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Seismic stratigraphy of McMurdo Sound, Antarctica: implications for glacially influenced early Cenozoic eustatic change?

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Abstract

Analyses by Barrett et al. (1989) of the stratigraphic sequences of the CIROS-1 drill core provided evidence of late Paleogene and early Neogene glacial advances and retreats that appear to correlate with the global eustatic curve of Haq et al. (1987). During Leg 2 of the *Polar Duke* 90 (PD90) cruise in the Ross Sea approximately 650 km of high-resolution seismic data were collected in McMurdo Sound with the main objective of facilitating regional correlation of stratigraphic events observed in the cores of the CIROS-1, DVDP-15, and MSSTS-1 drilling programs, and therefore providing an opportunity to test hypotheses on linkages between Cenozoic eustatic and Antarctic ice volume fluctuations.

Twenty unconformity-bound, seismic-stratigraphic sequences (labeled from top A to T) were identified in the McMurdo Sound PD90 data base. However, seismic data from the shallow shelf on which CIROS-1 was drilled show erosional surfaces at many levels, indicating a condensed section in this area. It is difficult to distinguish individual lithological units identified by Barrett et al. (1989) in the seismic data, but seismic units O, P and Q correspond to the upper Oligocene interval where they recognized 3 glacioeustatic events. These three sequences, totaling around 300 m in thickness, can be traced over a distance of almost 100 km. However, they lack the seismic characteristics of glacial facies identified by Anderson and Bartek (1992) and thus the significance of waxing and waning events suggested for upper Oligocene strata in CIROS-1 remains equivocal.

The younger sequences in the McMurdo Sound data base are largely Miocene (E–N), the oldest of these forming the upper 70 m in CIROS-1. These sequences can be traced 300 km north into the center of the Victoria Land basin, where they have seismic features characteristic of glacial facies. This suggests that ice sheets of continental scale (and hence large enough to affect eustasy) waxed and waned across the Ross Sea continental shelf at least 10 times during the Miocene. The data presented here for the Oligocene do not preclude similar ice sheet behavior, but are insufficient to test the hypothesis properly.

1. Introduction

During the last twenty years, scientific drilling has produced a great deal of new information on the Cenozoic geologic history of Antarctica. Drilling programs in the Ross Sea sector of the Antarctic continental margin include the Deep Sea Drilling Project during Leg 28 in the Ross Sea (Hayes and Frakes et al., 1975); the Dry Valley Drilling Project (DVDP) conducted primarily in the Dry Valleys of South Victoria Land and in McMurdo Sound (McKelvey, 1982; Webb and

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Wrenn, 1982; Brady, 1982; Kyle, 1981a,b). Later drilling programs in McMurdo Sound include the McMurdo Sound Sediment and Tectonic Studies-1 (MSSTS-1), with results largely reported in the volume edited by Barrett (1986), and the Cenozoic Investigation of the Ross Sea (CIROS-1) (Barrett et al., 1989). Ocean Drilling Program (ODP) activities in other sectors of Antarctica include drilling on the Weddell Sea and Maud Rise as reported by Barker et al. (1988), and the ODP drilling in the Prydz Bay region presented initially by Barron and Larson et al. (1989).

The objectives of these programs were to gain insight into the: (1) glacial history of Antarctica and (2) tectonic and stratigraphic evolution of the continental margin. Data generated by these drilling programs suggest that continent-wide glaciation occurred by the late Paleogene and that ice sheets waxed and waned on Antarctica throughout the remaining portion of the Cenozoic. These waxing and waning events may have occurred on a scale that significantly affected oceanic oxygen isotope compositions, eustasy, and global climate change. However, the drill sites are geographically dispersed, so it is possible that the glacial deposits found in the cores from these sites may only represent small ice caps or local alpine glacial conditions rather than regional or Antarctic wide glacial events.

This investigation focuses on the McMurdo Sound area, located in the southwest corner of the Ross Sea, itself part of a large embayment in the Antarctic coastline that lies on the boundary between East and West Antarctica (Fig. 1a). The Sound is known to be underlain by Cenozoic strata that are closer than any other accessible strata to the East Antarctic Ice Sheet. The Cenozoic geological record on land is limited and controversial (Clapperton and Sugden, 1990; Webb and Harwood, 1991) and, hence, drilling offshore has been carried out to sample strata that should record the waxing and waning of the ice sheet in the past.

The most successful drilling to date has been the CIROS-1 drill hole (Fig. 1b), which was cored 12 km offshore from 27 to 702 m below the sea floor (bsf) with 98% recovery (Barrett, 1989). The upper part of the sequence (above an unconformity at 366 m) comprises beds of diamictite, mudstone, sandstone and some conglomerate from early Oligocene to earliest Miocene in age (31–22 Ma, Harwood et al., 1989). The lower part is deep water mudstone with turbidite sand and conglomerate and occasional diamictite, ranging in age from early Oligocene (>34 Ma) to middle Eocene (around 45 Ma, Hannah, 1994, in prep.).

The CIROS-1 core has been interpreted by Barrett et al. (1989) in terms of lithostratigraphic facies that indicate presence or absence of grounded ice and rising or falling sea level. The core contains biostratigraphic facies (diatomaceous muds containing flora) that require open water conditions and lithostratigraphic facies (diamictites containing faceted and striated pebbles, with sparse fossils) indicative of subglacial conditions. Barrett et al. (1989) say in the Late Oligocene–early Miocene part of the core at least three, and possibly four periods of glacial advance and retreat over the drill site, which they correlated with the coastal onlap–offlap events of Haq et al. (1987) in the same time period (Fig. 2). As a consequence, they favored that curve as a global recorder of Antarctic ice volume changes over the Miller et al. (1987) oxygen isotope curve, which showed little variation throughout the Oligocene, but a major shift at the Eocene/Oligocene boundary.

One means for testing this interpretation of the CIROS-1 core was to determine the lateral extent of events recognized in the core and, hence, decide whether they were of regional (ice sheet scale) or only local significance. To this end, seismic profiles were acquired in McMurdo Sound and the Ross Sea (Fig. 1) during Leg 2 of R/V *Polar Duke*'s (PD90) expedition (Bartek and Anderson, 1990). The overall objective of the cruise was to acquire a high resolution seismic reflection data base that should, in conjunction with existing drill core from DSDP holes 270–273, MSSTS-1 and CIROS-1, provide the basis for a high resolution seismic stratigraphy for Cenozoic strata of the region. These data could then be used to decide whether the glacial and sea level events in CIROS-1 were local or shelf wide in extent. In this paper we will present data that indicate that the origin of the Oligocene glacial waxing and waning events

