravel. Some apparently massive beds are amalgamated and some beds show a thin conglomerate bed at the base. Facies 5 sandstone is also locally weakly to moderately bioturbated and contains marine macrofossils. These sandstones contain isolated intervals of soft-sediment deformation. As with Facies 4, Facies 5 is best-developed below 350 mbsf, and rare above this level.

Interpretation

Dilute marine tractional currents are the most likely depositional mechanism for this facies, as for Facies 4. Slightly shallower water depths and/or slightly greater levels of sand supply are suggested by the coarser grain-size and the changes in sedimentary structures, with outflow currents dominating formative processes. The facies may locally appear massive because of uniformity of grain size, rather than as a consequence of depositional process or post-depositional mixing. By analogy with Facies 4, the medium- to coarse-grained sandstones of Facies 5 may indicate sediment deposition close to the shoreline of glaciofluvial/glaciodeltaic outwash systems.

FACIES 6 – STRATIFIED DIAMICTITE

Description

The stratified diamictites of Facies 6 are clast-rich to clast-poor, sandy or muddy and most commonly exhibit no apparent clast orientation, although clast a-axes are locally aligned with stratification (Cape Roberts Science Team, 1999, Fig. 3.2g). The stratification style is most commonly laminated and thinly bedded, varying from being weakly- to well-defined. Stratification is formed by mudstone, siltstone and very fine- to very coarse-grained sandstone strata which vary in their mud content. Strata are also produced by increasing mean sand size from finer in the diamictite matrix to coarser in the laminae, or by varying proportions of mud. Clasts are angular to rounded and locally are all of one lithology, for example, dolerite (see Talarico et al., this volume). Facies 6 commonly grades into or out of massive diamictite (Facies 7) and thinner beds of the facies are locally interstratified with a variety of other facies. Soft-sediment deformation is locally strong, particularly clastic intrusions, shear planes and injection structures involving wispy trails of light-coloured fine-grained material that locally define a boxwork structure. Stratified diamictites show no evidence of bioturbation, but some include marine macrofossils (mainly disarticulated shell fragments).

Interpretation

The poorly sorted character and presence of outsized clasts in some units allows alternative interpretations of this facies. The diamictite with some stratification may originate from debris-flow deposition in an ice-proximal glacimarine setting. Alternatively, ice-rafting processes may have introduced both gravel-grade clasts and some finer-grained sediment. Some units, especially those that grade into and out of massive diamictites may have been deposited from direct rain-out of debris from ice (eg., close-packed icebergs adjacent to a tidewater glacier terminus) that was also affected by bottom currents to produce the stratification. A further possible

explanation for this facies, at least in part, is that it results from subglacial sediment accumulation. Pending further investigations, it is not yet possible to discriminate between these alternatives.

FACIES 7 – MASSIVE DIAMICTITE

Description

Massive diamictite of Facies 7 is more common than stratified diamictite but it too varies from being clast-rich to clast-poor and may be sandy or muddy (Cape Roberts Science Team, 1999, Fig. 3.2h & i). Where the matrix is sandy, the diamictite locally grades into sandstone by decreasing clast content, whereas where the matrix is muddy, the diamictite locally grades through pebbly mudstone into mudstone via decreasing clast content. Locally the mud content of sandy diamictite increases with the decrease in clast content. At the other extreme, clasts locally increase in abundance to grade into matrix-supported conglomerate. Where Facies 7 does not grade from underlying units, the lower contact is sharp and in many cases loaded or otherwise soft-sediment deformed. Most commonly, clasts have no apparent orientation but rarely a-axes have an apparent preferred sub-horizontal orientation. Clasts range from angular to rounded and at one location a clast rests on top of a crack in an underlying one. Thinner beds of this facies are in places interstratified with mudstones, sandstones and stratified diamictites. Marine macrofossil and pumiceous lapilli are included in sediments of this facies but are very local. Soft-sediment deformation structures, as described for Facies 6, are also abundant in Facies 7.

Interpretation

The possible array of depositional processes and environments for Facies 7 is as for Facies 6. The likelihood of subglacial deposits being represented in Facies 7 is, however, considerably greater than for Facies 6. Studies of soft-sediment deformation structures and microfabrics (Passchier et al., this volume; Hiemstra & van der Meer, this volume) may shed further light on this possibility.

FACIES 8 – RHYTHMICALLY INTERSTRATIFIED SANDSTONE AND MUDSTONE

Description

At several points in the core, very fine- and fine-grained sandstone occurs rhythmically interstratified with mudstone where individual beds are typically 1-2 cm thick (Cape Roberts Science Team, 1999, Fig. 3.2i). This distinctive association of lithologies is defined as Facies 8. Such intervals are generally <1 m thick, and most directly overlie or are interstratified with Facies 6/7 diamictites. Sandstone beds are internally either massive or vaguely flat laminated, and have sharp contacts. Dispersed granules and pebbles are present and locally deform laminae beneath them, but outsized clasts may also occur locally as one-grain-thick granule laminae. Some soft-sediment deformation was noted, mainly load structures.

Interpretation

The rhythmically interbedded sandstone-mudstone nature of this facies, together with its close association with diamictites, is suggestive of glacier terminal plume cyclopsam and cyclopel deposits (Mackiewicz et al., 1984; Cowan et al., 1997). Such deposits have been found to originate from suspension settling from turbid plumes under highly sediment-charged conditions in the proximal glacimarine environment adjacent to certain modern temperate and Arctic, tidewater glaciers.

FACIES 9 – CLAST-SUPPORTED CONGLOMERATE

Description

The clast-supported conglomerate of Facies 9 is generally pebble to cobble grade, poorly sorted and contains angular to subrounded clasts with a matrix of poorly sorted, very fine-grained sand to granules (Cape Roberts Science Team, 1999, Fig. 3.2j). Clast composition varies downhole: for details see Talarico *et al*. (this volume). No preferred clast orientation is evident in most occurrences of this facies, and some units include angular clasts among the more common subangular to subrounded debris. No body or trace fossils were noted in this facies. Units of Facies 9 are nearly all <0.5 m thick, and most commonly have sharp lower contacts but locally grade up from sandstones through matrix-supported conglomerate into the clast-supported conglomerate. However, this facies commonly grades upward into matrix-supported conglomerate by decreasing clast content. Internally, Facies 9 may grade normally from cobble to small pebble conglomerate. Additionally, in a few instances Facies 9 and 10 gradationally overlie or underlie the diamictites of Facies 6 and 7.

Interpretation

The close association between Facies 9/10 and 6/7 (diamictites) suggests a depositional setting close to the terminus of a tidewater glacier. The better sorted and rounded nature of coarse clasts, however, indicates a greater degree of hydraulic sorting and transport by current and/or wave action. Accordingly, it is suggested that Facies 9 and 10 were deposited in shallow marine environments close to subglacial or glaciodeltaic discharge points, from turbulent but often sediment-charged water flows. Further sediment contributions may have come from suspension rainout, and from floating ice. The absence of thick, erosively-based and structured conglomerates argues against a glaciofluvial origin for this facies in CRP-2/2A.

