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Correlation of Seismic Reflectors with CRP 2/2A, Victoria Land Basin, Antarctica

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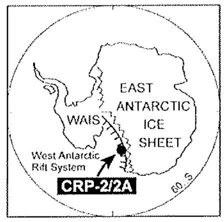

Abstract - Seismic reflection data collected in the region offshore Cape Roberts reveals a seaward dipping seismic sequence that thickens into the Victoria Land Basin. CRP-2/2A cored this sequence to a depth of 624 mbsl; equivalent to 525 ms two-way-time below the seafloor reflection. At least 15 reflection events can be identified in the seismic data and can be related to lithologic changes within core and down-hole electrical logs by deriving a time-depth relationship from whole-core velocity measurements. A limited vertical seismic profile experiment was completed in CRP-2A between the seafloor and 127 mbsf (Cape Roberts Science Team, 1999). Together with synthetic seismograms and the depth converted seismic section we have been able to correlate most of the seismic units at Cape Roberts with lithologic sequence boundaries documented in the core. The crucial V3/V4 seismic sequence boundary of Cooper & Davey (1987) is at 90 mbsf in CRP-2 and V4/V5 is at approximately 440 mbsf.

INTRODUCTION

An important component of the stratigraphic drilling project at Cape Roberts (CRP Program) is successfully integrating the down hole geology with geophysical data. In particular, successfully linking seismic reflection data into the drill hole geology at CRP-2A is required to extend the geology away from the well site. The link between the seismic data and the drill hole geology is provided by down-hole sonic velocities, core velocity measurements, and vertical seismic profiles (VSP). The geophysical logs allow the computation of vertical incidence synthetic seismograms that can be compared with the seismic reflection data. In this paper, we show a synthetic seismogram from logs of CRP-2A and the corresponding processed multi- and single- channel seismic reflection data that cross CRP-2/2A. We then discuss the correlation of the synthetic data to the observed reflection data and to the drill hole lithology. This analysis is a critical step for understanding the geological and climate history of the basin margin in McMurdo Sound.

The integration of these results with seismic stratigraphy developed and defined for the Victoria Land Basin (Cooper & Davey, 1987) is discussed in a companion paper (Davey et al., this volume).

SEISMIC REFLECTION DATA

The primary data set for drillhole correlation is the single-channel seismic (SCS) data from the NBP9601 cruise (Hamilton et. al., 1998, and Fig. 1). In particular, two profiles cross close to the drill site; NBP9601-89 passes E-W and 300 m south of the drill hole and NBP9601-93 passes N-S, about 400 m east (Fig. 1). These data sets include a minimum amount of processing to preserve both true amplitude and relative trace-to-trace amplitudes, *i.e.*, no deconvolution or f-k filtering, or trace averaging were applied. However, the core at CRP-2A penetrated strata below the seafloor multiple. The use of multi-channel seismic data can significantly reduce seafloor multiple energy and improves the correlation of events below the multiple (Hamilton et. al, 1998). But, signal processing that helps to remove multiple energy and improves the correlation of events below the multiple also usually degrades shallow signal quality. For this reason we used both data sets in our interpretations: multichannel seismic (MCS) data to provide stratigraphic correlations below the multiple, and SCS data to map shallow sequences and seismic facies. Details of processing MCS data are given in Hamilton et al (1998).

The near-offset (normal incidence) seismic traces were not migrated. The effect of migrating data is to steepen dipping structures, but near-surface gently dipping events retain their shallow dip. Accurate migration requires detailed velocity information, which is not available for single-channel data. The velocity measurements from cores and sonic logs could be used to construct a two-dimensional interval velocity model. This has not been attempted since no reliable estimates of lateral velocity variations are available.

VSP

VSP travel-time data can be used to determine velocities to serve as a basis for comparison with down-hole sonic and core measurements and can also be used to tie directly

