Terra Antartica
Initial Report on CRP-3
2000, 7 (1/2)

7 - Summary of Results

INTRODUCTION

When drilling began at CRP-3 there was still the expectation that this final hole of the project would pass down from the sub-polar marine glacial sediments cored in CRP-2A into temperate or even warm-climate marine or terrestrial sediments beneath. This was not to be. The 939 m of strata cored by CRP-3 yielded but a mere 3 m.y. of Cenozoic time (31-34 Ma), an unconformity representing around 300 m.y., and over 100 m of Devonian strata beneath. The last section of this report presents the current state of the chronostratigraphy for these strata. It also provides a summary of both the depositional record of the Victoria Land Basin margin during this short but dynamic period of its development, and the tectonic history of this part of the West Antarctic Rift System.

The dating of core from the upper part of CRP-3 is found to be well constrained by diatom and calcareous nannofossil datums to within the early Oligocene epoch (31 to 33 Ma) for the upper 200 m. Potential for improving the dating extends to around 360 mbsf and possibly further with magnetostratigraphy, more biostratigraphical sampling and from Sr-isotope analysis of macrofossil shell material. The age of the oldest Cenozoic strata, resting on the Devonian Beacon Supergroup sandstone at 823 mbsf, is judged to be "earliest Oligocene and possibly latest Eocene" and *c*. 34 Ma. This judgement is based on the prospect that strata down to 350 mbsf or even deeper lie within Chron 12R (see Chapter 6), and hence within the 31 to 33 Ma age bracket, and the increasing coarseness of sediment to the basin floor, which implies initial very rapid sedimentation.

Depositional styles and trends in CRP-3 core are reviewed from the initial deposition of sandstone breccia as sub-aerial talus on a hillside near sea level to the sandy glacial sediment deposited in outer shelf depths at the top of the core. The sediment becomes finer upcore from coarse dolerite gravel and Beacon-sourced sand on the margins of first an alluvial fan and then a shallow marine delta front. Marine conditions persisted with intervals of finer grained sediment increasing above *c*. 360 m. Although it seems that there were glaciers on land during the deposition of the oldest sediment, there is no indication that they influenced sedimentation at the drill site directly until around the 300 m level when indications of grounding line oscillation appear. The pattern of sequences so well developed in CRP-2A can still be seen above this level, but is simplified and obscured below it.

Evidence of climate on land, although not reviewed in this section, is described earlier from clay mineralogy in Chapter 4 and from terrestrial palynology in Chapter 5. Climatic evidence is mentioned in brief here because it confirms the persistence of a cold climate from earliest Oligocene times. In particular the terrestrial palynomorphs, though present in low numbers on account of the relatively coarse sediment, also show the low diversity characteristic of cold climates, even in the few samples where they are common. The assemblages from CRP-3 record a woody vegetation with *Nothofagus* and podocarps occurring as a low scrub or closed forest intermediate between that of Eocene erratics from McMurdo Sound and the sparse tundra found in lower Miocene core from CRP-1 and upper CRP-2A. In addition, the clay mineral assemblages from 410 mbsf and above are characterised by chlorite and illite , which dominate modern high-latitude sediment, but are largely smectite-bearing below 650 mbsf, indicating the erosion of products of a warmer climate. The inference from these observations is that climate on land was most likely warmer just prior to the initiation of deposition in the Victoria Land Basin, but cold for the period represented by CRP-3.

The surprising achievement of CRP-3 was to core through the oldest Cenozoic strata in the Victoria Land Basin, and into a basement that had stratigraphical significance. Tectonic implications of these and other observations form the third main part of this summary section, with comment on basin subsidence history, age of initial rifting (probably not much older than the oldest sediment cored) and the total post-Jurassic displacement across this margin of the West Antarctic Rift System. Post-early Oligocene faulting is classic dip slip, but a shear zone below 790 mbsf and fractures beneath indicate oblique shear that is not readily explained. This section also reviews data on erosion history from clasts and sand composition, concluding that most of the sediment below 200 mbsf in CRP-3 came from the 2000-m-thick Beacon sandstone (first upper coal-bearing feldspathic beds and then lower quartzose beds). The base of these strata now lies at around 1500 m above basement granitoids in the foothills of the mountains west of Cape Roberts, but most basin subsidence and probably mountain uplift also had been completed by 17 Ma. Indeed clasts of granitoid can be found in the core to depths of 780 mbsf (see Chapter 4), indicating that erosion of the mountains had cut through to the basement by earliest Oligocene times (like granitoid clasts in CIROS-1 core 70 km south and of similar age, Barrett, 1989). Most mountain uplift was plainly an early Cenozoic event.

The section ends with some conclusions and comments on further related work.

CHRONOLOGY

The biostratigraphical framework for CRP-3 is provided primarily by diatoms with additional data from calcareous nannofossils. There is considerable variation in the abundance and preservational quality of the microfossils throughout the core (see chapter 5), and this variation affects the degree of biostratigraphical resolution. In addition, these pelagic diatom and calcareous nannofossil assemblages differ significantly from those of coeval open oceanic sites in the Southern Ocean, so that only some of the calibrated biohorizons are present in CRP-3. Nevertheless, there is concordance between the age determinations provided by the diatom and calcareous nannofossil data, suggesting that the age determinations are robust. Biostratigraphical age control by pelagic microphytoplankton fossils is restricted to the upper 200 mbsf of the CRP-3 sequence.

Diatom assemblages above 48.4 mbsf contain both *Cavitatus jouseanus* and *Rhizosolenia antarctica*, indicating the *C. jouseanus* Zone of early Oligocene age. The FAD of *C. jouseanus* has been calibrated from several Southern Ocean deep-sea sites, both directly and indirectly, to the palaeomagnetical time scale. This datum occurs within the lower part of Chron C12n at ODP Site 748 on the central Kerguelen Plateau (Harwood & Maruyama, 1992). Based on the time scale of Berggren et al. (1995), the inferred age of this datum is approximately 30.9 Ma. Further to the south, at Kerguelen Plateau ODP Site 744, this datum lies close to the C12n/C12r boundary in the lower *Chiasmolithus altus* nannofossil Zone (Baldauf & Barron, 1991; Barron et al., 1991), corresponding to a similar age of approximately 31 Ma. *Cavitatus jouseanus* tends to be rare and sporadic in occurrence near its first appearance at oceanic sites, as noted by Fenner (1984) for DSDP Site 274 and Harwood & Matuyama (1991) for ODP Site 748. This suggests that the FAD of *C. jouseanus* may be slightly older than reported from Southern Ocean deep-sea sites. As a result, a conservative placement of this datum near the top of Chron C12r is adopted herein (chapter 5).

The interval from 49.68 to 68.60 mbsf contains *Rhizosolenia antarctica* without *C. jouseanus*, indicating the *R. antarctica* Zone of early Oligocene age. The base of this zone, defined by the FAD of *R. antarctica*, corresponds with a significant degradation in the preservation and abundance of siliceous microfossils downcore. The actual absence of *R. antarctica* in the underlying rock cannot be reliably ascertained at this time. It is likely, therefore, that the FAD is not the evolutionary first appearance but a diagenetically mediated one. Thus, the lower boundary of this zone must remain tentatively placed for the present. The FAD of *R. antarctica* at Falkland Plateau DSDP Site 511 occurs within the *Blackites spinosus* nannofossil Zone (in Chron C12r) of early Oligocene age (Fenner, 1984). Further to the south at ODP Site 744 on the Kerguelen Plateau, this FAD occurs in the lower *Blackites spinosus* nannofossil Zone (Chron C13; Baldauf & Barron, 1991; Barron et al., 1991). These occurrences suggest an age of approximately 33 Ma for this datum. Given the tentative placement of this biohorizon in CRP-3 (discussed above), this age must be considered a maximum age estimation for this part of the core.

The calcareous nannofossil *Transversopontis pulcheroides* has its LAD at 114 mbsf in an interval of relatively high microfossil abundance. This species has its LAD near the centre of the *Blackites spinosus* Zone on the Falkland Plateau (Wise, 1983) at both Sites 511 and 513. Assuming that the entirety of the zone is present at Site 511, which has the more complete record, this FAD correlates to the mid-point of the zone. This extrapolates to an age of approximately 32.4 ± 0.5 Ma.

Siliceous microfossils occur as poorly preserved, sparse assemblages from *c*. 70 to 195 mbsf. Despite this, the species composition indicates the age of these assemblages. In general, the composition of the assemblages indicates that they are dissolved counterparts of those from above 70 mbsf. The absence of the highly dissolution-resistant *Hemiaulus caracteristicus* in these assemblages indicates that they are younger than the LAD of that species. The LAD of *H. caracteristicus* is well-dated within Chron C13n on the southern Kerguelen Plateau (Site 744; Baldauf & Barron, 1991), indicating an age of *c*. 33 Ma. The absence of this species in the upper 200 mbsf of CRP-3 indicates that this interval is younger than this age.

Initial characterization of the palaeomagnetical sequence is complete through the upper 350 mbsf. This interval is dominated by reversed polarity with relatively thin intervals of normal polarity (chapter 6). These thin intervals of normal polarity are interpreted to represent cryptochrons (short polarity intervals with durations <30 ky). All of the biostratigraphical information indicates that the upper 200 mbsf of CRP-3 was deposited between 31 and 33 Ma. Since this 200 m is part of the continuous sequence of reversed polarity, it follows that the entire sequence is probably part of a single polarity chron. Given that this is part of a single continuous interval, the age and the dominantly reversed polarity indicate that it must represent part of Chron 12r of early Oligocene age.

The sediment accumulation rate for this interval can be calculated following these assumptions. As discussed below, it is not possible at present to estimate the thickness of any sedimentary rock above the top of CRP-3 that may be part of this reversed polarity interval. In addition, palaeomagnetical results are currently not available for the interval below 350 mbsf (chapter 6). Thus, any estimation of sediment accumulation rate must be regarded as a minimum. Berggren et al. (1995) assigned a duration of 2.12 Ma for Chron 12r. Thus, a minimum sediment accumulation rate for the upper 350 m of CRP-3 is approximately 165 m/m.y. This rate is entirely reasonable given the type of sediment (coarse grain clastics) and the sedimentary environment (glaciomarine). This rate is also close to the average sediment accumulation rate calculated for the upper *c*. 300 m of CRP-2.

Chronological characterization of the interval below 350 mbsf is difficult at this time. Many palaeontological and palaeomagnetical samples remain to be examined. Initial inspections suggest that some portions of the core material may not yield any conclusive age information (chapters 5 and 6). There are data that imply that the base of the section above the sandstones identified as Beacon Supergroup may be as young as early Oligocene (marine palynomorphs) or as old as late Eocene (terrestrial palynomorphs) in age, but neither of these estimates can be considered in any way conclusive. In addition, none of the material identified as Beacon Supergroup has yielded fossil material. The material intruding this Beacon Supergroup probably will be dateable by one or more methods, and this may help restrict the age of some of the associated sedimentary material.

CORRELATION BETWEEN CRP-2A AND CRP-3

The location of CRP-3 was selected to provide core that had a stratigraphical overlap (<100 m) with the lowest core from CRP-2A (see Introduction chapter). However, a revision of the seismic data suggests that the lower strata cored by CRP-2A truncate against reflector "l" and that the uppermost strata cored by CRP-3 truncate through downlap against reflector "o" (Fig. 7.1). Thus, there may not be a stratigraphical overlap between these drill holes.