FACIES 10 – MATRIX-SUPPORTED CONGLOMERATE

Description

Facies 10 is matrix-supported conglomerate which is typically massive and very poorly to poorly sorted (Cape Roberts Science Team, 1999, Fig. 3.2j). Its characteristics

are similar to those of Facies 9 but clasts are fewer and are dispersed within the poorly sorted very fine-grained sand granule-grade matrix. The conglomerates appear to have higher proportions of angular clasts than do clast supported varieties. As described under Facies 9, this facies may grade to clast-supported conglomerates, sandstones and diamictites by varying clast content and matrix character.

Interpretation

The similarity in lithology and context between Facies 9 and Facies 10 suggests a similar interpretation for both facies (see above). Highly sediment-charged flows are suggested as the depositional process for Facies 10, on the basis of the more-matrix-rich (though still sand-dominated matrix) of Facies 10.

FACIES 11 – INTRAFORMATIONAL CLAST BRECCIA

Description

Intraformational clast breccia, containing angular pebble and cobble-sized clasts of mudstone (Facies 1), interlaminated mudstone/sandstone (Facies 2) and fine-grained sandstone (Facies 2) set in a matrix of mud-rich, poorly sorted, very fine- to medium-grained sandstone, is defined as Facies 11. The clasts are dominantly angular but some are subangular to subrounded; they generally have no apparent preferred orientation (although some elongate clasts were noted defining a crude stratification locally), and the breccia is generally clast-supported with a clast content of 70-80%. Some thinner beds contain lower concentrations of clasts, suspended within the matrix of the host sandstone bed. This facies occurs at a number of places in the core, but most notably in the distinctive interval 307-326 mbsf (in close association with Facies 2A, as noted above), where several occurrences include one discrete bed 4.5 m thick (Cape Roberts Science Team, 1999, Fig. 3.2k). Upper and lower contacts are sharp, and in the case of the base of the thick bed somewhat irregular with small dish-and-pillar structures. The thick bed also contains some internal evidence of soft-sediment deformation, in the form of microfaults and convolute bedding.

Interpretation

The concentrations of generally angular, coarse intraformational debris in Facies 11 suggest reworking of previously deposited marine sediments. The thinner beds with "floating" clasts have been discussed above (Facies 2A) and interpreted in terms of sediment gravity flow processes. The thick bed is also interpreted as the deposit of a mass flow that transported intraformational debris a short distance. The clast-packed fabric could be interpreted as the product of a turbulent flow such as a turbidity flow, but may alternatively reflect local transformation of a submarine slope failure into a more viscous flow such as a debris flow. The thick bed shows many of the characteristics of geologically recent submarine debris flows such as the Sahara, Canary and Bear Island Trough Mouth Fan flows (Gee et al., 1999; Masson et al., 1998; Laberg & Vorren, 1995, respectively). As to the triggering mechanism for the thick bed, a glacial origin seems unlikely as the bed is enclosed by several metres of thinly interbedded sandstone/siltstone (Facies 2A), and no debris of obvious glacial derivation was noted in this interval. Given the relatively deep-water interpretation of this interval, a cyclical loading mechanism also seems unlikely, and a tectonic (seismic) trigger is here suggested as the most plausible explanation.

FACIES 12 – VOLCANICLASTIC LAPILLISTONES

Description

Although volcaniclastic debris (ash and pumice lapilli) is dispersed through several sections of the core, beds containing significant proportions of such juvenile volcanic detritus occur only within one interval (109-114 mbsf: Unit 7.2). Volcaniclastic rocks are grouped into Facies 12, within which three sub-facies can be recognised based on differences in fabric and in the development or absence of stratification (Cape Roberts Science Team, 1999, Fig. 3.2l). Facies 12A comprises a single bed of pumice lapillistone 1.22 m thick, which has a sharp, planar base, is reverse graded in its basal part and then essentially massive and unstratified above. The rock is composed principally of well sorted, angular – subrounded pumice clasts < 10 mm (mean 6 mm: Cape Roberts Science Team, 1999), with virtually no dilution by non-volcanic debris. Clasts account for c. 90% of the rock, with no matrix evident. Local evidence of clast imbrication was noted in places where elongate clasts occurred. Facies 12B consists of sharp-bounded, generally composite beds of pumice lapillistone < 25 cm thick, in some cases interbedded with pumice clast-bearing sandstones. Single beds of this sub-facies are normally graded. Facies 12B is distinguished by a lower volcaniclastic content, and a well sorted, stratified fabric, with size-sorted laminae common. Flat lamination is the most widely-developed stratification type, with some clast imbrication also evident. Facies 12C comprises a single bed of pumice lapillistone where the clast content is *c*. 30%, the fabric matrix-supported and the matrix fine- to medium-grained, mud-rich sand. Clasts are generally dispersed throughout the bed, but are concentrated at the bed top. Pumice clasts are of similar size to the other sub-facies, and moderately sorted. No stratification was evident apart from a local vague, wispy structure, and a flame structure marked the basal contact with the underlying mudstone (Facies 1).

Interpretation

The dominance of juvenile pyroclastic debris within Facies 12 indicates volcanic eruptions contemporaneous with sediment accumulation. The interbedding of Facies 12 with other facies described above, however, suggests a submarine environment of deposition which, given the lack of evidence for subaqueous eruption (hyaloclastites, coherent volcanic rocks), in turn suggests that pyroclastic debris settled through the water column and either

accumulated directly or was reworked by sea-floor currents. In this context, Facies 12A is interpreted as the product of direct settling of tephra fallout, possibly from a single eruption (Cape Roberts Science Team, 1999). To produce a bed of virtually pure pumice 1.2 m thick after settling through tens of metres of water would require a highly explosive and voluminous eruption. The presence of several further discrete ash beds within Sub-Unit 7.2, however, suggests that several eruptions occurred over a discrete period of time, although their characteristics suggest that they were reworked to some extent. Facies 12B contains stratification and other evidence of particle transportation which suggest reworking of fallout debris by dilute marine currents. Facies 12C, with its mud-rich, matrix-supported fabric, is suggestive of sediment accumulation from a viscous mass flow such as a debris flow. Facies 12B and 12C together indicate that volcanic fallout was supplied in a number of discrete (probably modest) eruptive events, and then reworked by marine processes.

Depositional Environment

The sequence recovered in CRP-2/2A is dominated by facies representative of shallow marine settings as is indicated by the sporadic occurrence of marine fossils through the core, and of characteristic physical sedimentary structures in certain facies. The array of depositional environments recorded in the core is similar to that interpreted from CRP-1 (Cape Roberts Science Team, 1998; Fielding et al., 1998), although the greater variety of facies recognisable in CRP-2/2A has allowed a more detailed process and environmental interpretation.