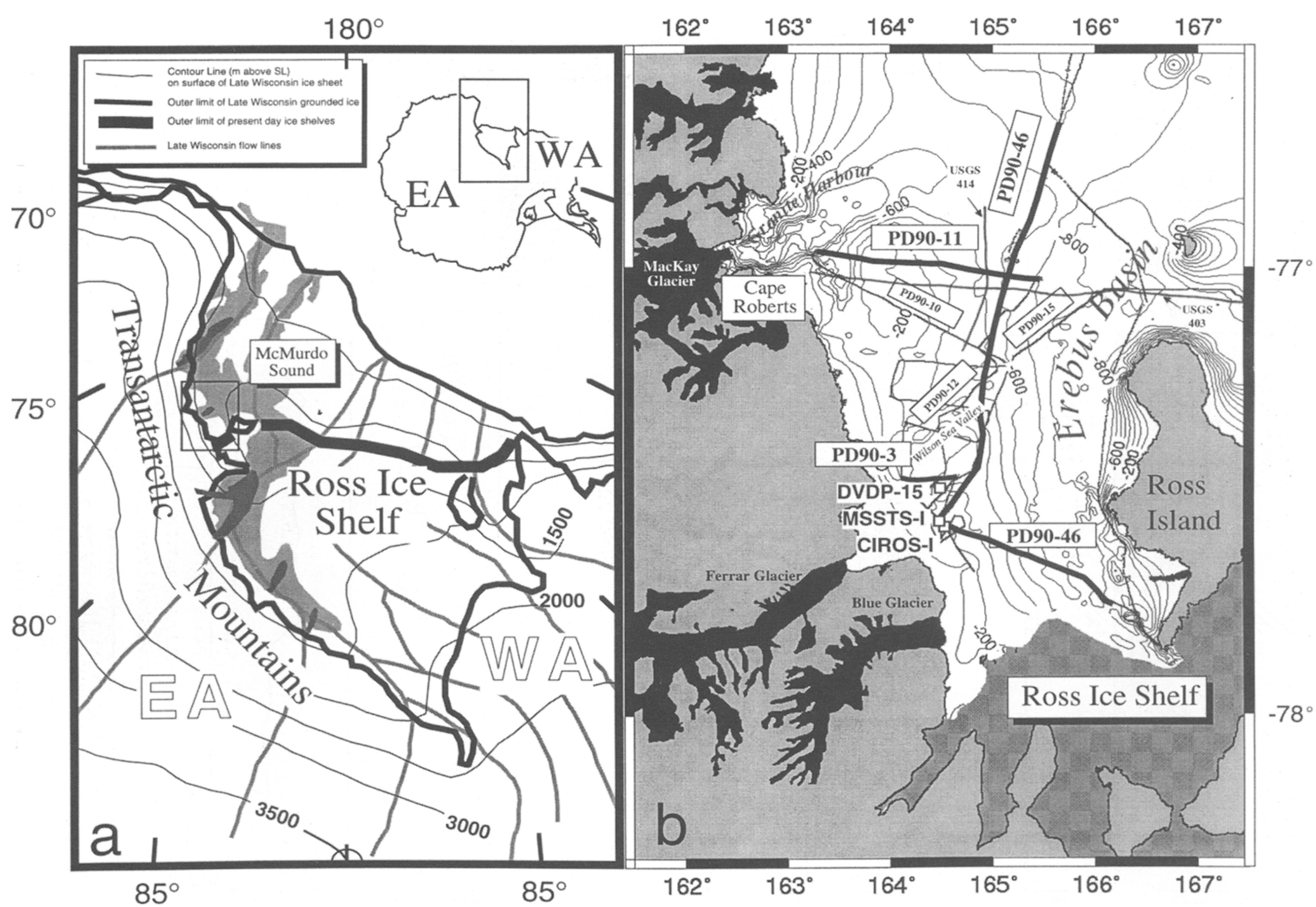
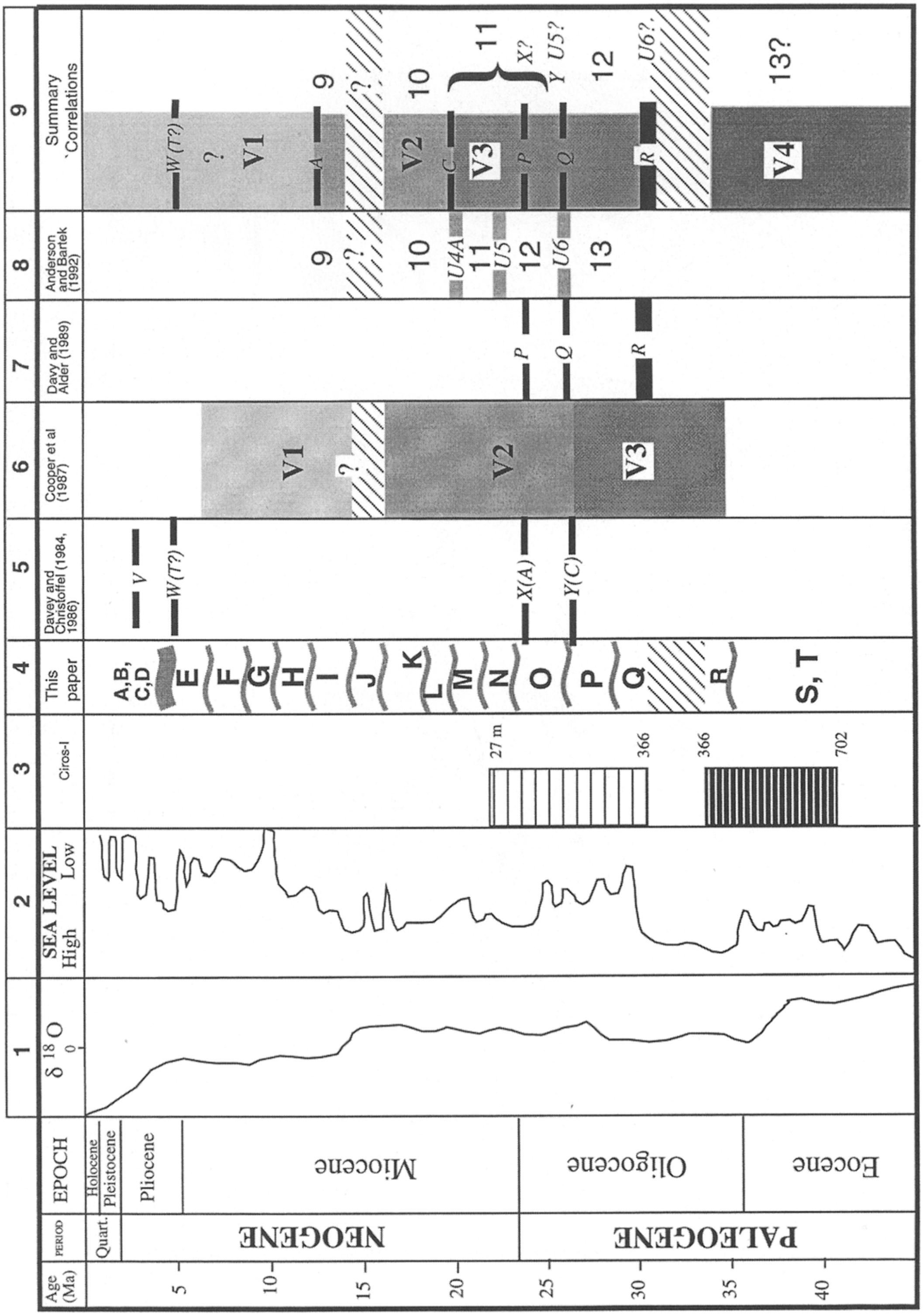


Fig. 1. (a) Map of location of the Ross Sea, Transantarctic Mountains, and drainage of the continental-scale East (*EA*) and West Antarctic (*WA*) Ice sheets into the Ross Sea. The extent of the West Antarctic Ice sheet at its maximum extent during the late Wisconsinan is from numerical simulations (Stuiver et al., 1981). (b) Map of the study area showing bathymetry in the area, the locations of the *MSSTS* and *CIROS-1* drill sites, alpine glaciers, and the locations of seismic profiles acquired during PD90 survey. Profiles presented in this paper are highlighted in with a bold.



Age (Ma)
5
10
15
20
25
30
35
40
PERIOD
Quart.
NEOGENE
PALEOGENE
EPOCH
Holocene
Pleistocene
Pliocene
Miocene
Oligocene
Eocene
1
δ 18 O
0
2
SEA LEVEL
High
Low
3
Ciros-I
27 m
366
366
702
4
This paper
A,B, C,D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S, T
5
Davey and Christoffel (1984, 1986)
V
W(T?)
X(A)
Y(C)
6
Cooper et al (1987)
V1
?
V2
V3
7
Davy and Alder (1989)
P
Q
R
8
Anderson and Bartek (1992)
9
?
10
U4A
11
U5
12
U6
13
9
Summary Correlations
W(T?)
?
V1
A
9
?
V2
10
C
V3
11
P
X?
Y U5?
Q
12
R
U6?
V4
13?

