Terra Antartica
2001, **8**(3), 217-224

TERRA ANTARTICA
AN ANTARCTIC EARTH SCIENCE JOURNAL

Facies Architecture of the CRP-3 Drillhole, Victoria Land Basin, Antarctica

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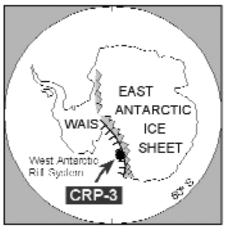
Received 7 November 2000; *accepted in revised form* 10 October 2001



Abstract - The Cenozoic Victoria Land Basin (VLB) stratigraphic section penetrated by CRP-3 is mostly of Early Oligocene age. It contains an array of lithofacies comprising fine-grained mudrocks, interlaminated and interbedded mudrocks/sandstones, mud-rich and mud-poor sandstones, conglomerates and diamctites that are together interpreted as the products of shallow marine to possibly non-marine environments of deposition, affected by the periodic advance and retreat of tidewater glaciers. This lithofacies assemblage can be readily rationalised using the facies scheme designed originally for CRP-2/2A, and published previously. The uppermost 330 metres below sea floor (mbsf) shows a cyclical arrangement of lithofacies also similar to that recognised throughout CRP-2/2A, and interpreted to reflect cyclical variations in relative sea-level driven by ice volume fluctuations (“Motif A”). Between 330 and 480 mbsf, a series of less clearly cyclical units, generally fining-upward but nonetheless incorporating a significant subset of the facies assemblage, has been identified and noted in the Initial Report as “Motif B. Below 480 mbsf, the section is arranged into a repetitive succession of fining-upward units, each of which comprises dolerite clast conglomerate at the base passing upward into relatively thick intervals of sandstones. The cycles present down 480 mbsf are defined as sequences, each interpreted to record cyclical variation of relative sea-level. The thickness distribution of sequences in CRP-3 provides some insights into the geological variables controlling sediment accumulation in the Early Oligocene section.

The uppermost part of the section in CRP-3 comprises two or three thick, complete sequences that show a broadly symmetrical arrangement of lithofacies (similar to Sequences 9-11 in CRP-2/2A). This suggests a period of relatively rapid tectonic subsidence, which allowed preservation of the complete facies cycle. Below Sequence 3, however, is a considerable interval of thin, incomplete and erosionally truncated sequences (4-23), which incorporates both the remainder of Motif A sequences and all Motif B sequences recognised. The thinner and more truncated sequences suggest sediment accumulation under conditions of reduced accommodation, and given the lack of evidence for glacial conditions (see Powell et al., this volume) tends to argue for a period of reduced tectonic subsidence. The section below 480 mbsf consists of a series of fining-upward, conglomerate to sandstone intervals which cannot be readily interpreted in terms of relative sea-level change. A relatively mudrock-rich interval above the basal conglomerate/breccia (782-762 mbsf) may record initial flooding of the basin during early rift subsidence.

The lithostratigraphy summarised above has been linked to seismic reflection data using depth conversion techniques (Henrys et al., this volume). The three uppermost reflectors (“o”, “p” and “q”) correlate to the package of thick sequences 1-3, and several deeper reflectors can also be correlated to sequence boundaries. The package of thick Sequences 1-3 shows a sheet-like cross-sectional geometry on seismic reflection lines, unlike the similar package recognised in CRP-2/2A.

INTRODUCTION

The cores acquired during drilling of CRP-1, -2/2A and -3 have provided a hitherto unavailable, virtually complete sample through the Oligocene and Miocene stratigraphy of the western Victoria Land Basin (Cape Roberts Science Team, 1998, 1999, 2000). The lithostratigraphy of the succession, and a sequence stratigraphic framework that embraces all but the basal few hundred metres of section, have been reported in the above-mentioned volumes and in Fielding et al. (1998, 2000). The succession in CRP-2/2A was found to contain a record of depositional cyclicity on a variety of scales, and together with geochronological and other data has allowed differentiation of the principal geological controls on stratigraphic architecture (Fielding et al., 2000). A key element of this latter analysis was the correlation between lithostratigraphic and sequence stratigraphic boundaries, and their equivalent horizons on seismic reflection records, which allowed the cross-sectional geometry of sequences to be elucidated. Facies patterns, sequence architecture and thickness patterns and cross-sectional geometry were then integrated to provide a framework in which tectonic and climatic/glacioeustatic controls could be isolated (Fielding et al., 2000).