From the individual facies and their sequences, the shallow marine settings appear to have varied from the shoreface to wave base and beyond, but they also appear to include deltaic and/or grounding-line fan settings with large fluvial discharges and their associated delta/fan front and prodeltaic/fan sediment gravity flow deposits as well as cyclopels and cyclopsams. The fan setting and perhaps the deltaic setting too, are associated with ice-contact and ice-proximal environments. The intimate association of fan sediments with debris-flow diamictites and major penecontemporaneous sediment deformation is a common grounding-line association. Indeed, the volume of sediment associated with melt-water influx, and the apparently rapid nature of deposition with consequent slumping and redistribution, indicate a polythermal to temperate glacial condition, especially in the older strata of Oligocene age. The deformation in the sequence may also be associated with glacial over-riding and, although the fabric analyses thus far indicate no strong subglacial till fabric, some of the diamictites may also be subglacially derived. If subglacial deposition has occurred, then based on the marine character of the sequence, the most logical inference would be for glaciers to have been grounded in the sea. During periods when glaciers advanced into the sea the grounding line deposits may have formed morainal banks, sufficient to produce mass flow and sediment redeposition. Isolated banks may have also created restricted circulation conditions on their shoreward side during some time periods as is indicated by some macrofossil assemblages and some of the darker Facies 1 mudstones which represent distal glacimarine and paraglacial conditions. Independent of the glacial and marine settings, nearby volcanic eruptions contributed volcanic ash of various compositions, some of which was subsequently reworked by marine currents.

SEQUENCE STRATIGRAPHY

Results of a preliminary sequence stratigraphic analysis of CRP-2/2A drill core are presented in Cape Roberts Science Team (1999). The framework reported in that volume is retained here, with 24 unconformity-bound, glaciomarine depositional sequences spanning the early-Oligocene to Quaternary (Fig. 1). The facies analysis reported above is used as the basis for the interpretation of palaeoenvironments for all parts of the depositional sequences. Our analysis follows the approach applied by Fielding et al. (1998) to the CRP-1 drill core, and is based on the premise that changes in grain-size reflect changes in depositional energy, and therefore, broadly correspond to changes in palaeobathymetry. Such a contention is also supported by interpretation of the depth palaeoecology of constituent macrofaunal assemblages (Taviani & Beu, this volume). Powell et al. (this volume) provide an alternative but similar interpretation of the stratigraphy.

VERTICAL ORGANISATION OF FACIES

The recognition of vertically-stacked cyclical facies successions, bounded by sharp erosion surfaces that mark prominent lithological dislocations, has allowed the cored interval to be subdivided into sequences. Sequences can be divided into four parts as follows, in ascending stratigraphic order (Fig. 2): (1) a sharp-based, poorly sorted coarse-grained unit (2-20 m thick) comprising diamictite, pebbly sandstone and/or conglomerate (Facies 6, 7, 9, 10), (2) a fining-upwards interval (up to 25 m thick) of muddy sandstone (Facies 3) which passes up-section into interbedded sandstone/mudstone (Facies 2), (3) a mudstone (Facies 1: up to 30 m thick) that is marked at the base in some cases by a condensed fossiliferous interval, passing gradationally upwards into a more sandstone-rich section (Facies 3 and 4: up to 20 m thick), and (4) a sharp-based, well sorted, medium- to coarse-grained sandstone (Facies 5), in places with interbedded/interlaminated sandstones and mudstones (Facies 2, 6: 2-10 m thick).

Sequence boundaries

Hiatal surfaces bounding CRP-2/2A sequences are sharp, unweathered, planar surfaces that cut across mudstone or sandstone facies of the underlying sequences, and mark abrupt facies dislocations between these underlying strata and superjacent diamictites and conglomerates (Fig. 2). It is suggested here that sequence boundaries coincide with *glacial surfaces of erosion* (GSE), which record periods of local glacial advance across the sea-floor during glacio-eustatic sea-level fall (*e.g.* Fielding et al., 1998). In contrast to the traditional Exxon definition of the sequence boundary, which was developed from

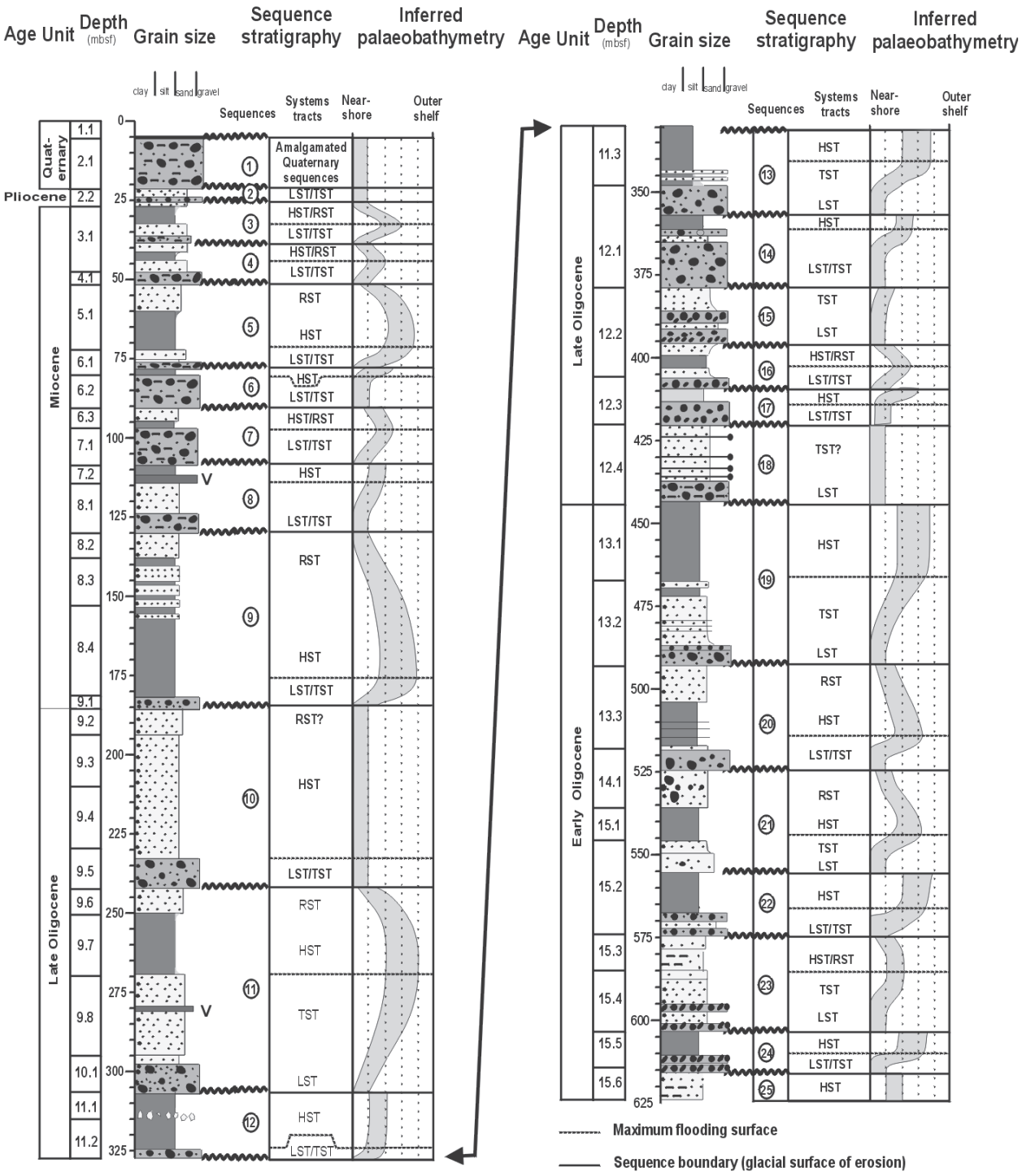

Fig. 1 - Composite stratigraphic log of the CRP-2/2A drill core showing sequence stratigraphic architecture and an inferred palaeobathymetric curve for sequences.

studies of non-glaciated continental margins (*e.g.* Vail, 1987), GSEs do not necessarily mark a basinward migration and downward shift of the shoreline during falling relative sea-level. Rather, they are the product of erosion caused by the grounding of advancing glacier ice onto the sea-floor, which may occur independently of relative sea-level oscillations and produce an unconformity of only local areal extent.