Fig. 2. Summary of seismic stratigraphic units in the Western Ross Sea and interpretation of correlations among published units and two sea level proxies of oxygen isotopes (Miller et al., 1987) and coastal onlap (Haq et al., 1987). (1) Stratigraphic units used in this paper, twenty pre-Pleistocene units are identified in McMurdo Sound. (2) Davey and Christoffel (1984) correlated reflectors *A* and *C* of Northey et al. (1975) to hiatuses *X* and *Y* by Webb (1983) in MSSTS-1 core. These hiatuses were dated as Late Oligocene/Early–Middle Miocene and Middle–Late Eocene/late Oligocene, respectively. Reflector *W* is the Wong and Christoffel *T* unconformity. (3) Davey and Christoffel (1986) revised the ages of reflectors *X*(*A*) and *Y*(*C*) to 24.5 and 26 Ma. based on a revised biostratigraphy of the MSSTS-1 core (Harwood (1986) using diatom flora and paleomagnetic correlations. (4) Interpretation of USGS multichannel data (Cooper et al. (1987) identified a number of stratigraphic units. Where USGS lines cross PD90-profiles in north Victoria Land, near DSDP site 273, units *V2* and *V3* can be correlated to the lower Miocene. (5) Three major reflectors were identified in seismic data recorded on the ice adjacent to the CIROS-1 site (Davey and Alder, 1989); (6) Anderson and Bartek (1992) recognized a number of unconformity-bound sequences in the Ross Sea. The top of Unit *10* is recognised in both DSDP Sites 272 and 273 as the Disconformity of Savage and Ciesielski (1983) and spans the time interval 18.2 to 14.1 Ma. (7) Previous seismic nomenclature used in McMurdo is summarized and correlated to the stratigraphic units identified in this paper. Correlation of PD90 to reflectors identified by Northey et al. (1975) indicates that reflectors *A* and *C* correlate to top of units *I* and *L*. In McMurdo Sound PD90 units *F*, *G*, *J*, and *K* comprise unit *V2* while at least *L*, *M*, and *N* correspond to the upper portion of *V3*. We recognize units *X* and *Y* as initially recognised by Webb (1983) in MSSTS-1 as belonging to a block of Oligocene/upper Eocene.

recorded at CIROS-1 is still ambiguous. Seismic stratigraphic correlations from the CIROS-1 site still do not provide a conclusive means of determining whether the Oligocene events recorded at CIROS-1 are the result of continental-scale glacial fluctuation or merely the result of the changing volume of local alpine glaciers. Both scenarios are tenable when one is only able to evaluate the record based solely upon core from one location. However, correlation in this presentation of PD90 data to USGS seismic data (Cooper et al., 1987) and DSDP Site 273 (Hayes et al., 1975; Savage and Ciesielski, 1983) suggest that early Miocene glacial events recorded in the strata of CIROS-1 are extensive, and therefore reflect shelf-wide glaciation.

2. Methods

Approximately 6000 km of seismic data were collected within the Ross Sea and McMurdo Sound ($\approx$650 km) in 1990. During the survey of the shelf a new seismic source, the G.I. (Generator/Injector) gun, was utilized. This 150 in^3 "bubble-free" air gun produces a "clean" outgoing signal with a 0–150 Hz frequency spectrum. The G.I. gun frequently provided subbottom penetration between 1.0 and 1.5 seconds two-way-travel-time. High quality digital and analog data were acquired on a single channel Litton-Teledyne streamer. GPS receivers were utilized for navigation during data acquisition. Details of the data processing are discussed in Anderson and Bartek (1992). However, it is important to note that these are single channel data, so it is not possible to utilize NMO corrections to dampen the multiple. Predictive deconvolution was attempted, but the irregular nature of the sea floor and the underlying sequences caused it to adversely effect data quality and it did not remove the effect of the multiple.

Matching synthetic seismograms to observed single channel and stacked data assisted in seismic stratigraphic interpretation (Fig. 3). In this study, synthetic seismograms were calculated using the method of Kennett (1981). This algorithm calculates plane-wave reflection and transmission com-

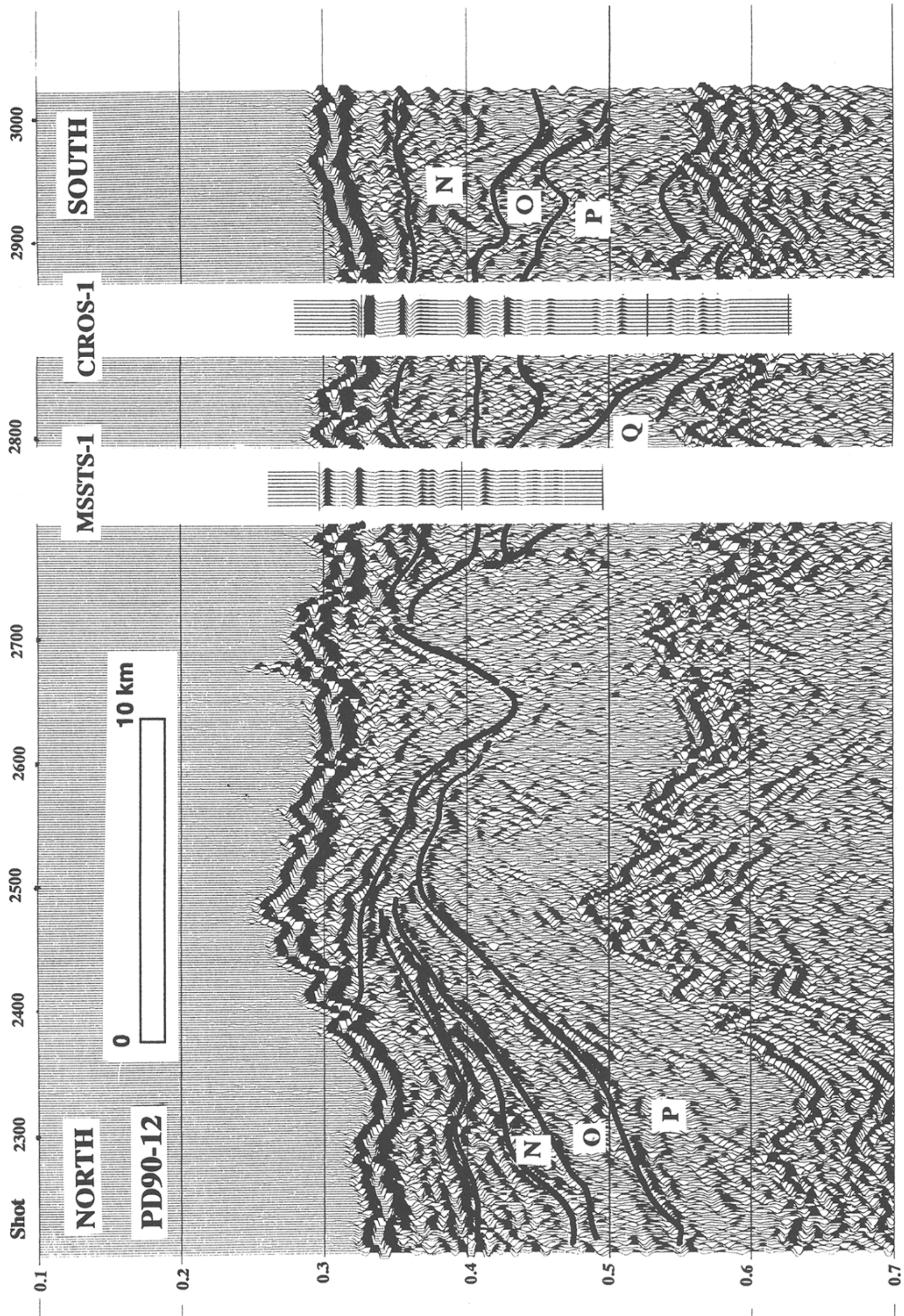


Fig. 3. Expanded view of PD90-12 and the correlation of synthetic seismograms for CIROS-1 and MSSTS-1. The stratigraphic geometry of units *O* and *P* show how these units sit adjacent to the isolated block strata that was cored in MSSTS-1.

ponents using standard filter theory. Input to the synthetic seismogram program requires layer density and velocity data which were provided by the CIROS-1 core (Fig. 4). Input of required layer density and velocity data, which were obtained from the CIROS-1 core (White, 1989). The synthetic seismogram from the CIROS-1 data was used to link the cored sequence to the PD90 seismic data.