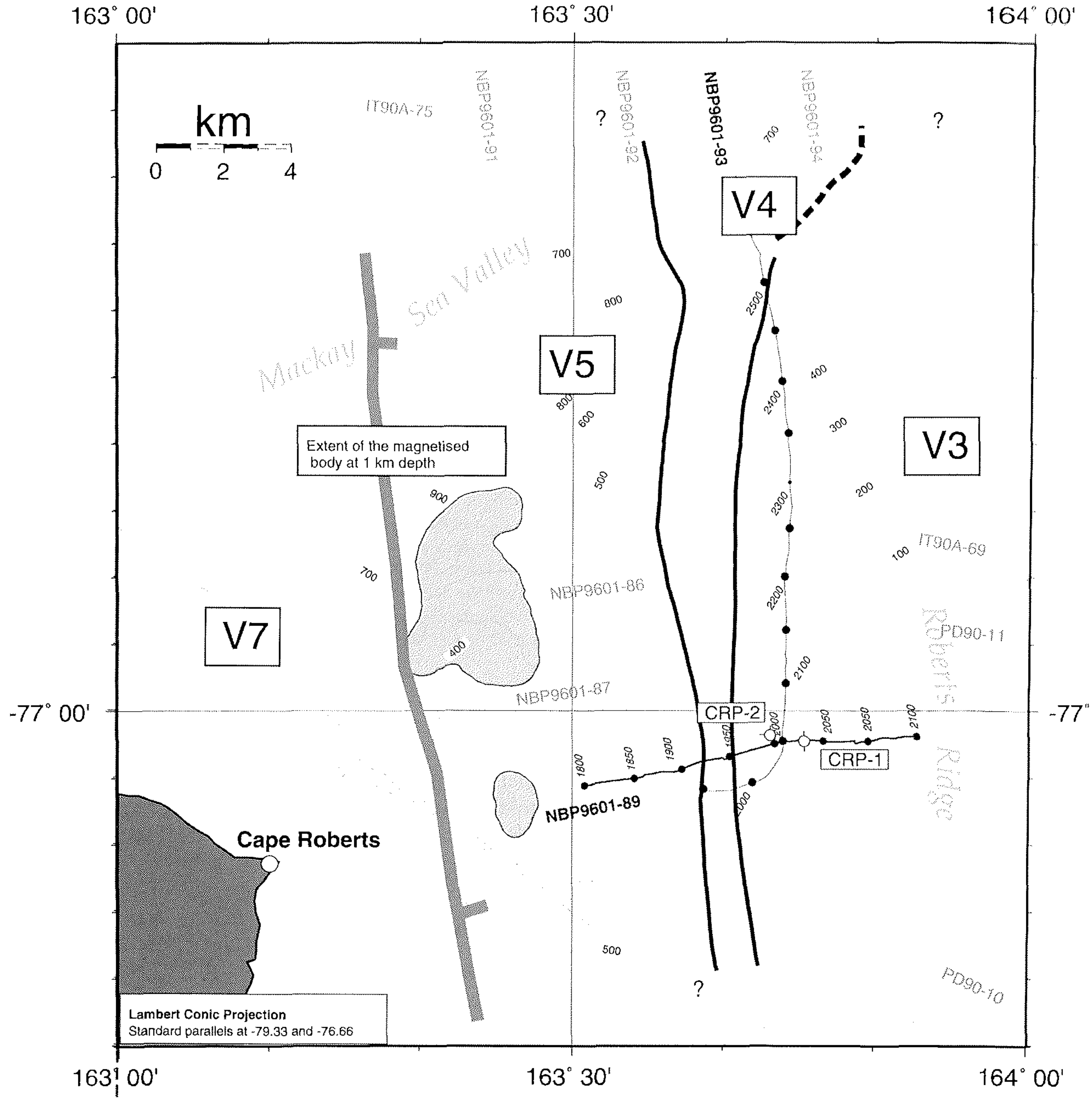

Fig. 1 - Location map.

into marine seismic reflection data. Potentially, VSP data can also provide information about strata below the bottom of the well. Only a limited vertical seismic profile experiment was completed in CRP-2A between the seafloor and 127 mbsf (Cape Roberts Science Team, 1999). Processing steps for the VSP are given in table 1 and included steps to enhance up-going seismic waves. Depth-migration of these data allows for shot offset and water depth, and results in a 2-D stack, with reflections subsequently in the depth and horizontal-offset domain. The transform-migration algorithm used to stack the VSP is similar to the transform technique described by Cassel et al. (1984), in that it carries out a (limited-angle) Kirchhoff depth migration of the data and does not assume horizontal layering, but allows dipping layers. The velocity model for this process is defined by a series of layers with

Tab. 1 - Vertical Seismic Profile processing schedule

- Geometry placed in headers
- Trace editing of noisy traces
- Orientation of the 2 horizontal components
- Selective muting of small sections of the shots,
- Bandpass filtering (13-17-110-120 Hz).
- f-k separation of up-going and down-going arrivals
- Deconvolution : designed on downgoing energy, but not applied
- Selective muting of small sections of the shots,
- Incrementally stacking with different velocities, to determine optimum migration velocity parameters
- Limited-angle Kirchhoff migration with final velocity model
- Static applied to allow for sea-floor depth
- Spherical divergence gain applied for display

uniform velocity (averaged from core measurements), separated by plane dipping layers. The degree to which this migration is successful depends on the ability to separate the up and down-going energy and on the success of multiple suppression. In the case of CRP-2 the suppression of multiple energy was only partially successful and we are only confident in coherent reflections to 250 mbsf. Figure 2 shows the final stack resulting from transformation of the data. The horizontal spacing between the output seismic traces is 1 meter.

DOWN-HOLE LOGGING DATA AND MEASUREMENTS ON CORES

Whole core physical properties were made at the Cape Roberts drill site (Cape Roberts Science Team, 1999; and Niessen et al, this volume) and included wet bulk density (ρ) and P-wave velocity (Vp). A down-hole density tool was also run from 64 mbsf to the bottom of the well and was completed in two phases. Sonic velocity logging could only be completed on two sections of the well (63 – 167 mbsf and 200 – 440 mbsf).

Density values range from 1.5 to 3.1 gcm^{-3} with the average value being 2.0 gcm^{-3}. Clasts within diamictites show a wide distribution of velocities from 3.0 km/s to values greater than 6 km/s. Figure 2 shows velocity measurements, together with data from the sonic tool, plotted as a function of depth. From near the sea floor to a depth of 300 m velocities are close to 2.0 km/s and densities are less than 2.4 gcm-3. Variations in density and velocity are most pronounced at depths greater than 440 m where Vp increases to greater than 5 km/s. In general, data from core measurements and down-hole tools agree very well and we are therefore confident in using the core measurements for determining synthetic seismograms in the absence of a complete sonic log.

GENERATION OF SYNTHETIC SEISMOGRAMS

Reliable down-hole density and velocity data, as well as seismic impedances $z = \rho$ Vp, and reflection coefficients $R = (z_2 - z_1)/(z_2 + z_1)$, permitted synthetic seismograms to be calculated.

