Cenozoic climate and sea level history from glacimarine strata off the Victoria Land coast, Cape Roberts Project, Antarctica

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ABSTRACT

This paper reviews the record of past climate and sea level from 34 to 17 Ma provided by continuous core through 1500 m of shallow marine strata off the Victoria Land coast of Antarctica. The site was selected because it is close to the edge of the East Antarctic Ice Sheet. Previous drilling and seismic surveys had suggested a thick seaward-dipping sequence of Oligocene and older age close to the coast. However, the floor of the basin, lower Devonian sandstone, was encountered beneath uppermost Eocene conglomerate. The strata were deposited in a rift basin just seaward of the Transantarctic Mountains c. 20 m.y. after uplift began. Sediment was delivered by rivers and glaciers both from and behind the mountains from the East Antarctic interior. Sediment accumulation was rapid and the record more complete for the period 34 to 31 m.y., but then slowed as basin subsidence declined, leaving major time gaps, but still a representative record of the entire time span. Basin filling kept pace with subsidence. The sedimentary facies – conglomerate, sandstone and mudstone with marine fossils throughout – are typical of the coastal margin of a subsiding sedimentary basin, with the addition of diamictite beds in the upper 900 m recording marine-terminating glaciers that extended periodically beyond the coast. Deposition was characterised by repetitive vertical facies successions of conglomerate and fine sandstone in the lower part of the section and by cyclic facies successions of diamictite, sandstone and mudstone from a few to over 60 m thick in the upper part. These are thought to reflect glacio-eustatic changes in sea level on a wave-dominated coast in concert with advance and retreat of piedmont ice onto the continental shelf, with diamicton and sand (nearshore) grading upwards to mud (shelf) and then to sand (inner shelf to shoreline). Tephra dating of two cycles at 23.98 and 24.22 Ma allows their correlation with 40,000 years cycles in the deep-sea isotope record, and ascribed to eustatic sea-level changes of 30–60 m. This suggests that the cyclicity of the Cape Roberts section reflects the influence of the earth's varying orbital parameters on climate and sea level, with over 50 sedimentary cycles preserved out of the possible 200–400 cycles during this time period. The Cape Roberts section also records a dramatic increase in glacial influence at around 33 Ma, with the proportion of glacial facies ranging from 10 to 30% of the sedimentary section through to 17 Ma. The section also records a progressive shift from chemical to physical weathering (decline in CIA index and increase in % illite-chlorite) from 33 to 25 Ma, and a decline in marine palynomorphs characteristic of fresh melt water mingling over the same interval. The terrestrial pollen record records interglacial climate and indicates this to be cool temperate for the entire period from 34 to 17 Ma though slightly cooler from c. 25 Ma.

Keywords Cape Roberts Project, Cenozoic, palaeoclimate, sequence stratigraphy, glacio-marine facies, Antarctic margin.

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INTRODUCTION

Until the early 1970s it was believed that the ice ages spanned just the last 2 million years of earth history – the Quaternary Period (Flint, 1971). That view changed with the drilling of the Ross Sea and Southern Ocean in 1973 by the *Glomar Challenger*, revealing both a physical record of glaciation that began at least 25 million years ago (Hayes and Frakes, 1975) and a proxy record from deep-sea sediments indicating a fall in temperature (and maybe increase in ice volume) both at the Eocene-Oligocene boundary and in the middle Miocene (Shackleton & Kennett, 1975). The Quaternary ice ages had become Cenozoic in their span – at least in the Southern Hemisphere.

In the decade that followed, analysis of seismic sequences from the world's continental margins showed repeated patterns of coastal advance and retreat on time scales of 10^5 to 10^6 years. These changes could be traced back at least to Cretaceous times, with a significant sea-level fall in mid-Oligocene (Vail *et al.*, 1977); more substance was added in a review a decade later by Haq *et al.* (1987). This new view of the way in which strata are deposited and preserved in basins on continental margins, termed sequence stratigraphy (Posamentier *et al.*, 1988), presumed that cyclic fluctuations of tens to hundreds of metres in sea level on time scales ranging from hundreds of thousands to millions of years. Some found flaws in the simple conceptual model from which the early interpretations were made (e.g. Miall, 1991). However, others have shown how the concept can provide a sound basis for interpreting sea-level changes by testing them on well-dated Quaternary strata, representing a period for which the history of eustatic sea level change is reasonably well established (e.g. Carter *et al.*, 1991). In the meantime improvements in chronology of deep-sea cores through both biostratigraphy and magnetostratigraphy have allowed the assembly of a deep-sea oxygen isotope record from many different sites that showed trends in ocean temperature and ice volume (Miller *et al.*, 1987), with an emerging view that the first continent-wide ice sheet formed on Antarctica in earliest Oligocene times (Wise *et al.*, 1991).

The deep-sea isotope community and sequence stratigraphers have both continued to gather their 'far-field' proxy data as a basis for interpreting past climate and sea-level history through Cenozoic (and older) times (e.g. Zachos *et al.*, 2001; Billups & Schrag, 2003; Miller *et al.*, 2005). At the same time a smaller community has been investigating the Antarctic margin itself for records of past climate, some through seismic surveys and offshore drilling under the auspices of the ANTOSTRAT project (Cooper *et al.*, 1991, 1995) and others through investigations on land (reviewed in Barrett, 1996), though land-based investigations have been frustrated by the poorly fossiliferous and fragmentary record of Cenozoic geological history on the Antarctic continent itself.

One location on the Antarctic margin that has proved especially instructive for Cenozoic climate history has been in the southwest corner of the Ross Sea (Fig. 1). Here a series of drilling projects between 1973 and 1999 (reviewed in Hambrey *et al.*, 2002) cored the western margin of the Victoria Land Basin, one of a north-sound-trending troughs that form part of the West Antarctic Rift System (Behrendt, 1999). The most recent of the series, the Cape Roberts Project, resulted in continuous core (95% recovery) that spans the time period from 34 to 17 Ma, and contains a fragmentary, but nevertheless valuable, coastal record of varying climate, ice conditions and sea level representing most of that period (Cape Roberts Science Team, 1998, 1999, 2000). The purpose of this paper is to summarise the results of this work.

The drilling off Cape Roberts took place from a sea-ice platform in three successive field seasons (from late 1997 to late 1999), coring a more-or-less continuous stratigraphic section of 1500 m of uppermost Eocene to lower Miocene strata (34 to 17 Ma). The initial results and scientific reports have been published in a series of special issues of Terra Antartica (http://www.mna.it/english/Publications/TAP/terranta.html#Special). The drilling itself was a significant technical achievement and is documented in Cowie (2002).

This review first outlines the regional setting in which the Cenozoic strata off Cape Roberts were deposited, and the general character and chronology of the sequence. The strata are then described in terms of a small number of characteristic facies, largely organised as facies successions and interpreted in terms of a glacial sequence stratigraphic model. A case is made for the Oligocene-lower

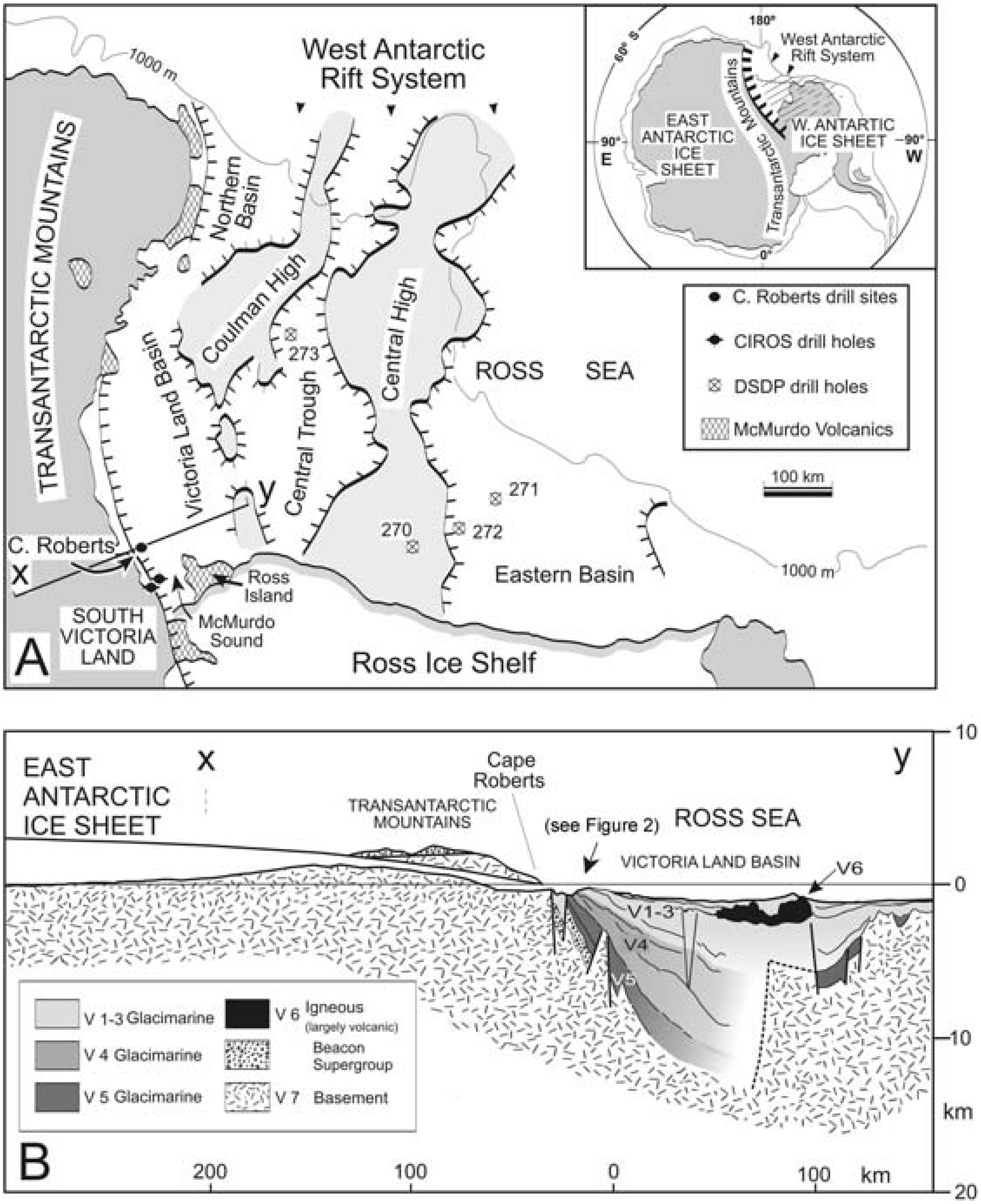

Fig. 1 Setting for Cape Roberts Project drilling on the western margin of West Antarctic Rift System (from Cape Roberts Science Team, 1998). (A) The Ross Sea region, showing the location of the Victoria Land Basin adjacent to the Transantarctic Mountains, and the location of drill sites in the area; 'x–y' shows the section line for B. (B) Cross-section from the East Antarctic interior across the Transantarctic Mountains to the Ross Sea, showing the proximity of the East Antarctic Ice Sheet to the Victoria Land Basin, and hence the potential for strata filling the basin to record climatic and tectonic events from this part of the Antarctic margin. The cross-section has been modified to reflect new knowledge from the Cape Roberts Project, notably the Beacon sandstone flooring the basin, and a new interpretation of the basin fill from Fielding *et al*. (2006) and Wilson *et al*. (unpub. data).

Miocene sequence being deposited in a nearshore marine environment on an open coast with sedimentation strongly influenced by both waves and glaciers discharging into the sea. The cycles record both glacial maxima when ice flowed from the inland ice sheet that lies to the west through the mountains to the coast, at times grounding in the shallow water in the vicinity of the drill site, and periods of glacial retreat, and higher sea level when rivers carried sediment to the coast to be distributed alongshore by waves and currents. Changes in the proportion of glacial facies and in indicators of physical/chemical weathering and temperature, all of which imply a cooling trend, are shown in terms of discrete time periods through the Cape Roberts section, and the implications discussed.

REGIONAL SETTING

Cape Roberts lies on the Transantarctic Mountain Front, a 30-km-wide zone between the rising Transantarctic Mountains to the west and the Victoria Land Basin to the east, and representing the western margin of the West Antarctic Rift System (Fig. 1). The Transantarctic Mountain Front extends for around 1000 km to Cape Adare in the north and over 3000 km to the south, the topographic relief across it typically being around 4000 m. Today the mountains form a significant barrier to the flow of ice through outlet glaciers to the Ross Ice Shelf and Ross Sea.