Notwithstanding these added complications inherent in glaciated basin margins, we view the sequence boundaries recorded in the cored interval (Fig. 1) as primarily reflecting glacier advance in concert with a eustatic drawdown of base-level. Such a contention is supported by the recognition of faunal and sedimentological evidence for palaeobathymetric deepening and shallowing cycles within sequences. That grounded ice may have passed periodically through the site of CRP-2/2A is consistent with the location of the drillsite in the palaeo-Mackay Valley close to the western margin of the West Antarctic Rift System.

Because many of the diamicts exhibit characteristics that are compatible with basal tills: multimodal grain size,

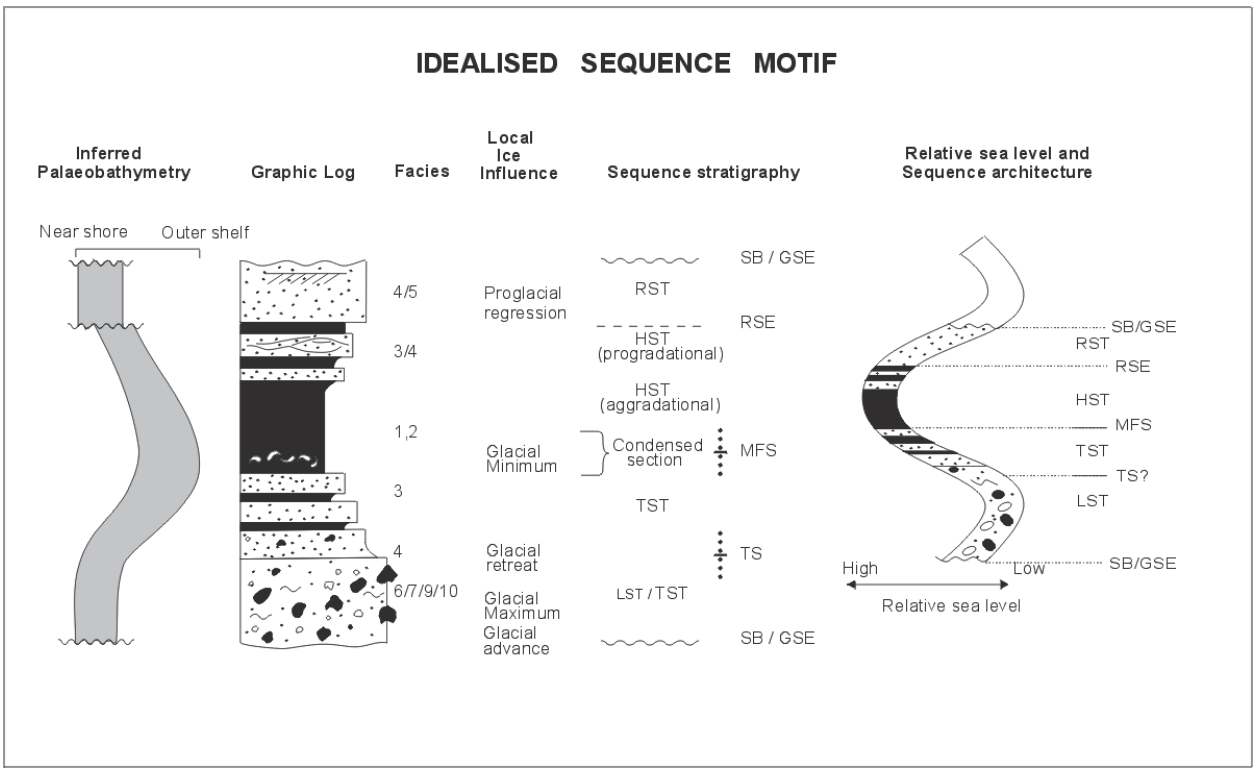

Fig. 2 - Typical motif of depositional sequences recognised in CRP-2/2A. SB/GSE – Sequence Boundary/Glacial Surface of Erosion. TS – Transgressive Surface. MFS – Maximum Flooding Surface. RSE – Regressive Surface of Erosion. LST – Lowstand Systems Tract. TST – Transgressive Systems Tract. HST – Highstand Systems Tract. RST – Regressive Systems Tract.

vague lamination, shear surfaces, injection structures and *in situ* brecciation, and overlie sharp erosional surfaces, we interpret twenty-two of the twenty-four sequence-bounding unconformities and basal diamicts to have formed in a setting that could potentially have been landward of the glacial maximum ice front. In such a setting, scouring by advancing grounded ice may have removed substantial parts of subjacent sequences. Consequently, CRP-2/2A sequences display various degrees of top-truncation. The preservation of shallow water regressive facies in the upper parts of twelve of the twenty-four sequences implies that glacial erosion may have occurred within close proximity to the contemporary shoreline.

The basal portions of Sequences 3 and 21 represent positions basinward of the glacial-maximum grounding line. These sequences display sharp erosional lower boundaries, but commence with sandstone facies (3 and 5, respectively) instead of diamictite immediately above the sequence boundary. The absence of diamictite and the occurrence of sharp-based sandstone leads us to interpret these sequence boundaries as current-scoured surfaces formed offshore from a subglacial stream or clastic shoreline. They may represent regressive surfaces of erosion cut towards the end of sea-level fall, and/or ravinement surfaces associated with landward passage of the shoreface during the ensuing transgression.

Lowstand and transgressive systems tracts

The coarse-grained basal units of the sequences comprise massive (Facies 7) and stratified (Facies 8) diamictite together with clast- (Facies 9) and matrix- (Facies 10) supported conglomerate. Diamictites are consistent with a combination of glaciomarine processes including subglacial entrainment during ice advance, melt-out and rainout during ice withdrawal, and proglacial debris-flow deposition with ice rafting. Conglomerate facies are also consistent with ice-proximal glaciomarine sedimentation and probably represent glaciodeltaic deposits, possibly with some deposits from subglacial streams. Distinguishing subglacial tills deposited during ice advance from proglacial tills deposited during retreat is inherently difficult in core, as the sedimentological characteristics of these deposits are not mutually exclusive in modern glacial environments. Therefore, the coarse-grained, basal facies are considered to have a polyphase origin representing ice-proximal deposition during advance and withdrawal of glacier ice within a shallow marine setting.

Consequently, basal diamictite and conglomerate facies are assigned to both the *lowstand systems tract* (LST) and the *transgressive systems tract* (TST). It is generally not possible to identify the LST/TST boundary in the CRP-2/2A core. However, given the paucity of facies that can be immediately interpreted as of subglacial origin, it is suggested that the basal diamictites comprise a predominantly transgressive record of glacial retreat. Upper portions of TSTs display clear fining-upwards trends and are mostly capped by a mudstone (in some instances, fossiliferous) unit interpreted as the *condensed section* corresponding to a zone of maximum water depth and lowest sedimentation rate in a cycle.