Synthetic seismograms were generated using a reflectivity algorithm (Kennett 1981) for normal incidence data. This method accounts for all normally incident waves and their multiples; seafloor multiples are not included. Input is in terms of P-wave velocity, density, attenuation, and depth or thickness of horizontal layers. Attenuation is assumed to be infinite in all cases presented here. No attenuation measurements were made on core samples and, unless Q (seismic wave attenuation quality factor) is low, velocity dispersion effects are assumed to be small. Velocity and density values for the different layers, apart from the sediments immediately below the seafloor, were derived from measurements on core samples. The properties of the seafloor were determined by trial-and-error matching of the observed and calculated water bottom reflections. To accurately match the sea floor and other reflection events we convolved the synthetic impedance function with a source wavelet derived from the seismic data. An estimate of the source wavelet for SCS data can be derived by summing traces along the seafloor horizon. The convolved synthetic traces were subjected to the same processing sequence as the observed single-channel seismic data and shot gathers (*i.e.* same filter and gains) and displayed with identical plotting parameters. The seafloor cannot be used to derive a source wavelet for the MCS data since seismic processing distorts the character of the seafloor reflection. For this reason we have chosen to display the same synthetic data with both data sets.

RESULTS

We have taken the logs of sonic velocity and density from the whole-core logging and used these to derive a two-way travel-time-depth relationship. We have used the travel-time-depth curve (Fig. 2) to convert the seismic travel times measured on the seismic section to true depth. Together with synthetic seismograms (shown in Fig. 3), the time-depth curve has then been used to link the seismic data with the lithological logs (Fig. 2). CRP-2/2A reached a depth of 624.15 mbsf, equivalent to 525 ms two-way-time (twt) bsf. At least 15 seismic events can be identified at this depth or above (a to o). Seismic events were determined by correlating the highest amplitude positive seismic wavelet peaks, that were laterally continuous away from the drill hole, and can be related to the cored section. Table 2 summarizes the correlation between seismic reflectors from line NBP9601-89 and lithostratigraphical units and sequences in CRP-2.

The interpretation here will be limited to an analysis of the major units; detailed linkages are uncertain because of the low resolution of the seismic signal (wavelength ~ 30 m). However, reflectivity and impedance data (Fig. 2), and changes in physical properties that extend over about 20 m have been used to improve correlations. For example, the highest reflection coefficients are encountered at the base of the core where diamictite lithologies have the highest velocities. Continuous layers of this lithology will yield bright and laterally continuous reflectors. We also note that diamictites do not always correspond to a significant velocity or impedance change (*e.g.* at 230 mbsf), and in some cases strong and continuous reflectors have no associated change in velocity (*e.g.* see reflector "f" at 220 ms twt bsf in Fig. 2). Differences between the synthetic seismograms and the seismic reflection data (Fig. 3) can arise because the Fresnel zone of the reflection data takes in a larger area than just the borehole (about 100 m radius at 1 s) and therefore includes reflections generated by rocks and structures surrounding the borehole. In the synthetic seismograms, the computed reflections represent only the information sampled in the borehole. Given the limitations of the data we have been able to establish that all of our 15 seismic events are close to or are associated with a stratigraphic sequence boundary (Fig. 2 and Tab. 2). Independent mapping of seismic data, in the region, has