A composite of palaeontological, magnetic polarity, and lithological information provides data to examine possible overlap or underlap (gap) between these two drill holes (Fig. 7.2). Six siliceous microfossil taxa range to the top of CRP-3 but are not present in the lower diatom-bearing intervals of CRP-2A (above *c*. 565 mbsf), suggesting a stratigraphical gap or underlap between the two holes. However, a 60-m interval at the base of CRP-2A that is barren of diatoms complicates this interpretation of overlap or gap. Several species of palynomorphs are in common between the two drill holes, but are long-ranging. *Lejeunocysta* sp. #7 has the shortest range in both drill cores. Foraminiferal assemblages are facies-controlled and offer no basis for correlation. A broad mussel-bearing zone in CRP-2A (from 442 mbsf to the bottom of the hole) may continue with the uppermost 11 mbsf of CRP-3. Magnetostratigraphical data for the lower part of CRP-2A are mixed, but most of the lower 35 m is of normal polarity. In contrast, the upper 200 m of CRP-3 is almost entirely of reversed polarity, with normal polarity in the uppermost metres of the recovered core.

The upper ranges of the six diatom taxa in question may have terminated within the interval of poor preservation in CPR-2A (Fig. 7.2), but this record is lost due to dissolution of the diatoms. Alternatively, given the rapid rates of sediment accumulation and assuming the absence of a significant unconformity within the barren zone, the truncation of the diatom ranges may indicate a stratigraphical gap between these two drill cores. If an overlap exists, magnetostratigraphical data indicate that it must be less than 5 m. Lithological and sequence stratigraphic data suggest that there is no overlap (Fig.□.3).

DEPOSITIONAL HISTORY

INTRODUCTION

The depositional history derived from the CRP-2/2A core was intimately concerned with the history of growth and decay of the Antarctic ice sheet. However, in the case of CRP-3, although it is clear that glacial advance and retreat played a significant part in the depositional history of the upper third of the core, the lower portion was less directly influenced by glacial processes. Base-level fluctuations, evident in the CRP-2/2A core and sometimes associated with glacial advance and retreat, are not clearly distinguishable in the lower two-thirds of the CRP-3 core. This may be because of a rapid sedimentation rate, coupled with rapid and continuous subsidence of the basin and uplift of the source area.

Lithological and facies relationships are summarised in columns presented in figure 7.4.

The Victoria Land Basin succession represented in the CRP-3 drillcore can be divided into six main lithofacies associations, in upward succession:

1. monomictic conglomerate and breccia, derived from the Beacon Supergroup (823.11-822.88 mbsf);
2. clast-supported conglomerate and minor sandstones (822.88-789.77 mbsf);
3. muddy sandstones with subordinate conglomerates (798.77-~580 mbsf);
4. clean sandstones with subordinate conglomerates (~580-378.36 mbsf);
5. muddy sandstones and mudstones, with subordinate conglomerates and diamictites (378.36-0.00 mbsf).

LITHOFACIES ASSOCIATION 1: MONOMICTIC CONGLOMERATE AND BRECCIA

This lithofacies association is limited to the lowest 23 cm of Victoria Land Basin section, immediately above the basal unconformity at 823.11 mbsf (Fig. 7.5). Clast-supported breccia, consisting of unsorted angular clasts (up to 6 cm) of Beacon Supergroup quartzitic sandstone, in a matrix of quartzose sandstone, rests directly on the basal unconformity surface, and extends up to 822.94 mbsf, 17 cm above the unconformity.

The breccia is separated by an irregular wavy surface from an overlying matrix-supported conglomerate. Clasts in the conglomerate are up to 2 cm across and are of Beacon Supergroup quartzitic sandstone; they are within a matrix of quartzose sandstone. This conglomeratic facies extends up to 822.88 mbsf, giving a thickness of 6 cm.

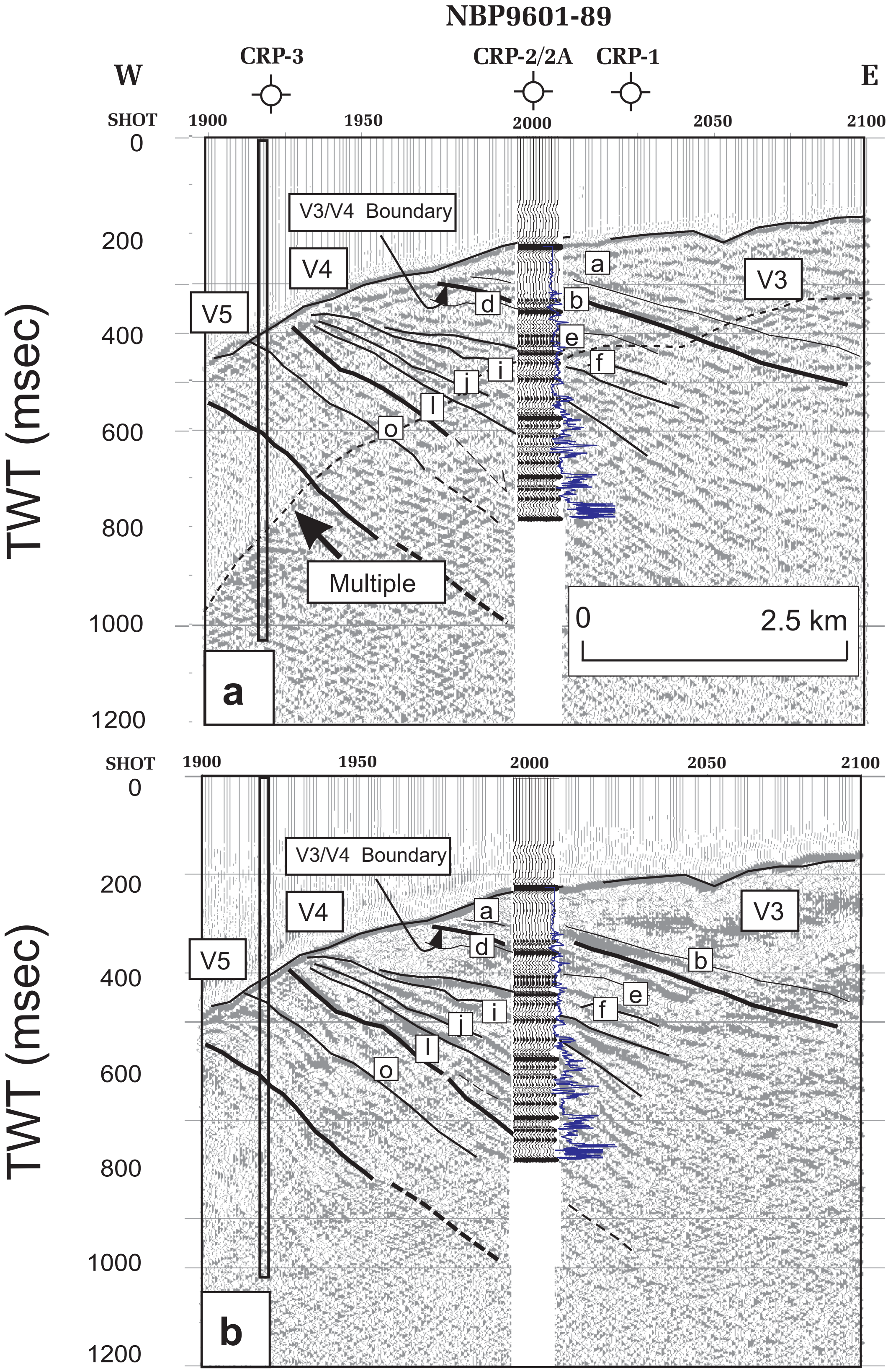


Fig. 7.1 - Section of seismic profile NBP9601-89 showing detail of the overlap of CRP-2/2A and CRP3 with synthetic seismic data and measured velocity log from CRP-2. Note the truncation of reflectors by reflector "l" in the re-processed multichannel data (b), which is not evident in the single channel data (a).

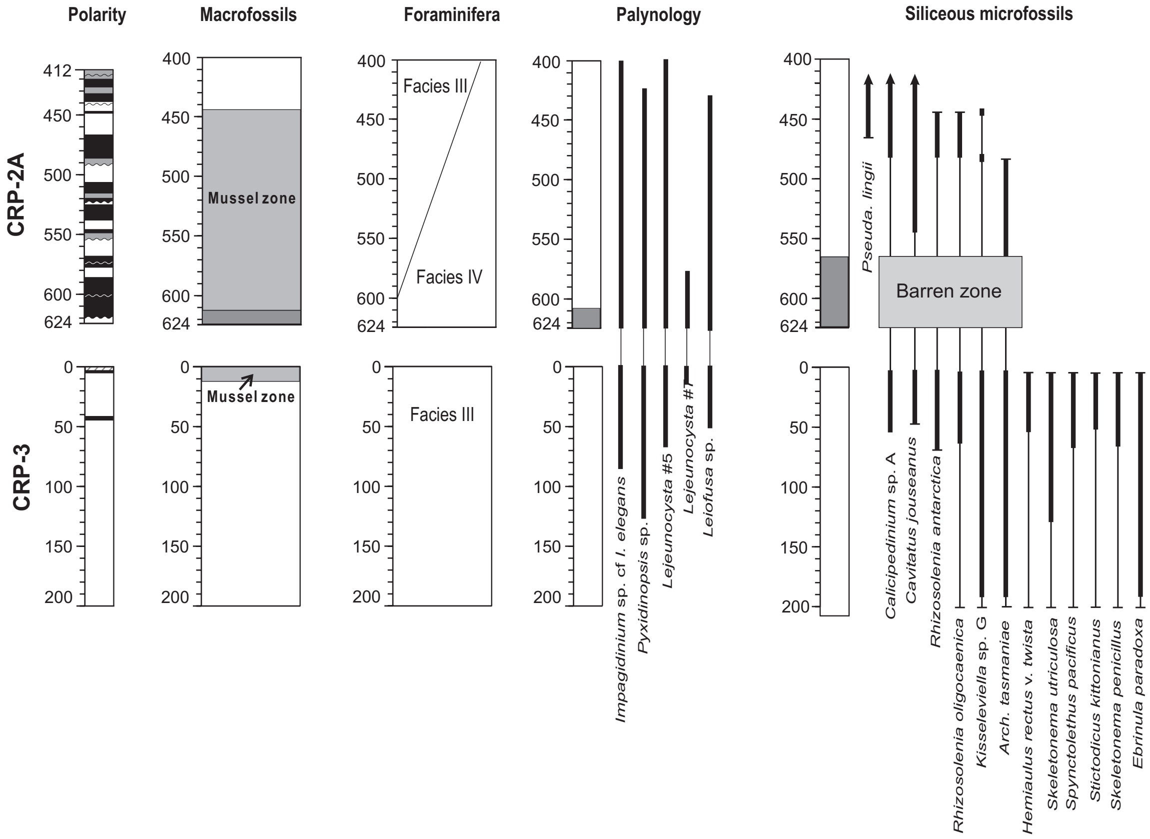


Fig. 7.2 - A compilation of palaeontological and magnetostratigraphical data from the upper 200 m of CRP-3 and the lower 224 m of CRP-2A. The data indicate a varying degree of possible overlap (dark grey boxes) with each set of data. Magnetostratigraphy provides the strongest indication that little to no overlap is possible.