The synthetic seismogram generated from the CIROS-1 data was used to correlate the stratigraphy from the CIROS-1 core to the PD90 seismic data (Fig. 3). A fundamental difference between our analysis of seismic data in McMurdo Sound and earlier investigations is that sequences, rather than individual reflectors, were identified and correlated. This is significant because in an environment such as McMurdo Sound where many reflectors merge at locations where unconformities are present, the sequence analysis of the data provides a better relative age framework. When following only reflectors it is very difficult to identify relative ages of strata and to trace them through the study area. In this study the only way to identify a stratigraphy and correlate it to core ground-truth was by first working out the sequence

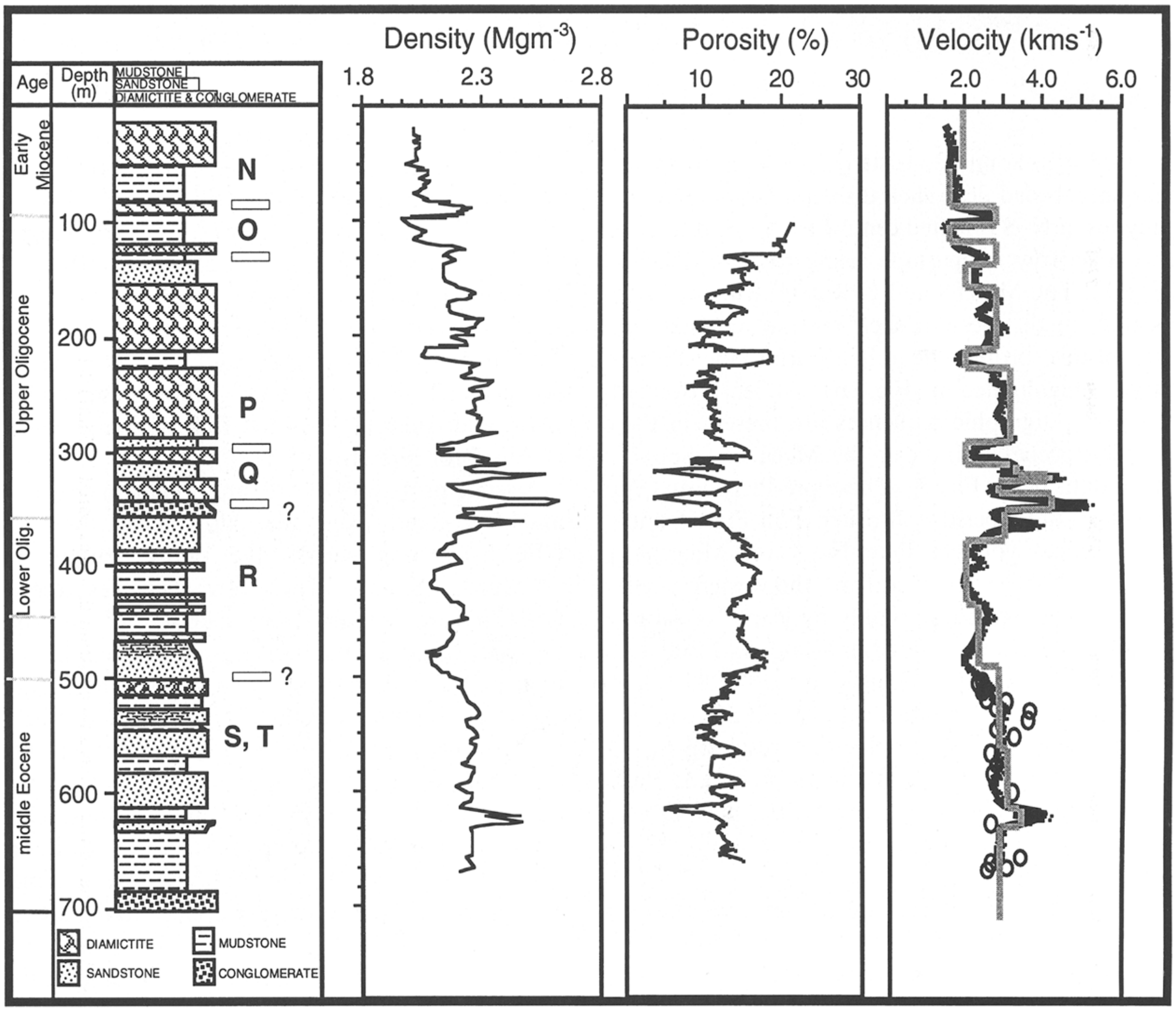


Fig. 4. Diagram showing core velocity and sediment density data used in producing the synthetic seismogram used to correlate the CIROS-1 drilling data to seismic profiles.

stratigraphy of the area, and them correlating sequences to the synthetic seismogram. Approaching the problem from the other end, that is picking out a prominent reflector in the synthetic seismograph and correlating it away, we frequently found that the reflector prominent at the site, was often terminated a short distance from the site and we were left with nothing to carry away from the site. Seismic sequences identified in the PD90 data are bounded by unconformities, as indicated by stratal pattern terminations (onlap, toplap, and downlap). Correlation of the sequences through the data set required iterative passes of correlating units around the intersections of profiles.

3. Results

McMurdo Sound consists of, along its western margin, a broad deep shelf dissected by submarine canyons, a N–S oriented central trough and to the east a narrow steep slope rising to Ross Island (Fig. 1). The MSSTS and CIROS-1 drill sites are located on the western shelf and are crossed by the seismic profiles acquired during the PD90 survey (highlighted in Fig. 1b). At least twenty seismic-stratigraphic sequences are present in the pre-Pleistocene(?) strata of the McMurdo Sound PD90 data base (Fig. 5). These pre-Pleistocene(?) sequences are labeled A through T in Figs. 5 and 6. Sequences younger than N (lower Miocene) have largely been removed from the western shelf of McMurdo Sound, probably by glacial erosion. Vitrinite reflectance studies indicate that 500 to 1000 m of strata are missing (Lowery, 1989). As a consequence, the strata near the sea floor have high densities and high velocities, resulting in a high acoustic impedance at the sea floor and the very strong multiple that obscures the portion of the record that corresponds to the lower half of CIROS-1.