The firmest indication of the initial growth of the Transantarctic Mountains comes from fission-track data that point to the first significant denudation of the McMurdo sector of the Transantarctic Mountains around 55 Ma, though other sectors of the Transantarctic Mountains record denudation events in the late Cretaceous Period also (Fitzgerald, 1992). The first direct physical evidence of the Transantarctic Mountains as a significant feature comes from the oldest strata cored in the CIROS-1 drill-hole, drilled in 1986 70 km south of Cape Roberts. These include granitic clasts eroded from exposed basement to the west, implying that the Transantarctic Mountains were at least half of their present height, for erosion had even then cut through the more than 2000 m of Devonian-Jurassic Gondwana cover beds to basement (Barrett, 1989).

The Transantarctic Mountains are thought to have risen highest in late Cenozoic time because of the extreme relief they now show between summit and valley floor levels, around 50% more than mountains in temperate regions (Stern *et al.*, 2005). They attributed this increase in relief to middle Miocene cooling that froze mountain tops while outlet glaciers continued to excavate. This same continent-wide cooling would have also reduced sediment supply to the Antarctic continental shelf. Expansions of the Antarctic Ice Sheet have eroded to the shelf edge since its inception in the earliest Oligocene (Hambrey *et al.*, 1992, Anderson, 1999), but the present deep shelf (on average around 500 m) may have resulted from the reduced sediment supply from a largely frozen continent since middle Miocene times.

Today's extreme topography of the Transantarctic Mountains provides a striking contrast to the subdued submarine relief across the Ross Sea, as shown in the recent bathymetric compilation by Davey (2004). Provenance studies from cores taken from the north-south-trending Victoria Land Basin show the basin-fill to have been derived from the adjacent mountains themselves (George, 1989; Sandroni & Talarico, 2001). Eastward-dipping basin geometry and late Cenozoic erosion along the Transantarctic Mountain Front have exposed the oldest strata in the basin in several seismic sections perpendicular to the Transantarctic Mountain Front (Cooper *et al.*, 1995), most notably off Granite Harbour (Barrett *et al.*, 1995; Bartek *et al.*, 1996), the site of the Cape Roberts Project drill sites. Environmental and technical constraints required the selection of three sites in order to core the entire sequence (Figs. 2, 3).

Although the Transantarctic Mountains have been a persistent feature of the region since early Cenozoic time, coastal bathymetry today, with variations in nearshore water-depth from less than 100 m to more than 1000 m, is far more extreme than offshore bathymetric variations during the deposition of the Oligocene–Lower Miocene strata cored off Cape Roberts. The sea-floor relief through that period can be gauged from coast-parallel seismic lines (e.g. NBP9601–93), which passed close to CRP-2/2A (Fig. 4). Resolution is low (~20 m), but the records show persistent stratification parallel to the coast over distances of many kilometres. This contrasts with the channelling many tens of

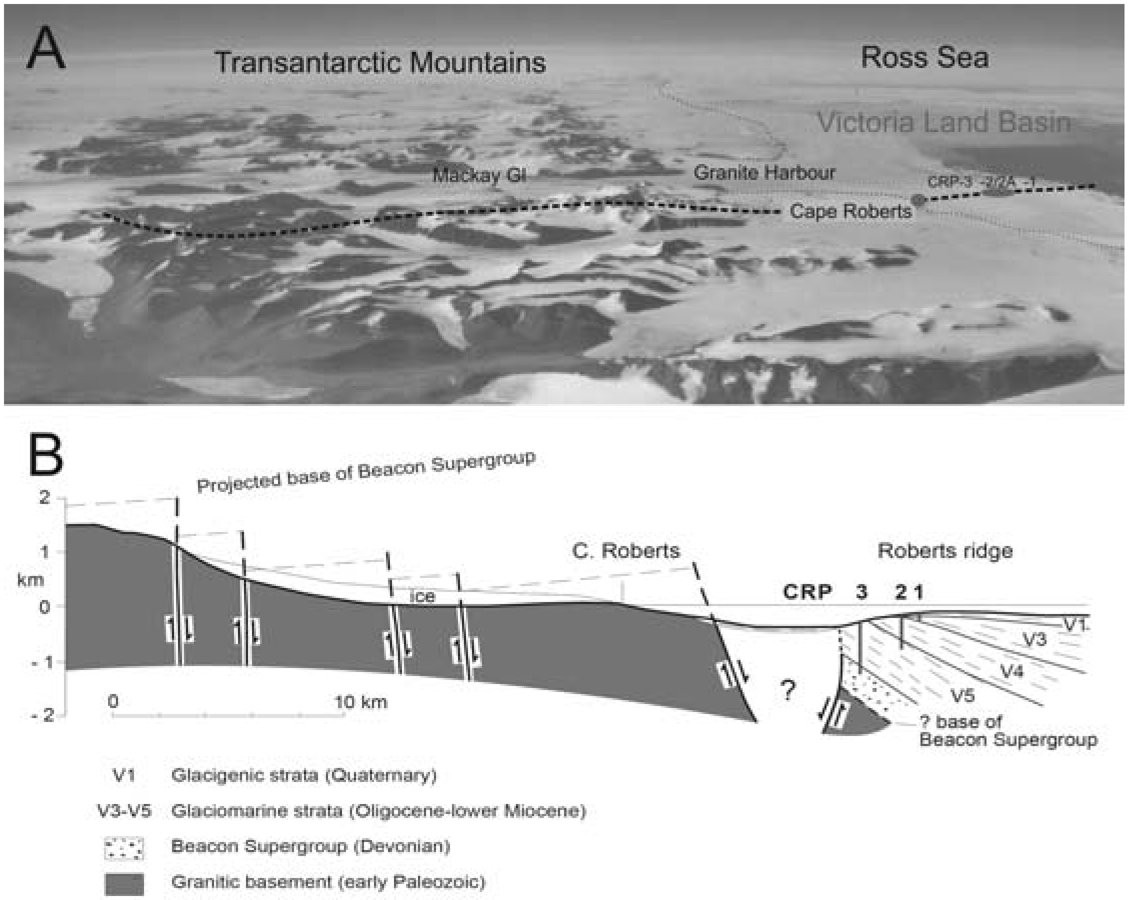

Fig. 2 View north along the Transantarctic Mountains and geological cross-section. (A) Areal photograph (from US Navy photo TMA 2202 F33 141) showing the well-defined topographic boundary between the Transantarctic Mountains and the Ross Sea, as well as the location of the Cape Roberts drill holes and the cross-section below. (B) Geological cross-section (from Cape Roberts Science Team, 2000), showing the geological structure across the Transantarctic Mountain Front (basement faults after Fitzgerald, 1992), and the location and context of the Cape Roberts drill holes near the edge of the Victoria Land Basin.

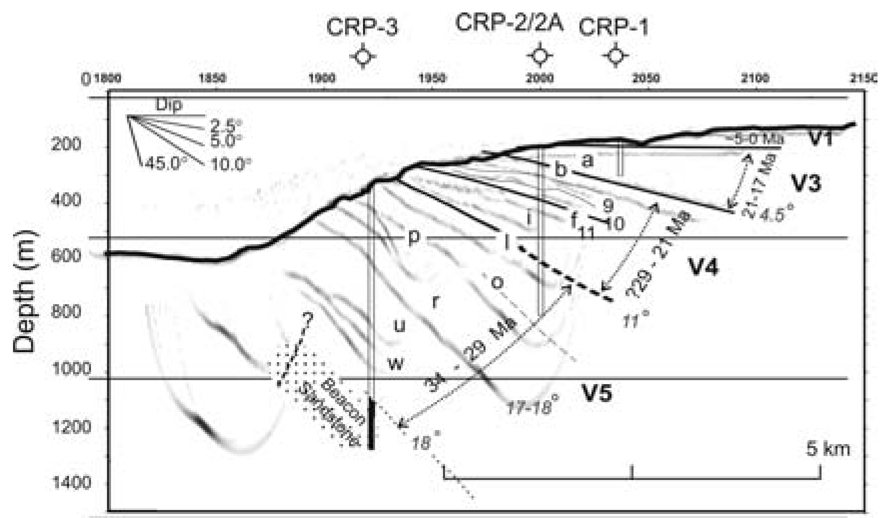

Fig. 3 Seismic stratigraphy of the sequence cored off Cape Roberts (from Henrys *et al.*, 2001), showing drill site locations and chronology.

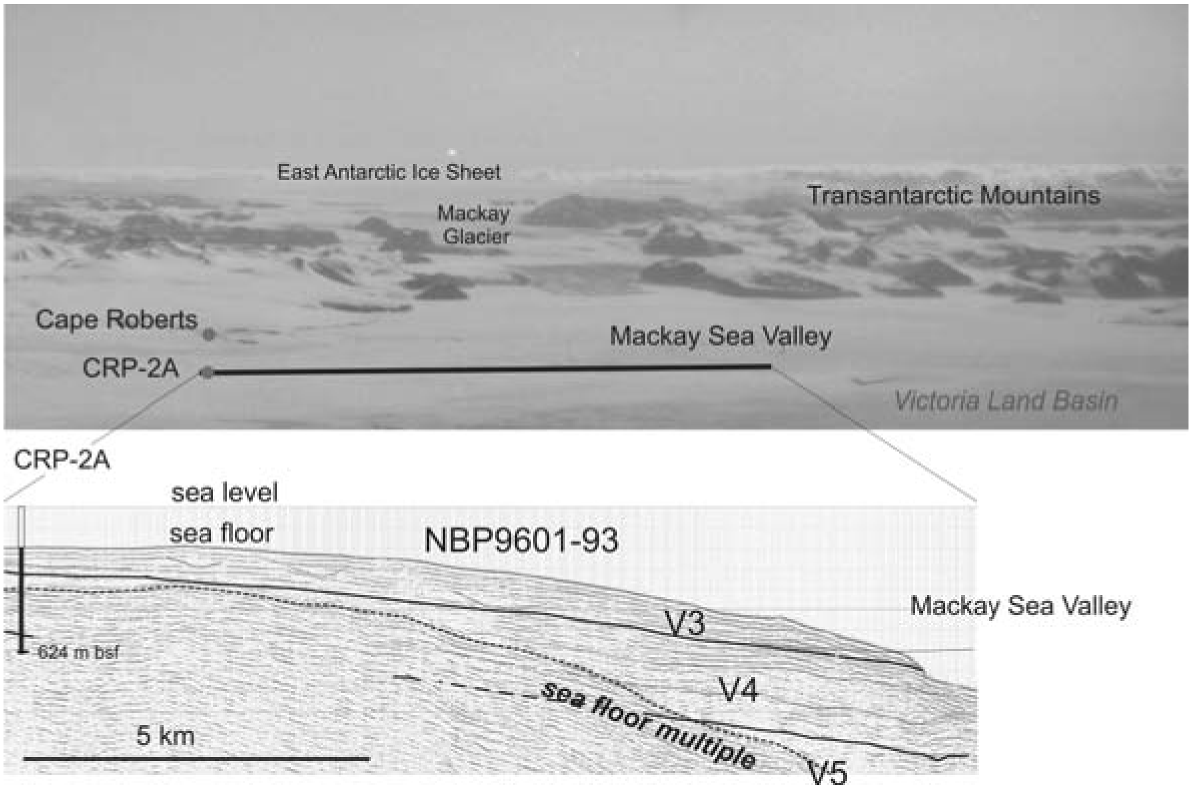

Fig. 4 View of the Transantarctic Mountains from the Ross Sea (US Navy Photo TMA 1558 F33 69). The seismic section beneath (Henrys *et al.*, 2000), which is roughly perpendicular to the regional dip of the strata, shows the parallel stratification and lateral continuity of Oligocene – lower Miocene section cored by CRP2A. This contrasts with the broad channelling many tens of metres deep and hundreds of m across in younger (?late Miocene or Pliocene) strata, and the present day Mackay Sea Valley which is around 800 m deep and 10 km across.

metres deep and hundreds of m across in younger (?late Miocene or Pliocene) strata, and the extreme Quaternary channelling of the Mackay Glacier to form the Mackay Sea Valley.

In summary, the simple seaward-dipping geometry and the coast-parallel persistence of stratification suggested even before drilling that the Cape Roberts section was likely to be a useful recorder of ice, sea level and climate for much of middle Cenozoic time.

BACKGROUND TO CORE DESCRIPTION AND ANALYSIS

With the awareness that the project would most likely be coring a complex mix of glacial and non-glacial strata that might range from terrestrial to shelf facies, a workshop was convened prior to the drilling to compile a core-logging manual for consistent visual core description (Hambrey *et al.*, 1997), and agreement on the tasks for core-log presentation and analysis. The sedimentological results of the project appear in three main forms

1 The Initial Reports, with a project authorship and completed immediately after the drilling. These included detailed (4 m to a page) core logs, and were intended to be primarily descriptive.
2 The Scientific Reports, with summary descriptions, laboratory analyses and more considered interpretations, with individual authorship, completed within a year of the drilling.
3 Subsequent papers in the open literature.