Depositional Processes and Environment

The angular and unsorted nature of the monomictic breccia suggests that it is unlikely to have been transported by water. It is inferred to be talus, deposited adjacent to steep topography. The erosionally overlying monomictic conglomerate has undergone some degree of aqueous transport, resulting in the rounding of clasts, but has a poorly-sorted matrix, suggesting that there has been minimal sorting and transport has been only for a short distance. Deposition from a debris flow or sheet flow on an alluvial fan, adjacent to steep topography, is inferred.

LITHOFACIES ASSOCIATION 2: CLAST-SUPPORTED CONGLOMERATE, WITH MINOR THIN SANDSTONES

This lithofacies association extends from 822.88 to 789.77 mbsf, a thickness of 33.11 m. The conglomerate (mainly Facies 9), is dominated by well-rounded boulders and cobbles of dolerite, some over 1 m in diameter. However, smaller clasts of Beacon Supergroup quartzose sandstone are included, particularly towards the base. The base of the unit rests on an erosion surface of irregular relief cut into the underlying quartzose conglomerate of Association 1. The basal conglomerate is clast-supported, and exhibits coarse-tail coarsening-upward over about 85 cm. At the base, clasts are less than 1 cm across and are an admixture of rounded dolerite and quartzite which coarsen upward into angular blocks of quartzitic sandstone and larger rounded dolerite boulders now supported by matrix. Dolerite clasts in the lower few centimetres appear altered, and may have been subjected to weathering processes.

The bulk of the association, however, consists of rounded and subordinate subrounded and subangular, clast-supported boulders and cobbles. These are dominated by dolerite but with subordinate sandstone clasts. Sandstones are quartzose, angular to subangular and up to 70 cm across. They decrease in proportion upward until they are absent in the upper half of the unit. Interspersed with the conglomerate beds in the lower half of the assemblage are thin (up to 50-cm thick), medium to coarse-grained sandstone beds of Facies 5, many showing reverse grading.

A change in the succession occurs from approximately 804 mbsf, the upper portion of the association, where quartzitic sandstone clasts are lacking and where the conglomerates include more matrix, in some instances becoming matrix-supported. Interbedded thin sandstones

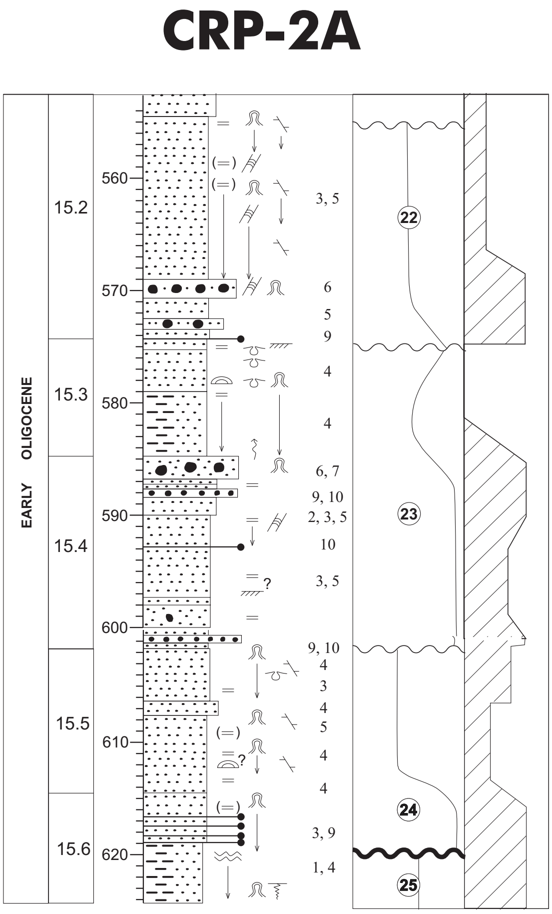
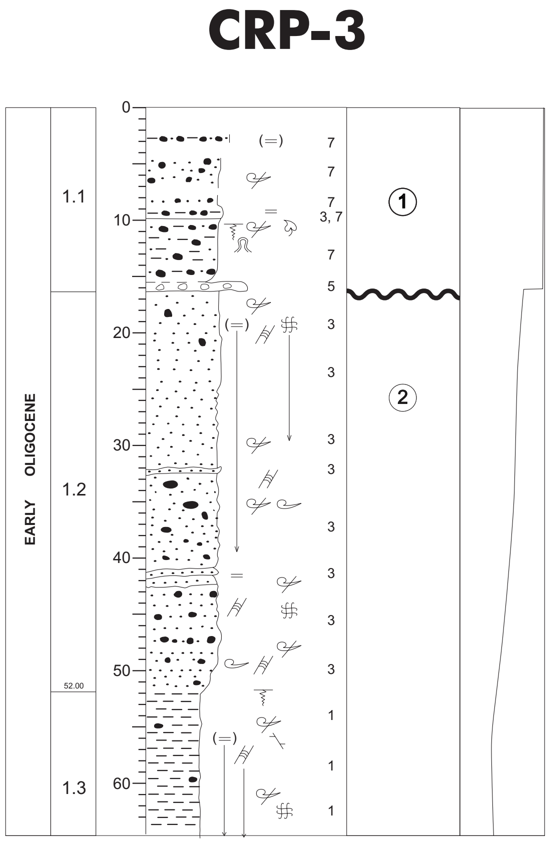


Fig. 7.3 - Comparison of lithologic logs and sequences of the lower 60 m of CRP-2A and the upper 60 m of CRP-3 showing differences that support the absence of overlap between the two drill holes. For a key see appendix 3.1 in the chapter on Lithostratigraphy and Sedimentology.



appear muddy, and there are mudstone horizons interbedded with the conglomerates. Clasts are dominantly well-rounded dolerite, but rounded pebbles of mudstone are also present. In the interval from 789.77 to 805.60 mbsf shearing has caused many of the clasts to be veined and fractured, and the matrix is cataclastic and slickensided.

This interval, described as a dolerite (cataclastic) breccia on the 1:20 scale core logs, displays evidence of intense shearing and fracturing. We initially considered the possibility that the clasts could be the result of fracturing and shearing of a dolerite body. However, studies of clast roundness characteristics (see section on Clast Features) indicate that the body is primarily a sedimentary deposit that has been subsequently modified by shearing. The presence in it of sedimentary clasts, and the occurrence of spores and pollen together with woody material and tissue (see section on Palynology) further support this.

Depositional Processes and Environment

Clasts in the association are well-rounded, suggesting that water transport has played a major part in depositional processes. However, the continued but declining presence

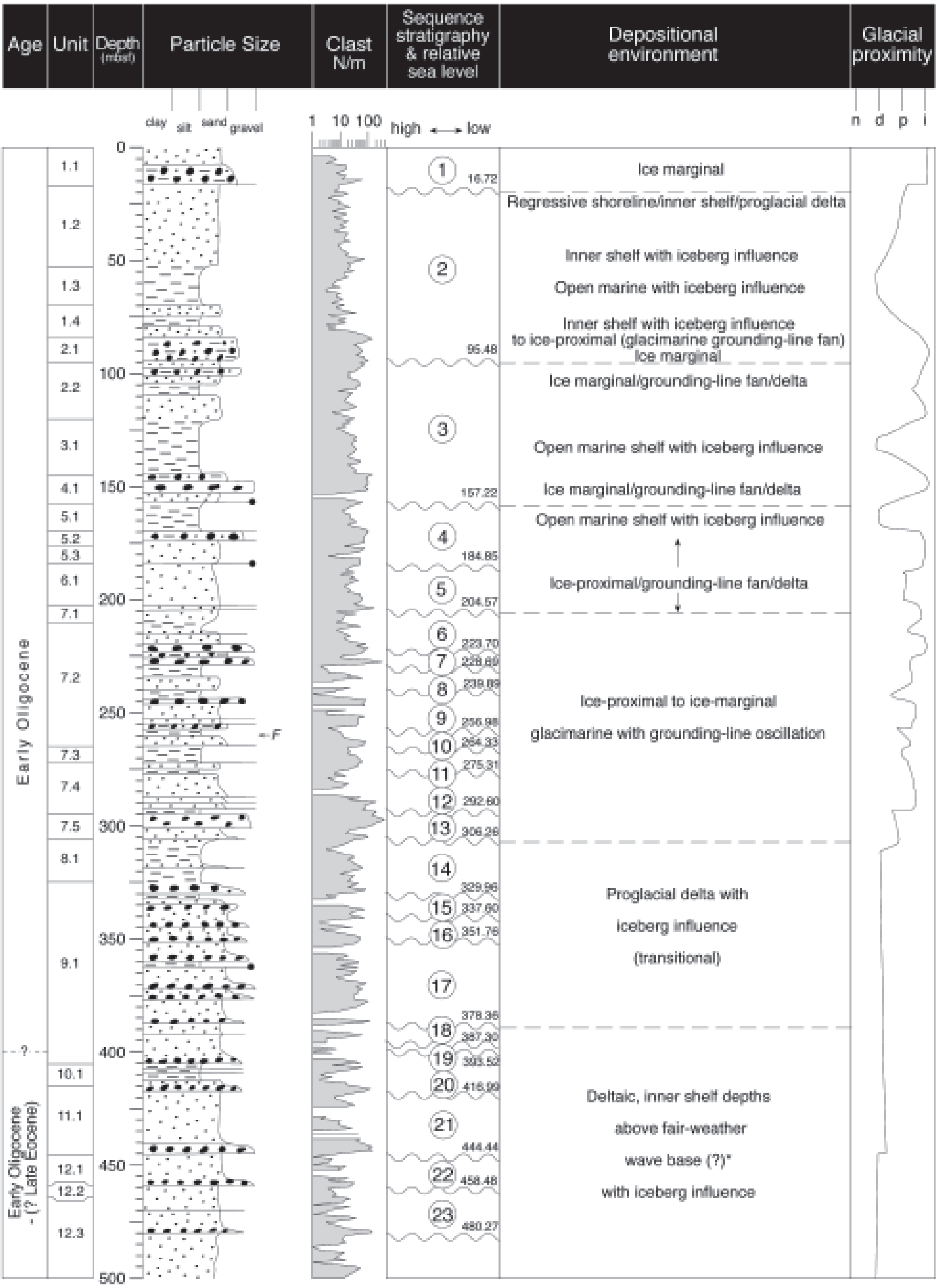


Fig. 7.4 - Stratigraphical summary and interpretation of the CRP-3 core. For *, see text for alternative minority opinion.