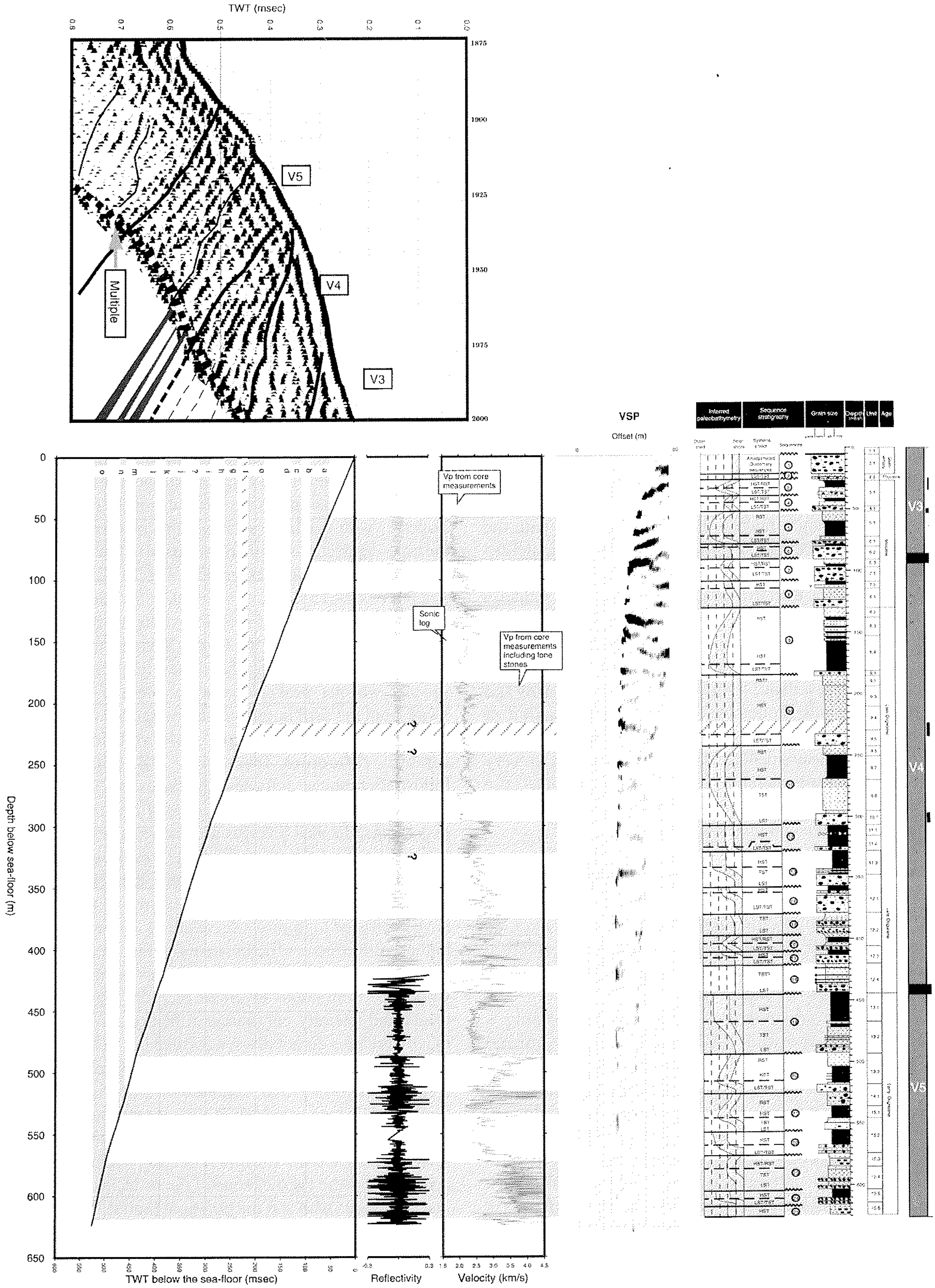

Fig. 2 - Composite figure. Seismic data, , time-depth correlation, velocity reflectivity, VSP, and core-based lithology sequences.

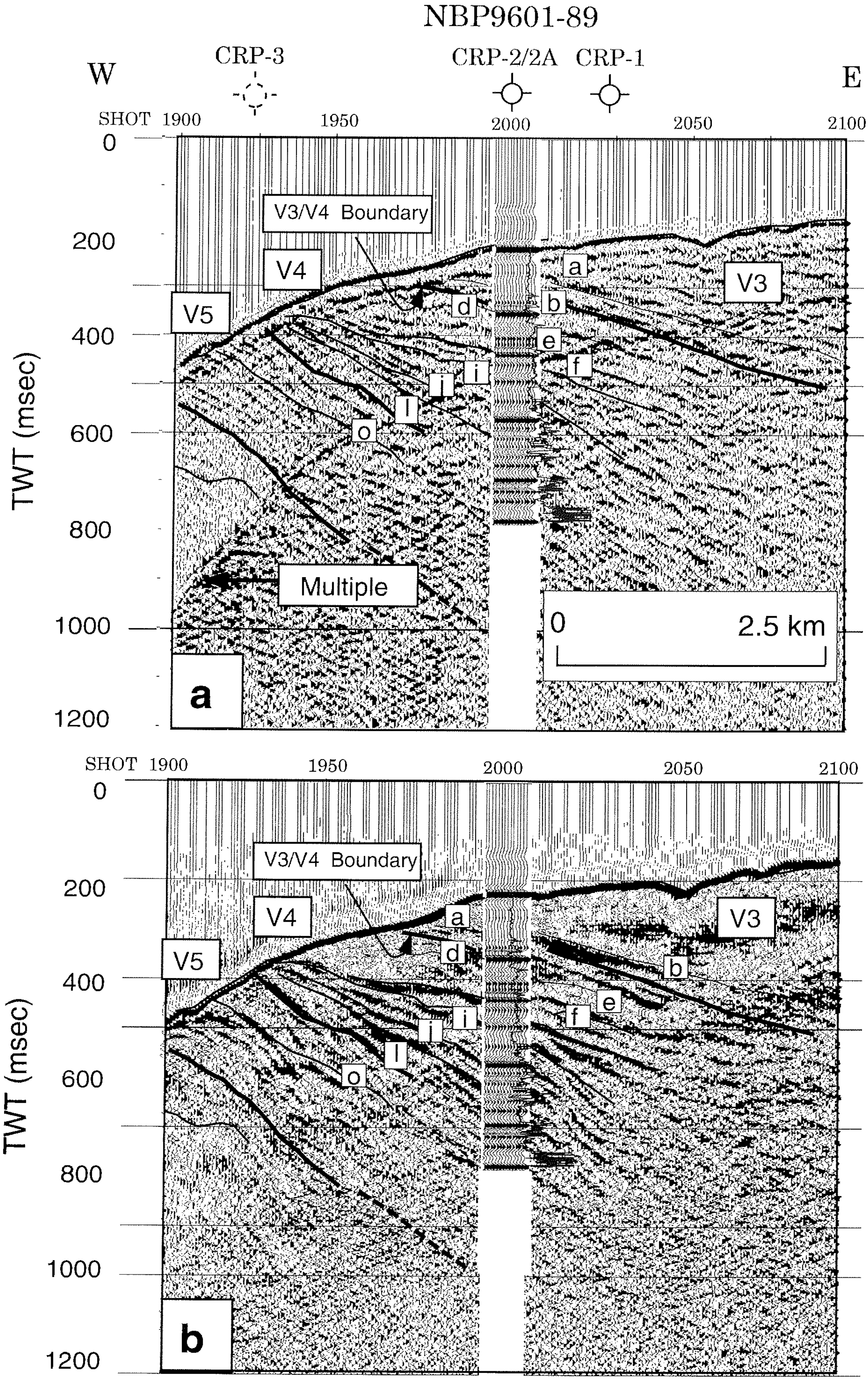

Fig. 3 - Cut away section NBP9601-89 with synthetic seismogram from CRP-2 for a) SCS, b) MSC.

identified at least 3 major seismic sequence boundaries identified on the basis of regional unconformities (V3, V4, and V5). These units have been further refined, into at least 10 seismic sequences, based on detailed mapping of SCS data (Henrys et al, 1998; Bartek et al, 1996). We have chosen in this paper to group individual seismic sequences bounded by seismic events (a – o) into the larger units, because they offer the chance of highlighting significant basin-wide climate and tectonic episodes.