Glacimarine sediments are inherently varied in texture, composition and sedimentary structures, and while a continuous drill core confers significant advantage in providing a continuous stratigraphic record, it gives no indication of the lateral significance of particular lithologies. Seismic records provide some help in a gross way but only on a scale of tens of metres, being limited by their resolution. As a consequence there were vigorous on-site discussions on criteria for the various facies, and the meaning and significance of many features seen in the core, different people having seen the same feature in different geological contexts. These issues were resolved mostly through discussion, and an agreement to acknowledge differences in interpretation. This took time and a consistent and broadly accepted facies scheme was not established until the Initial Report on CRP-2/2A was produced (Cape Roberts Science Team, 2000). This scheme was tested, and accepted with minor modification for CRP-3 (Cape Roberts Science Team, 2001). It was subsequently used in several papers in the Scientific Reports for CRP-2/2A and CRP-3, as well as papers in the open literature (Powell & Cooper, 2002; Hambrey *et al.*, 2002).

A feature of the project has been the development of a sequence stratigraphic model for explaining the cycles or facies successions that were evident through most of the cored section. Sequence stratigraphy is fundamentally based on changing relative sea level, and requires a degree of wave energy to erode, remove and deposit sand nearshore and mud offshore as rising and falling sea level drives marine transgressions and regressions. Those leading the facies analysis tended to emphasise the glacial aspects of the sediments, whereas those leading the sequence stratigraphy emphasised the role of sea level. These differences are evident in the early reports, but have now been resolved (this paper; Dunbar *et al*., in press).

The basis of all analyses of the Cape Roberts cores has been the visual core descriptions, compiled at the Cape Roberts camp from the split core face by a team of four sedimentologists led by Ken Woolfe, who also drafted the 4 m-page logs for core from all three sites. These logs were checked, corrected and studied further by a separate team of about six sedimentologists at Crary Lab, McMurdo Station, led for CRP-1 by Mike Hambrey (Cape Roberts Science Team, 1998), CRP-2/2A by Chris Fielding (Cape Roberts Science Team, 1999) and CRP-3 by Malcolm Laird (Cape Roberts Science Team, 2000).

The Initial Report for each site included a summary description of the core in terms of lithostratigraphical units (LSUs), subunits and facies within subunits. These were determined normally within 48 hours of the core arriving at the camp. The LSUs were a necessary convenience for timely core description, and were useful for summary descriptions for the Initial Reports. However, as drilling proceeded, an appreciation of the whole core grew, a separate sequence stratigraphic terminology was developed that recognised the cyclic nature of the section, with sequence boundaries that did not necessarily correspond with lithostratigraphical units. For those working on cyclostratigraphical aspects of the core, sequence boundaries and the sequence numbering scheme of Fielding *et al.* (2001) became a more convenient reference frame.

The 4 m-per-page logs provide an excellent record, along with the core images available on CD, of the gross lithology, of sedimentary structures and of clasts that feature prominently throughout the sequence. The estimates of mud content, however, can be significantly in error in sediments with a coarse 'tail' – 12 out of 118 samples from CRP-2/2A were described as sandstone but found to have sand contents ranging from only 11 to 39% (Barrett & Anderson, 2000). Where trends in mud content are important for environmental interpretation, then visual core descriptions need to be checked against analytical results.

THE CAPE ROBERTS SECTION

Cape Roberts section is described in terms of 5 sedimentary units, from oldest to youngest:

1 quartz sandstone, 116 m thick, and bearing a very strong similarity to Devonian sandstone cropping out in the adjacent Transantarctic Mountains;
2 conglomerate (uppermost Eocene), 33 m thick;
3 sandstone and minor conglomerate (uppermost Eocene-lower Oligocene), 460 m thick;
4 diamictite, sandstone, mudstone cycles (lower Oligocene-lower Miocene), 1010 m thick;
5 diamicton and minor muddy sand (Pliocene, Quaternary), up to 44 m thick.

A lithologic log is shown as Figure 5, and the facies for each unit or facies association are reviewed below, but first the chronology of the Cenozoic section is reviewed.

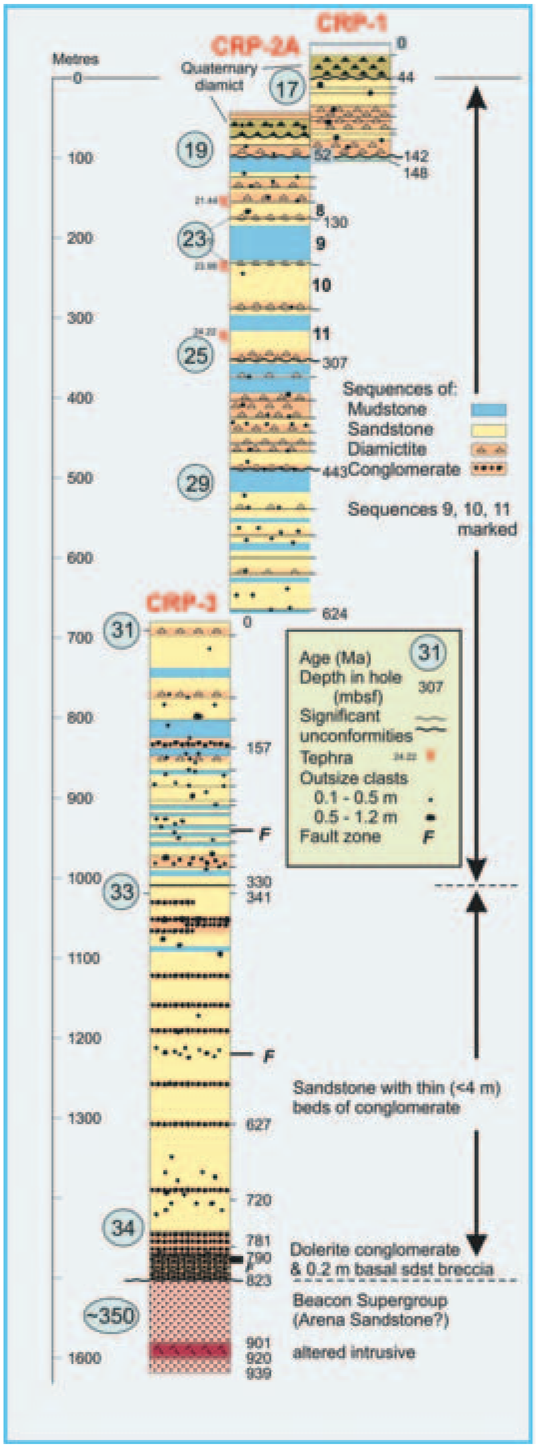

Fig. 5 Lithologic log summarising the section cored by the Cape Roberts Project (adapted from Barrett, 2001). The chronology has been adjusted to conform to the Gradstein *et al.* (2004) timescale (see Naish *et al.*, in press).

Chronology of the CRP Cenozoic section

The Cenozoic section has been dated from biostratigraphical and chronostratigraphical datums in conjunction with a high resolution magnetostratigraphy. The age models developed during and after drilling (Cape Roberts Science Team, 1998, 1999, 2000; Roberts *et al.*, 1998; Lavelle, 1998; Wilson *et al.*, 2000; Hannah *et al.*, 2001) have now been refined, and summarised by Florindo *et al.* (2005). A revised chronology, outlined below, has provided the basis for Table 1 and the ages of ten major lithological divisions (including the basal conglomerate) from 34 to 17 Ma in the Cenozoic pre-Pliocene section.

In particular, an adjustment has been made to the chronology of CRP sequences across the Oligocene–Miocene boundary to conform with recent astrochronological recalibration of this interval (summarised in Gradstein, 2004). The new 'floating' astronomical calibration relies on a statistical match (coherency) between the climate proxy records from ODP Site 1090 and the orbital target curve with a time-step of 2.4 Ma. This precludes an age for the Oligocene–Miocene Boundary of 24.0 Ma as proposed by Wilson *et al.* (2002), and is also inconsistent with the geomagnetic polarity timescale (GPTS) of Cande & Kent (1995) and Berggren *et al.* (1995).

In the new astrochronology the Ar-Ar tephra ages for normal-polarity sequences 10 and 11 (23.98 and 24.22 Ma) place them in short normal polarity chrons (C7n1n and C7n2n respectively). Consequently, these sequences can be uniquely matched to individual 40-kyr cycles on the composite oxygen isotope stratigraphy of ODP sites 929/1090 (Naish *et al.*, in press) – c. 600-kyrs earlier than the 40-kyr cycle correlation presented by Naish *et al.* (2001a). Sequence 9, whose age is constrained only by the 21.44 Ma ash in Sequence 8 above, could like in either C6n3n or C6n2n. Thus the Oligocene-Miocene boundary at 23.02 Ma could correspond to the unconformities below, or above Sequence 9. Here, it is placed at the base of Sequence 8, representing a period of extensive erosion in the western Ross Sea associated with ice sheet expansion equivalent to global sea-level lowering of ~50 m during the earliest Miocene Mi-1 event (Pekar & DeConto, 2006).

Table 1 Main chronological subdivisions and thicknesses of the strata cored in the CRP drillholes (modified from Florindo *et al.*, 2005, following Gradstein *et al.*, 2004). Depths to lithological divisions expressed as mbsf (metres below sea floor) and cmd (cumulative metres drilled through Cenozoic strata below the Miocene-Quaternary boundary in CRP-1 and CRP2/2A). Ages are approximate. See text for explanation

A G E		CRP-1		CRP-2/2A		CRP-3		Lithological subdivisions	
		m bsf	*cmd*	m bsf	*cmd*	m bsf	*cmd*	*Thickness*	*Lithologies*
	Quaternary	0.00		5.54					
	0–2 Ma	−43.55		−21.16				44 m	Diamicton
C	Pliocene			21.16					Muddy sand/
	~2–3 Ma			−26.79					Sandy mud
E									
	Early Mio	43.55	*0.00*	26.79					
N	17–19 Ma	−141.60	*−98.05*	−52.63				98 m	
	Early Mio	141.60	*98.05*	52.63	*98.05*				
O	19–23 Ma	−147.69*	*−104.14**	−130.27	*−175.69*			78 m	
	Late Olig			130.27	*175.69*				*Cycles of*
Z	23–25 Ma			−306.65	*−352.07*			176 m	Diamictite,
				306.65	*352.07*				Sandstone and
O	25–29 Ma			−442.99	*478.41*			135 m	Mudstone
				442.99	*478.41*				
I	29–31 Ma			−624.15*	*−669.57**			181 m	
C	Early Olig					2.80	*682.37+*		
	31–33 Ma					−329.96	*−1009.53*	340 m+	
	Early Olig					329.96	*1009.53*		
	33–34 Ma					−789.77	*−1469.34*		Sandstone,
								460 m	minor congl
	Latest Eocene					789.77	*1469.34*		
	34 Ma					−823.10	*1502.67*	33 m	Conglomerate
DEVONIAN						823.10			Qtz sandstone
~350 Ma						−939.42*			
to convert m bsf to cmd		For CRP-1 subtract 43.55 m *bottom of hole		For CRP-2A add 45.42 m *bottom of hole		For CRP-3 add 679.57 m *bottom of hole		+ includes 10 m interval between base of CRP-2A and top of CRP-3	

The Eocene–Oligocene boundary is of particular interest because it was about that time that the deep-sea isotope shift marks the development of the first large Antarctic ice sheet (Zachos *et al.*, 1992). The boundary is most likely to lie in or just above a 33-m-thick conglomerate at the base of the Cape Roberts Cenozoic section. The conglomerate is unfossiliferous and unsuitable for magnetostratigraphy, but the overlying 400 m of sandstone and minor conglomerate include fine beds that show a well-defined polarity zonation (Florindo *et al.*, 2001). These show a largely reversed interval in the upper part that can be identified as C12r on the GPTS (now 31.1 to 33.3 Ma in Gradstein *et al.*, 2004) with the aid of several biostratigraphic datums and Sr isotope ages around 31 Ma in the upper

200 m of CRP-3 (Hannah *et al.*, 2001). Below this lies a normal interval from 340.8 to 627.3 mbsf identified as C13n (now 33.27 to 33.74 Ma in Gradstein *et al.*, 2004), and a further reversed interval below with two thin intervals of normal polarity, regarded as possible cryptochrons (Florindo *et al.*, 2001). The sedimentation rate for that 0.47 Ma interval is 606 m/m.y., which projects the Eocene–Oligocene boundary (33.9 Ma) to be just under 100 m deeper ~725 mbsf. The lower part of the section is significantly more gravelly, implying a higher sedimentation rate, and the boundary may well be deeper still. However for this review it is placed at the base of the sandstone interval in Table 1 and the age rounded to 34 Ma. It is worth noting that although a number of marine palynomorphs were found in samples from the lowest part of this interval (781 and 789 mbsf) they do not contain any elements of the warm late Eocene Transantarctic Flora (Hannah *et al.*, 2001), indicating that the latest Eocene cooling took place before sedimentation began in the Cape Roberts section.