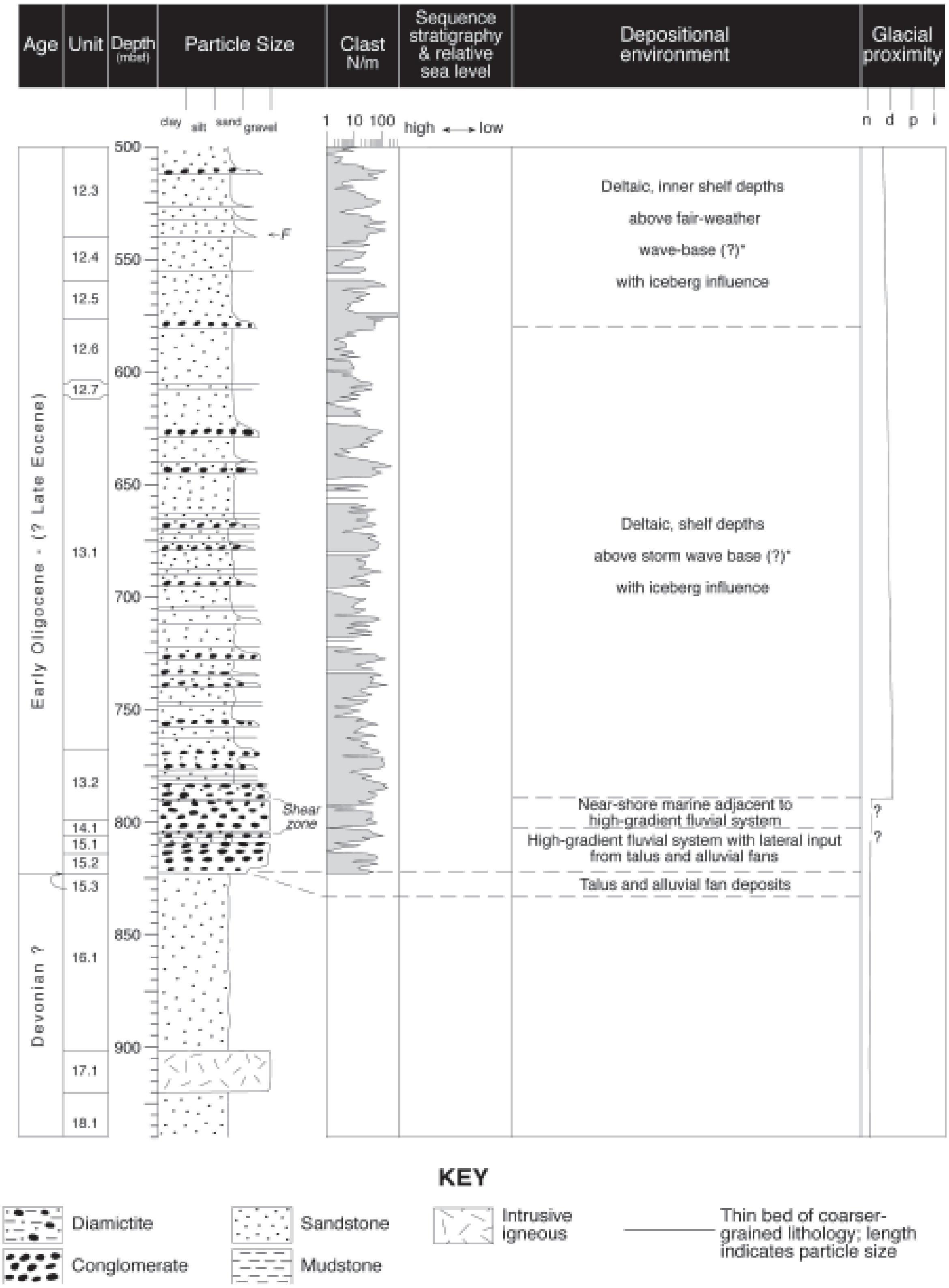


Fig. 7.4 - continued.

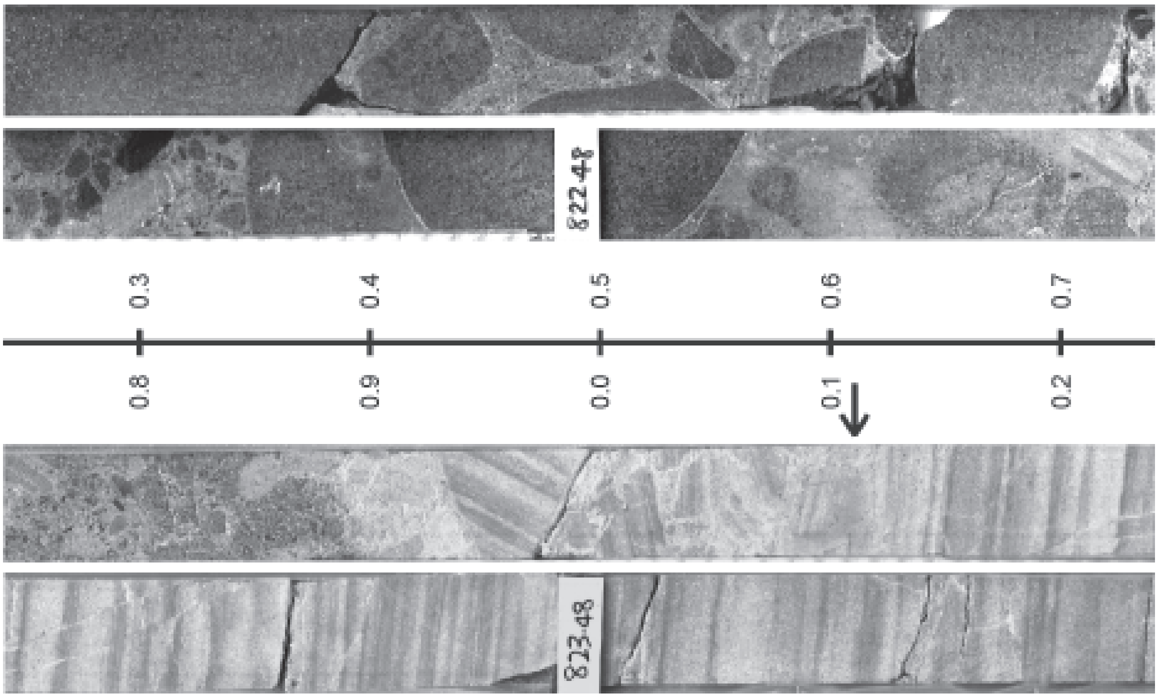


Fig. 7.5 - Core image of the basal unconformity (arrowed) of the Victoria Land Basin at 823.11 mbsf in CRP-3. Strata beneath the unconformity are laminated quartzose sandstone of the Beacon Supergroup. The unconformity is overlain by thin (17 cm) clast-supported sandstone breccia followed by 6 cm of matrix-supported fine conglomerate. This is overlain by, and in sharp contact with, a much thicker sequence of rounded and clast-supported cobbles and boulders, mainly of dolerite. The scale is in metres and keyed to the depth tags, which are in mbsf.

up the core of angular clasts of quartzitic sandstone, many in discrete layers, throughout the lower half of the succession, indicates that local debris showing little sign of transport (talus?) was still being shed into the environment. Similarly, thin reverse graded beds of monomictic quartzose sandstone are inferred to be local debris flow deposits on alluvial fans. However, the dominant lithofacies of large, well-rounded, clast-supported dolerite boulder conglomerate, suggests a fluvial environment with sufficient energy to remove fine grains and to transport boulders in excess of one metre. The environment of deposition for the lower part of the succession is inferred to be a high-gradient fluvial system accessing a dolerite source area, with lateral input from more local alluvial fans and talus slopes fed by cliffs of quartzitic sandstones of the Beacon Supergroup.

Upcore from approximately 804 mbsf quartzose sandstone clasts are absent and the quartzose sandstone component is limited to thin, stratified units and conglomeratic matrix. Concomitantly, mud becomes a major matrix component. Although large quantities of gravel and boulders were transported and deposited, the environment was quiet enough to allow mud and fine sand to accumulate occasionally. A fan-delta consisting of a steep-gradient fluvial system debouching into the sea is a possible environment for these deposits.

LITHOFACIES ASSOCIATION 3: MUDDY SANDSTONES WITH SUBORDINATE CONGLOMERATES

The massive, clast-supported conglomerates end at 798.77 mbsf, above which are pebble to cobble conglomerates and pebbly sandstones up to approximately 767.70 mbsf. Upcore from that sandstones become slightly muddy (Facies 3), with subordinate, mainly matrix-supported conglomerates (Facies 10) up to about 580 mbsf. Conglomerates become a minor constituent in the upper portion of this association between approximately 660 and 580 mbsf. The association also includes rare intervals of moderately to well-sorted sandstones of Facies 4 and 5, as far as 580 mbsf, incorporating LSU 13.1 and 13.2. The lithofacies association forms a generally fining upward succession, with conglomerates and pebbly sandstones dominating in the lower third, grading up to a sandstone-dominated succession. Soft-sediment deformation occurs sporadically throughout the association, most commonly throughout the lower half, associated with a higher mud content.

The slightly muddy sandstones range from vaguely stratified to well-stratified, dominated by parallel lamination, but also with intervals of ripple cross-lamination and cross-stratification. Convex-upward and low-angle divergent laminae, particularly between 767 and 744 mbsf, may represent hummocky cross-stratification. Soft-sediment deformation is present locally within the muddy fine-grained sandstones. Sandstone beds commonly show a generally fining-upward trend from a thin layer of fine gravel or granules at the base, often with rapid transition upwards through increasingly finer sandstone, in many cases with good cross lamination. Thickness of individual sandstone beds ranges up to 2 m.

Although the sandstones appear muddy macroscopically, microscopical examination of some samples suggests that the clay cement filling the interstices between grains is diagenetic and derived from post-depositional fluids (see section on Diagenesis), rather than it being modified primary matrix. Thus, at the time of deposition many of the sands were probably clean.

Many conglomerates, particularly in the lower portion of the association, show grading to sandstone in their uppermost few centimetres. A few are symmetrically graded or ungraded. In the upper portion of the association, many conglomerates have gradational contacts, although sharp-based conglomerates also occur. Individual conglomerate beds range up to 4 m thick.

Marine palynomorphs and a macrofossil occur in the lowest part of the association at 781 mbsf, showing that this part of the section at least is marine. Striated clasts occur at several locations throughout the association (see section on Clast Features). Outsized clasts, some of which are angular, occur in every lithofacies (see section on Clast Features), and angular gravel forms a constituent in most conglomerates. It also occurs as isolated clasts on bedding planes of well-sorted sandstones. Soft-sediment deformation is relatively common, particularly in the lower half of the succession.

Depositional Processes and Environment

The depositional environment is clearly marine, at least at 781 mbsf, because of the presence of marine fossils.

The common occurrence of thick, poorly-sorted matrix-supported conglomerate units, many showing crude grading in their upper portions, and the absence within the conglomerate units of traction features, suggests deposition by sediment-gravity flows. A number of conglomerate units are graded throughout and were probably deposited by debris flows or high-density turbidity currents.

Likewise, the fining-upwards trend evident in many of the sandstone beds may also indicate deposition from sediment-gravity flows. Alternatively, they may represent deposition in offshore bars, or deposition by periodic floodwaters from a feeder fluvial system. The slightly muddy nature of sandstones and the presence of soft-sediment deformation suggest rapid sedimentation and entrainment of water and fines.

Of alternative depositional environments, the most probable is relatively shallow water. The site was probably not very distant from a debouching high-gradient fluvial system, whence periodic floodwaters brought both coarse and fine sediments. This system may have been a glacifluvial outwash plain fed by glaciers up-valley to enhance episodic discharge. In this scenario sediment was entrained as high-density turbidity currents or debris flows either by the flood waters themselves, or by retrogressive failure and slumping from a delta edge down a delta front (*e.g.* Carlson et al., 1989, 1992). Both finer-grained delta-top sandstones and sandy delta front deposits were likely to have been above storm wave base, as indicated by both hummocky cross-stratification, which is generally inferred to be representative of storm deposits and therefore formed above storm wave base (Harms et al., 1975), and common cross stratification. These structures suggest that wave action, including storm-wave action, sorted and redeposited the finer-grained deposits.

A minority of us considered that both the conglomerates and the thick fining-upward sandstone units constituted turbidites, which frequently show an array of sedimentary structures formed during a declining flow regime arranged as Bouma sequences, although all intervals are not always present. The volume of sediment transported to form each unit and the cobble size of the coarsest debris was thought to require a gravity-driven mechanism of deposition, probably episodic, high-volume, high-density turbulent flows. A laterally extensive slope was thought be required to provide acceleration for the flowing suspension, and a base of slope setting in relatively deep water was suggested.