CRP-3 was drilled in October/November, 2000 to

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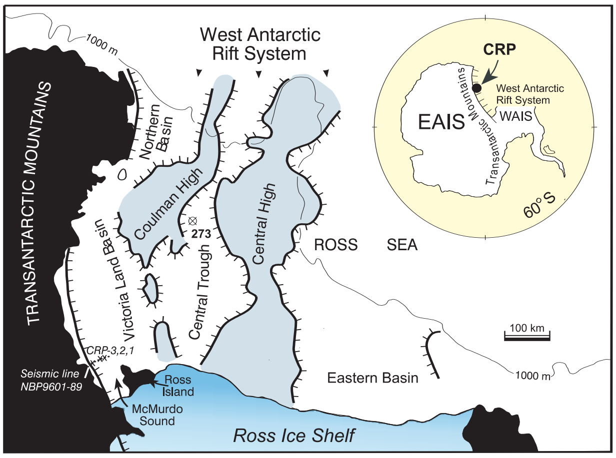


Fig. 1 - Map showing the location of CRP drillholes and seismic reflection line NBP9601-89 close to the western margin of the Victoria Land Basin in McMurdo Sound, Antarctica.

a total depth of 939.42 mbsf. The hole cored a section through mainly Early Oligocene strata to an angular unconformity at the base of the VLB and into underlying Beacon Supergroup strata of interpreted Devonian age, thereby completing a vertical stratigraphic transect through the VLB (Cape Roberts Science Team, 2000; Figs. 1, 2). An underlap of tens of metres was interpreted between the base of the section penetrated by CRP-2/2A and the top of –3.

In this paper, we summarise the lithostratigraphy of CRP-3, describe the styles of cyclicity evident in the stratigraphy, and interpret these patterns in terms of the balance between tectonic, climatic/glacioeustatic and sediment supply controls. These results are then compared to the younger section encountered in CRP-2/2A, and conclusions drawn as to the geological history of the VLB in the Cape Roberts area.

FACIES ANALYSIS

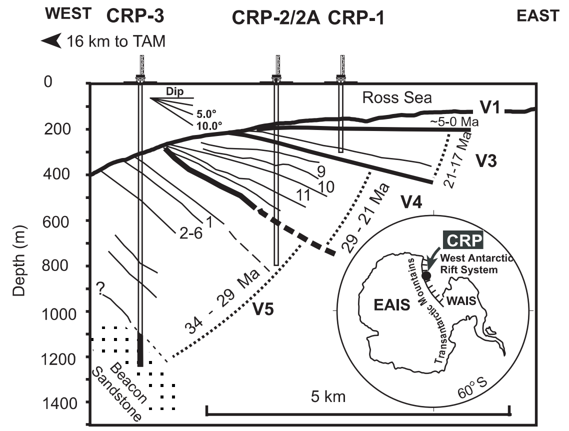
A facies scheme initially designed to account for the CRP-1 core (Cape Roberts Science Team, 1998) was expanded to take into account the greater variety of lithologies encountered in CRP-2/2A (Cape Roberts Science Team, 1999) and a variant of this scheme was reported by Fielding et al. (2000). This same scheme was adopted for CRP-3, since the array of lithofacies encountered in the final hole was comparable to that in CRP-2/2A, albeit with rather different proportions and vertical successions of the various facies. A summary of this facies scheme is given in table 1. The facies recognised are interpreted to reflect a range of depositional processes and environments, from ice-proximal proglacial deposits (and possibly subglacial in certain intervals) to distal glacimarine, and from alluvial/colluvial fan and fan delta deposits to shoreface and offshore shelf/ramp deposits (see Powell et al., this volume, for further details). Although there are few unambiguous indicators of palaeo-water depth in the lower part of the Cainozoic succession, a deep-water turbidite fan system such as has been championed by a minority of sedimentologists represented in Cape Roberts Science Team (2000) is not justified by data.