The first well-dated interval above the CRP-3 core begins at an unconformity in CRP-2A at 306.27 mbsf with the appearance of volcanic debris from the McMurdo Volcanic Group. Sanidine was dated from a clast 13 m above the unconformity at 24.98 Ma, and further clasts, as well as tephras (Fig. 5), have been dated from higher in the core (McIntosh, 2000). As noted above, tephras within cycles 11, 10 and 8 have provided chronological pinning points for the magnetostratigraphy in recognizing Milankovitch cyclicity in this interval of CRP-2A (Naish *et al.*, 2001a; Naish *et al.*, in press).

The CRP-2A section below 306.27 mbsf is magnetostratigraphically complex and has no reliable biostratigraphic datums. It represents a long time span (~6 m.y.), but has a significant lithological break at 442.99 mbsf, separating a finer diamictite-poor interval from a diamictite-rich interval above. This boundary also corresponds with seismic reflector 'l' of Henrys *et al.* (2001), shown in Figure 3. The upper part of the lower interval includes a number of miliolid shell fragments in place that have yielded Sr ages in the range 29 to 31 Ma. The interval has therefore been split into a lower 31–29 Ma unit and an upper 29–25 Ma unit, though it is likely that there is significant time missing at the unconformities at 442.99 and 306.27 mbsf.

The youngest well-dated tephra in the section, the interval from 109 to 114 mbsf in CRP-2A, provides an age of 21.44 Ma. For the ~160 m of lower Miocene strata above this the chronology depends on diatom datums, Sr isotope ages and volcanic clast ages with lower precision. However, this is still sufficient to establish an age of around 17 Ma for the youngest few tens of metres of the Cape Roberts section.

The Oligocene–lower Miocene strata are overlain by a thin cover of soft largely Quaternary diamicton and muddy sand that is 44 m thick in CRP-1 and 27 m thick in CRP-2/2A. The CRP-1 sediments were considered entirely late Quaternary on microfossil evidence (Cape Roberts Science Team, 1998). Subsequently a shell bed from 32 to 34 mbsf has been the subject of detailed study, and is well-dated from magnetostratigraphy, diatom datums and Sr isotopic ratios at 1.1 Ma (Scherer *et al.*, 2006). The 21 m of Late Quaternary diamicton in CRP-2/2A is underlain by 6 m of a sandier diamicton with Pliocene foraminifera that were considered contemporaneous (Webb & Strong, 2000). The post-Oligocene cover at CRP-3 is less than 3 m thick, and none was recovered.

Quartz sandstone (Devonian)

The oldest Cape Roberts core is over 100 m of light reddish brown quartz-cemented quartz sandstone cored form beneath the Cenozoic section in CRP-3. The strata just below and above the contact are shown in Figure 6. The lithology below the contact closely resembles Devonian Taylor Group sandstone 50 km inland and around 3000 m higher in the adjacent Transantarctic Mountains (Turnbull *et al.*, 1994). The sandstone is well sorted, lacking both pebbles and mud, and with grain size varying from medium to very coarse. The bedding in some places is massive and in others well stratified, with small- and medium-scale cross-lamination superimposed on the regional 15° dip. The laminae are typically defined by a single grain-size and in places form low angle ripple structures. Some intervals show colour mottling that might have resulted from soft-sediment deformation or bioturbation. This assemblage of features has been interpreted to

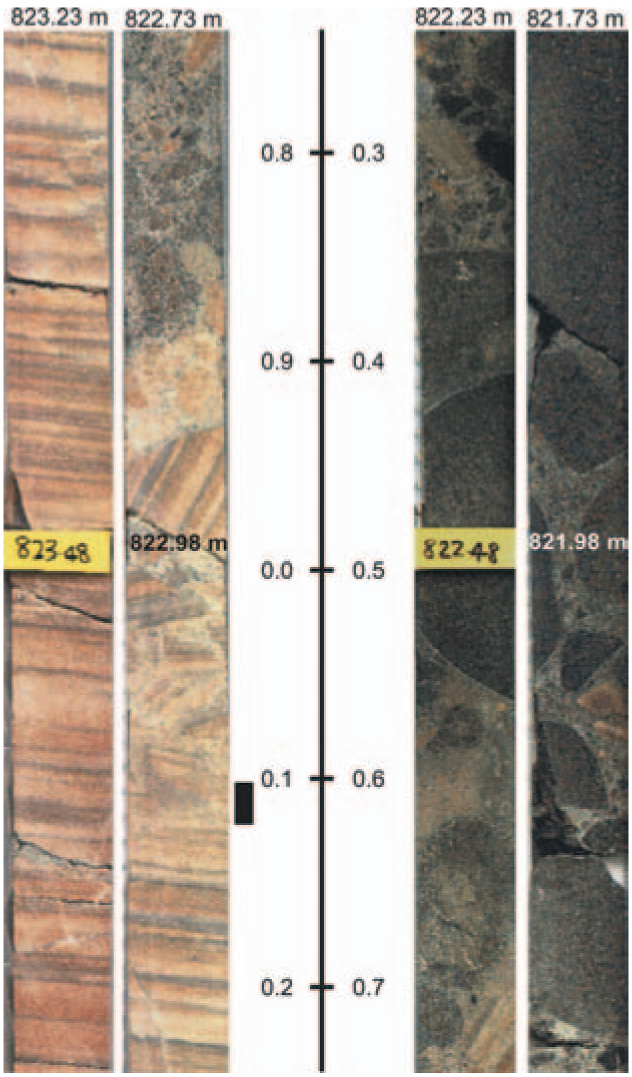

Fig. 6 The floor of the Victoria Land Basin cored in CRP-3, showing the finely laminated reddish brown quartz sandstone of the lower Taylor Group (Beacon Supergroup) overlain at 823.10 mbsf by angular sandstone talus for around 20 cm and then pebble to boulder conglomerate of Ferrar Dolerite. (Modified from Cape Roberts Science Team, 2000.)

represent a sub-humid to semi-arid continental setting with both fluvial and aeolian activity (Cape Roberts Science Team, 2000, p. 73). The interval also includes a 20-m-thick highly altered basic igneous intrusion. This, along with the quartzose nature of the sandstone, led to the correlation of these beds with the lower part of the Beacon Supergroup (Taylor Group) of early Devonian age.

Note on Cenozoic facies treatment

The characteristics of each facies in the Cape Roberts section are outlined in Appendix 1 (page 286) and summarised in Table 2, with the proportions of each facies from each time period shown in Table 3. The summary is based largely on Cape Roberts Science Team (1998, 1999, 2000), Powell *et al.* (2000, Table 1), and Fielding *et al.* (2000), with textural data from De Santis & Barrett (1998), Barrett & Anderson (2000, Table 2) and Barrett (2001, Table 2). The scheme is based on that of Powell *et al.* (2000) and Fielding *et al.* (2000) for describing and interpreting the CRP-2/2A core, and adopted from a simplified form used by Hambrey *et al.* (2002) for reviewing the late Oligocene and early Miocene glacimarine sedimentation from Ross Sea cores.

Conglomerate (uppermost Eocene)

CRP-3 823–790 mbsf (summarised from Cape Roberts Science Team, 2000)

The oldest bed in the Cenozoic sequence is a 17-cm-thick clast-supported breccia of quartz sandstone like the bedrock beneath (Fig. 6), overlain by 6 cm of matrix-supported conglomerate of the same quartz sandstone, in turn overlain by around 12 m of coarse conglomerate with cobbles and boulders up to 1.9 m long. The clasts are mostly dark Ferrar dolerite, a resistant lithology derived from sills within the Beacon Supergroup. The remainder of the unit comprises pebbly sandstone beds and coarse sedimentary breccia of dolerite clasts, which is also part of a 10-m-thick shear zone that runs through the upper part of this interval.

The basal sandstone breccia is interpreted as talus on sloping Taylor Group sandstone, with the overlying dolerite conglomerate brought in by high gradient streams. The overlying pebbly sandstone and breccia is seen as a mix of fluvial and talus debris. A granitoid clast 8 m above the base indicates that denudation of the Transantarctic Mountains had reached basement by the time this part of the Victoria Land Basin had began to subside. This interval included a mix of clast-supported and matrix-supported conglomerate, but no evidence of glacial influence in the form of facets or striae was found.

Table 2 A summary of the main CRP lithofacies, based on Powell *et al.* (2000, 2001), with a brief interpretation. Appendix 1 provides more detail

Lithofacies	Depositional process
1. Mudstone; minor lonestones	Hemipelagic suspension settling, with iceberg rafting
2. Interstratified sandstone and mudstone	Hemipelagic settling with sediment gravity-flows or wave/current action
3. Poorly sorted (muddy) very fine to coarse sandstone	Sediment gravity-flows or offshore-transition mixing
4/5. Moderately to well sorted, fine to coarse sandstone	Nearshore wave-grading and/or current sorting
6. Stratified diamictite	Subglacial or debris-flow deposition, or heavy rain-out from floating ice
7. Massive diamictite	Subglacial melting of basal debris layer
8. Sandstone-siltstone rhythmite	Suspension settling from turbid plumes
9. Clast-supported conglomerate	Fluvial or shallow marine deposition; discharge from subglacial streams?
10. Matrix-supported conglomerate	Sediment gravity-flows
11. Mudstone breccia	Mass-flow redeposition or subglacial shearing
12. Non-welded lapillistone	Airfall of volcanic ash through water; reworking by currents and gravity flows

Sandstone and subordinate conglomerate (uppermost Eocene-lower Oligocene)

CRP-3 790–330 mbsf (summarised from Cape Roberts Science Team, 2000)

This interval comprises around 460 m of fine- to medium-grain sandstone, with subordinate thin conglomerate beds, some clast-supported and others matrix-supported, and mostly in the lower 200 m. The sandstones range from vaguely stratified to well stratified, mostly parallel-, but with some small and medium scale cross-stratification, and some suggestion of hummocky cross-stratification with rare thin intervals of soft-sediment deformation. No biogenic structures were noted. Units are typically thick-bedded, and commonly show a fining upward trend from a thin conglomerate at the base. This is more evident above 480 mbsf, where Fielding *et al.* (2001) suggested that the beds show a simple cyclicity that might lend itself to sequence stratigraphic analysis.

Biogenic indicators are extremely rare, but clearly indicate a marine depositional environment, with a modiolid mussel at 781 mbsf and a gastropod mould at 359 mbsf, and marine palynomorphs occur in five samples between 789 and 440 mbsf.

The sandstones in the lower 200 m were initially described as 'muddy', giving way up section to clean well-sorted sandstones above 580 mbsf. The 'mud' has been subsequently identified as diagenetic smectite (Wise *et al.*, 2001). The post-depositional nature of the 'mud' has also been inferred from the texture of the matrix in these samples, which have virtually no silt but 'clay' forming between 10 and 21% of the sample (Barrett, 2001). These sediments were originally designated as facies 3, but as the 'mud' is post-depositional then they should be included in facies 5, as has been done in Table 2.

The conglomerate clasts are pebble to cobble-sized, and mostly a mix of pre-Devonian granitoids and Jurassic Ferrar Dolerite, sills of which intrude the Beacon Supergroup. In addition to the conglomerate beds the interval also includes a number of isolated out-sized clasts (more than 0.1 m long and more than 100 times larger than the enclosing grain size). Seven of these were striated, the lowest only a few metres above the basal conglomerate. Striated clasts were also found in the conglomerate beds (Atkins, 2001).

This interval was interpreted by most as representing inner shelf sedimentation above fair-weather wave-base with ice berg influence but no direct evidence of an ice margin close to the site (Cape Roberts Science Team, 2000). A minority view considered the interval to have been dominated by deposition from high-density sediment gravity flows in a deep water base-of-slope setting. However, in view of the stratal geometry and the shallow water character of the overlying strata this seems now most unlikely.