Whatever the primary environment, it was under some glacial influence in the form of iceberg rafting. Outsized and angular clasts are incongruous in the primary depositional environments envisioned for this association and indicate that glaciation in Antarctica at this time was sufficiently strong to support glaciers to sea level somewhere in the region.

LITHOFACIES ASSOCIATION 4: CLEAN SANDSTONES WITH SUBORDINATE CONGLOMERATES

The muddy sandstones of Association 3 die out gradationally upwards, and are replaced increasingly by beds of clean fine- to medium-grained sandstone of Facies 5. The first thick units of clean sandstones appear at approximately 580 mbsf and persist until about 340 mbsf. However, from about 364 mbsf upwards, intercalations of mudstone and slightly muddy sandstone begin to appear and become more common upwards; the first diamictites also appear.

The dominant lithofacies is light-coloured, clean, fine- to medium-grained sandstone, with minor pebbly sandstone to pebble conglomerate. The sandstones are clean, without a muddy matrix, and are dominantly well-sorted with equigranular well-rounded quartz grains. A minor component consists of clean but poorly-sorted subangular to subrounded quartz grains, some with a coating consisting of a clay mineral which gives a greenish-grey hue to the sediment. Most beds exhibit vague to well-developed parallel stratification. Cross-bedding is common, and low-angle divergent laminae, coupled with apparent convex-upwards lamination at 520 and 558 mbsf, may indicate hummocky cross-stratification. Mottling, possibly representing burrowing, is present at scattered horizons. Other evidence of life is limited to extremely rare and questionable macrofossil fragments. However, thin-section study of the clean sandstone reveals that it is strongly cemented with calcite (see section on Diagenesis), some of which may have been derived from detrital shelly material.

As in Association 3, sandstone beds commonly show a generally fining-upward trend from a thin layer of fine gravel or granules at the base. The fining often occurs as a rapid transition upwards through increasingly finer sandstone with moderate to well-developed planar lamination.

The subordinate conglomerates are poorly-sorted, matrix- to clast-supported, with a matrix of fine-grained sandstone, and contain angular to well-rounded clasts consisting almost entirely of dolerite. Conglomerate beds commonly have sharp bases and frequently show crude normal grading, consisting either of coarse-tail grading, or of massive conglomerate passing with rapid transition upwards into laminated sandstone.

As for Association 3, outsized clasts occur in association with angular clasts isolated on bedding planes of the well-sorted sandstone, and within conglomerates. Striated clasts also occur rarely (see section on Clast Features).

Depositional Processes and Environment

Shelly material is rare, and possible bioturbation is limited to two stratigraphical intervals. However, the widespread occurrence of carbonate cement suggests that more shelly material may have originally been present, although it does not account for the quantity of cementation. A marine environment is inferred for the association.

The architecture of the sandstone and conglomerate facies are very similar to those in Association 3. The main differences are that many of the sandstones are well-sorted and are carbonate cemented rather than clay cemented, and that conglomerates form a much lower proportion of the sediments. The low mud content of Association 4 compared with Association 3 is emphasised by the relative scarcity of soft-sediment deformation.

The sediments of Association 4 were most likely to have been deposited in a shallow-water marine setting. This was probably shallower than Association 3 because the apparent cleanness and better sorting of the sandstones and the much more common large-scale cross-bedding suggest a greater influence of wave or current activity. Again, the possible occurrence of hummocky cross stratification suggests that the succession was deposited above storm wave base. Deposition as delta-front deposits seems probable. The graded conglomerates may have been deposited, as for Association 3, as high-density turbidity currents or debris flows forming delta-front deposits.

A minority view considers that, as for Association 3, both the conglomerates and the thick fining-upward sandstone units were likely to have been deposited as sediment gravity flows in deeper waters considerably below wave base.

Association 4 is under iceberg influence as described for Association 3, with glaciers probably supplying much of the sediment for the association from further inland.

LITHOFACIES ASSOCIATION 5: MUDDY SANDSTONES AND MUDSTONES, WITH SUBORDINATE CONGLOMERATES AND DIAMICTITES

Above *c*. 378 mbsf, the nature of the sediments changes significantly. They become notably more muddy, with thick units of mudstone (Facies 1) and poorly-sorted, muddy, very fine to coarse-grained sandstone of Facies 3. Moderately sorted, stratified or massive, medium- to coarse-grained sandstones of Facies 5, and matrix-supported conglomerates of Facies 10 form subordinate but important units. The new and significant facies is massive diamictite of Facies 7, which occurs with increasing frequency and unit thickness towards the top of the drillcore.

Association 5 is also notable for the common occurrence of trace fossils and shelly fossils, including unbroken shells. Soft-sediment deformation structures are also common throughout; cross stratification is rare.

Units of mudstone, often with shelly fossils and burrow mottling, are up to 24-m thick. The mudstone is commonly sandy, stratified at a decimetre scale, and contains dispersed clasts. Soft-sediment deformation and water-escape structures are common. Lonestones locally appear to penetrate underlying laminae.

Fine-grained muddy sandstone with dispersed clasts is also common, grading locally into clast-poor, sandy diamictite. The dispersed clasts are dominated by dolerite, with granule-sized coal fragments and small clasts of granitoids appearing intermittently. Various forms of soft-sediment deformation are common to pervasive, including load casts, load balls and deformed bedding, sedimentary dykes and water-escape structures. Some sandstone beds show loading into underlying mudstones, and slumping is evident at some horizons.

Conglomerate units are commonly matrix-supported, and moderately to poorly-sorted with angular to rounded clasts. Crude upward-fining, with coarse-tail grading in conglomerate beds which may be in excess of 1-m thick, is relatively common. Diamictites, some in excess of 6-m thick, occur sporadically throughout the facies association, but are most common in the upper part. They vary from clast-poor sandy to muddy diamictite, which is commonly weakly stratified to locally massive, and muddy sandstone with dispersed clasts.

Depositional Processes and Environment

The depositional environment is clearly fully marine, as shown by the common presence of macro- and microfossils, trace fossils and frequent bioturbation. Foraminiferal studies in the section of core from 0 - ~200 mbsf suggest that deposition occurred in mid- to outer-shelf depths (50-200 m: see section on Foraminifera); and study of macrofossils in the section of core from 16.72-300 mbsf indicates deposition within much the same range (30-120 m: see section on Macrofossils). Macrofossils from the uppermost part of the core (0-16.72 mbsf) suggest slightly increased depth ranges between 100-300 m.

Probably the most critical lithofacies from the point of view of environment is diamictite, which in previous Cape Roberts drillcores has been interpreted mainly as having a direct or indirect glacial origin. The diamictitic character may originate from debris-flow deposition primarily originating from ice-contact deposits, or some units, especially those that grade into and out of massive diamictites, may be from direct rain-out of ice-borne debris that is then acted on by currents. Alternatively, subglacial tills can exhibit these types of structures. Massive diamictite is the facies most likely to be of subglacial origin, although it too may originate from debris-flow processes associated with ice contact, or rain-out processes. Based on the association of other lithofacies with diamictites, the subglacial origin for diamicts thus far appears unlikely.

Conglomerate units which show coarse-tail grading are inferred to be debris-flow deposits, either directly associated with ice-marginal processes, or deposited at the base of locally developed slopes. Slump structures and other evidence of downhill creep within muddy sandstone and mudstone facies also suggest the presence of a slope or glacial pushing or overriding. The combination of Lithofacies 2 and 8 is common in ice-proximal glacimarine settings associated with grounding-line fans and subglacial stream discharges (Powell, 1990).

Many sandstone beds that are ungraded and show poor lamination are inferred to be the results of deposition by traction currents. Others, which show some grading and which are loaded into underlying mudstones, show indications of rapid deposition and entrainment of water, causing soft-sediment deformation and suggesting emplacement by sediment gravity flow.

These facies are interpreted in terms of deposition in glacimarine and open coastal/shelf environments by a combination of traction currents, fall-out from suspension, sediment-gravity flows and rain-out from icebergs. Proximity to a glacial terminus is inferred to account for deposition of diamictites, conglomerates and associated Lithofacies 2 and 8. Better-sorted sandstones are likely to have been deposited in a relatively shallow marine environment, possibly as delta top or delta front deposits. The periodic occurrence of diamictites suggests a cyclic history of glacial advance and retreat for the period of time covered by Association 1. Based on the inferred degree of meltwater influence on the succession, a cool-temperate to sub-polar climate is inferred, similar to that at the base of CRP-2/2A.

BASIN HISTORY

The genesis of the western margin of the Victoria Land Basin is encapsulated in the first few centimetres above a sharp, nearly planar contact with basement Beacon Supergroup quartzose sandstone at 823.11 mbsf. This contact, which is an unconformity, is overlain by a thin sequence of breccia and conglomerate composed of Beacon Supergroup sandstone, and inferred to represent debris deposited on talus and alluvial fans (Lithofacies Association 1). These deposits imply a steep topography in a subaerial environment, probably caused by vertical movement on boundary faults during the initial phase of Victoria Land Basin rifting.

These earliest deposits are followed by a sedimentary system dominated by conglomerate deposited initially in a high-gradient fluvial system, and then in close-inshore marine conditions. This association (Lithofacies Association 2) suggests sedimentation on a subaerial to marine fan-delta system as an adjacent fault scarp(s) erodes and continued basin subsidence occurs.

The overlying deposits are dominated initially by conglomerates and granular sands and then by a mixture of conglomerates and muddy sandstones (Lithofacies Association 3). This association records a phase of rapid subsidence and basin infilling indicating high sedimentation rates. Some sedimentary structures in the sands may suggest that the basin floor was mainly within shelf depths, and at times probably shallower than storm wave-base. The basin appears to be shallower from about 580 m upwards, containing an abundance of clean, well-sorted sand with common traction current features, and only a minor conglomerate component (Lithofacies Association 4). We infer that the nature of these sediments reflects a decline in the pace of subsidence, allowing the basin to fill to a higher level. The pace of uplift also declined slightly, resulting in lower gradients and dominant deposition of sand, in a shallow-marine environment with active current and wave activity possibly above fair-weather wave-base.

The common rounded pebbles in pebbly sandstones and conglomerates in both lithofacies associations suggest derivation from a nearby fluvial system, and deposition was probably on the marine portion of a delta. Sediment gravity-flows were triggered either by floods in the fluvial system, or by seismic activity along the active adjacent fault system, and deposited as delta front sands and conglomerates: the well-sorted sands were deposited largely on the delta top where they were exposed to winnowing wave and current action. The primary environment was under some glacial influence in the form of iceberg rafting, indicating that glaciation at this time was sufficiently strong to support glaciers to sea level somewhere in the region.

From about 380 mbsf upwards, the nature of the sedimentary record changes. Well-sorted clean sands become rare and are replaced by muddy sands, and mud, diamictites and conglomerates become more prominent upcore (Lithofacies Association 5). Soft-sediment deformation and fluid-escape structures become common, and rare slumps occur. Water depths indicated by the fossil record are mainly in the mid to outer shelf range, although the top 16 m of core may be deeper, suggesting that the basin is generally deepening. The facies association indicates a glacimarine and open shelf environment, subject to cyclical glacial advances and retreats. Proximity to a glacier terminus is inferred to account for deposition of diamictites and conglomerates, associated with morainal banks and grounding-line fans. Although rapid sedimentation is suggested by the high water content of the finer-grained sediments, the apparent continued deepening of the basin indicates that subsidence was outpacing sediment.