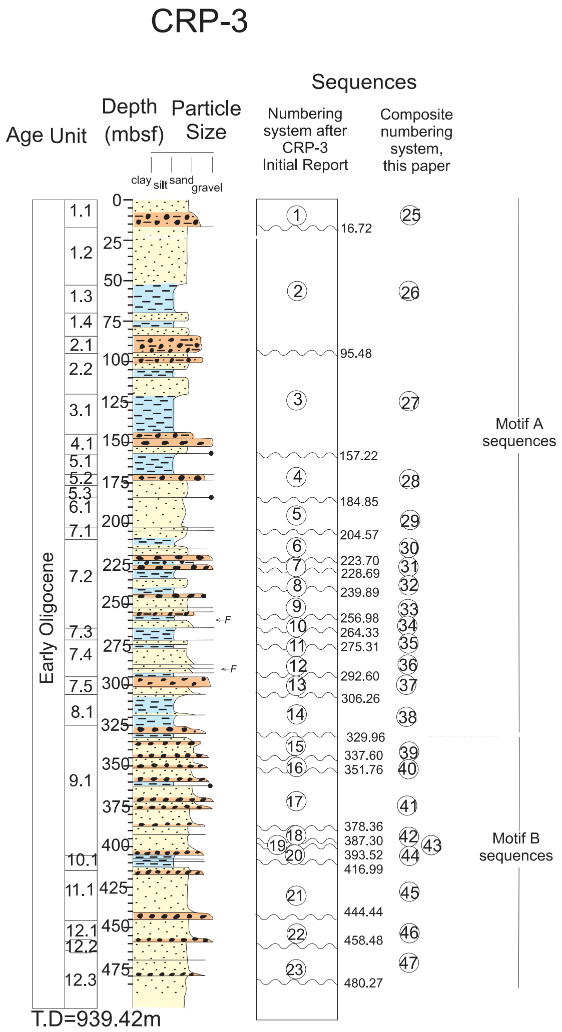
SEQUENCE STRATIGRAPHIC FRAMEWORK

A sequence stratigraphic model was first proposed to account for cyclicity in vertical lithofacies stacking patterns observed in CRP-1 (Cape Roberts Science Team, 1998; Fielding et al., 1998), and was employed with modifications to subdivide CRP-2/2A (Cape Roberts Science Team, 1999; Fielding et al., 2000). This model is constructed similarly to conventional

Tab. 1 - List of lithofacies recognised in CRP-3 (a modification of the facies scheme constructed for CRP-2/2A), together with interpretation, and distribution of facies in CRP-3.

Facies	***Lithology***	***Interpretation***	***Distribution in CRP-3***
1	Mudstone	Settling from suspension in offshore water depths	Common down to 329.96 mbsf, rare below this depth except between 762-782 mbsf
2	Interstratified sandstone/mudstone	Low-energy tractional flows and fallout from suspension	As for Facies 1
3	Poorly sorted, muddy sandstone	High-energy deposits of ?density flows	Abundant above 378.36 mbsf and within 580-789.77 mbsf
4	Well-sorted, clean, fine-grained, stratified sandstone	Deposits of dilute, tractional flows in shoreface water depths	Uncommon between 378.36-580 mbsf, no occurrences elsewhere
5	Well-sorted, clean, fine- to medium-grained sandstone	Deposits of dilute tractional flows in shallow marine waters	Common between 378.36-580 mbsf, less common through remainder of hole
6	Stratified diamictite	Subglacial or ice-contact proglacial marine deposition	Uncommon at intervals above 378.36 mbsf
7	Massive diamictite	Subglacial or ice-contact proglacial marine deposition	Uncommon at intervals above 378.36 mbsf
8	Rhythmically interstratified sandstone and siltstone	Deposition from turbid overflow plumes associated with glacier snout efflux	Rare above 378.36 mbsf
9	Clast-supported conglomerate	Deposition from a variety of processes in shallow marine waters	Common throughout the hole
10	Matrix-supported conglomerate	Deposition from a variety of processes in shallow marine waters	Common throughout the hole