Diamictite, sandstone, mudstone (Oligocene-lower Miocene)

CRP-3 above 330 mbsf, CRP-2A up to 27 mbsf, CRP-1 up to 44 mbsf

This interval includes a range of shallow marine facies with a strong glacial influence and exhibiting a well-developed cyclicity. The evidence for the glacial influence comes from several indicators, including the diamictic texture of a significant proportion of this interval, based on both visual core description and textural analysis, common out-sized clasts, and the faceting (between 10 and 50%) and striae (around 5%) on clasts in all facies (Atkins, 2001). No trend through time was seen in clast surface features. Atkins (2001) noted that clasts averaged subrounded for the older CRP-3 samples, and subrounded to subangular for the younger CRP-2/2A samples, but this simply reflects most older samples coming from conglomerates and younger samples from diamictites. Micromorphological studies of 26 thin sections from diamictites in the upper part of CRP-2A revealed that three showed clear evidence of grounding, with about half the remainder providing some indication of subglacial shearing (van der Meer, 2000).

The interval is just over 1000 m thick, cored with 98% recovery, and has been the object of both detailed and comprehensive sedimentological description and interpretation both in the Initial Reports and subsequent papers by Fielding *et al.* (1998, 2000, 2001), Naish *et al.* (2001a, b) and Powell *et al.* (1998, 2000, 2001). Most of the focus in these papers has been on the cyclic character of this interval, described briefly below, but considered in a following section on sequence stratigraphy. Facies descriptions and proportions may be found in Appendix 1 and Tables 2 and 3. The comment that follows is a summary and interpretive overview.

The lowest part of this interval begins with the first record of grounded ice off shore, massive diamictite with striated clasts at 330 mbsf in CRP-3. Around 10% of the whole interval is diamictite and a similar proportion of the same interval comprises conglomerate transported offshore most likely by a mix of high fluvial discharge and redeposition by waves or sediment gravity-flows beyond. However the most common facies is mudstone (37%). When combined with facies 2, which includes hemipelagic mud as background sedimentation, they record almost half of the section being deposited close to or below wave base. However, a full 20% of the section is facies 5, moderately- to well-sorted sand, very likely wave- or current-sorted in this coastal setting, suggesting that the drill sites site lay at or close to sea level periodically throughout this interval. Facies 1–5 all include lonestones, many faceted and a few striated, that record floating ice during interglacial periods that might have been icebergs from tidewater glaciers, sea-ice or river-ice. The overlying strata all have a higher proportion of glacial facies, and less conglomerate, which virtually disappears above 307 mbsf in CRP-2A, perhaps reflecting less influence from flood discharge. No particular trend is evident in the sandstone and mudstone facies.

The massive diamictites of facies 7 are interpreted as basal glacial debris deposited beneath wet-based glacier ice, implying that the ice front of the time extending beyond the drill site. The stratified diamictites of facies 6, which are commonly interbedded with moderately- to well-sorted sandstone (facies 5) and clast-supported conglomerate (facies 9) may represent deposition in subglacial channels near the ice margin or in grounding line fans beyond. These facies are typically overlain by moderately- to well-sorted sandstones (facies 4/5), becoming poorly sorted (facies 3) before passing into alternating sandstone and mudstone (facies 2) or mudstone (facies 1). Mudstone of facies 1 commonly grades up into sandstones of facies 3 to 5, inferred to represent falling sea level.

This pattern is most obvious in the half dozen cycles that are more than 20 m thick, and for which a simple facies model is shown in Figure 7 for both

Table 3 Percentages of each facies are given for each major lithological division in the section. The section begins with a basal conglomerate and sandstone (facies 4/5 and 9/10) of latest Eocene and earliest Oligocene age in CRP-3, passing up through the cycles of diamictite, sandstone and mudstone (largely facies 1–7) of Oligocene and early Miocene times in CRP-3 and CRP-2A, and is capped by a thin diamictite-dominated Quaternary section in CRP-1. The Quaternary (and Pliocene) strata of CRP-2/2A are similar in facies to the Quaternary strata of CRP-1

		CRP-3			CRP-2/2A				CRP-1	
Lithofacies	Age in Ma	~34	34–33	33–31	31–29	29–25	25–23	23–19	19–17	0–2
1.	Mudstone		2	37	18	17	29	21	26	
2.	Interstrat. sandst/mudstone		2	10	13	16	4	1	19	
3.	Poorly sorted sandstone		[a]	11	17	9	21	12	15	19
4/5.	Mod to well sorted sandst		83	20	37	14	33	37	10	
6.	Stratified diamictite			1	1	16	2	2	3	73
7.	Massive diamictite			9	9	17	10	23	27	
8.	Rhythmite			2		1	1			
9.	Clast-supported congl	41	6	4	2	4		Tr		
10.	Matrix-supported congl	59	7	6	3	2		Tr		
11.	Mudstone breccia						Tr	Tr	1	
12.	Non-welded lapillistone						Tr	3	Tr	
		100	100	100	100		100	100	100	92[b]
		33 m	460 m	327 m	181 m	129 m	176 m	78 m	95 m	19 m

[a] 29% originally assigned to facies 3, but mud diagenetic, so added to facies 5.
[b] 8% lime packstone.

glacial and interglacial times. A perspective view of the Victoria Land coast for both glacial and interglacial times is shown as Figure 8. Detailed studies of the core indicate far more complexity than can be depicted here, particularly with regard to decimetre-scale soft sediment deformation, and in a few places metre–scale brecciated intervals, which have been variously interpreted as a result of slope instability, mass movement and subglacial shearing. Redeposition by sediment gravity flows may well have also been active from time to time. Nevertheless the context of an open coast outlined earlier, and the nature of the diatom flora suggest a relatively nearshore marine environment, with coastal neritic diatoms dominating over open ocean types (Scherer *et al.*, 2000). Indeed in early Miocene times waters were occasionally sufficiently shallow for a significant proportion of benthic diatoms to be deposited (Harwood *et al.*, 1998).

Diamicton, muddy sandstone (Pliocene, Quaternary)

CRP-2/2A above 26.79 mbsf, CRP-1 above 43.55 mbsf

The strata above the lower Miocene section are entirely Quaternary in age at CRP-1. Little was recovered above 19 mbsf, but below this it comprised largely unlithified diamicton with clasts of dolerite and granite up to boulder size, and lesser muddy sand beds with scattered pebbles. The diamictons are presumed to have formed closing to the grounding line of an ice shelf or glacier tongue when ice that was covering the nearby foothills was more extensive than that of today. Powell *et al.* (1998) provide a useful perspective view of the Victoria Land coast at this time.

A shelly interval between 33.75 and 31.90 mbsf in CRP-1 has yielded a macrofossil fauna of more than 60 species (Taviani *et al.*, 1998, Taviani &

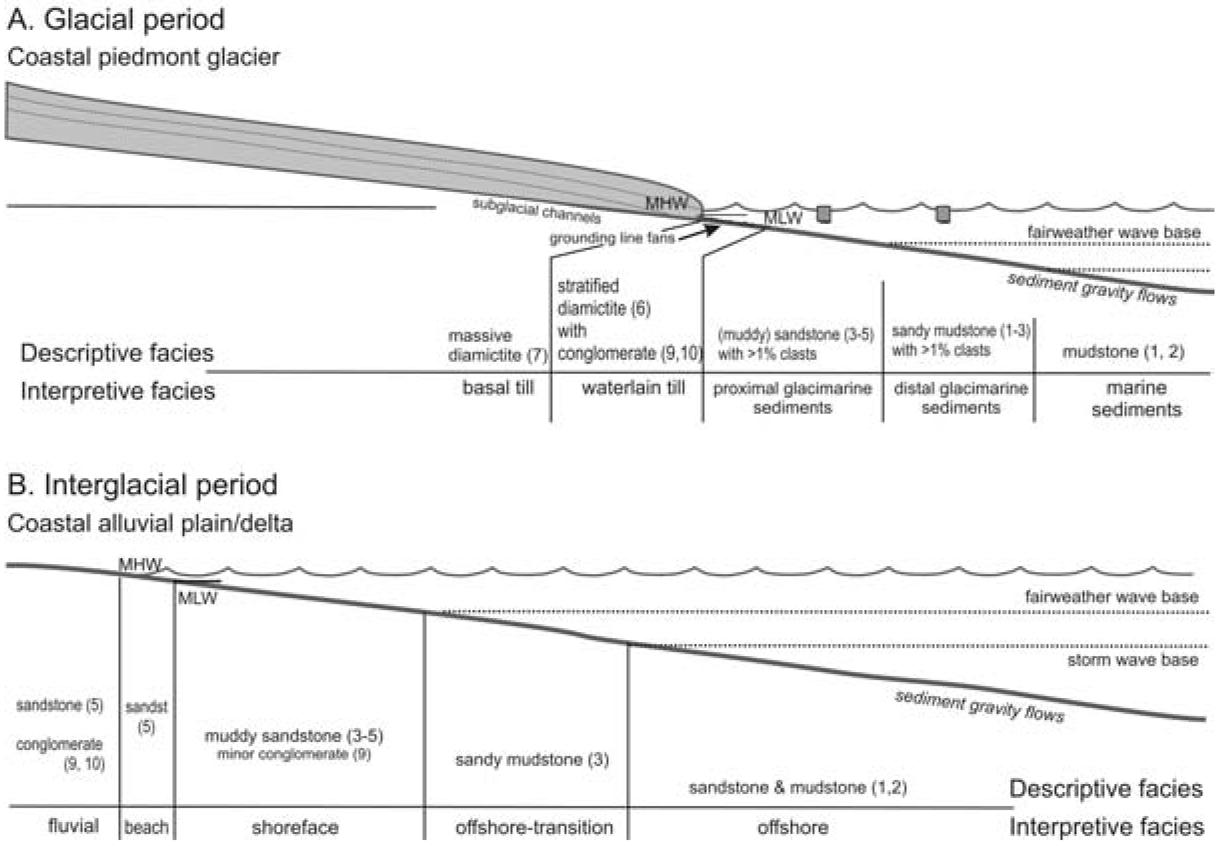

Fig. 7 Facies model for the deposition of sedimentary strata off Cape Roberts during Oligocene (post 33 Ma) and early Miocene times (developed from Hambrey *et al.*, 1989) for glacial (A) and interglacial (B) periods. In both cases wave- and/or current-sorted sand near the shore grade into mud below wave base offshore. During glacial periods glaciers deposited sediment directly over the drillsites as the ice margin advanced beyond them. During interglacial periods sediment was delivered to the coast largely by rivers but striated lonestones suggest some glacial ice still reached the coast in a few places.

Beu, 2003). They are largely molluscs (>40 species) followed by bryozoa (>14 species) and polychaetes (3 species). Diatoms are largely species of *Fragiliopsis* and *Thalassiosira*, with few sea ice-related diatoms, indicating ice-free conditions for much of the year (Bohaty *et al.*, 1998). Recent work has shown the age of this interval to correspond to Marine Isotope Stage 31 at 1.07 Ma (Scherer *et al.*, 2006).

Quaternary diamicton with minor sand was encountered in CRP-2, the first hole drilled in 1999, although little was recovered of the top 5 m. The diamicton contains abundant marine benthic Quaternary foraminifera. Below 21 mbsf, however, a 6-m-thick interval of muddy sand includes a 2.4-m-thick bed of diamicton with an *in situ* foraminiferal fauna of 21 marine benthic species that indicate a Pliocene age (Webb & Strong, 1998). These authors noted deposits of similar age above sea level in lower Taylor Valley and Wright in the Dry Valleys region of adjacent Victoria Land, which implies ~200 m of post-Pliocene uplift across the Transantarctic Mountain Front.