TECTONIC HISTORY

BASIN HISTORY

CRP-3 cored the oldest part of the Cenozoic sequence off Cape Roberts, with biostratigraphical work showing that all of the core is of early Oligocene age, possibly extending into the latest Eocene at the base of the section at 823 mbsf. If we include the lower Oligocene strata in CRP-2A below the unconformity at 443 mbsf in CRP-2A, and accept a small stratigraphical gap between the two holes (see section on Chronology), we find that *c*. 1 000 m of lower Oligocene strata are present at the western edge of the Victoria Land Basin. Assuming the age at the base of the Cenozoic strata is *c*. 34 Ma, this represents at an average rate of net sediment accumulation *c*. 200 m/m.y.

The consensus view of the depositional setting for the CRP-3 strata is that all but the lowermost section is shallow marine. The consistency of the depositional setting, never far from the shoreline, suggests steady, rapid subsidence and an abundant sediment supply to fill the basin continuously. Although more chronological data and more complete palaeobathymetrical data are being gathered for a more rigorous and complete analysis (Wilson et al., in preparation), a diagram has been prepared to show the history of basin subsidence (Fig. 7.6). The diagram is presented as if for a stratigraphical column located at CRP-1, but is based on ages and thicknesses from all three CRP drill holes. The trend indicates rapid subsidence from *c*. 34 to 31 Ma, much slower subsidence from 31 to 16 Ma, and from that time no net basin subsidence to the present.

A subaerial erosion surface marks the basal contact between the lower Oligocene (or possibly uppermost Eocene) strata and underlying quartz sandstone interpreted to be part of the Devonian Taylor Group, the lower part of the Beacon Supergroup. The sandstone is considered most likely to be part of the Arena Sandstone, a formation that typically lies 400 to 600 m above the Kukri Erosion Surface (Barrett & Webb, 1973; Woolfe et al., 1989). This surface is a major regional unconformity separating Beacon strata from underlying upper Precambrian-Ordovician igneous and metamorphic basement rocks.

The presence of rift-basin fill resting directly on Devonian Beacon Supergroup strata has several important tectonic implications:

1) the major part of the Beacon section, the sills of Ferrar Dolerite within it and the overlying Kirkpatrick Basalt, must have been eroded prior to or coeval with the early phases of down-faulting that displaced the Beacon to form the rift-basin floor;
2) the age of the Cenozoic strata just above the unconformity on the Beacon most likely represents the age of the rifting event that formed this section of the Victoria Land Basin. USGS seismic line 403/404 shows that almost most of the floor of the basin off Cape Roberts is younger than the oldest Cenozoic strata cored in CRP-3 (Fig. 7.7), and
3) the Beacon strata cored in CRP-3 provide a marker horizon that can be matched with reasonable confidence to the middle part of the Devonian Beacon strata in the adjacent Transantarctic Mountains. This suggests *c*. 3 000 m of down-to-the-east displacement across the Transantarctic Mountain Front (Fig. 7.8).

A key result of CRP drilling has been the demonstration that most of the regional seismic sequences originally correlated through the Victoria Land Basin by

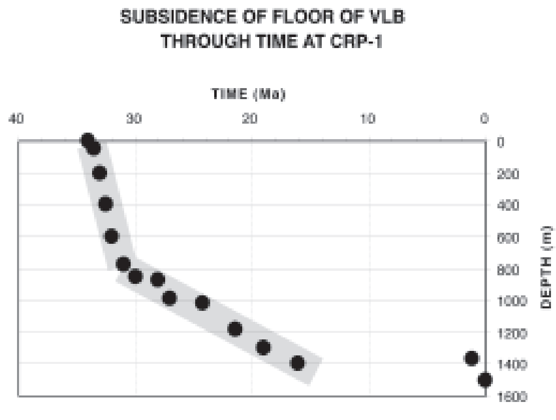


Fig. 7.6 - Diagram showing the subsidence of the floor of the Victoria Land Basin at CRP-1 through time, projecting data from CRP-2 and CRP-3 to the CRP-1 site. No account has been taken of compaction, or of the many unconformities. The diagram shows a short period of rapid subsidence from 34 to 31 Ma, followed by a longer period of slower subsidence to 16 Ma with virtually no net subsidence from that time to the present day.

Tab. 7.1 - Comparison of ages for seismic sequences inferred from regional geological data in 1987 compared with the ages established from Cape Roberts core. Ages from the core are found to be much younger than expected.

Sequence	Cooper et al., 1987	Cape Roberts Science Team
V1	E.-M. Miocene to Present	Quaternary
V2	Late Oligocene to E.-M. Miocene	?
V3	Paleogene to late Oligocene	E. Miocene at base
V4	Paleogene and/or older	Late Oligocene
V5	Cretaceous to early Paleogene	Early Oligocene (possibly latest Eocene)
V6	Paleogene to Holocene, & Jurassic to Paleogene	Late Oligocene-Holocene (McMurdo Volcs), & Jurassic (Ferrar Supergroup)
*V7	Precambrian to E. Paleozoic	Precambrian to E. Paleozoic

Cooper et al. (1987) are much younger than was inferred from the regional geology (Tab. 7.1). The V4/V5 sequence boundary was transected in CRP-2A at *c.* 443 mbsf, coincident with a upper/lower Oligocene unconformity (Henrys et al., in press). A series of seismic events, informally labeled o-v, have been identified from preliminary analysis of the vertical seismic profiling in CRP-3 and seismic reflection interpretation (see section on Correlation of Seismic Reflectors). These reflectors must all mark lower Oligocene horizons, and all occur within the V5 seismic sequence, which extends to the floor of the basin a few kilometres east of CRP-1 on Roberts ridge (Fig. 7.7).

Seismic sequence V6 comprises the discontinuous to chaotic reflections that occur at shallow depths in some places and at large depths in the middle of the basin. It

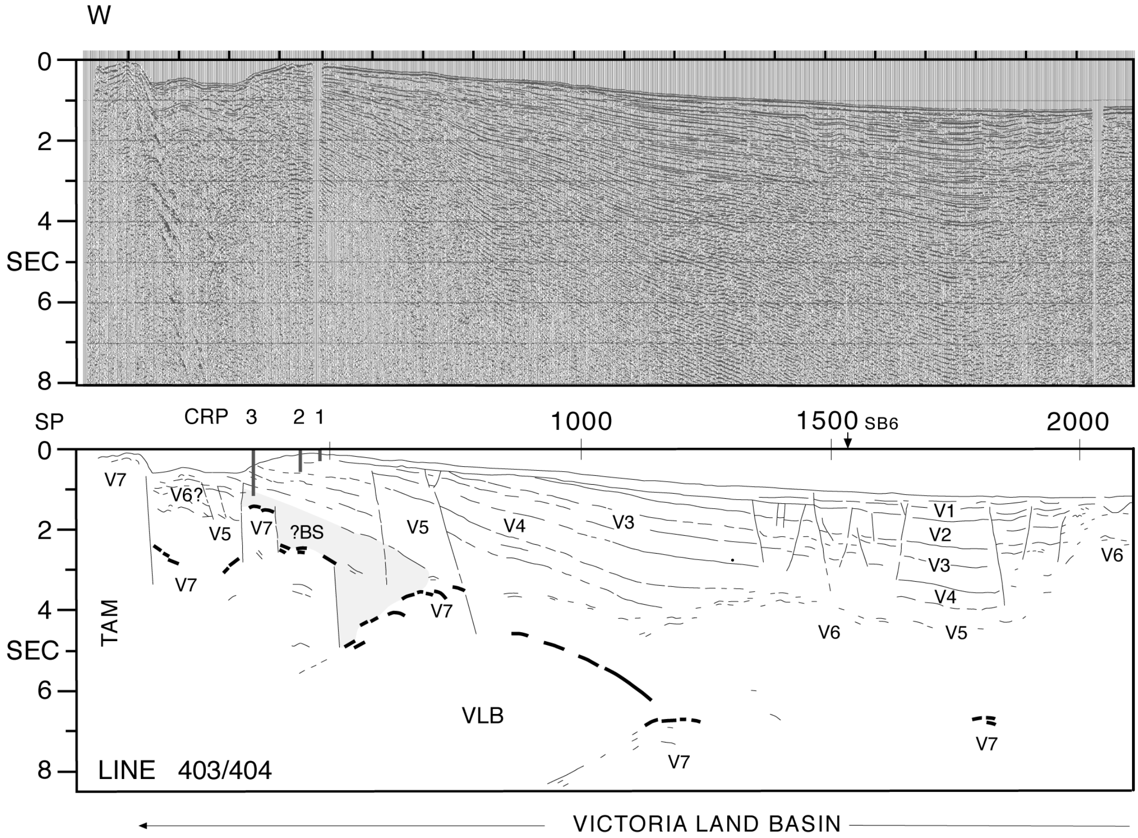


Fig. 7.7 - Seismic section showing the western margin of the Victoria Land Basin off Cape Roberts (from Cooper et al., 1987, plate 2). The 3 CRP holes are projected onto the section, which runs less than 2 km to the north. The section shows that the Cenozoic strata to be onlapping to the east, and indicates that CRP-3 cored into the oldest body of Cenozoic strata in the basin. As CRP-3 cored into lower Beacon Supergroup strata at 823 mbsf, we show the Beacon to underlie the Cenozoic sequence for several km eastward into the basin.

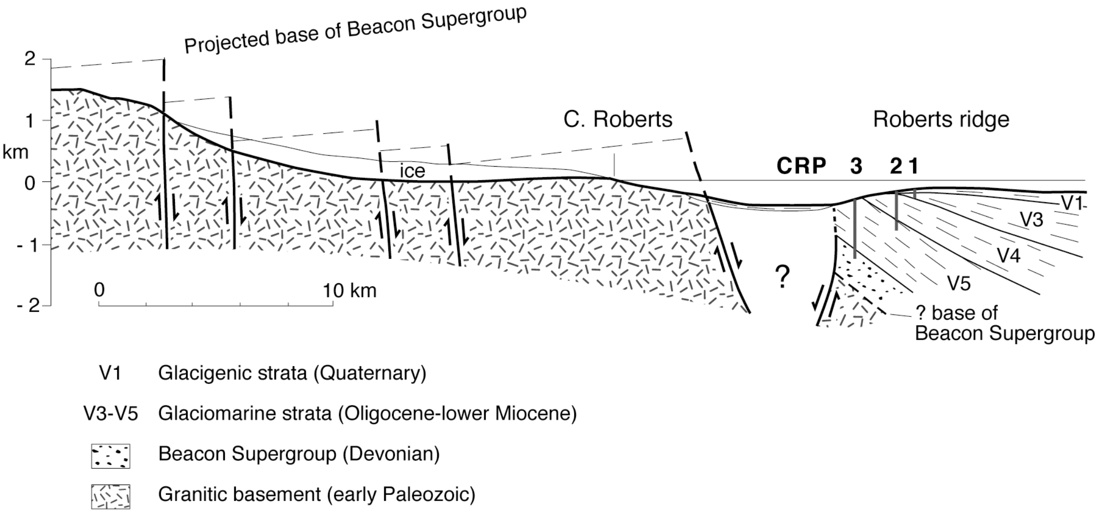


Fig. 7.8 - Schematic cross-section across the Transantarctic Mountain Front, showing our current view of the geometric relationship between the Cenozoic strata at the western margin of the Victoria Land Basin, the Beacon Supergroup strata beneath, and the granitic basement of the Transantarctic Mountains. The faults to the west of Cape Roberts, and their displacements, have been taken from Fitzgerald (1992, Fig. 21).

lies just beneath the sea floor off volcanic Beaufort Island, and hence is in part McMurdo Volcanic Group, but it was considered also to include Paleogene (as yet unsampled early rift volcanic rocks) or possibly Mesozoic (Ferrar Supergroup) at depth in the middle of the basin. It was not mapped west under Roberts ridge, where seismic sequence V5 rests directly on V7, but was tentatively inferred in the small graben with magnetic anomaly between Roberts ridge and the coast (Cooper et al., 1987, plate 2). Perhaps the intrusive body in CRP-3 is a sample of this unit.