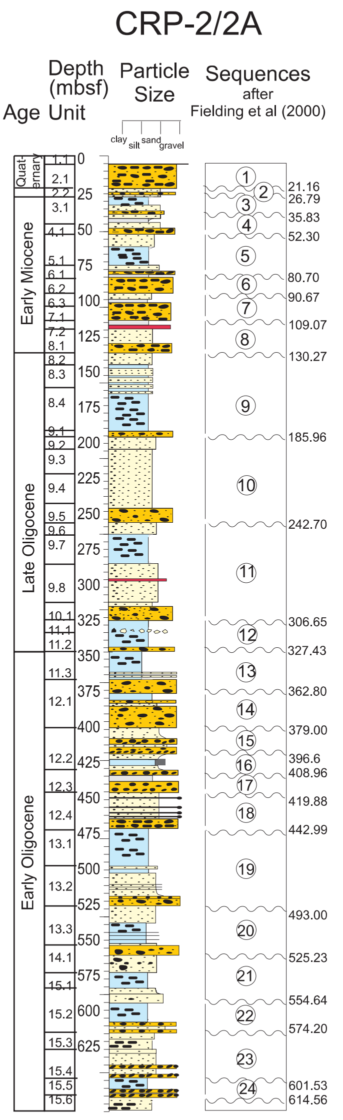


Fig. 2 - Graphical log illustrating the vertical distribution of lithologies in CRP-2/2A and -3, their division into sequences where applicable, and the vertical limits of sequence Motifs A and B. Note the progressive downward-coarsening of the Cenozoic section (after Naish et al., this volume).

sequence stratigraphic models for non-glaciated continental margins, and interprets cyclical facies patterns in terms of cyclical variations in relative sea-level (using the fundamental premise that grain-size, as a proxy for depositional energy in the marine environment, is a function of water depth, and taking into account the complications that will arise in a glaciated continental margin system). However, the model differs from conventional sequence stratigraphic models in that the sequence boundary is designated as a glacial surface of erosion and interpreted to record the advance of a glacial ice body towards or across the study site.

The complete cycle can be arbitrarily divided into four parts, in ascending order: 1) a sharply-based, coarse-grained interval dominated by diamictites