THE V3/V4 BOUNDARY

A re-evaluation of the correlation of seismic reflection data from the central Victoria Land Basin to the CRP drill sites (Henrys et al, 1998) suggested that the interpreted correlations are not unequivocal Seismic stratigraphy of the Victoria Land Basin was established by Cooper and Davey (1987), who identified a number of major seismic units (V1-V5) separated by basin-wide reflectors. Inferred

Tab. 2 - Correlation between seismic reflectors, reflectivity and velocity values from measurements on the core, and lithostratigraphical units in CRP-2.

Seismic Reflector		**Lithostratigraphical correlation and depth**	**Comments and inferences**
	twt bsf (ms)		
a*	50	LSU 4.1 at 48 - 52 mbsf and base of Sequence 4	Gently dipping reflector at a 4-m-thick diamict; corresponds to minor velocity & impedance change. Correlates to CRP-1.
b*	83	Boundary between LSU 6.2 And LSU 6.3 at 90 mbsf and near base of Sequence 6	Significant impedance and velocity change; 8-m-thick diamictite. **V3/V4 Boundary and base of seismic sequence Q.**
c	110	Boundary between LSU7.1 And LSU 7.2 at 109 mbsf and near base of Sequence 7	Major impedance change between thick diamictite (7.1) and an ash-bearing unit with a 1.2-m-thick ash bed. Reflection not strong.
d	145	Near the base of LSU 8.1 at 125-130 mbsf and base of Sequence 8	Velocity increase within lower part of a diamictite; **Oligocene-Miocene boundary** placed at 130 m on Biostratigraphical evidence. Minor reflector.
e*	180/ 190	Boundary between LSU 9.1 and 9.2 at 183 mbsf or between LSU 9.2 and 183 at 194 mbsf; near base of Sequence 9	Sharp increases in velocity in diamictite and sandstone, respectively; appear to correspond to weak seismic reflectors.
f*	215	Boundary within LSU 9.4 at 220 mbsf	Reflector "f" does not corresponds to any identifiable velocity change. **Base of seismic sequence R.**
Sea-floor multiple intersects CRP-2A at 220 ms bsf. Below this, interpretation of reflectors is more difficult.			
g	241	Possibly bonndary between LSU 9.5 and 9.6 at *c.* 240 mbsf and base of Sequence 10	
h	265	Middle of LSU 9.8 at *c.* 276 mbsf	Velocity fall and increased reflection coefficient.
i*	290	LSU 10.1 at 296 - 306 mbsf and base of Sequence 11	Sharp velocity increase at top of unit, associated with impedance changes; an equally sharp decrease velocity at the base of LSU 10.1 corresponds to a major impedance change and angular unconformity **Major time break in Chronology and base of seismic sequence S.**
**	315	Base of LSU 11.2 at *c.* 328 mbsf and base of Sequence 12	Slight velocity increase.
j*	350	Boundary within LSU 12.1 at *c.* 365 or boundary between LSU 12.1 and LSU 12.2 at 365 - 378 mbsf and base of Sequence 14	Velocity increase and significant change in reflectivity; marks the beginning of a zone of highly variable physical properties down to 420 mbsf.
k	380	LSU 12.3 at 420 mbsf and base of Sequence 17	LU 12 contains several thick diamictites of varying impedance and velocity, but only that in the base of LSU 12.3 corresponds to a step of significant dnration.
l*	405	LSU 12.4 to LSU 13.1 at 437 - 443 mbsf and base of Sequence 18	Top of 6-m-thick diamictite corresponds to major velocity change and to a reflector extrapolated through the sea-floor mnltiple. **Most likely candidate for V4/V5 and major time break in chronology and base of seismic sequence T.**
m*	440	Boundary between LSU 13.2 and LSU 13.3 at 495 mbsf and base of Sequence 19	Corresponds to significant velocity change and a reflector.
Second sea-floor multiple intersects CRP-2A at 440 ms bsf. Below this, interpretation of reflectors is much more difficult.			
n	460/ 475	Boundary between LSU13.3 and LSU 14.1 at 516 mbsf and near the base of Sequence 20 or 21	Corresponds to a significant velocity change and a faint reflector.
o*	490/ 520	Base of LSU 15.2 at 570 mbsf and near the base of Sequence 22	Lowest significant velocity change in CRP-2A, within well-cemented sandstone; corresponds to a major reflector traced to a 100-m wide bench on the sea floor at *c.* 570 m below sea-floor.

LSU - Lithostratigraphical Sub-Unit; *strongest and most persistent reflectors; **not seen on large scale near trace plot.

ages for the sequences from correlations using seismic data have been too old when compared with the drilled data to date. The recent availability of several regional sections of high quality detailed processed MCS data from R/V Explora (Brancolini et al, 1995) and the processed MCS data from the detailed survey of Roberts Ridge by R/V N B Palmer (see Fig. 1 for location) meant that some of the uncertainties in correlation beneath the seafloor multiple could be resolved (see Davey et al, this volume). One of the main tests of the CRP-2 bore hole was to sample and calibrate stratigraphically two critical seismic reflectors, one separating V3 from V4 (Q and R in the nomenclature of Bartek et. al 1996), where two alternative correlations were established, and the other V4 from V5 (Henrys et al., 1998 and Figs. 2, 3, 4).

V3/V4 is a prominent unconformity on seismic reflection data that intersects the seafloor at 270 msec (twt) on line NBP9601-89 ("b" in Figs. 2, 3, 4) and is observed as a strong reflector on VSP data at 90 mbsf. The nature of the V3/V4 seismic sequence boundary sampled by CRP-2 is best seen on the north-south strike line, NBP9601-93, that extends along the length of Roberts Ridge (Fig. 5). On dip lines east of Roberts Ridge V3/V4 is beneath the seafloor multiple and is only recognized on MCS data and on intermediate resolution SCS data in places where water depths are greater than 500 m (Bartek et al, 1996; Barrett et al, 1995). However, along NBP9601-89 and 93 the seismic sequences of V3 downlap onto an erosional surface that dips northeast (about 3 degrees). In the core this boundary is a sequence boundary that separates a massive diamictite of subglacial origin (LSU 6.2) from a poorly sorted sand (LSU 6.3).