Seismic sequence V7 is acoustic basement for the region, and comprises rocks that pre-dated the Victoria Land Basin. This unit was interpreted to include igneous and metamorphic rocks of Ordovician and older age, and probably the sedimentary Beacon Supergroup and the igneous Ferrar Group. V7 was inferred by Cooper et al. (1987) to lie at approximately 1.0 seconds TWT beneath the western margin of Roberts ridge, but CRP-3 cored into Beacon Supergroup strata, a unit previously considered part of the ‘acoustic basement’, at 823.11 mbsf, considerably shallower than the 1.0 second reflector (shown below CRP-3 in Fig. 7.7). We think, therefore, that the reflector identified by Cooper et al. (1987) instead marks the top of an igneous or metamorphic (or both) basement underlying the Beacon strata. On the seismic profiles in proximity to CRP-3, the region beneath *c*. 770 mbsf is obscured by a strong multiple, making it impossible at present to identify or trace reflectors that may correspond to the Oligocene/Beacon unconformity surface.

The dip pattern documented in CRP-2/2A, with gradually steepening dip with depth (Jarrard et al., in press), continues in CRP-3, where dips steepen from *c*. 10° up to *c*. 22° above the unconformity truncating the Beacon strata . The dip direction appears to be toward the east-northeast, based on preliminary interpretation of dipmeter and BHTV data. In addition, these log data, as well as analysis of bedding dip on whole-core scan images, indicate that there is little angular discordance between the Oligocene strata and the Devonian Beacon strata across the unconformity (the downhole logging data indicate that the dips are similar but the Beacon has a more northerly dip direction). This is surprising because in similar settings down-faulted strata typically dip toward the uplifted block.

East-west seismic reflection profiles also show a fanning array of stratal wedges that thicken to the east. The greater subsidence to the east indicates either growth faulting on a west-dipping, west-side-down normal fault zone, or greater thermal subsidence along the basin axis, or both. Regional seismic lines (Cooper & Davey, 1987; Brancolini et al., 1995) show that this east-dipping, eastward-thickening pattern continues at least to the eastern margin of the Terror Rift. Tracing the Oligocene seismic reflectors cored in CRP eastward, they disappear beneath the base of the seismic lines and indicate that over 8 km of Oligocene strata are present within the Victoria Land Basin.

IGNEOUS INTRUSION

An igneous body *c*. 16 m in vertical thickness intrudes the Beacon strata between 901 and 918 mbsf. The igneous rock is pervasively altered such that no original mineralogy is preserved. All four chemical analyses carried out are highly altered, but trace element ratios suggest a sub-alkaline chemical affinity, which excludes the McMurdo Volcanic Group (see section in Petrology).

Possible origins for the body are a previously undiscovered phase of the Jurassic Ferrar Dolerite, which forms extensive sills, and in places dykes, within Beacon strata cropping out within the Transantarctic Mountains, or a heretofore unrecognised episode of early rift-related magmatism (older than 34 Ma). An aeromagnetic survey over the Cape Roberts region documented a strong anomaly to the west and northwest of the CRP drill sites, modelled as a sheet-like igneous body (Bozzo et al., 1997). It is possible that the igneous body cored in CRP-3 is related to this body.

DEFORMATION

Naturally-formed microfaults are particularly abundant in the Oligocene strata cored in CRP-3. Most of the microfaults cutting the Oligocene strata are dip-slip normal. The density of small faults in CRP-3 records significant strain, suggesting proximity to one or more major faults. Three larger-scale faults of unknown displacement were cored in CRP-3. Faults at 260 and 540 mbsf are brittle faults characterized by veining and high-fracture permeabilities, whereas a third is inferred from a zone of shear between 790 and 806 mbsf that includes cataclastic features.

Striae on fault surfaces record a kinematic change down-core from consistent dip-slip motion to more complex oblique shearing within the shear zone below 790 mbsf. The oblique shear pattern is continuous into and is characteristic of the entire lower section of the core, including the Devonian Beacon sandstone. All observed faults above 823 mbsf cut strata of earliest Oligocene age, and must therefore be Oligocene or younger. It is not yet possible to say whether the two kinematic types mark discrete deformation episodes or, alternatively, whether all the deformation is the same age, but there is a partitioning of strain between different faults or with depth in the section.

The attitude of the larger-scale fault planes is hard to estimate. None close to CRP-3 can be seen in the seismic data. If the large faults are parallel to small faults imaged by the BHTV, it is possible that the fault at 260 mbsf dips eastward, and the fault at 790 mbsf dips westward. However, further analysis of seismic, log, and core-based data will be required to provide adequate constraints on orientation. VSP data provide 3 depths to the top of a strong reflector at 790 mbsf, indicating a plane dipping *c.* 10° to the east. This plane has the same depth and strike as the top of the sheared layer of coarse conglomerate found in the core at this level, though a shallower dip than estimated from well logs. The VSP data do not indicate any offset of strata by a fault through the drill hole at this level.

Both the Beacon strata and the intrusive igneous body are characterized by extensive faulting. Brecciation of the Beacon sandstone is also very common, associated with injections of clastic material. These deformation features are atypical of Beacon strata that crop out in the Transantarctic Mountains. The deformation is therefore likely to be due to rift-related down-faulting along the Transantarctic Mountains Front. This brecciation and mobilisation may also have been associated with intrusion-related hydrothermal activity.

PROVENANCE AND TRANSANTARCTIC MOUNTAINS UPLIFT

Petrological investigations in CRP-3 have revealed a continuation of compositional trends observed in CRP-1 and CRP-2/2A (Cape Roberts Science Team, 1998, 1999). The absence of fresh alkaline volcanic detritus below *c.* 300 mbsf (*c.* 25 Ma) in CRP-2A continues down to the oldest Cenozoic strata in CRP-3. However, this observation is tempered by the presence in CRP-3 of rare grains of fresh brown, green and colourless glass of unknown composition. If that glass is alkaline in composition, its scarcity and the very fine size of the fragments suggest that it represents products of eruptions from a volcanic source distant from the McMurdo Sound region. Possible sources include the alkaline volcanic centres in northern Victoria Land.

The uppermost 200 m of CRP-3 is dominated by clasts of Ferrar Supergroup (dolerite and basalt). The sand grains also show peak values for clinopyroxene, which has its sole source in the Ferrar Supergroup in CRP-3. In the bulk mineralogy XRD study, feldspar/quartz (F/Q) ratios are high and alkali feldspar/quartz (K/Q) ratios are low, indicating enhanced Ferrar-derived plagioclase above *c.* 200 mbsf. Below 200 mbsf, Ferrar clasts diminish in abundance, and there is a notable increase in the proportion of sedimentary rock types that were probably derived mainly from the Beacon Supergroup. This is also evident from sand grain modes, which are dominated by quartz grains (mean value for total quartz grains *c.* 82%), and reflected in diminished F/Q ratios from XRD study. The proportions of rounded grains (Qr/Qa>0.3) between 200 and 500 mbsf also has significance because this ratio offers a proxy for the relative proportion of rounded quartz grains contributed by the lower Beacon Supergroup (Devonian Taylor Group). These relationships suggest that the change at *c.* 200 mbsf represents a down-core shift from basement-dominated detritus to more detritus derived from the Beacon-Ferrar 'cover' sequence. Such a down-core shift was also recognised at the 307 mbsf unconformity in CRP-2A (Smellie, in press; Talarico et al., in press). The significance of its recurrence in CRP-3 is still unclear.

The sand-grain modes and XRD bulk mineralogy investigations also highlight a second possible petrological transition, although it is not supported by any evidence from the clast studies. At *c*. 550 mbsf, the sand mode and bulk mineralogy studies show a series of coincident compositional changes affecting samples below that depth. These include a diminished proportion of quartz and increased feldspar grains, much lower Qr/Qa ratios, higher F/Q ratios, and much lower K/Q ratios. These petrological changes suggest that the provenance has undergone a compositional shift to detritus dominated by material derived from the *upper* Beacon Supergroup (Permian–Triassic Victoria Group), which the sandstone resembles to a remarkable degree. Work is in progress to assess this view.

Coal fragments of sand and granule size have been observed in CRP-3 from 150 mbsf to a depth of 780 mbsf (see the Petrology chapter and the core logs in the Supplement to this volume). These extend up-section to the unconformity at 307 mbsf in CRP-2A. The coal is of high rank and almost certainly from the Weller Coal Measures, a 180- to 250-m-thick formation with coal beds totalling 10 to 35 m in thickness that today crop out *c*. 100 km to the west in the Transantarctic Mountains (see section descriptions in Barrett & Webb, 1973). Terrestrial palynomorphs of Permian, Triassic and Jurassic age also record a Beacon provenance (see section on Palynology). Some of these forms are much less thermally altered than palynomorphs from outcrops in the mountains, and they are, therefore, presumed to have been eroded from Beacon strata with a smaller proportion of intrusive dolerite, perhaps further inland. The provenance implications of the distribution of coal fragments and palynomorphs as compared with petrological provenance indicators are not clear, and plainly deserve further study.

IMPLICATIONS FOR REGIONAL RIFT HISTORY

The Cape Roberts site is only the second place along the Transantarctic Mountains rift shoulder where offset of Beacon strata along the frontal fault system can be directly demonstrated. At Cape Surprise, in the central Transantarctic Mountains near Shackleton Glacier, Barrett (1965) documented down-faulted Beacon at the coast, estimating 5 000 m displacement. At Cape Roberts, assuming a marker horizon at the level of the Devonian Arena Sandstone, the offset is estimated at *c*. 3 000 m.

Fission-track data from the Transantarctic Mountains in southern Victoria Land indicate that large-scale uplift commenced at *c*. 55 Ma (Fitzgerald, 1992). Although no lower Eocene strata are present at the Cape Roberts site, the unconformity documented in CRP-3 shows that a thick section of Beacon Supergroup and Ferrar Supergroup must have been eroded prior to the earliest Oligocene, and this erosion could have occurred during Eocene mountain uplift.

The great thickness of Oligocene strata that can now be demonstrated in the Victoria Land Basin shows that rapid basin subsidence began no later than the earliest Oligocene and possibly somewhat earlier, slowing significantly in late Oligocene and Miocene times. The Oligocene and younger faulting of the strata implies syn-depositional rifting, although the geometry of faulting remains to be determined. This major rifting event in the western Ross Sea is contemporaneous with, and very likely related to, newly documented sea-floor spreading in the Adare Trough, immediately north of the northern Victoria Land continental margin (Cande et al., 2000).