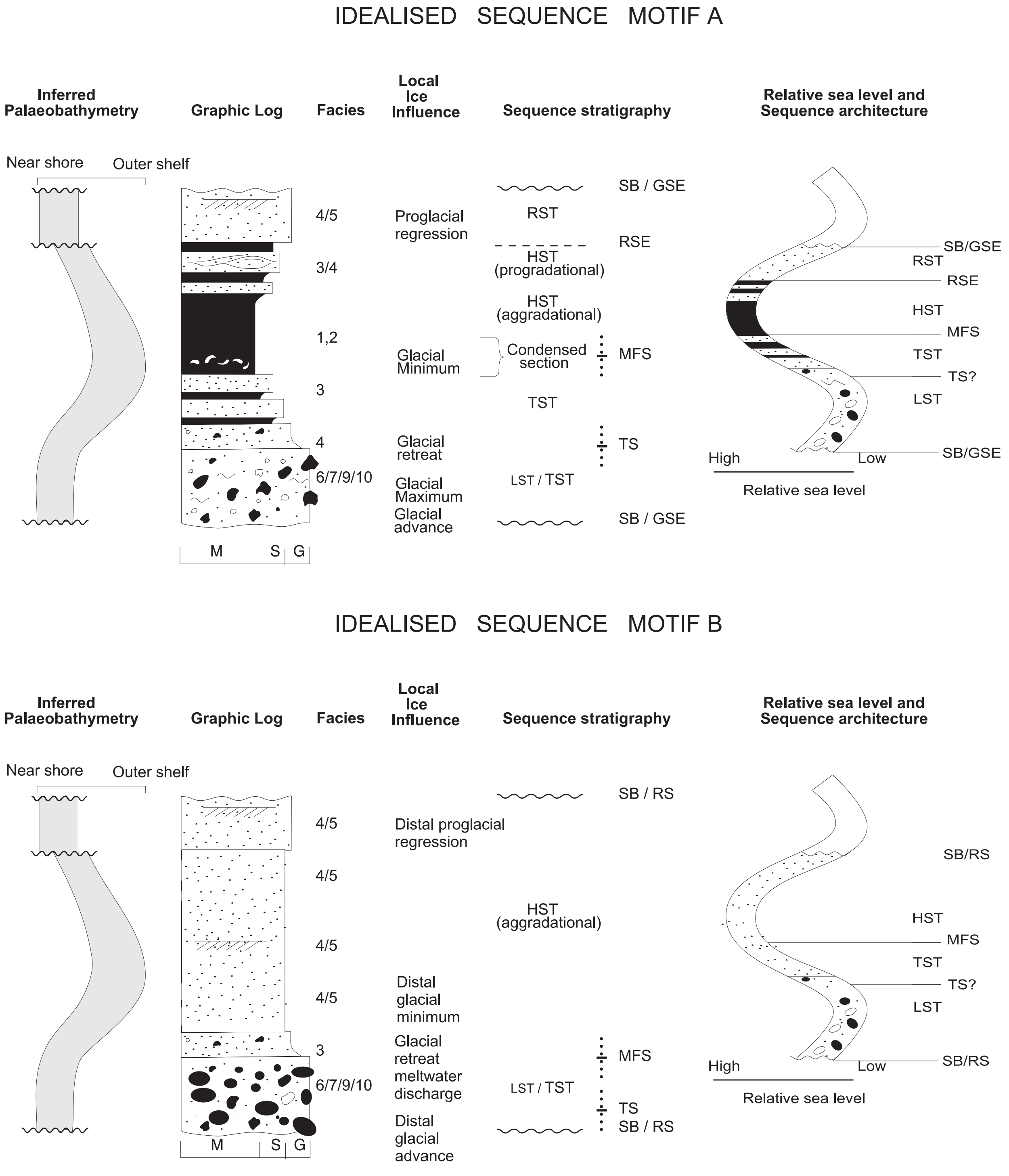


Fig. 3 - Diagram showing the character of sequences in the Cape Roberts drillholes, and their interpretation. A) fully-developed sequence Motif "A", B) less fully developed/cryptic Motif "B". SB/GSE – Sequence Boundary/Glacial Surface of Erosion, SB/RS – Sequence boundary amalgamated with transgressive Ravinement Surface, 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. Facies codes are explained in Table 1.

(Facies 6-8) and conglomerates (Facies 9/10), which rest on a recognisable surface of erosion (defined as the Sequence Boundary), 2) a typically fining-upward interval of sandstones and interlaminated facies (2-5), 3) a mudstone (Facies 1) that passes up into progressively coarser-grained sediments (Facies 2-5), and 4) an often sharp-based interval of well-stratified, clean sandstones (Facies 4, 5). Such vertical successions form a fining-upward then coarsening-upward interval, are interpreted as sequences, and interpreted to record a cycle of glacial retreat and subsequent advance (Fig. 3A). Relatively thick sequences are also more complete, preserving a broadly symmetrical cycle in terms of facies grain-size, whereas less thick sequences tend to show top-truncation, recording erosion (or non-deposition) of the upper part during the subsequent glacial advance (Fig. 3A).

Using the rationale summarised above, CRP-1 was divided into eight sequences, and the longer core of CRP-2/2A into twenty-five sequences. It was recognised that some of these sequences were relatively thick and complete in terms of the succession of facies, whereas others were thin, dominated by coarse-grained facies and generally strongly top-truncated and amalgamated. Attention has been drawn to the preservation of three relatively thick and complete sequences (Sequences 9-11) in CRP-2/2A by Fielding et al. (2000) and the palaeoclimatic and other signals preserved in those sequences is explored by Naish et al. (2001).

In CRP-3, the upper part of the hole (0-329.96 mbsf) can again be readily divided into sequences using the same criteria as previously. Between this depth and 480.27 mbsf, a succession of mostly fining-upward cycles preserving some elements of the sequence architecture were recognised, but mostly lacking diamictites at the base and finer-grained facies typical of the central part of the other sequences. In order to separate these two cyclical patterns, the uppermost part (Sequences 1-14: 0-309.96 mbsf) were defined in the Initial Report (Cape Roberts Science Team, 2000) as “Motif A” (Fig. 3A), and the interval below (Sequences 15-18: 329.96-480.27 mbsf) as “Motif B” (Fig. 3B). The section below 480.27 mbsf comprises a thick succession of monotonous sandstone intervals punctuated by fining-upward conglomerate-sandstone units, is not divisible into cycles, nor interpretable in terms of variations in relative sea-level. As noted in Cape Roberts Science Team (2000), it is possible that depositional cyclicity is preserved within these rocks, but such cyclicity is not identifiable at the macroscopic scale.

Alternatively, the erosional bases of conglomerate units could record the base of event deposits related to slope failures or some other geomorphic threshold during a time of voluminous coarse sediment supply, rather than representing lowstands of relative sea-level. We suggest that the interval referred to “Motif B” in Cape Roberts Science Team (2000) may be considered as a transitional style between the more clearly cyclical sequence pattern above and the sand and gravel-dominated, largely non-cyclical pattern below.