Seismic facies that comprise V3 (P and Q) are characterized on strike lines by high amplitude continuous and sub-horizontal lens-shaped reflector bodies. On NBP9601-93 channels cut these lenses, the widest being about 3 km and about 70 m deep (Fig. 5). Zones of transparent internal character with high amplitude basal reflectors distinguish channels. On dip lines the facies has a wedge geometry with individual units thickening eastward and appears to be internally more chaotic. Synthetic seismograms (Fig. 3) show a strong water bottom reflection but no reflections in the following 200 ms. Similarly, velocity data measured on CRP-1 cores (Niessen et al., 1998 and Fig. 3) show no marked boundaries. The resolution of the seismic data is not sufficient to resolve individual sequences recognized in the core but we infer that lens-shaped bodies seen on seismic are dominantly the preserved low stand (glacial) sediments; the base of seismic sequences P and Q correspond to the base of lithostratigraphic Sequences 4 and 6.

SEISMIC SEQUENCE V4 (SEQUENCE R)

To the north the Mackay Sea Valley cuts through Roberts Ridge and exposes older strata. The water depth in this trough is greater than 700 m - allowing seismic reflection data to image older lithologies above the water bottom multiple. Between shot points 2400 and 2550 on NBP9601-93 at least three unconformity-bound subsequences can be recognized within V4 (R, S, and T in the nomenclature of Bartek et al., 1996). The base of seismic unit R at 220 mbsf ("f" in Fig 2) was recognized as a major sequence boundary in earlier interpretations: the V4 boundary of Hamilton et al., (1998) and the lower alternate boundary of Henrys et al., (1998). This boundary does not coincide with any major time break within CRP-2A but is marked by an angular unconformity along NBP9601-89 (Figs. 3 & 4) where sequences below this interval steepen to more than 5° and may also be observed on VSP data. Along NBP9601-93 (Figs. 5 & 6) laterally discontinuous and low amplitude reflectors, that characterize unit R, overlie more hummocky and chaotic facies that dominate S and T. Locally, channels are also observed within this unit. Within CRP-2A sequence R is an amalgamation of 4 sequences (Sequences 7 – 10 in Fig. 2) dominated by well-sorted sands deposited in a highstand systems tract. Calculated reflection coefficients and synthetic seismograms for this interval show individual sequences will be only poorly imaged in seismic data although on the dip section for NBP9601-89 minor reflectors are found to coincide with sequence boundaries.

SEISMIC SEQUENCE V4 (SEQUENCE S)

Seismic sequence S is correlated with a single 65 m sequence stratigraphic unit (11) in CRP-2A. The base of S is identified as "i" (296 mbsf) and, like the base of seismic unit R, is a marked angular unconformity on dip lines. In the strike direction (NBP9601-93 and Figs. 5 & 6) the boundary is imaged as an irregular unconformity surface. The S/T boundary is also close (296 versus 306 mbsf) to a major sequence boundary (Sequence 11) and unconformity at 24 Ma (Cape Roberts Science Team, 1999). Petrographic analysis shows clasts above this boundary are dominated by McMurdo Volcanic Group and below by Kirkpatrick Basalt (Talarico, et al, this volume). Given these observations we interpret the base of S as a possible uplift event in the Transantarctic Mountains.

SEISMIC SEQUENCE V4 (SEQUENCE T)

High amplitude discontinuous reflectors that dip eastward along line NBP9601-89 (Figs. 3 & 4) characterize seismic sequence T, and are subhorizontal along strike (NBP9601-93 and Figs. 5 & 6). The lateral variation in amplitude within sequence T is attributed to strong internal scattering from high velocity (greater than 4 km/s) diamictite layers that are prevalent in the core below 300 mbsf. Seismic sequence T is correlated with 5 thin (less than 25 m thick) stratigraphic sequences. The base of T is recognized as the boundary that separates V4 and V5 and is identified as reflector "l" at 440 mbsf in the detailed seismic correlation with CRP-2 (Tab. 2). The base of seismic sequence T corresponds to the base of lithostratigraphic Sequence 18 and is believed to be a significant chronostratigraphic break in CRP-2 at 29 Ma (Wilson et al., chronostratigraphy, this volume).