Comparison of seismic stratigraphic sequences in profiles passing over drill sites (PD90-12 and -46) with the cored sequence using synthetic seismograms (Fig. 3) provides the basis for correlation. Several of the seismic sequences were intersected in the CIROS-1 drill hole at depths shown in Table 1. Velocities were taken from Figs. 4 and 3 sequence boundaries were identified at the site. These boundaries correspond to downhole velocity increases of around 1 km/s, all from mudstone down to diamictite, occurring at 85 m for the base of N, at 121 m for the base of O, and at 300 m for the base of P. The base of Q is likely to represent the velocity peak at 348 m in the cemented fluvial conglomerates in the lower part of Unit 17 in the drill hole, though the base of the lithologic unit is 18 m below at 366 m. This last boundary is the most significant in the drill hole, representing a time break of 4 Myr and a major fall in sea level. The base of sequence R is probably close to the lower limit of the Early Oligocene mudstone and the top of the mid-Eocene turbidities at 500 m. No facies change has been identified with the base of S. The base of T could be the boulder conglomerate encountered at 696 m, 6 m above the base of the drill hole. Correlation of the seismic stratigraphic units to drill sites reveals that units A–N are older than Pleistocene but younger than the early Miocene strata of CIROS-1. Portions of units A–N may have been cored by MSSTS-1. Units A–D (?) appear to be Pliocene and units E(?)–N are Miocene. Correlations of our units to the reflector stratigraphy presented by Davy and Alder (1989) for CIROS-1 is presented in Fig. 2 for reference.

Seismic profiles PD90-12, and PD90-46 (Figs. 3 and 5) extend from the bathymetric high at CIROS-1 along nearly the entire length of McMurdo Sound. These two profiles cross CIROS-1 and many of the other seismic lines of the McMurdo PD90 data base and one small, unnamed submarine canyon at the southern end of the profile. Glacial erosion has removed much of the younger strata in the area around the CIROS-1 site leaving deposits characterized by high densities and velocities at the sea floor. The result is a high acoustic impedance at the sea floor and the very strong multiple that obscures the portion of the record that corresponds to the lower half of CIROS-1.

Evidence of glacial scouring of young near-surface units on the shelf can be seen in profile PD90-3 (Fig. 7). The massive trough-shaped unit just below the sea floor and truncating other

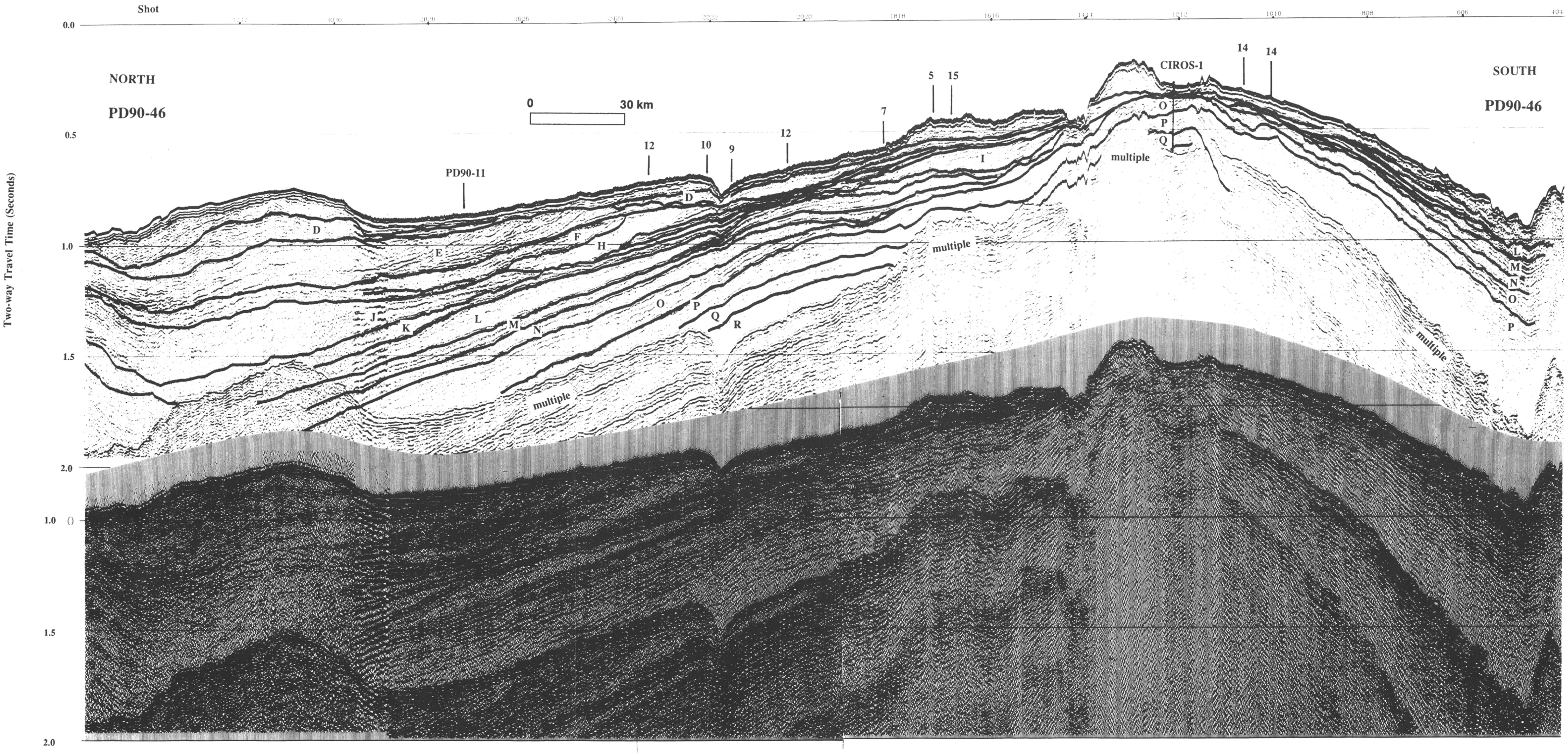


Fig. 5. Seismic profile and line drawing of PD90-46 (a and b). Profile PD90-46 extends along nearly the entire length of McMurdo Sound and illustrates correlation of stratigraphic units described in text away from CIROS-1 into deep water locales.