Highstand systems tracts

Where fossiliferous, the condensed section mudstone mentioned above contains molluscan fauna indicative of maximum water-depths in sequences (Taviani & Beu, this volume). This horizon is defined as the base of the *highstand systems tract*. A lower interval (up to 30 m) of massive to weakly laminated/bedded, bioturbated, sparsely fossiliferous mudstone and interlaminated mudstone/sandstone (Facies 1 and 2) typically passes upwards into more sandstone-dominated lithologies (Facies 3 and 4). Micro- and macrofaunal determinations show little or no change in water depth up-section in this lower interval. It is suggested that this regressive mudstone to sandstone interval results from sediment accumulation during the highstand and/or early fall of sea-level. Accordingly, this facies succession is assigned to the *highstand systems tract* (HST).

Highstand systems tract deposits are interpreted as having formed during the late rise, stillstand and early fall of a relative sea-level cycle (*e.g.* Vail, 1987, Posamentier et al., 1988). In offshore locations the *downlap surface* (DLS) marks the base of a HST, which is broadly coincident with the level of maximum palaeo-water depth termed the *maximum flooding surface* (MFS). At seismic scale the MFS represents a change from retrogradational to progradational cross-sectional stratal geometries (*e.g.* van Wagoner 1988, 1990). In CRP-2/2A drill core sequences, however, it is not possible to recognise downlap, and the overall geometry of sequences is not clear from seismic reflection data (but see below).

Regressive systems tracts

Twelve of the twenty-four CRP-2/2A sequences include in their upper parts a sharp-based shallow-marine sandstone interval (Facies 4 & 5) of probable innermost shelf origin. The occurrence of sharp-based shallow-marine sands at the top of sequences, the strongly progradational character of the succession, and the subsequent truncation by overlying GSEs, are all consistent with sediments deposited during a period of falling relative sea-level, or forced regression (Fig. 2). We tentatively interpret these regressive sandstones as having formed in a proglacial deltaic depositional environment seaward of the advancing ice front. In all cases the upper portions of sequences appear to have been overrun and truncated by the subsequent advancing glacier.

Strata deposited during gradual or stepwise forced regression accumulate as a basinward-descending and offlapping series of wedges, bounded below by an abruptly gradational (*e.g.* Naish & Kamp, 1997) or erosional downlap surface (*e.g.* Plint, 1988) and above by a subaerial unconformity (often removed by subsequent marine ravinement), which corresponds to the sequence boundary. Naish & Kamp (1997) have referred to this distinctive stratal package as the *regressive systems tract* (RST), and view it as the logical counterpart to the transgressive systems tract. In CRP-1 and CRP-2/2A, the upper bounding unconformity of the RST is marked by the GSE.

A schematic interpretation of the facies patterns associated with a glacial advance-retreat cycle, and the consequent stratigraphic stacking patterns, is given in figure 3. Sedimentological and faunal paleobathymetric indicators for sequences suggest that significant water depth changes of up to a few tens of metres may have occurred in concert with local glacial advance-retreat cycles.

SEQUENCE STACKING PATTERNS, AND CORRELATION WITH SEISMIC REFLECTION DATA

It has been noted above that some sequences recognised in CRP-2/2A are thick and relatively complete, whereas others are relatively thinner, and many show evidence of top-truncation. Indeed, certain sequences (notably 1, 2, 6, 8, 14 and 18) show amalgamation of coarse-grained facies and a complex facies architecture, suggesting that these sequences accumulated during periods of more complex and/or short-term relative sea-level fluctuation. A plot of sequence thickness downhole (Fig. 4) illustrates quasi-cyclical variation, with some abrupt changes. Most noteworthy are the abrupt decrease in sequence thickness at base Sequence 18, abrupt increase at base Sequence 11, and the abrupt decrease at base Sequence 8. The two abrupt decreases in sequence thickness noted above also correspond to the bases of amalgamated sequences, suggesting that those intervals accumulated during times of limited accommodation. The thickest sequences in the succession are Sequence 19, immediately below one of the abrupt decreases noted above, and Sequences 11, 10 and 9, immediately above the other abrupt decrease. This pattern suggests a control on accommodation that was independent of glacial and associated sea-level changes, and a tectonic (subsidence) control is proposed here.

Correlation between the depths of sequence boundaries presented in Cape Roberts Science Team (1999) and herein, with the interpreted depths of seismic reflectors recently reinterpreted by Henrys et al. (this volume) shows further support for a tectonic control on sequence stacking patterns. Every reflector recognised in Henrys et al.'s analysis corresponds to a sequence boundary as defined herein, with one exception (Reflector "f", which corresponds to the middle of Sequence 10: but see Woolfe et al., this volume, for an alternative correlation). figure 4 shows the relationship between sequence boundaries and reflectors recognised by Henrys et al., and figure 5 shows a portion of seismic line NBP-9601-89 with the reflectors recognised by Henrys et al. and the corresponding sequence stratigraphic features. Note that many of the reflectors correspond to the sequence boundaries noted above which mark abrupt changes in sequence thickness (eg., "l" = base Sequence 18, "I" = base Sequence 11, "d" = base Sequence 8), and that the base of every amalgamated sequence as listed above corresponds to a seismic reflector. Note further that the boundaries of the regionally widespread seismic sequences V4/V5 and V3/V4 correspond to the base of Sequences 18 and 6, respectively, and that the thick and relatively complete Sequences 9, 10 and 11 are identified individually by seismic reflectors.

For the first time in the history of the Cape Roberts Project, then, features recognisable on seismic reflection