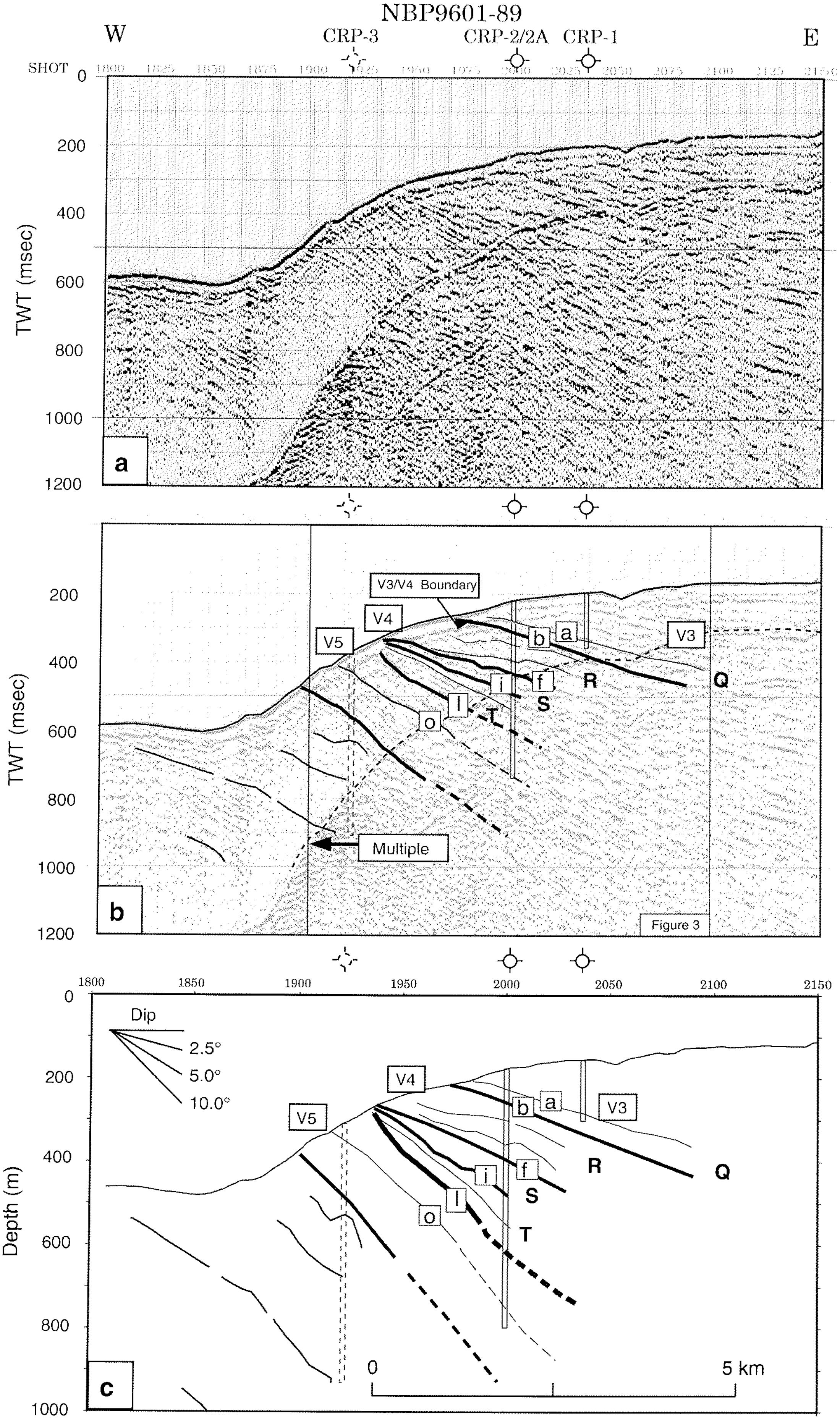

Fig. 4 - Seismic section for dip line NBP9601-89 (a), with interpretation of stratigraphic units V3, V4, V5 and subsequences Q, R, S, T together with major seismic reflector events identified in CRP-2 (b), and depth (c).

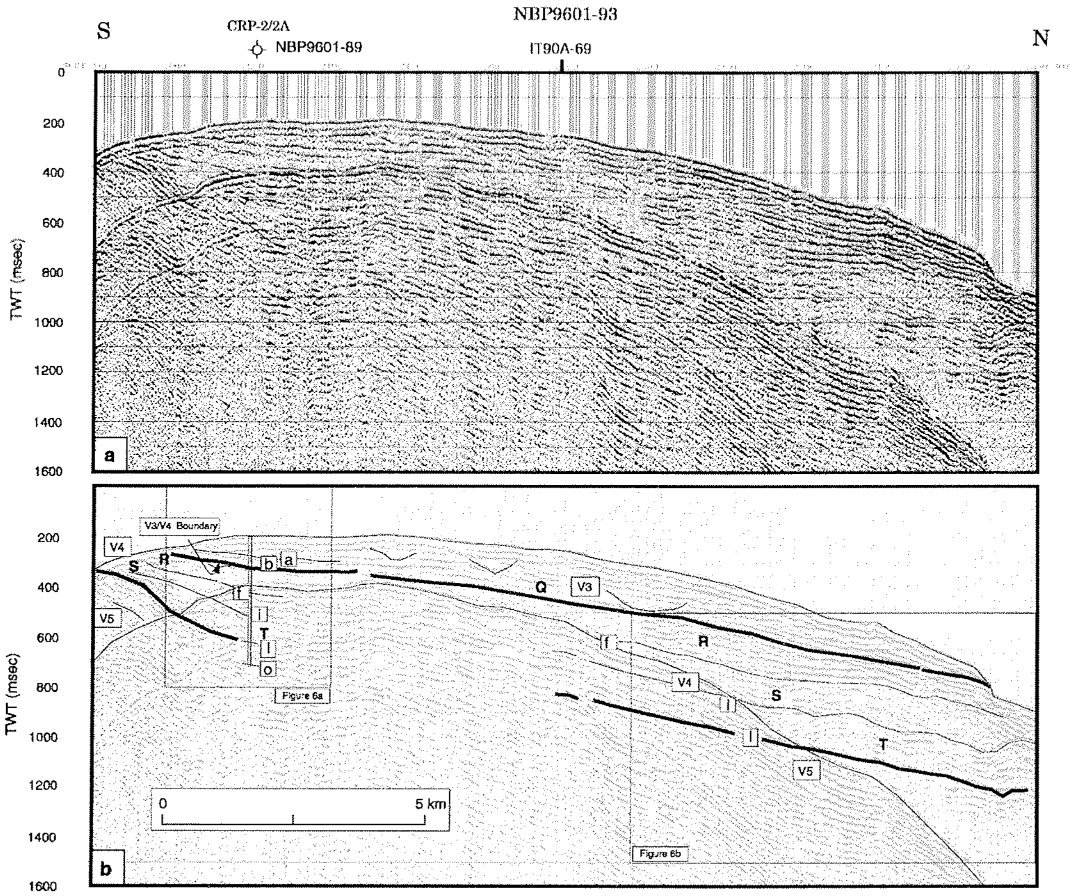

Fig. 5 - Seismic section for strike line NBP9601-93 (a), with interpretation of stratigraphic units V3, V4, V5 and subunits Q, R, S, T together with major seismic reflector events identified in CRP-2 (b).