SEQUENCE STRATIGRAPHIC ANALYSIS

Cenozoic glacial and sea-level cycles in the Victoria Land Basin were first recognised in late Oligocene glacigenic strata cored by MSSTS-1, a drill-hole off New Harbour 70 km south of Cape Roberts in 1979 (Barrett, 1986; Barrett *et al.*, 1987). Subsequently Hambrey *et al.* (1989) strengthened the concept using a simple facies approach to interpret

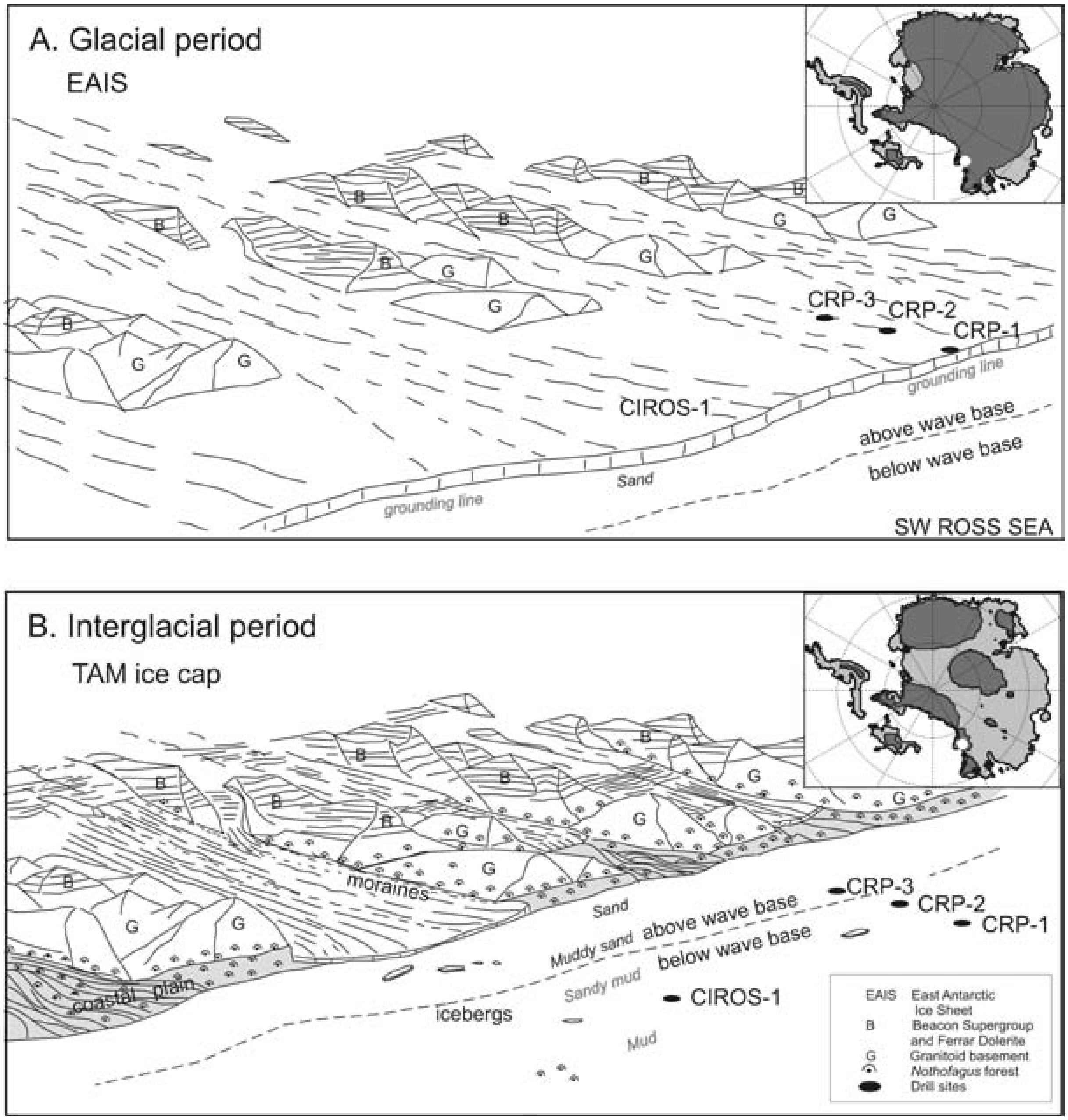

Fig. 8 View of the Victoria Land coast off Cape Roberts during Oligocene (post 33 Ma) and early Miocene times (developed from Hambrey *et al.*, 2002). (A) Glacial period, with an expanded inland ice sheet feeding thin temperate piedmont glaciers depositing sediment to a shallow shelf to be reworked by waves and currents nearshore with mud settling out offshore. (B) Interglacial period, with higher sea level and a much reduced ice sheet. Sediment carried to the coast largely by proglacial rivers. Low woodland beech forest at lower elevations. Insets for A and B show examples of the modelled extent of an ice sheet that might have existed during glacial and interglacial periods in early Oligocene times, representing 21×10^6 cubic km of ice (50 m of sea level equivalent) in A, and 10×10^6 cubic km of ice (24 m of sea level equivalent) in B (DeConto & Pollard, in press).

~300 m of upper Oligocene-lower Miocene strata from the nearby CIROS-1 drill hole in terms of glacial advance and retreat coinciding with sea-level fall and rise. However, the chronology of these strata was not sufficiently well established for correlating the cycles with the deep-sea oxygen isotope curve of Miller *et al.* (1987) and the Haq *et al.* (1987) onlap-offlap curve.

One of the goals of the Cape Roberts Project was to obtain a better-dated record of this time period, and at the same time apply a sequence stratigraphic approach to the Cape Roberts section. This was first achieved by Fielding *et al.* (1998) in the eight lower Miocene cycles from CRP-1, recognising a pattern of unconformity-based diamictite followed by sand and then mudstone as representing a retreat of the ice front over the drill site and a rise in sea level. However they noted that 'it is not generally possible to differentiate between true eustatic signals and local glacial advance/retreat cycles.' Although the chronology of CRP-1 was an improvement over CIROS-1, uncertainties of ~1 m.y. prevented meaningful correlation with the deep-sea oxygen isotope curve then being developed for the Pliocene and potentially older strata with ~0.01 m.y. resolution (Shackleton *et al.*, 1995).

The drilling of CRP-2/2A yielded a section that provided both well-developed cycles and the basis for a chronology that indicated they resulted from orbital forcing. Studies of this core provided more material for analysis, and resulted in an improved sequence stratigraphic model (Fig. 9) containing a *glacial surface of erosion* as an important element (Fielding *et al.*, 2000; Naish *et al.*, 2001a). Three cycles in particular, cycles 9, 10 and 11 in the scheme of Fielding *et al.* (2000), proved to be important because of their thickness and completeness, and also because of a similarity in scale and facies pattern to Plio-Pleistocene cycles of the Wanganui Basin, New Zealand (Fig. 10, Naish & Kamp, 1997), which had already been matched with the Milankovitch cycles of Quaternary deep-sea isotope curve. With the tephra-supported biomagnetostratigraphy, Naish *et al.* (2001a) were

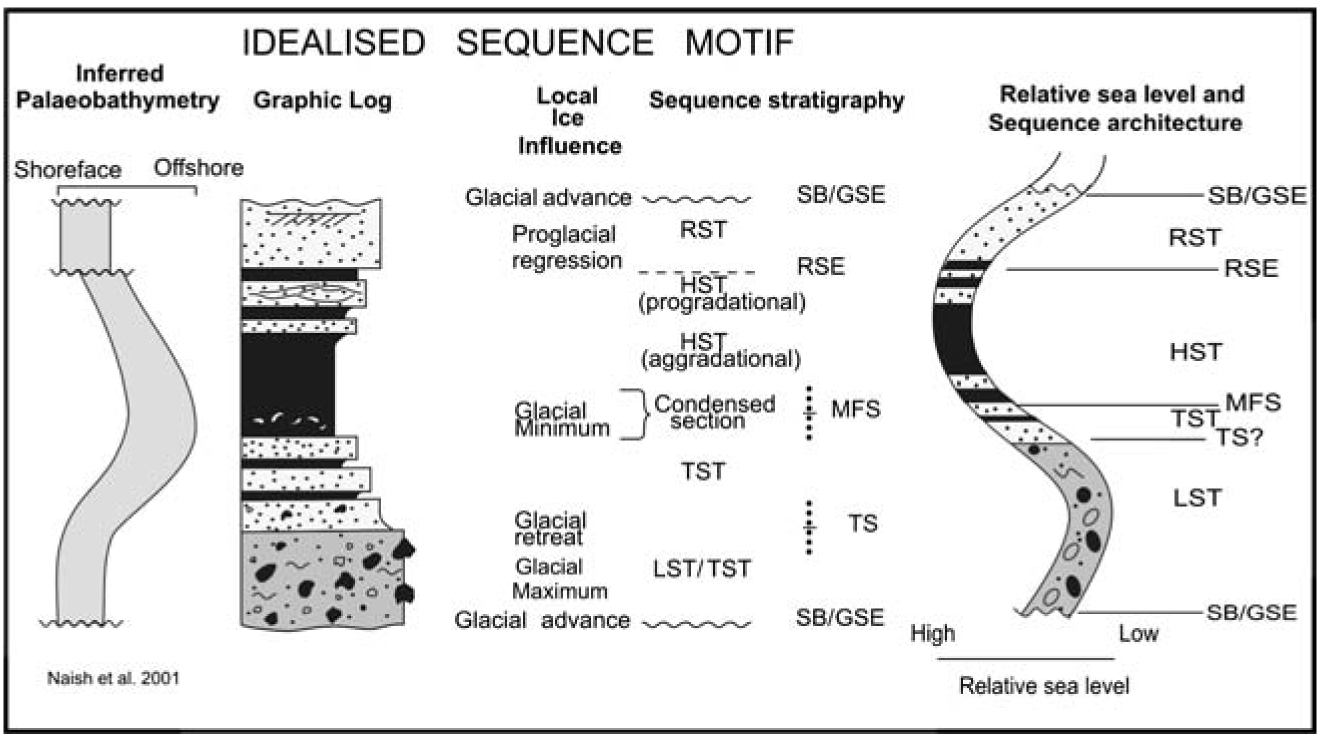

Fig. 9 Sequence stratigraphic model developed for strata cored by CRP-2A from Fielding *et al.*, 2000, and Naish *et al.*, 2001a). SB/GSE – Sequence Boundary-Glacial Surface of Erosion. TS – Transgressive Surface. MFS – Maximum Flooding Surface. RSE – Regressive Surface of Erosion. LST – Lowstand Systems Tract. TST – Transgressive Systems Tract. HST – Highstand Systems Tract. RST – Regressive Systems Tract.

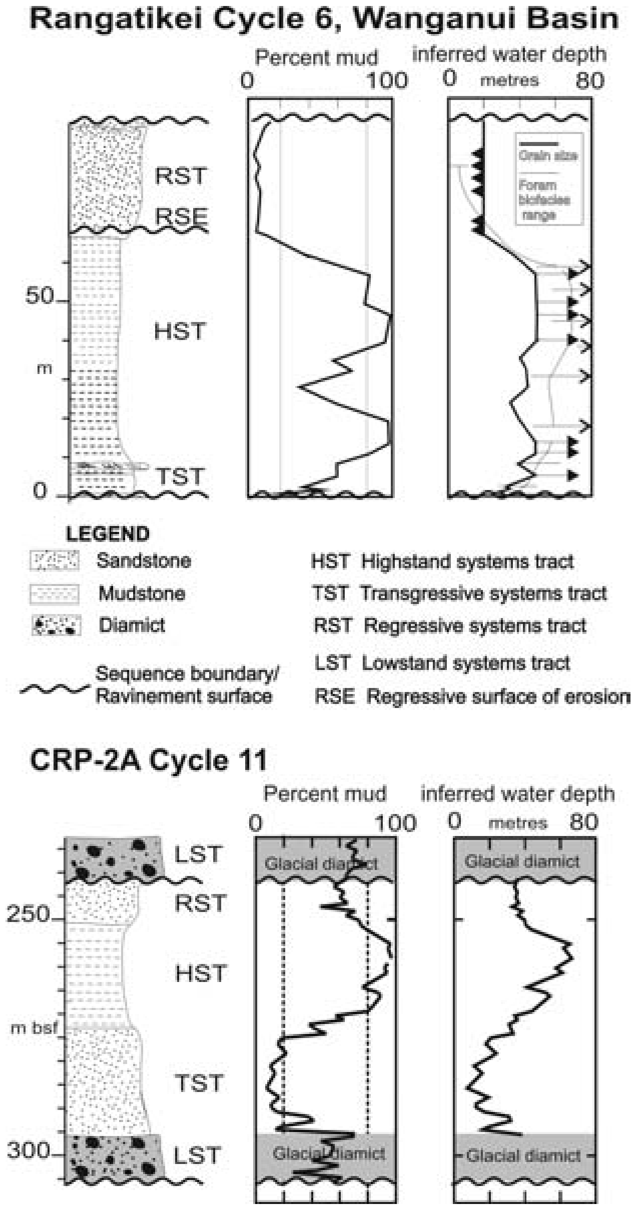

Fig. 10 Comparison of lithologies and water depth interpretations for late Pliocene cycle 6 from the Wanganui Basin, New Zealand, with a latest Oligocene cycle 11 from CRP-2A, showing similar patterns in texture and implied water depth change. For Rangatikei Cycle 6 the solid arrows indicate depths shallower or greater than value implied by grain size. Open arrows indicate water depths greater than value implied by forams.

able to match the three Cape Roberts cycles with cycles in a high resolution deep-sea isotope record from the South Atlantic Ocean (Zachos *et al.*, 1997; Paul *et al.*, 2000). Naish *et al.* (2001b) then used this indication of orbital forcing as the basis for frequency analysis of the rest of the cycles in the Cape Roberts sequence. The recent revision of the Cenozoic time scale, recalibrating the Oligocene-Miocene boundary, has resulted in a new and improved correlation with particular 40,000 year cycles that correspond to the Ar-Ar ages for each cycle at 23.98 and 24.22 Ma (Naish *et al.*, in press), as noted earlier.