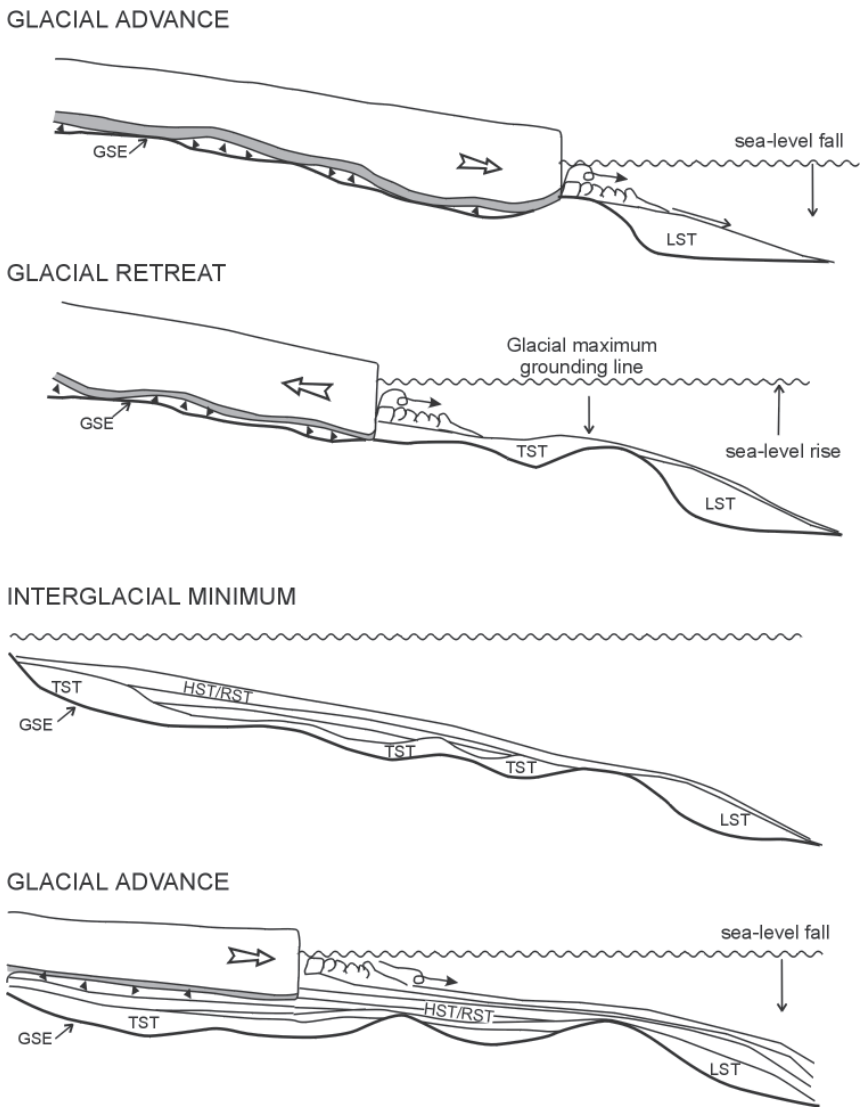

Fig. 3 - Series of schematic cross-sections to illustrate the lateral variations in lithofacies at various stages in a glacier advance-retreat cycle, and the consequent stratigraphic stacking patterns (abbreviations as for Fig. 2).

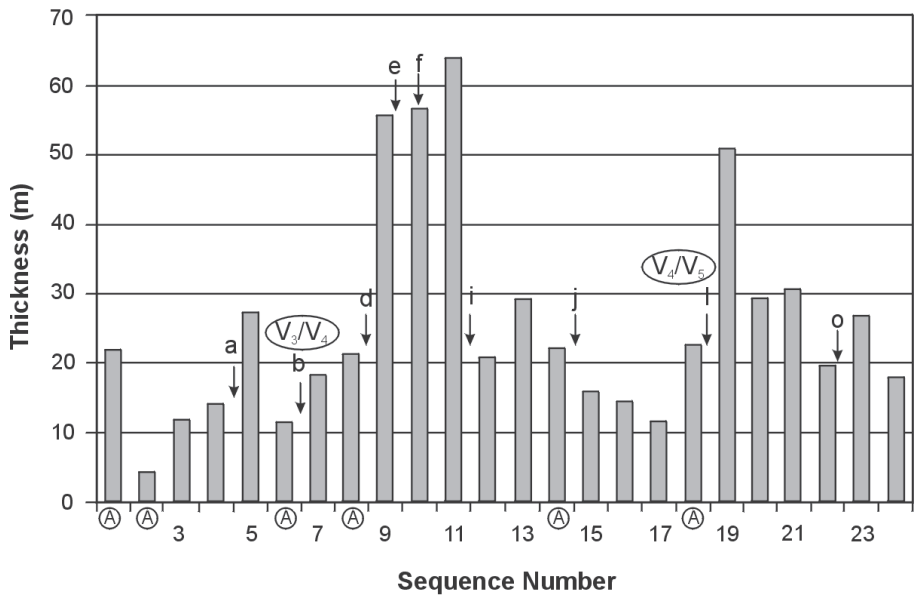

Fig. 4 - Plot of cycle thickness *vs* sequence number, highlighting long-duration, cyclical stacking pattern of sequences. Lower case letters at the boundaries of several sequences correspond to the seismic reflectors recognised by Henrys et al. (this volume). See also figure 5 for details of seismic interpretation. "A" denotes sequences that are amalgamated and truncated.

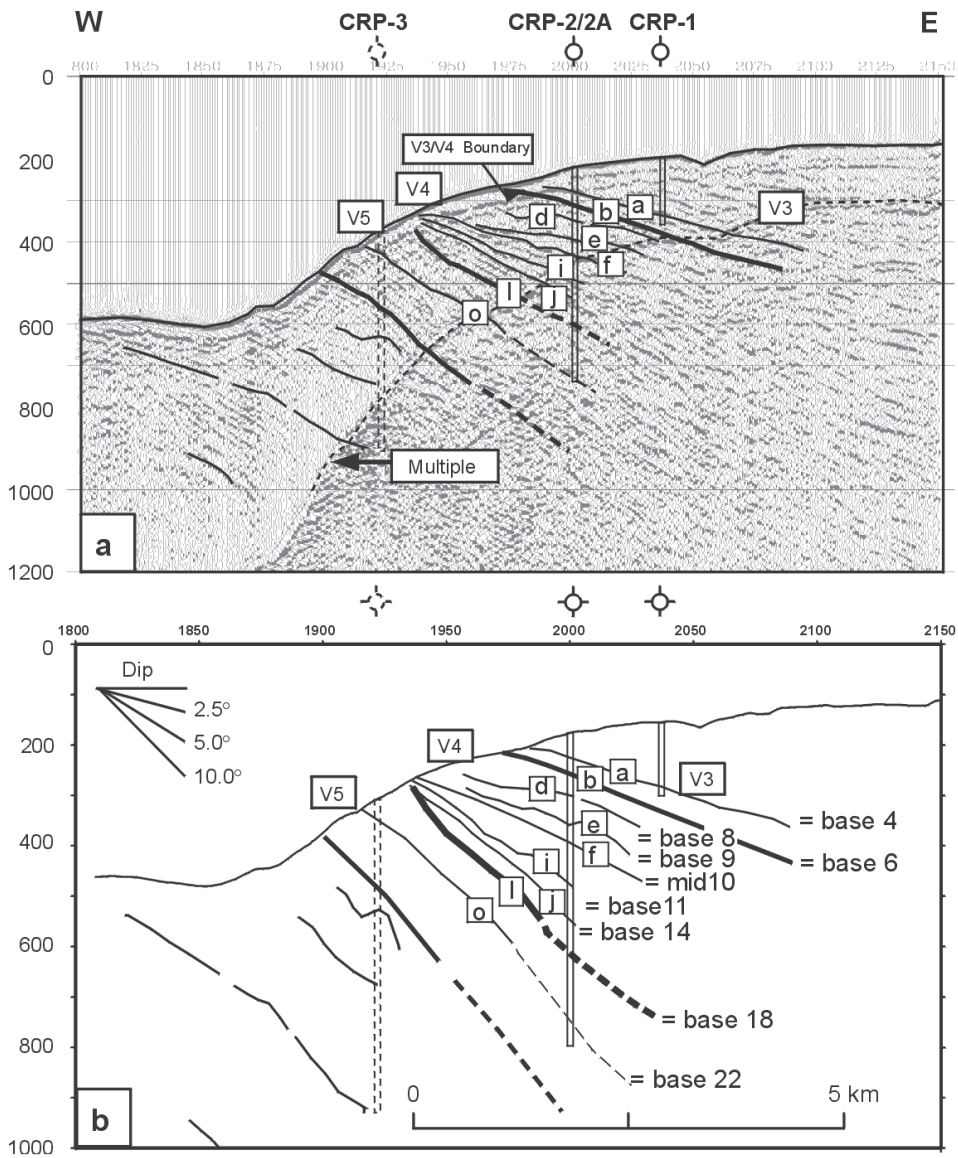

Fig. 5 - Interpretation of seismic line NBP9601-89 from Henrys et al. (this volume), showing the correspondence between reflectors (including the seismic sequence boundaries V3/V4 and V4/V5) and sequence boundaries identified independently from the core. See Henrys et al. (this volume) for depth correlation of reflectors.

data can be matched to stratigraphic horizons recognised in cores. This allows some interpretations to be made as to the cross-sectional geometry of sequences, which will contribute towards understanding the geological history of the western Victoria Land Basin.