SEISMIC SEQUENCE V5

Seismic sequences within V5 and beneath T have not been differentiated, although reflection data that cross the Mackay Sea Valley, north of Roberts Ridge, clearly show a thick sedimentary section. Cooper and Davey (1985, 1987) defined V5 on a distinct velocity increase in sonobuoy refraction data throughout most of the VLB. Velocities in V5 from refraction data are unusually high (>4.5 km/s) leading Cooper and Davey to speculate that this sequence was Paleogene and older. Core measurements have revealed that Vp increases below 440 m (V4/V5 boundary) caused

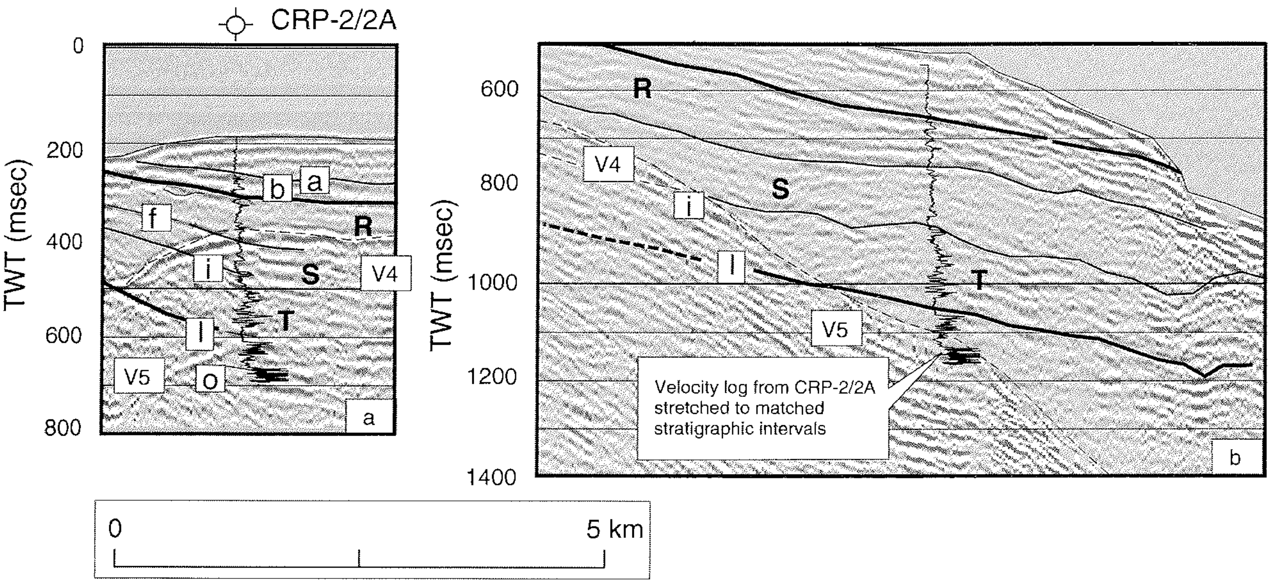

Fig. 6 - Detailed sections of strike line NBP9601-93 with measured velocity log from CRP-2 (a) around the drill site and b) at the northern end of the line where the section is cut by the Mackay sea valley.

by extensive carbonate cementation (Dietrich, this volume). Within some sandstones and diamictites layers velocity exceeds 5.0 km/s. The nature of V5 is likely to be revealed by drilling CRP-3.

CONCLUSION

Seismic stratigraphy of the Cape Roberts region was first established by Cooper and Davey (1987), who identified three major basin wide seismic units (V3-V5). In McMurdo Sound this stratigraphy was further refined into 10 seismic sequences (K – T) where R, S, and T were identified as part of Cooper and Davey (1985) unit V4 and inferred to correspond with early Oligocene and late Eocene rocks at depths greater than 366 m in CIROS-1 (Bartek et al., 1996). A number of these seismic units, including the three sub-seismic units of V4, were previously mapped across Roberts Ridge (Henrys et al., 1998) but could not confidently be identified. However, these major seismic sequences have now been identified in core recovered at CRP-2. In addition 15 separate seismic events have been identified on SCS and MCS lines crossing the drill site. All of these events are associated with stratigraphic sequences. Only one thick (50 m) stratigraphic sequence is able to correlate with a single seismic sequence (S) but the amalgamation of thinner stratigraphic sequences comprises other seismic sequences.

The V3/V4 boundary of Cooper & Davey (1987) is the base of seismic sequence Q at 90 mbsf in CRP-2A and is age dated at 21 Ma. The base of both S and T (V4/V5) are also believed to be significant chronostratigraphic breaks in CRP-2 at 24 and 29 Ma. V4 in McMurdo Sound can only be tied to CIROS-1 over the basin flank where units are beneath the seafloor multiple (Bücker et al., 1998, Henrys et al, 1998), younger than the inferred V4 units in CIROS-1. Clearly, a reassessment of seismic data in the area of CIROS-1 is required along with a reevaluation of the evolution of the VLB, since V5 rocks are Oligocene age in CRP-2A and not Paleocene or Cretaceous age as interpreted by Cooper and Davey (1985, 1987). The nature of V5 units is likely to be revealed by drilling CRP-3.

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