VERTICAL PATTERNS OF SEQUENCE DEVELOPMENT

As in CRP-2/2A (Fielding et al., 2000), variations in the thickness, relative completeness and other properties of sequences can be recognised in CRP-3. The downhole distribution of sequence thickness for both CRP-2/2A and CRP-3 is shown in figure 4. In this diagram, the underlap between the two holes is presumed to all lie within a single sequence (this is consistent with lithological patterns at the base of CRP-2/2A and the top of CRP-3), giving rise to a thick sequence 25 (= Sequence 1 of Cape Roberts Science Team, 2000). Taking this into account, the uppermost three (or two) sequences preserved in CRP-3 are unusually thick and complete in the context of sequences above and below (Fig. 4). Given the palaeoclimatic and other signals that have been recognised in a similar package of three thick sequences in CRP-2/2A (Sequences 9-11: Naish et al., 2001), it is here suggested that Sequences 25-27 of figure 4 (Sequences 1-3 of Cape Roberts Science Team, 2000) would constitute an interesting target for further research.

From Sequence 4 to Sequence 14 inclusive, there is a degree of top-truncation, but fine-grained facies occur in most sequences, allowing recognition of the sequence “Motif A” (Figs. 2, 3). All of these sequences, however, are thin and many are probably amalgamated. Sequences 15 to 23 inclusive (“Motif B”) show minor development of mudrock facies but are dominated by sandstones and gravel-grade facies, suggesting that any cyclical variation in depositional conditions was being overwhelmed by voluminous supply of coarse sediment. This trend is continued below 480.27 mbsf, where only fining-upward trends can be recognised, and these only at discrete intervals within the core.

The patterns summarised above can be interpreted in the same way as for CRP-2/2A (Fielding et al., 2000). The thick Sequences 1-3 (25-27) are interpreted to record a period of increased accommodation, during which cycles of relative sea-level change could be fully recorded by sediment accumulation. As the array of lithofacies is similar immediately above and below this package of three sequences, we infer that environmental conditions were similar, and that the change in accommodation was caused by a discrete period of accelerated subsidence (similar to our interpretation of Sequences

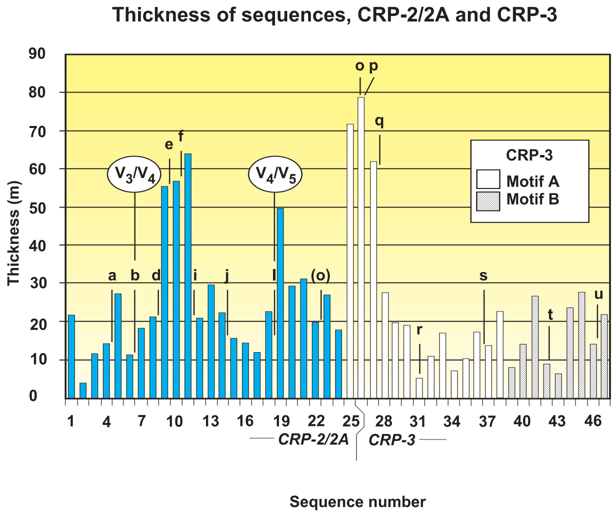


Fig. 4 - Plot of the distribution of sequence thickness in CRP-2/2A and CRP-3, showing the coincidence of sequence boundaries and other horizons with seismic reflectors (from Cape Roberts Science Team, 2000, and see Henrys et al., this volume). The uppermost sequence in CRP-3 (Sequence 25) is constructed on the assumption that the basal part of CRP-2/2A, the underlap between the two holes, and the uppermost part of CRP-3 all lie in one sequence. Note the occurrence of a package of thick (and relatively complete) sequences in the top part of CRP-3 (25-27), similar to Sequences 9-11 of CRP-2/2A. V3/V4 and V4/V5 refer to seismic sequence boundaries, and lower case letters to seismic reflectors.

9-11 in CRP-2/2A: Fielding et al., 2000).