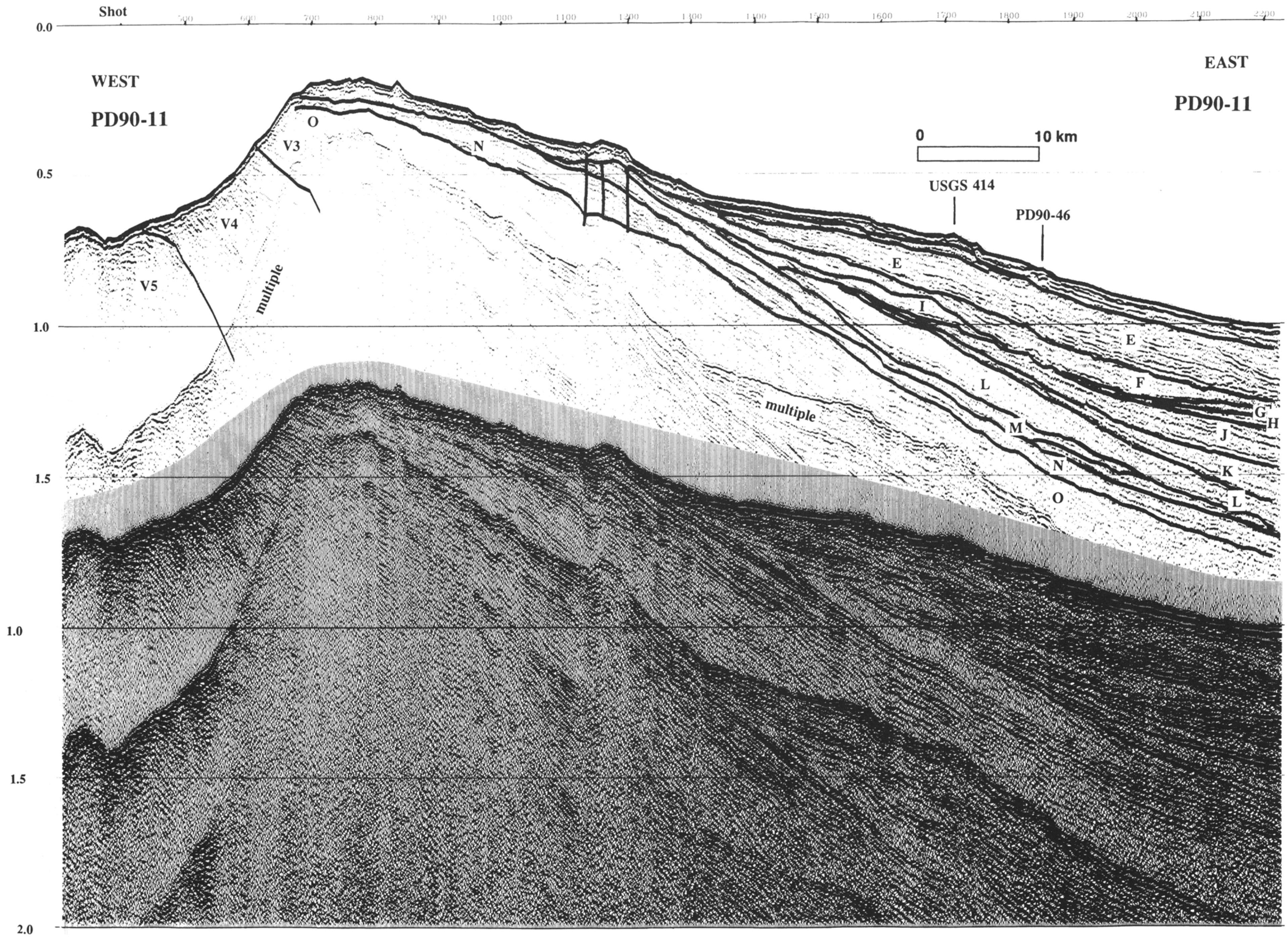


Fig. 6. Seismic profile and line drawing of PD90-11. Profile PD90-11 shows faulting of Paleogene and Neogene strata in northwest McMurdo Sound as well as an area where rocks that pre-date strata of CIROS-1 are accessible at shallow depth.

Table 1
Seismic sequences and boundaries from PD90-12 recognized in CIROS-1 drill hole, along with ages, thicknesses and lithologies. Two-Way-Travel Times (TWT) below the sea floor to the base of each sequence from Fig. 3 and interval velocity from Fig. 4

	Sequence interval		Calc. depth to base	Depth to age lit. change	Thickness	Facies from CIROS-1
	TWT (s)	Vel. (km/s)				
				?	20+ m	Diamictite
	0.045	2.0	45 m	48 m		
N				22–24 Myr	32 m	Mudstone
	0.090	2.0	90 m	80 m		
O				24–25 Myr	40 m	Diamictite top, then mudstone
	0.122	2.0	120 m	120 m		
P				25–29 Myr	165 m	Diamictite. Minor sands, muds
	0.233	3.0	289 m	300 m		
Q				29–30.5 Myr	81 m	Sandstone, conglomerate, diamictite unconformity
	0.263	3.5	342 m	366 m	4 Myr	
R				34.5–36 Myr	134 m	Deepwater mudstone, some sands and diamictite
	?	?	?	500 m		
S				c. 45 Myr	136 m	Turbidite sequence, minor diamictite
	?	?	?	636 m		
T				c. 45 Myr	60 m	Deepwater mudstone
	?		?	969 m		
?				?	6 m	Dolerite boulder conglomerate
				702 m		Bottom of drill hole

reflectors is similar to glacially carved troughs that have been described from the Eastern Basin of the Ross Sea by Alonso et al. (1992). An approximate age for sequences A to I can be estimated by comparing seismic profiles PD90-12 where it crosses MSSTS-1. Depths bsf are estimated assuming a velocity of 2.0 km/s (Davey and Christoffel, 1984). The angular unconformity at 80 ms (80 m bsf) in the profile at this point most likely separates strata in the upper 71 m of the drill hole that are known to be Upper Miocene and younger (Harwood, 1986) from those below 115 m that are Upper Oligocene (Harwood, 1986). This major unconformity is correlated to the intersection of PD90-12 and PD90-3, where it underlies the massive trough-shaped unit just below the sea floor on PD90-3 (Fig. 7). Another unconformity, hiatus "W" of Northey et al. (1975) lying at 30 ms bsf is according to Davey and Christoffel (1986) is in upper Pliocene strata in MSSTS-1, and is here considered to separate sequence E from the distinctly younger package A to D. DVDP-15 cored a young basaltic sand sequence from around 12 to 64 m bsf. This has been correlated on its distinctive lithology with Quaternary strata in the upper 100 m of the CIROS-2 drill hole in Ferrar Fjord (Barrett and Hambrey, 1992). The base of this interval appears to lie at about 160 ms above the angular unconformity on profile MPSL, a sparker profile presented by Bartek (1989) that crosses PD90-3.

Seismic sequences N through Q can be correlated away from the CIROS-1 site along profile PD90-46, being followed around obstructions by correlations to other profiles. PD90-46 (Fig. 5) shows numerous cross-cutting, massive sequences of Neogene age (sequence N and younger). Water depths along this profile range from 200 m in the southern end to nearly 600 m in the north. Seismic facies from sequence N through F on profiles PD90-12 and PD90-46 appear similar to subglacial facies in the Eastern Basin of the Ross Sea