The establishment of the sequence stratigraphic model for the mid-Cenozoic Cape Roberts cycles, and the correlation of particular sedimentary cycles on the Antarctic margin with oxygen-isotope cycles in the deep-sea record, was important because it showed that the Antarctic Ice Sheet in Oligocene and early Miocene times pulsated at Milankovitch frequencies (40,000/100,000 years). This view has been supported by experiments with coupled atmosphere–ice sheet models, which show the Antarctic Ice Sheet varying in volume from 10 to 50 m of sea level equivalent on the same frequencies, although with the greatest sensitivity for modelled atmospheric CO_2 levels between three and two times pre-industrial (De Conto & Pollard, 2003). While such modelling provides convincing images of ice sheet expansion and contraction on a continental scale, it is not yet capable of yielding images of the ice sheet margin on a scale of tens of kilometres. In the meantime the cartoons developed from the review of sedimentary facies above (Fig. 8) are offered as a realistic visualisation for glacial and interglacial scenarios.

Cyclic variations in sea level as a consequence of ice-volume change are now well documented for Quaternary times, and efforts to extend this back in time to track both cycles and trends continue (see for example Miller *et al.*, 2005, for the entire Phanerozoic). Most of this work has come from the analysis of deep-sea oxygen isotope records, with previous reviews by Miller *et al.* (1987) and Zachos *et al.* (2001), though the latter was more focussed on variations in orbital forcing than the temperature-ice volume ambiguity that is inherent in the oxygen isotope record. New methods of estimating temperature are being applied so that the sea level signal can be extracted, with Billups & Schrag (2003) and Lear *et al.* (2004) using the Mg/Ca ratio in carbonate shells as a palaeothermometer. Pekar *et al.* (2002) provided glacio-eustatic estimates by calibrating detrended apparent sea-level amplitudes to $\delta^{18}O$ amplitudes for Oi-events in deep-sea records (Pekar *et al.*, 2002), with Pekar and DeConto (2006) arguing for sea level (and ice-volume) fluctuations of between 30 and 60 m in early Miocene times.

The sequence stratigraphic model for the 54 cycles deposited off Cape Roberts from 31 to 17 million years ago suggests an independent approach to estimating past sea-level change based on the physical characteristics of nearshore sediments. Dunbar & Barrett (2005) studied patterns of sedimentation for coastal nearshore sediments, and reaffirmed the long-standing awareness that where the coast is aggrading, the sea floor sediment texture changes progressively from beach sand to offshore mud (Johnson, 1919; Swift, 1971). More importantly they showed a consistent relationship between mud-percent and water depth, on both seasonal and decadal time scales, and a further relationship between mud percent at a specified depth and wave energy. They concluded that if the wave climate were persistent for nearshore sediments on an open coast then variations in mud content could be used as a proxy for water depth, and if the strength of the wave climate could be estimated then values for water depth could also be determined.

This approach was tested with a late Pleistocene and a late Pliocene cycle from the Wanganui Basin, New Zealand, assuming with strong evidence that wave climate was similar to that of today, and where independent water depths could be estimated from foraminifera. There was close agreement. The textural approach has an advantage in higher resolution for depth trends, though there is lower confidence in depth values on account of the assumption regarding wave climate. Also it cannot register changes in water depths below wave base, where sediment is invariably mud, unless the coast is influenced by strong geostrophic or tidal currents or sediment gravity-flows, which have recognisable characteristics. Preliminary tests of this approach for the Cape Roberts cycles assuming a moderate wave climate indicate water-depth variations of several tens of metres (Fig. 10, Dunbar *et al.*, 2003; see also Dunbar *et al.*, 2007).

The interpretation of the Oligocene-lower Miocene Cape Roberts cycles offered here is based on two key points, the first inferred and the second observed:

1 Sediment was supplied by glaciers and rivers to a subsiding basin from the west across a long, straight open coast, and

2 The geometry of the strata parallel to the coast is persistent and planar.

The sequence stratigraphic interpretation, supported by textural patterns of modern coastal sediments, requires cyclic changes in sea level as the primary control on sedimentary facies architecture. However, without doubt the glacial influence, indicated by the diamictites, sediment gravity flows, sediment deformation and lonestones, is clear and extensive. This interpretation leads to two significant conclusions, one for tectonic history and the other for the value of the Cape Roberts section as a recorder of climate on the Antarctic margin.

1 The well-sorted sandstone facies closely associated with diamictite at many levels through the section indicates a regular return to sea level throughout the 17 m.y. history of the Cape Roberts section. Hence, the initially rapid and then declining net sedimentation-rate throughout the section records the subsidence history of the basin, and indeed this observation has been used in a new view of the tectonic history of the Victoria Land Basin (Fielding *et al.*, 2006; Wilson *et al.*, unpublished data).

2 A total of 54 cycles have been identified through the Cape Roberts section covering the period from 33 to 17 Ma (Fielding *et al.*, 2001; Naish *et al.*, 2001b). However there were most likely between 160 and 400 orbitally forced cycles in that time period, depending on the relative influence of eccentricity (100,000 years) and obliquity (40,000 years). Hence only 15 to 35% of these cycles have been preserved. However, these still have value for the glacial lowstands and interglacial highstands they record at many points through this 16 million year time-span.

CLIMATE TRENDS FROM THE CAPE ROBERTS SECTION

The Cape Roberts section records many cyclic variations in ice extent and sea level, as argued above. Here we review long-term trends in some simple climate proxies for the period represented by Cape Roberts (34 to 17 Ma). The proportion of glacial facies in the section are shown, but the more significant climate proxies are considered

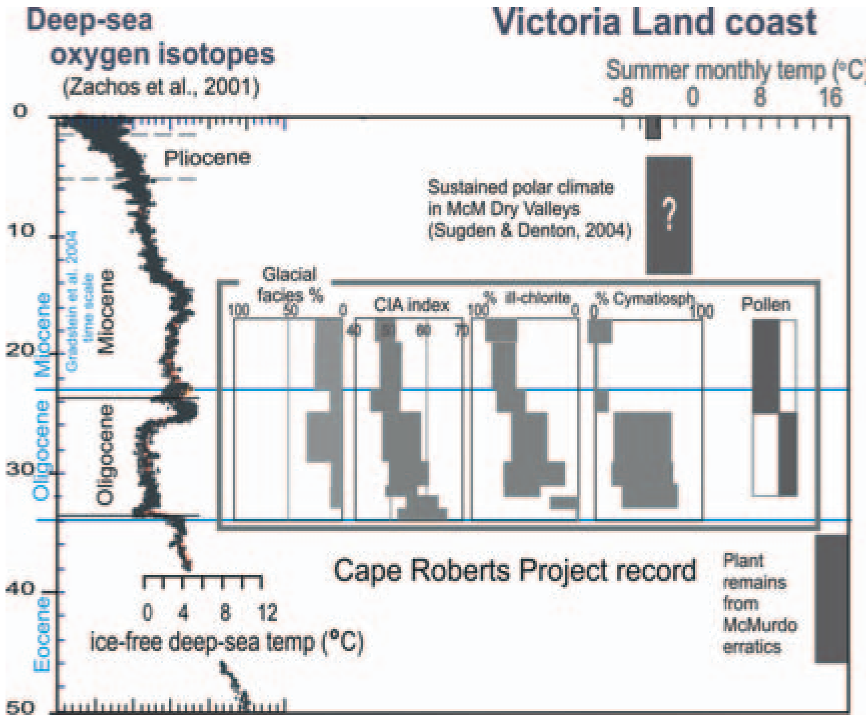

Fig. 11 Trends in climate proxies from the Cape Roberts section for the period from 34 to 17 Ma, compared with the composite deep-sea oxygen isotope curve of Zachos *et al.* (2001). Data were averaged for the time periods set out in Table 1, and are from the following sources: **1** % glacial facies (diamictites, facies 6 and 7) from Table 2; **2** CIA index from Passchier & Krissek (unpublished data); **3** % illite and chlorite in the clay fraction from Ehrmann *et al.* (2005); **4** Fresh water algae (*Cymatosphaera*) from M.J. Hannah (pers. comm., 2006). For sets 2–4 the bar is centred on the mean value, with the width representing ±1 standard deviation. Temperature estimates on the right are for interglacial periods and for mean summer monthly (December-January-February) temperature. For the last two million years it is based on the temperature records from Scott Base, Ross Island, since 1957 (–5°C).

to be the Chemical Index of Alteration (CIA) of Nesbitt & Young (1982), the percentage of illite and chlorite in the clay fraction and the percentage of cymatiosphaerids, marine algae that favour reduced salinities. In each case the data have been averaged for time periods of between one and four million years, and are shown in Figure 11. The climate proxies are compared with estimates of summer monthly temperature from terrestrial palynomorphs (and present-day measurements), and also a widely quoted global climate record for this period, the composite deep-sea oxygen isotope record of Zachos *et al.* (2001).

The oxygen isotope record is influenced largely by deep-sea temperature and the volume of ice on land, but recently Mg/Ca ratios on benthic foraminifera have been found to provide an independent estimate of temperature (Lear *et al.*, 2000, 2004). It is worth noting that both the composite oxygen isotope record and Mg/Ca ratios in the Eocene suggest that temperatures had declined sufficiently by 40 Ma to form small ice sheets on Antarctica (Billups & Schrag, 2003, Fig. 2), and that the dramatic 1 per mil shift in $\delta^{18}O$ at the Eocene-Oligocene boundary most likely resulted from an increase in ice volume (Lear *et al.*, 2004). Diamictites with exotic clasts at two locations on the Antarctic margin, Prydz Bay at 68°S and 70°E (Hambrey *et al.*, 1991) and Seymour Island at 65°S and 60°W (Ivany *et al.*, 2006) support this view in showing that continental ice reached beyond the present ice limits by earliest Oligocene times, with Prydz Bay diamictites possibly being a little older.

The Cape Roberts section does not provide a comparable record of the onset of Antarctic glaciation, most likely because of the barrier presented by the Transantarctic Mountains, which began rising 20 m.y. earlier (Barrett, 1999). However, the section does record out-sized striated clasts in sand just above the basal conglomerate at ~34 Ma, indicating calving of glacier ice at sea level. In this shallow marine coastal sedimentary section the appearance of diamictites suggests that grounded ice began to extend periodically beyond the Victoria Land coast at ~33 Ma. This continued for the rest of the Oligocene and early Miocene time, with glacial facies comprising 10 to 33% of the total thickness of the section.

The proportion of glacial facies in the section is not easy to interpret and may have as much or more to do with subsidence rates than the duration of ice covering the Cape Roberts sites. However the glacial facies do show that on at least 50 occasions, and most likely on many more, in the period from 33 to 17 Ma grounded ice extended on a broad front into the Ross Sea. We can also speculate that significant unconformities, at ~29, 25 and 23 Ma (442.99, 306.65 and 130.27 mbsf in CRP-2A), for example, represent substantial time loss as a consequence of glacial erosion through more extensive or persistent ice.

The balance between physical and chemical weathering as an indicator of climate through the Cape Roberts section is shown in two ways – through the CIA index and through clay mineralogy. The CIA is calculated from the relative abundances of Al, K, Ca, and Na oxides, and its magnitude increases as the extent of chemical weathering increases. Samples for this purpose were taken from diamictite and mudstone. Values range from ~50 for 'unweathered' feldspar-rich rocks and 70–75 for the 'average shale' to values near 100 for highly weathered sediments. Data were obtained through XRF analysis by Krissek & Kyle (2000, 2001) with further analysis by Passchier (2006), who has also corrected the analyses for biogenic and detrital carbonate.

The oldest strata, from 34 to 33 Ma, were almost entirely sandstone, and lacking mudstone or diamictite for analysis. The overlying finer-grained sediments from 33 to 32 Ma, however, gave CIA values varying considerably in the range between 55 and 65, indicating moderate chemical weathering, moving to between 50 and 60 from 32 to 25 Ma, suggesting a reduction in chemical weathering. Above this from 25 to 17 Ma CIA values showed less variation and centred on a value of around 50. Whether the initial decrease reflects cooling of coastal climate or a rapid but declining sediment accumulation rate during the initial phase of subsidence (Fielding *et al.*, 2006), it is plain that the trend is a declining one and the index itself is low and consistent with a cool to cold climate throughout the time represented by the Cape Roberts section. The range of values obtained from the Cape Roberts section is similar to those reported by Passchier (2004). Their analysis of 32 samples from ancient wet-based glacial deposits found between 1000 and 2500 m asl in the Transantarctic Mountains from 75 to 86°S; they yield a similar range (40–70) and average (55 ± 7) to the Cape Roberts section. Passchier (2006) has offered a more detailed analysis of these data.