Within the confines of the seismic line illustrated (Fig. 5), the two major seismic sequence boundaries show differing geometries. Reflectors below the V4/V5 boundary are broadly concordant, but those above onlap this boundary (reflector "l") to produce a fan-like arrangement of reflectors, the package thickening to the east. The V4/V5 boundary therefore conforms to the formal definition of a seismic sequence boundary in this area, and corresponds to a major unconformity identified from biostratigraphic data (base Sequence 18, intra-Early Oligocene unconformity: Cape Roberts Science Team, 1999). The stratigraphic interval enclosed by reflectors that onlap the V4/V5 boundary encompasses Sequences 18 to 9, inclusive. The lower part of this section, from base Sequence 18 to top Sequence 12, comprises a series of relatively thin and incomplete sequences some of which are amalgamated (Figs. 4 & 5). The uppermost part of this interval (Sequence 12) is dominated by thin-bedded mudstones and muddy sandstones interpreted as relatively deep-water turbidites (Facies 2A), and contains the thick, intraformational breccia interpreted as a submarine mass flow deposit (Facies 11).

Sequences 9, 10 and 11, the three thick and relatively complete sequences, show the most pronounced eastward thickening patterns and probably also onlapped the V4/V5 boundary, although the convergence has been removed by erosional truncation associated with formation of the modern sea-floor (Fig. 5). The base of Sequence 11 (reflector "i") is also an onlap surface, and corresponds to a major change in facies (see above), macro- and microfossils, composition of coarse clasts, and deformational features. Base Sequence 11/reflector "i"

was identified in Cape Roberts Science Team (1999) as a major unconformity possibly separating Early from Late Oligocene strata. The seismic geometry suggests strongly that Sequences 9, 10 and 11 accumulated during a time of rapid accommodation, which increased progressively eastward. The geometry shown by these sequences is comparable to that expected in half-grabens during a phase of active tectonic subsidence. It is therefore proposed that Sequences 9 to 11 accumulated during accelerated tectonic subsidence associated with the opening of a half-graben the bounding fault of which was located to the east of the Roberts Ridge, and that Sequence 12 with its turbidites and mass-flow breccia records the onset of this change in subsidence style. The major change in sediment provenance interpreted from clast compositions (Talarico et al., this volume) at the base of Sequence 11 further suggests that at this time major changes occurred in the dispersal of sediment from the immediate onshore region that is interpreted as the principal sediment source for the CRP-2/2A succession.

Within the package of three thick, complete sequences (9-11), a further major stratigraphic discontinuity occurs. The base of Sequence 9 (reflector "e") corresponds to an hiatus spanning the Late Oligocene/Early Miocene boundary (revised subsequent to initial investigations: Cape Roberts Science Team, 1999; Watkins & Villa, this volume; Wilson et al., this volume). Woolfe et al. (submitted) have proposed that this boundary may also coincide with the Mi1 event in oxygen isotope records (Zachos et al., 1997), which records a major drawdown of eustatic sea-level and increase in polar icecap volume. The highly scalloped cross-sectional geometry of reflector "e" on Line NBP9601-89 (Fig. 5) may be a consequence of erosion associated with the drawdown in sea-level.

The top of the interval of eastward-thickening sedimentary packages on the seismic line (Fig. 5) is at reflector "d", which corresponds to an abrupt decrease in sequence thickness (Fig. 4) and the base of the amalgamated/truncated Sequence 8. Clearly, this surface records an hiatus at the end of the period of rapid subsidence noted above, which was followed by a period of more modest accommodation. The seismic reflector geometry therefore argues for a discrete, Late Oligocene period of extensional subsidence that was both preceded and followed by periods of more even, (?thermal) subsidence.

In the area covered by figure 5, the V3/V4 boundary is characterised by more or less concordant reflector geometry both above and below the boundary. Elsewhere, however, truncation of underlying reflectors can be seen against this boundary, with onlap of overlying reflectors. The V3/V4 seismic sequence boundary corresponds to the base of the highly truncated/amalgamated Sequence 6 (Fig. 5), and may therefore also record a change in subsidence rate, if not in style.

Finally, the new seismic reinterpretation by Henrys et al. (this volume) allows a more robust correlation between CRP-1 and CRP-2/2A, as reflector "a" passes through both wells. This suggests that the base of Sequence 4 in CRP-2/2A (at 51.94 mbsf) corresponds to a similar, abrupt lithological change from muddy sandstones and interbedded mudstones to diamictite in CRP-1 (at 141.08 mbsf). This further suggests that of the pre-Pliocene sequences recognised in CRP-2/2A, only Sequences 3 and 4 are recorded in CRP-1, but that a further four Early Miocene sequences not penetrated in CRP-2/2A are preserved in CRP-1.

DISCUSSION: IMPLICATIONS FOR THE CENOZOIC BEHAVIOUR OF THE EAST ANTARCTIC ICE SHEET AND GLOBAL GLACIO-EUSTACY

The sequence stratigraphic interpretation of CRP-2/2A can play an important role in understanding (1) the long-term dynamics of the East Antarctic Ice Sheet, and (2) the degree to which Antarctic ice volume changes may have influenced global glacio-eustatic sea-level changes hypothesised for the Cenozoic Era. This is possible because CRP-2/2A is one of the first well-dated, ice-proximal glaciomarine, Antarctic sediment cores (along with CRP-1, CIROS-1 and –2, and MSSTS-1: see Cape Roberts Science Team, 1999). Cored holes in the McMurdo Sound region drilled prior to the Cape Roberts Project were sited close to land, and the stratigraphy recorded in those holes is complex and not obviously cyclical (Pyne et al., 1985; Barrett, 1986, 1989; Barrett & Hambrey, 1992). A facies and stratigraphic analysis of CIROS-1 by Hambrey (1989) interpreted the core in terms of principally glacial and proximal glaciomarine environments, whereas a reappraisal of that core by Fielding et al. (1997) placed more emphasis on marine and glaciomarine systems, and attempted a sequence stratigraphic analysis with limited success. CRP-1 was the first hole drilled in the region that preserves a clearly cyclical stratigraphy (Cape Roberts Science Team, 1998; Fielding et al., 1999). The more extensive record captured by CRP-2/2A now offers a previously unavailable opportunity to assess the long period controls on a strongly cyclical Cainozoic succession accumulated proximal to the Antarctic landmass.