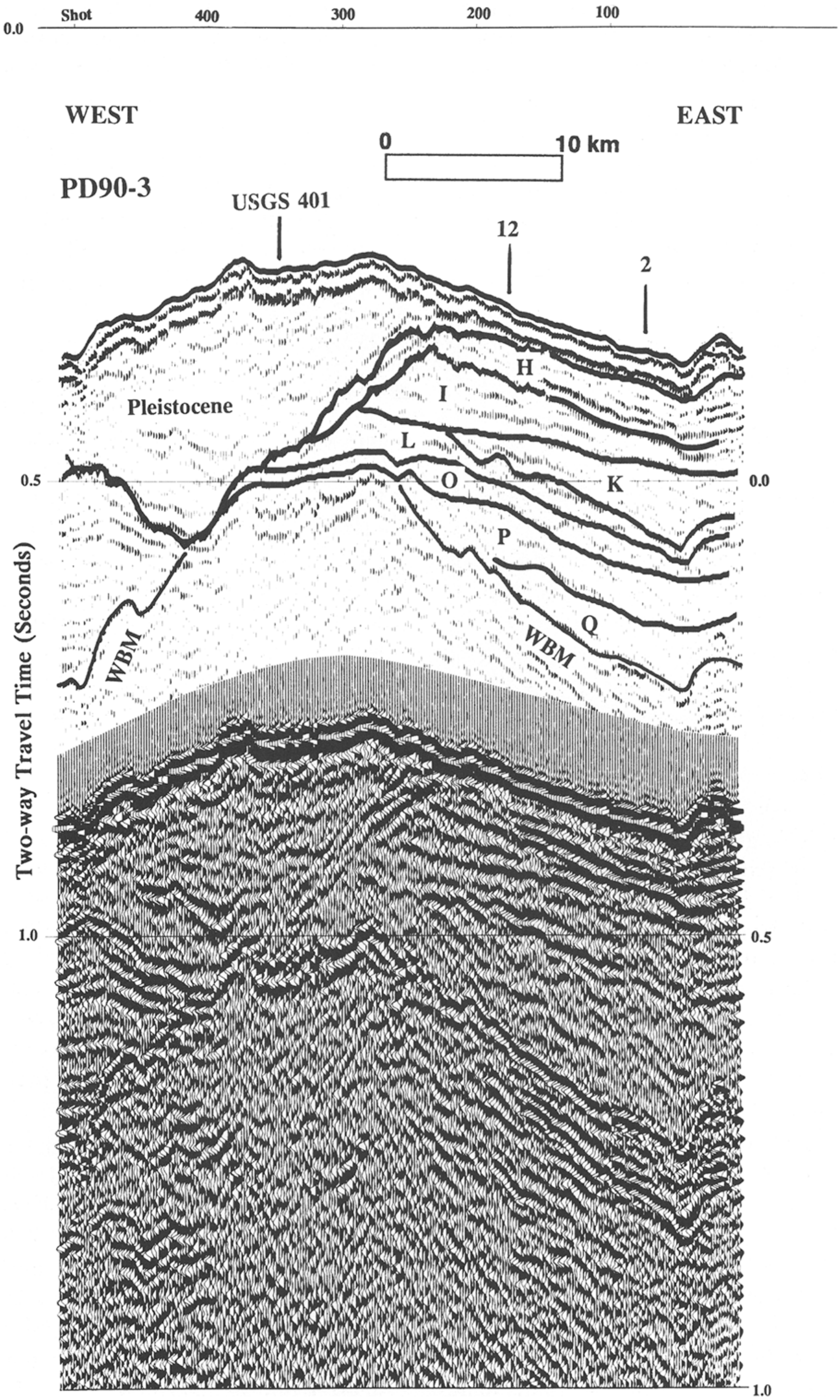


Fig. 7. Seismic profile and line drawing of PD90-3 from McMurdo Sound. Profile PD90-3 shows evidence of glacial scouring of the continental shelf in water depths that are now slightly less 200 m as indicated by the massive trough shaped unit just below the sea floor that truncates other reflectors. Strong water bottom multiples (*WBM*) are present on all seismic sections in McMurdo Sound.

(Anderson and Bartek, 1992). However, the facies are located at the mouth of the Wilson Sea Valley and their pod-like morphology suggests they may be submarine fan rather than subglacial deposits.

Strata dated through correlation with CIROS-1 can be traced on seismic profiles PD90-12 and PD90-46 to northern McMurdo Sound where the profiles cross lower resolution USGS lines 403 and 414 (Cooper et al., 1987). Correlations at this point indicate Cooper et al.'s unit V1 corresponds to PD90 sequences F, G, and H, and that the upper part of V2 corresponds to sequences J, K, and L, while units M and N correspond to USGS unit V3.

Units V1, V2, and V3 can be traced in the USGS profiles to a point about 330 km north of McMurdo Sound and off the North Victoria Land coast, where they cross PD90 profiles. Correlation to PD90-36 to DSDP site 273 indicates that Anderson and Bartek (1992) (A and B-92) unit 9 correlates to the interval between 42.5 m and 273 m (site stratigraphic units 1B and 2A) in site 273 and unit 10 correlates to interval between 273 m and 346.5 m (site stratigraphic units 2B) at site 273. These units are clay and silt rich units that contain lonestones that may be interpreted as glacial marine deposits (Hayes and Frakes et al., 1975). Alternatively deposits with similar lithologies and seismic stratigraphies have been interpreted by Bartek et al. (1991) as fore- and subglacial deposits associated with deposition from a layer of remobilized till produced by rapidly moving ice-streams (as per the model of Alley et al., 1989). Unit 10 can be correlated from site 273 along profile PD90-42 to USGS 410 shot point 360. Unit 9 is eroded along part of PD90-42 so it is difficult to correlate it along PD90-42 to USGS 410 shot point 360. However at the crossing of profile PD90-42 and USGS 410 it can be determined that A and B-92 unit 10 corresponds to USGS unit V2 which in turn correlates to lower Miocene McMurdo Sound units K, L, and M (Fig. 2). A and B-92 unit 9 appears to correspond to either lower USGS unit V1 or upper unit V2 which are lower and middle Miocene respectively. These units are also correlative to McMurdo units I through L (Fig. 2). We have correlated sequences in PD90-44 and PD90-45 that are equivalent to USGS unit V2 with strata in DSDP 273 that are dated as early Miocene and equivalent to A and B-92 unit 10. Portions of the Miocene sequences along profiles PD90-44 and 45 in the North Victoria Land area contain the distinctive glacial seismic facies shown in units 10 and 11 by Anderson and Bartek (1992). The glacially associated seismic facies of unit 10 in PD90-45 are broad U-shaped troughs that cross-cut one another similar to those illustrated by Anderson and Bartek (1992) and Alonso et al. (1992) in seismic sequences 1 through 6 of the cored glacial strata at DSDP site 273 in the Ross Sea.

The recognition of the glacial signature in Miocene sequences over an extensive region (from McMurdo Sound to the Eastern Basin of the Ross Sea) suggests that at least by Early Miocene there was glacial drainage in the Ross Sea sector of Antarctic of a magnitude to influence eustasy and other proxies of ice volume measurably. It may not be coincidental that the Haq et al. (1987) sea level curve has about the same number of Miocene sea level cycles (10) as there are Miocene seismic sequences in McMurdo Sound.

4. Discussion

Numerous seismic data sets have been acquired in the last 25 years in an effort to test hypotheses on the glacial history of Antarctica and the tectonic and stratigraphic evolution of the continental margin. In the Ross Sea and McMurdo Sound, a wide variety of seismic data bases were collected to facilitate correlation of events from one locality to the another (*Ross Sea*: Houtz and Meijer, 1970; Houtz and Davey, 1973; Cooper et al., 1987; Karl et al., 1987; Sato et al., 1984; Hinz and Block, 1983; Brancolini, 1990; Bartek and Anderson, 1990; Zayatz et al., 1990); *McMurdo Sound area*: Northey et al., 1975; Wong and Christoffel, 1981; Davey and Christoffel, 1984, 1986; Davy and Alder, 1989; Bartek and Anderson, 1990; Brancolini, 1990; Anderson and Bartek, 1992). This work has been fruitful in that it has yielded a rough chronostratigraphic framework for Cenozoic glacial and climatic events of the Ross Sea.

Bartek et al. (1991) examined seismic data from the Ross Sea continental margin and also found a match to the Haq et al. (1987) curve. Bartek et al. (1991) compared seismic data from the Ross Sea continental margin to data published from localities far removed from Antarctica (such as Indonesia, New Jersey, Africa, North Slope of Alaska among others) and found a good correspondence in the timing of Neogene shelf aggradational and progradational episodes on these margins. Timing for correlation between events in different regions was based on micropaleotology, paleomagnetics, oxygen isotope records (where available) at the non-Antarctic sites and micropaleontologic dating from the published analyses of DSDP drill core from the Ross Sea. Recovery from much of the DSDP drilling in the Ross Sea was not very good, so this was the weak link in correlation to other margins and it basically only permits us to recognize and correlate intervals where the margins were retreating, aggrading, show a mix of aggradation and progradation, to situations where the margin is prograded seaward dramatically. The unconformities that bound the Neogene sequences on the Ross Sea margin appear to have been produced by glacial erosional processes (Bartek and Anderson, 1990; Anderson and Bartek, 1992), while the unconformities that separate aggradational and progradational units on the other margins are the product of eustatic change (Vail et al., 1977). These observations suggest that there may be a link between the ice volume fluctuations that left an imprint on the Ross Sea stratigraphy and the eustatic events that produced the unconformity bound units on the other margins. An important caveat to these observations is that an analysis of the prograding sequences of the Antarctic continental margin conducted by Cooper et al. (1991) suggest that the timing of progradation (and perhaps ice advance) varies around Antarctica. It is also important to note that CIROS-1 is located in a basin along the eastern flank of the Transantarctic Mountains and it is difficult to assess whether the deepening and shallowing events documented by Barrett et al. (1989) are related to some combination of "structural" tectonic activity and erosion by waxing and waning of local alpine glaciers (i.e. the local alpine drainage of McMurdo Sound that is illustrated in Fig. 1b versus the continental-scale ice sheet and outlet drainage displayed in Fig. 1a). To date, attempts to correlate seismic data from the McMurdo Sound drill sites (an area that contains the oldest record of Cenozoic glacial activity in this sector of Antarctica) to other areas of the Ross Sea has yielded ambiguous results (Cooper et al., 1987; Davy and Alder, 1989). At this point it appears as though correlation of direct evidence of early Paleogene Antarctic climatic events (i.e. subglacial deposits and erosional unconformities as opposed to proxies such as oxygen isotopes) to the eustatic record or other indicators of global climatic change is still not clear. Indeed, it is still difficult to correlate events reliably between various portions of the Antarctic margin. These ambiguities need to be resolved to improve understanding of the dynamics of Antarctic ice sheets. This will, in turn, improve our understanding of relative importance of the mechanisms controlling eustatic change, a topic that is still controversial (Sahagian and Watts, 1991).