CONCLUSIONS AND FUTURE PLANS

Drilling of CRP-3 completes the coring planned for the Cape Roberts Project. With a depth of 939.46 m, it exceeded the target depth of 700 m by around 30% and created a new record for bedrock drilling in Antarctica. Core recovery was 97%, with losses mostly in the upper 10 m and occasional loose sand between 400 and 600 mbsf.

If CRP-2/2A fed largely the climatic goals of the project, with its fine record of early Miocene glacial cyclicity and the means of dating it, CRP-3 has provided a treat for the tectonic objectives, revealing

i) the total post-Jurassic offset across the margin of the West Antarctic Rift System off Cape Roberts (*c*.3000□m),
ii) the age and nature of the oldest sediment in this section of the Victoria Land Basin (34 Ma, conglomerate), and
iii) subsidence history for the life of the basin (rapid from 34 to 31 Ma, then slower to 17 Ma and with none at all after then).

Further work on analysis of fractures, along with core oriented from bore hole televiewer data, will contribute directions of movements from which changes in regional stress regime through time can be deduced.

The recovery of 116 m of Beacon sandstone and intrusive was significant not only in providing a reference plane for calculating offset across the margin of the West Antarctic Rift System, but also in showing that with CRP-3 the entire Cenozoic section off Cape Roberts had been cored. The seismic section figured by Cooper et al. (1987) had previously shown that these were the oldest strata in the basin (7.7). We can therefore conclude that there is no further point in coring off Cape Roberts to find the transition into strata representing warm Eocene times. The Eocene McMurdo erratics show that such strata do exist, but we must now presume that they occur only to the south of their current position (Minna Bluff, 150 km south of Cape Roberts), and must have been eroded from beneath the Ross Ice Shelf (Levy and Harwood, 1999).

Despite the discovery from CRP-3 that deposition began in the Victoria Land Basin just after the late Eocene cooling, there was some success in extracting a climate record from the core. The cyclic patterns recognised in the strata of CRP-2A continue down into the upper part of CRP-3. Below *c*. 300 m the motif

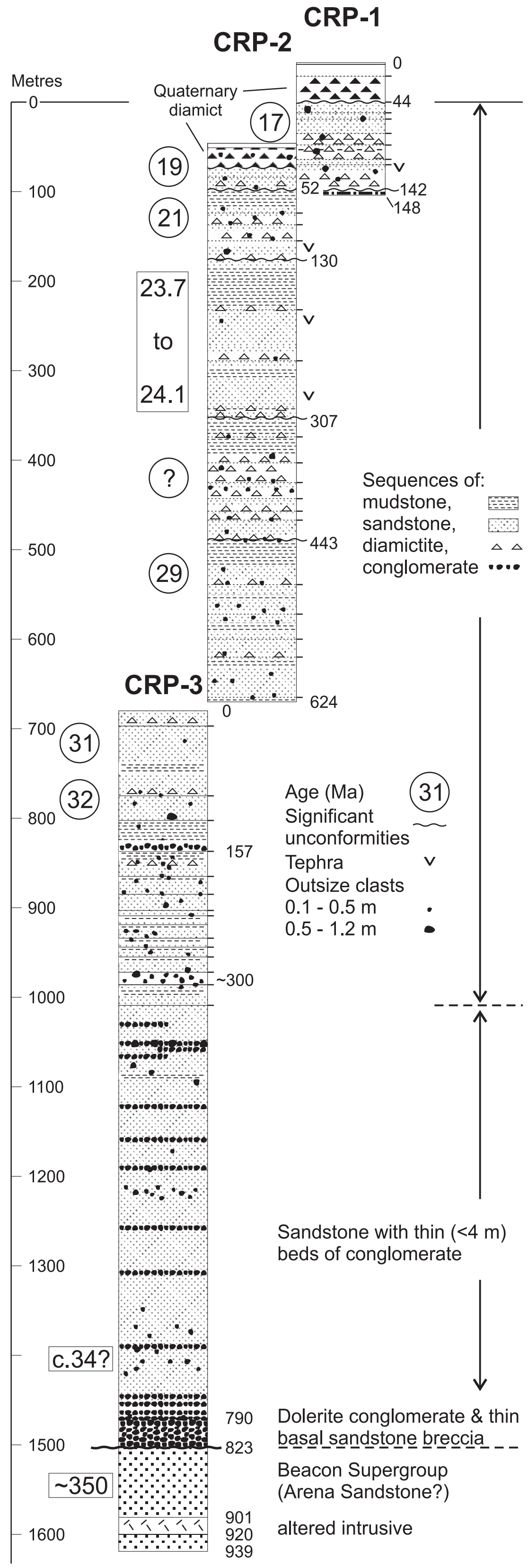


Fig. 7.9 - Composite stratigraphic section from CRP-1, 2A and 3 for the western margin of the victoria Land Basin. Lithologic data and stratigraphic data are from CRST (1998) and CRST (1999) and this volume. Chronology for CRP-2A from Wilson et al. (in press).

changes as sediment becomes coarser downhole to comprise largely sandstone with significant conglomerate beds. Much of the obvious glacial character of this lower section of core has been lost, but reminders persist in the occasional survival of small striated clasts, and the occurrence of isolated and out-sized clasts (>0.1 m) to within a few tens of m of the base of the Cenozoic section. Analysis of a range of biotic and lithological datasets will be important in reaching an understanding of the causes of the cyclicity but possibly none so important as the range of high quality downhole logs and core properties measurements that were recovered from almost the entire drillhole.

Biostratigraphical datums indicate that the upper 200 m of CRP-3 lies in the range 31 to 33 Ma, though deeper strata could also fall within this range. Virtually no siliceous or calcareous microfossils were found below this level in the initial survey, because of either dissolution or higher sedimentation rates or most likely both, though further searches are planned. Preliminary magneto-stratigraphic data suggest that the upper 350 m represents C12R – further work on this, and on Sr isotopes from shell material, which occur down to 350 mbsf, will help strengthen the chronostratigraphy in at least the upper part of CRP-3.

Despite the sparse biotic record, marine palynomorphs were extracted as far down as 781 mbsf, revealing further species (eventually to be part of a robust new biostratigraphical scheme for Antarctic margin sediments), but plainly not old enough to have included the warm Eocene Transantarctic Flora of Wilson (1967). Terrestrial palynomorphs, though sparse, also represent an important record of climate back to 34 Ma in the adjacent mountains, which at that time supported, near sea level at least, a relatively cold-climate, low diversity woody vegetation of low scrub or closed forest.

Work on tectonic, depositional, climatic, and chronostratigraphical aspects of the CRP-3 core will continue over the next few months, with results presented at a workshop in Columbus, Ohio, in September, 2000. These results will be published as contributions to the third and final volume of Scientific Results from the Cape Roberts Project in early 2001.

The 3 Cape Roberts drill holes have now cored a total of 72 m of Quaternary (and some Pliocene) strata, and a sequence around 1500 m thick (cored a total of 1523 m but with 31 m overlap between CRP-1 and CRP-2, and a gap of the order of no more than a few tens of m between CRP-2A and CRP-3) (Fig. 7.9; Tab. 7.2). In addition, CRP-3 cored 116 m into the bedrock floor of the basin. Recovery for the entire cored interval has averaged just over 95%.

As work continues on CRP-3, ODP Leg 188 is coring on the continental shelf and slope in Prydz Bay (Fig. 7.10), seeking an early glacial, and if possible a pre-glacial, record of climate from the other side of the continent. The search for more detailed paleoclimatic data is also the main justification for two further ODP legs proposed for

Tab. 7.2 - Data on cored strata at the three Cape Roberts drill sites.

	CRP-1 (1997)	*CRP-2/2A (1998)*	*CRP-3 (1999)*
WATER DEPTH	153 m	178 m	295 m
Depth to top of first core	15 mbsf	5 mbsf	2 mbsf
Quaternary (-Pliocene)	28 m	22 m	0
Older Cenozoic strata	105 m	597 m	821 m
Stratigraphical overlap between holes	31 m overlap between CRP-1 and CRP-2		Gap of m to 10s of m between CRP-2A and CRP–3
Basement			116 m
Recovery (avr – 95%)	86%	94%	97%
TOTAL DEPTH BSF	148 mbsf	624 mbsf	939 mbsf
Downhole logging	Nil	340/540/620 m	910-920 m

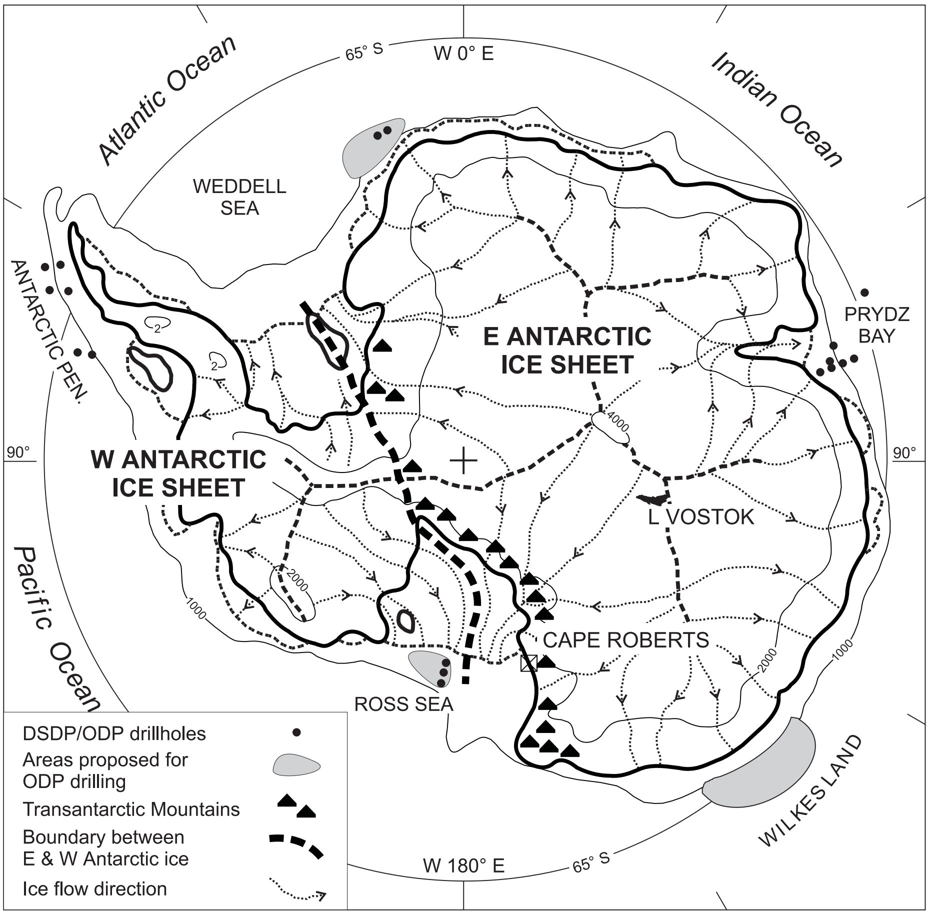


Fig. 7.10 - Map of Antarctica, showing regions where future deep earth sampling is being planned.

the eastern Ross Sea and Wilkes Land. These studies will provide complementary data to those from the Cape Roberts Project for testing ice-sheet and climate models being developed to improve our understanding of the global climate system (Webb & Cooper, 1999). In addition, principals from Cape Roberts countries are examining means by which equipment and experience can be maintained for further work with the Cape Roberts drilling system at a number of places around the Antarctic margin where deep earth sampling may be required for climatic or tectonic objectives. In the longer term this might include sub-glacial Lake Vostok.