The detrital clay mineral record is a long established climate proxy for tracking long term climate change, and especially in the Antarctic region (Ehrmann *et al.*, 1992). Illite and chlorite are known to result from physical weathering under a cool dry climate, and kaolinite and smectite are normally being derived from chemical weathering under a warm humid climate. Care is required if authigenic clays are present or the strata include easily weathered volcanic detritus. The CRP clay record shows here is summarised from Ehrmann *et al.* (2005).

The basal Oligocene sandstones of the Cape Roberts section have virtually no detrital clay, but as noted earlier they have significant amounts of authigenic smectite, which is of no climatic significance. The interval from 33 to 32 Ma, however, includes fine-grained sediments with much poorly crystallised smectite but still little illite or chlorite (average ~10%). The proportions change dramatically in the following period, from 34 to 33 Ma, to >40% from 32 to 25 Ma, and rise further ~70% from 23 to 17 Ma. These data suggest initially a cool but mild climate, becoming consistently cold from 32 to 25 Ma, perhaps with milder episodes 31 to 29 Ma, and then becoming more frigid from 25 to 17 Ma.

The marine palynomorphs in the Cape Roberts section are common (Hannah *et al.*, 2000, 2001) and include prasinophyte algae, largely the genus *Cymatiosphaera*, well known from the modern Arctic Ocean. There they prefer areas of high freshwater inflow near the mouths of estuaries and fiords (Mudie, 1992). In the open coastal setting off Cape Roberts their abundance is taken to indicate periods of glacial melting that generate extensive freshwater discharges reaching several km offshore. The five palynomorph-bearing samples from 34 to 33 Ma included only one that was productive, possibly because this part of the section is almost entirely sandstone. Above this, however, in the interval representing the period from 33 to 23 Ma, they represent between 30 and 45% of the marine palynoflora, though individual samples vary from a few to almost 90%, suggesting periods of extensive meltwater extending offshore. In the upper part of the section marine palynomorph abundance is high but the proportion of *Cymatiosphaera* is low, and mostly less than 10%, implying reduced melt-water flows and a cooler climate.

The terrestrial palynomorph record is sparse but significant because the assemblages comprise largely modern forms of vegetation. That said, the temperature estimates, although carefully considered are quite speculative, with the detailed reasoning to be found in papers by Raine (1998), Askin & Raine (2000) & Raine & Askin (2001). Further work by Prebble *et al.* (2006) on the detail of two cycles at 31 and 24 Ma confirmed the cooling trend found in the initial work but also found that *Nothofagus* was more persistent in the late Oligocene than previously thought. A goal of this work was to seek changes in the glacial-interglacial pollen assemblage, but these could not be resolved because of a combination of low numbers from the extractions and probable pene-contemporaneous reworking. This suggests that the published assessments that follow are likely to represent an interglacial rather than a glacial climate. This flora consisted of a 'a low-diversity woody vegetation with several species of *Nothofagus* and podocarpaceous conifers' (Raine & Askin, 2001) for the period from 33 to 25 Ma, and from about 25 Ma of a scrub-tundra mosaic with similar *Nothofagus* and podocarpaceous conifers, but an increasing tundra-derived bryophytic [moss] and distinct angiosperm component (Prebble *et al.*, 2006; Raine *et al.*, 2006). The scrub and woodland are compared with the Pacific coast of southern South America, where precipitation is high and mean summer monthly temperatures range from 8 to 12°C. The tundra vegetation represents a colder, periglacial climate, perhaps at higher elevation or in more exposed sites.

To provide context for the temperatures estimated for the Cape Roberts palynomorph record, the present-day mean summer temperature is shown, along with a speculative assessment that the regional climate has been polar for the last 14 Ma based on the persistence of dated geomorphic features in the McMurdo Dry Valleys (Marchant *et al.*, 1996; Sugden & Denton, 2004). Temperatures are also estimated for the period immediately preceding the earliest Cape Roberts record from a more diverse terrestrial palynomorph assemblage that was extracted from middle to late Eocene erratics from southern McMurdo Sound (Askin, 2000).

In summary, the indicators of ice and climate in the Cape Roberts section indicate initially a cold climate for the period from 34 to 33 Ma, with limited glacial influence most likely on account of the barrier presented by the adjacent Transantarctic Mountains. From 33 Ma onwards, however, the cycles of diamictite, sand and mud, left a record of glacial advance and retreat that was synchronised with sea-level fall and rise that is considered a response to huge fluctuations of a dynamic Antarctic ice sheet. The record shows no significant indication of the loss of ice or a clear and persistent warming of the Antarctic region to be expected from the 1 per mil fall at around 25 Ma in the composite deep-sea isotope curve.

Re-analysis of high-latitude ODP sites by Pekar *et al.* (2006) indicates that around this time (24.4 and 23.0 Ma) the Antarctic Ice Sheet was as large as or larger than that of today. They suggested that the isotopic shift is better explained by a strengthening of warmer deep waters originating from the North Atlantic coupled with a reduction in Antarctic deep-water, resulting in a warming of bottom water temperatures in many of the ocean basins, rather than a change in ice volume or surface temperature. They also concluded that ice volume ranged from 50% to 125% of the present-day ice sheet in early Miocene times by calibrating high-resolution records from ODP Sites 1090 and 1218 (Pekar & DeConto, 2006). The Cape Roberts record is consistent with that conclusion.

CONCLUDING REMARKS

The Cape Roberts section represents a collection of fragments of history of the Antarctic margin from the time the ice sheet had just formed until shortly before it became persistent around 14 Ma ago. The sand and minor conglomerate of the first million years is likely to be primarily of regional tectonic interest, with the subsequent period from 33 to 17 Ma of wider climatic interest for its record of the cycles of the continental ice sheet. Although only 20 to 30% of the cycles experienced by the Antarctic margin have been preserved at all, a number have survived with most or all elements intact (e.g. cycle 4 in CRP-1, Cycles 8–11 and 19 in CRP-2A, Cycles 2 and 3 in CRP-3). With their thickness ranging from 26 to 80 m, and considering the time they represent – 40,000 or 100,000 years – they offer obvious potential for high-resolution palaeoclimate studies of the Antarctic margin when the earth was shifting from a high to a low CO_2 world (Pagani *et al.*, 2005).

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APPENDIX 1

SUMMARY DESCRIPTION OF FACIES FROM CENOZOIC STRATA DESCRIBED FROM CRP DRILL CORES

Note: Dispersed clasts or lonestones are a prominent feature throughout Facies 1–5 (mudstone through to sandstone) and facies 8 (rhythmite). They range in size from small pebble to cobble-size, and from angular to rounded. A few are faceted and striated (Atkins, 2001). Lithologies are largely granitoid and dolerite, with lesser amounts of metamorphic and sedimentary types, all sourced from the adjacent Transantarctic Mountains (Talarico et al., 2000, Sandroni & Talarico, 2001).

Facies 1, mudstone with lonestones, is typically a massive slightly sandy clayey silt, although 20% sand is not uncommon. Gravel rarely accounts for more than 0.2%. Fine sand and silt laminae are common and there is little bioturbation. Microfossils include diatoms (common), benthic foraminifera, and both marine and terrestrial palynomorphs, the latter presumably from vegetated ice-free parts of the adjacent coast. The facies also includes a few molluscs.

This facies is interpreted as fine-grained sediment discharged from rivers or glaciers on land and carried offshore to settle out below wave-base along with coarser sediment from floating ice.

Facies 2, interstratified sandstone and mudstone, is characterised by beds of both fine sandstone and mudstone tens of centimentres thick, with sands commonly parallel- and ripple-laminated, and fining upward to mudstones. Some thin intervals show intense soft-sediment deformation.

This facies is interpreted as a mix of hemipelagic sedimentation below wave base, interrupted periodically by occasional low density sediment gravity flows, perhaps triggered by floods or storm events.

Facies 3, poorly sorted muddy very fine to coarse-grained sandstone, varies considerably in texture, although typically it is massive or weakly stratified, with normal grading. Finer beds are ripple-laminated. Thin conglomerates occur at the base of coarse-grained beds. The very poor sorting of this facies has led to several samples visually described as sandstone, analysing as sandy mudstone with 30% fine/very fine sand, 50% silt and 20% clay.

This facies has been interpreted to form from high density sediment gravity flows or by turbid plumes originating from heavy fluvial discharge. Alternatively some intervals could represent mixing between shoreface sand and offshore mud during periods of changing sea level.

Facies 4, a moderately to well-sorted fine sandstone, exhibits planar and low-angle cross-lamination, and in places is interbedded with very fine, medium and coarse sandstones. Recent reviews (e.g. Hambrey *et al.*, 2002) have included it with Facies 5.

Facies 5, a moderately to well sorted stratified or massive, fine to medium-grained sandstone, is typically massive and planar to cross-stratified. Textural analysis shows this facies to be mostly moderately well sorted, but also to have matrix that is far more clay-rich than Facies 1, suggesting that much of the clay migh be of diagenetic origin, and that the facies was better sorted when deposited.

This facies is interpreted as a shoreface deposit influenced primarily by waves and currents.

Facies 6, a stratified diamictite, is a mixture of gravel (>1%), sand and mud, with stratification evident from variations in colour, texture or clast density. It commonly has gravel, sand or silt interbeds, and locally shows strong soft-sediment deformation.

This facies can be interpreted to result from subglacial melt-out through the water column from a floating ice margin. Alternatively, it may have been the product of a debris-flow. This might itself have been fed by subglacial meltwater discharge.

Facies 7, a massive diamictite, is an unstratified mixture of gravel, sand and mud in beds from decimetres to several metres in thickness. Upper and lower contacts are well-defined, though they may be graded. Lower contacts can also be sharp and with indications of loading. Some though not all clast fabrics show a preferred orientation (Atkins, 2001). Samples taken for microtextural analysis by thin section also show rotational structures and other features that indicate that they experienced shearing, possibly by grounded ice (Van der Meer, 2000).

This facies is most likely to have formed near the margin of a temperate glacier from melting of the basal debris layer.

Facies 8, rhythmically interstratified sandstone and siltstone, is characterised by thin silt laminae, thin turbiditic sands and single-grain-thick sand laminae, and is quite unusual, forming <1% of the section.

This facies has been seen to form through suspension settling from turbid plumes accompanied by occasional low density turbidity currents.

Facies 9, a clast-supported conglomerate, is massive, poorly sorted and commonly grades from cobble to small pebble grade, with a matrix of fine- to coarse-grained sand. Clasts are typically moderately to well rounded, but almost invariably include angular clasts too.

The facies is submarine from its close association with other marine facies, but may have formed close to points of fluvial or subglacial meltwater discharge close to or beyond the coast. It could also represent redeposition of such gravels further offshore by sediment gravity flow.

Facies 10, a poorly sorted matrix-supported conglomerate, has the same features as Facies 9, but the clasts are 'floating' in the sandy matrix and it typically has a higher proportion of angular clasts.

It too is interpreted as the product of fluvial or subglacial meltwater discharge, possibly redeposited by sediment gravity flow.

Facies 11, a mudstone breccia, comprises angular fragments of mudstone (with some very fine sandstone) several centimetres across in a matrix of muddy fine sandstone. It was found in just a few places (<0.5% of the section), the most striking being a 4-m-thick bed with clasts up to 75 mm long and intensively brecciated at the base from 311 to 315.5 mbsf in CRP-2A (Cape Roberts Science Team, 2000, Fig. 3.2 k).

These can be interpreted as mass-movement events, induced either by earthquakes or shearing from grounded ice.

Facies 12, comprises phonolitic tephras erupted from ~24 Ma and above ~300 mbsf in CRP-2A (Armienti *et al.*, 2001). Volcanic glass, crystals and clasts can be seen in the core face both dispersed and concentrated as laminae. Several discreet tephra layers were encountered, the most spectacular being a series between 109 and 114 mbsf in CRP-2A, and including a reverse- to normal-graded 1.2-m-thick pumiceous lapillistone. It does not include volcanogenic sandstones with as much as 30% glass and lithic fragments (Smellie, 2000).

This facies is interpreted as volcanic airfall debris deposited through water, in most cases reworked by currents and in some redeposited by sediment gravity-flows. Ar-Ar dating of feldspars and other volcanic material from these deposits, along with some volcanic clasts, has been crucial for the chronology of the period from 25 to 17 Ma (Cape Roberts Science Team, 1998, 1999; Florindo *et al.*, 2005).