Twenty-four cycles of local advance and retreat of glacier ice during the Oligocene to Quaternary can be identified on the basis of the facies and sequence stratigraphic analysis of the CRP-2/2A drill core. The Quaternary and Pliocene intervals, Sequences 1 and 2 respectively, are probably an amalgamated series of sequences recording a cryptic and very incomplete glacial history of the last 5 Ma. That the Quaternary record lies within a normal polarity interval interpreted as Bruhnes Chron suggests that high amplitude climatic variations characteristic of the last 700 ka may have driven major glacial episodes, destroying much of the earlier Plio-Pleistocene stratigraphic record. Although punctuated by significant unconformities, the Oligocene-early Miocene section of the drill core is relatively more complete with 6 sequences preserved in the early Miocene and 16 sequences representing the Oligocene.

A chronology presented for CRP-2/2A in Cape Roberts Science Team (1999) and Wilson et al. (this volume) indicates that the thick interval of the core between 130.27 m and 306.65 m spanning Sequences 9, 10, and 11 accumulated in c. 300 ka. The age of these sequences is

constrained by the last occurrence of *Dictyococcites bisectus* (23.9 Ma) at 144.44 m, and the Ar/Ar age of the ash at 280.7 m (24.22±0.05 Ma). Furthermore, the Wilson et al. (this volume) time model indicates that the 8 underlying Sequences 12-18 (306.65 - 442.96 m) may have accumulated in as little as c. 800 ky. The integrated chronology for CRP-2/2A implies that individual depositional sequences in certain parts of the core (particularly Sequences 9, 10 and 11) may correspond to an approximately *quasi*-periodic duration of 100 ka, the period of the Milankovitch eccentricity parameter.

The causal link between astronomical-forcing of climate and sedimentation has been well-established since the seminal work of Hays et al. (1976) on deep-sea benthic $\delta^{18}O$ records, yet the exact origin of the orbital control at the 100 ka frequency band remains contentious (summarised in Paul and Berger, 1999). *Eccentricity* of Earth's orbit around the sun (Berger & Loutre, 1994), or periodic variations in *inclination* of the Earth's ecliptic have been proposed as possible mechanisms. The latter is considered to drive 100 ka cycles in the accretion of meteoroids and interplanetary dust particles to the atmosphere (Muller & MacDonald, 1997). The problem with eccentricity as a driving mechanism is that while the eccentricity frequencies are prominent in many cyclic sediment records, they lack power in orbital time series compared with stronger obliquity and precession spectral peaks (*e.g.* Imbrie et al., 1984). Nevertheless, regardless of its origin, the 100 ka orbital beat imparted a profound control on insolation and periodic changes in the continental ice volume and sea-level during the late Cenozoic, and is the most clearly-developed frequency of sequences in the CRP-2/2A core.

On geological timescales, continental ice sheets influence critical components of the Earth system including sea-level, land/sea surface coverage, planetary albedo, continental weathering rates, ocean chemistry and ocean circulation. Efforts to understand the nature of pre-Pliocene changes in global climate require a fundamental understanding of the behaviour of the Antarctic ice sheets. Glaciomarine sediments recovered on or near Antarctica strongly suggest the presence of grounded ice over much of Antarctica since earliest Oligocene (*e.g.* Barrett 1989, Barron et al., 1989, Schlich et al., 1989; Hambrey et al., 1991, Breza and Wise, 1992). This evidence is consistent with the benthic foraminiferal oxygen isotope records from the southern ocean, which show a ubiquitous increase of > 1.0 ‰ coeval with a period of widespread ice rafting at 33.5 Ma (*e.g.* Shackleton and Kennett, 1975; Kennett and Shackleton, 1976; Keigwin, 1980; Miller and Thomas, 1985, Zachos et al. 1992, 1996). The high-resolution benthic $\delta^{18}O$ record of ODP Hole 744 is dominated by Milankovitch periodicities (100 ka and 41 ka) superimposed on longer term isotopic variations for the entire Oligocene (Zachos et al., 1996).

Such oxygen isotope data from deep-sea sediment cores are commonly taken as a direct proxy for global ice-volume. While temperature dependent fractionation between seawater and calcite also causes the $\delta^{18}O$ value to increase, in Pliocene isotope records, such effects are considered to account for no more than 1/3 of the overall $\delta^{18}O$ shift (Naish, 1998; Pillans et al, 1998). Application of the conservative 1/3 temperature to 2/3 ice volume calibration to the Oligocene $\delta^{18}O$ data implies substantial orbital control on the size of the Antarctic ice sheet during this time, with ice volume changes equivalent to global sea-level changes of 30-40 m amplitude (using the $\delta^{18}O$ sea-level calibration of Chappell and Shackleton 1986; Pillans et al., 1998).

Broad constraints on the amplitudes of palaeobathymetric fluctuations in CRP-2/2A reveal cyclical changes in water depth from shoreline-inner shelf to outer shelf water depths, perhaps of 50 m magnitude. These water depth changes are likely to result from the combined influence of eustasy, local tectonism, and sediment supply factors. The isolation of the eustatic sea-level component from a continental-margin sedimentary succession is inherently difficult to achieve. At this stage it has not been possible to estimate the amplitude of any glacio-eustatic component, but the inferred changes in water depth that are illustrated in figure 4 are consistent with the magnitude of eustatic water depth changes inferred for the Oligo-Miocene from seismic records (Haq et al. 1988), and deep ocean oxygen isotope records (Zachos et al. 1996; Abreu & Anderson, 1998).

CONCLUSIONS

The Cainozoic succession of CRP-2/2A has been rationalised into 12 recurrent lithofacies, reflecting marine, glaciomarine and possible glacial environments of deposition. The vertical arrangement of these facies is strongly cyclical, and 24 sharply-based sequences have been recognised, each interpreted to record a cycle of local glacial advance and retreat with attendant changes in palaeobathymetry. Although as yet unconfirmed, it is suggested that many of these cycles may correspond to changes in glacio-eustatic sea-level. The cycles can be correlated to seismic reflectors, allowing an interpretation of the cross-sectional stratigraphic geometry evident from seismic reflection records. At least one major period of rapid, asymmetrical, possibly half-graben subsidence is recorded, which produced three thick and relatively complete sequences. This interval is bounded above and below by the record of slower, more uniform, possibly thermal subsidence that resulted in the accumulation of numerous, thinner and truncated/amalgamated sequences.

Together with the revised age model for CRP-2/2A (Wilson et al., this volume), this analysis demonstrates that the cored interval contains an incomplete record of the Oligocene-Quaternary of the western Ross Sea with large periods of time represented at sequence-bounding unconformities, and that where sequences are preserved, subsidence and sedimentation rates were comparatively high. Furthermore, this analysis allows the identification and separation of tectonic from climatic (possibly glacio-eustatic) controls on the Cainozoic stratigraphy of the Antarctic continental margin perhaps for the first time. The CRP-2/2A core, therefore, represents an important reference point for resolving the long-term dynamics of

the East Antarctic Ice Sheet, and may allow a significant contribution to our understanding of the origin and nature of global eustatic sea-level in pre-Pliocene Earth History.

ACKNOWLEDGEMENTS

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