CORRELATION WITH SEISMIC STRATIGRAPHY

As in CRP-2/2A, the significant reflectors recognisable on seismic reflection data across the drillsite (Cape Roberts Science Team, 2000) can be correlated with sequence boundaries to a considerable degree (Henrys et al., this volume). The correspondence between seismic reflectors and sequence boundaries in CRP-3 is shown on figure 4, and the cross-sectional geometry of these reflectors and intervening stratigraphic intervals is illustrated in figure 5. Reflectors "o", "p" and "q" lie within the package of thick Sequences 25-27, and define the cross-sectional geometry of those intervals as tabular, rather than the eastward-thickening wedge recognised for Sequences 9-11 in CRP-2/2A (Figs. 4, 5). With the exception of reflector "t", which lies within a sequence (17), all other significant reflectors noted in Cape Roberts Science Team (2000) correspond to the base of sequences (Fig. 4). The cross-sectional stratal geometry indicated by these reflectors is apparently tabular, and no evidence of asymmetrical subsidence distribution such as might be expected during early rift development can be recognised (at least, not from

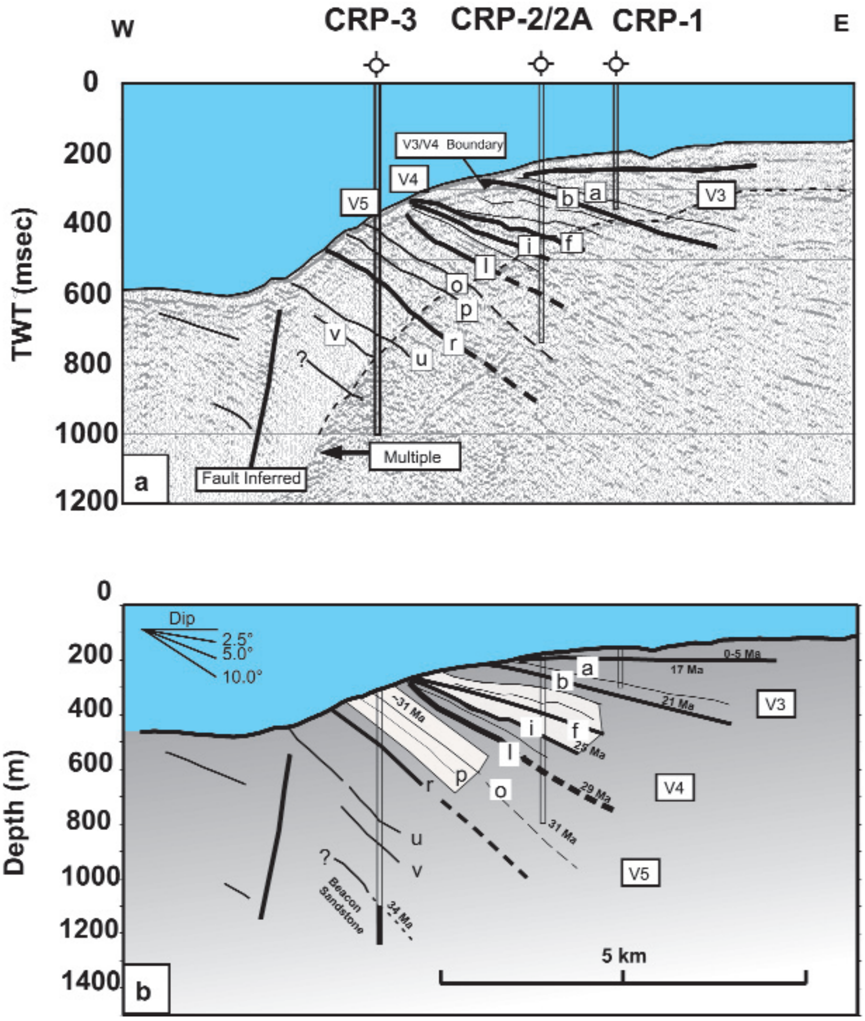


Fig. 5a - Seismic reflection line NBP9601-89 with interpretation of major reflectors, and *b.* line drawing of those interpretations to illustrate the tabular cross-sectional geometry of the section penetrated by CRP-3. The packages of thick and relatively complete Sequences 9-11 and 25-27 are highlighted in white. V3, V4 and V5 are the seismic sequences of Cooper et al. (1987).

Tab. 2 - Summary of Lithofacies Associations recognised in CRP-3 (from Cape Roberts Science Team, 2000), extent to which sequences are developed in those associations, and an interpretation in terms of controlling geological processes.

Lithofacies Association	*Depth Interval*	*Dominant Lithologies*	*Sequence Development*	*Controlling Processes*
5	378.36-0 mbsf	Muddy sandstones and mudstones (minor diamictites and conglomerates)	Sequence Motif A down to 329.96 mbsf, Sequence Motif B below	Decrease in coarse sediment supply, onset of glacial advance/retreat cycles, period of rapid subsidence from 0-157.22 mbsf)
4	580-378.36 mbsf	Clean sandstones (minor conglomerates)	Sequence Motif B down to 480.27 mbsf, no sequences recognisable below	Slowing of subsidence, marine shelf environment established and maintained by coarse sediment supply
3	789.77-580 mbsf	Muddy sandstones (minor conglomerates, mudrock-bearing interval near base)	No sequences recognisable	Marine flooding at base, relatively deep environment (probably shelfal) during initial rift subsidence, recovery with time due to increased sediment supply
2	822.88-789.77 mbsf	Conglomerates (minor sandstones)	No sequences recognisable	Accumulation of base-of-slope colluvial deposits at onset of rift subsidence
1	823.11-822.88 mbsf	Monomictic breccia/conglomerate	No sequences recognisable	Weathering of exposed Beacon basement

Line NBP9601-89).

CONCLUSIONS

As in previous Cape Roberts Project drillholes, the vertical distribution of lithofacies in CRP-3 appears to be cyclical as far down the hole as 480.27 mbsf, and is here interpreted in terms of cycles of relative sea-level change associated with climatic cycles and/or cycles of glacial advance and retreat. A package of two or three relatively thick and complete (in terms of facies succession) sequences is recognised in the uppermost part of CRP-3, and interpreted to record period of increased accommodation. Given the similarity between these Sequences (25-27) and Sequences 9-11 in CRP-2/2A, they may be expected to yield important additional palaeoecological and palaeoclimatological information in the future. Unlike in previous drillholes, however, the character of cycles changes progressively downhole from the previously recognised style (termed "Motif A") into a more cryptic and incomplete sequence style (termed "Motif B"). This in turn passes downward into predominantly coarse-grained facies that cannot be resolved into cyclical sequences.

Sequence boundaries can be correlated with prominent seismic reflectors recognised from seismic line NBP9601-89, and illustrate a dominantly tabular cross-sectional stratal geometry, with no evidence of eastward-thickening wedge geometry recognisable in part of the interval penetrated by CRP-2/2A. This tabular geometry also describes the package of thick sequences recognised in the uppermost part of CRP-3. The latter is interpreted to record a period of accelerated subsidence, given that the array of lithofacies is similar above, within and below this interval.

The distribution of lithofacies and sequence character in CRP-3 change somewhat systematically uphole from the basement contact at 823.11 mbsf, and these changes can be interpreted in terms of the early history of the rift basin (Tab. 2). Lithofacies Associations 1 and 2 of Cape Roberts Science Team (2000) are interpreted as recording initial accumulation of mainly gravel-grade sediment in base-of-slope colluvial fans, over an indeterminate period of time during the ?Late Eocene. With time, this environment was probably drowned by marine flooding, as rift subsidence began to accelerate. The flooding event is recorded in a mudrock-bearing and relatively fine-grained interval at the base of Lithofacies Association 3 (dominated overall by muddy sandstone with lesser conglomerate). This interval probably records the deepest water environment sampled by CRP-3, although even this probably still lay in shelfal depths from facies characteristics. The overlying Facies Associations 3 and 4 record a gradual change from muddy sandstone-dominated facies (density current deposits) to clean sandstone-dominated facies (dilute tractional current deposits in shoreface water depths). The initial oversupply of coarse-grained sediment gradually decreased upward, allowing the preservation of some cyclical changes in lithofacies. In the upper part of the hole, Lithofacies Association 5 records a progressive change to less voluminous sediment supply, which concomitant with palaeoclimatic changes indicated by the occurrence of diamictites and related facies, allowed the formation of fully-developed cyclical sequences. Changes in accommodation (subsidence) during this latter time controlled the extent to which the various components of sequences were preserved.

ACKNOWLEDGEMENTS - We are proud to acknowledge the superb effort of the Cape Roberts Project drillsite team in executing CRP-3, which completed a vertical traverse through the stratigraphy of the Victoria Land Basin. We also acknowledge the logistical support offered by the New Zealand and US Antarctic Programmes, without which none of this would have been possible. All scientists and support staff involved in the Cape Roberts Project are thanked for their help, advice, and vigorous scientific debate which have together made the experience such a rewarding one for us. Greg Browne (IGNS – New Zealand) and Peter Kamp (Waikato University, New Zealand) are thanked for their reviews of the submitted manuscript. KJW and CRF were supported by two out-of-cycle Large Grants from the Australian Research Council.

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