Alternative interpretations for the origin of unconformity bound seismic sequences of McMurdo Sound include: (1) deposition of and erosion of strata in a basin undergoing uplift on its western flank in response to uplift of the Transantarctic Mountains, (2) deposition of strata and production of unconformities as local alpine glaciers waxed and waned, (3) deposition of strata and production of unconformities as continental-scale glaciers fluctuated, or (4) some combination of all of the above. Fission track investigations of the Transantarctic Mountains indicate that fifty million years ago uplift of the mountains increased from 15 m/Myr to 100 m/Myr (Fitzgerald et al., 1987), and it continued at this high rate until the late Cenozoic. It may have decreased to 50 m/Myr (50–105 m/Myr during the Late Pliocene) according to Smith and Drewry (1984). Within this interval (ca. 50–2 Ma), at least 20 unconformity bound sequences have been identified and correlated. Angular unconformities at the top of seismic sequences in this area may correspond to pulses of rapid uplift or fault movement that are not detectable via fission track dating. Our work shows angular tilting of Miocene strata [MPSL of Bartek

(1989) and PD90-3] overlain by relatively flat-lying trough scoured Plio-Pleistocene sequences. This suggests an uplift event in the Transantarctic Mountains in a short interval in the late Miocene–early Pliocene. Onlap on these unconformities may correspond to erosion of uplifted rocks and deposition in the adjacent rift basin. Faults have been identified on profiles PD90-11 (Fig. 6) and appear to post-date late Miocene deposition.

Alternatively, strata within these sequences may correspond to sedimentary sequences produced through glacial activity. Unconformities in this scenario are the product of erosion during maximum glacial advance. The question of glacial origin may be answered by cores of diamictites that contain striated and faceted pebbles from the upper Paleogene–Neogene unconformity bounded sequences. These cores should be collected from areas where the section is expanded and correlation to seismic data is more definitive. Until cores of this strata are available, this hypothesis must remain untested. However, strata from the relatively condensed section of CIROS-1 contain striated and faceted pebbles in diamicties which are interpreted by Barrett, et al. (1989) as evidence of glacial activity in interval of interest. The question of the nature of the glacial activity (local alpine glaciers versus continental-scale ice sheets) that produced the unconformity bound sequences cored at CIROS-1 may be answered by correlation of the unconformity bound units on a regional basis.

The map of the McMurdo Sound area shows the presence of local alpine glaciers in close proximity to the locations for the CIROS-1 and MSSTS drill sites. Late Quaternary advance and retreat of alpine glaciers in this area are known to be out of phase with ice sheet fluctuations (Denton et al., 1970; Drewry, 1980). Thus, the record of glacial activity at CIROS-1 may or may not be in phase with eustatic events. However, modeling studies and investigations of pebble provenance in tills and glacial marine deposits indicate that the Ross Sea has been the recipient of ice flowing from both the East and West Antarctic Ice Sheets (Hughes et al., 1981 and Barrett, 1975, respectively). This portion of the Antarctic receives about a quarter of the drainage of the Antarctic ice sheets. Thus, the stratigraphic record of grounding line migration in the Ross Sea Sector may serve as a "barometer" of Antarctic ice volume change throughout much of the Cenozoic. The key is to discriminate local glacial activity from continental ice sheet fluctuation. Continental-scale glaciation will manifest itself in the form of regionally extensive, unconformity bound, diamictite sequences while alpine glacial deposits will be restricted to small areas.

Oligocene units O and P can be traced at least 55 km north of the CIROS-1 site before being obscured by the multiple. However, seismic facies in these units show only minor evidence of glacial features and it is not possible at the moment to correlate these units over an extensive area of the shelf. When we refer to distinctive seismic facies we refer to facies similar to those identified by Anderson and Bartek (1992), and King et al. (1991) where it is possible to identify broad (50 km wide troughs often cross-cutting, with no evidence of lateral accretion, and primarily filled with chaotic to reflector free facies, or Till Deltas or Aprons, or Till tongues). Therefore existing seismic data provide relatively little support for the interpretation of CIROS-1 data as indicative of pre-Miocene glacial waxing and waning of a magnitude large enough to be associated with large eustatic fluctuations.

However, an area where more insight into the Paleogene (and perhaps Mesozoic) climatic history of a high southern latitude environment exists along profiles PD90-10 and 11. These profiles cross lines PD90-12 and PD90-46 and correlations along these profiles to CIROS-1 indicate that the strata that outcrop at the shallow end of PD90-11 (Fig. 6) offshore Cape Roberts are older than the material recovered from the base of CIROS-1. Thus, pre-lower Oligocene rocks are exposed, or at worst are covered by a only thin veneer (<10 m) of sediment in this area.

5. Conclusions

More than 20 unconformity bound seismic sequences (Fig. 5) have been identified in the 650 km of data collected in McMurdo Sound, Antarctica. Several of these unconformities were correlated to sequences of the CIROS-1 drill site. Diamictite sequences in the strata recovered in the CIROS-1 core were originally interpreted as the product of glacial fluctuation that occurred on a scale that was large enough to effect Paleogene eustasy (Barrett et al., 1989). A test of this hypothesis requires that the sequences contain glacial facies, and correlation of the units with subglacial facies must be demonstrated over an extensive portion of the continental margin in order to suggest that the volume of ice involved would be large enough to effect eustasy. Correlations and seismic facies analysis of the upper Eocene and Oligocene section cored at CIROS-1 suggest that the succession lacks extensive glacial seismic facies, so the correlation of the ice volume fluctuation record at CIROS-1 to the Haq et al. (1987) eustatic curve is still equivocal.

The claim that glacial/interglacial changes in the CIROS-1 drill core were the product of glacio-eustasy could not be properly tested for the Paleogene strata. Most of the sequences identified in the core (N to T) could be traced over 70 km north to the Cape Roberts area, but did not show clear glacial seismic facies characteristics. However, Miocene seismic stratigraphic sequences from McMurdo Sound contain glacial seismic facies that can be traced 300 km north toward the continental margin. This indicates that continental glaciers were draining onto the Ross Sea margin by the early Miocene, and that Antarctic ice volume fluctuations at this time may well have been large enough to affect eustasy.

The data presented in this paper do not preclude large pre-Miocene Antarctic ice sheets, but are not yet of a sufficient resolution to test the hypothesis properly. Further improvement in technology is needed to trace units on the scale of individual till units, and improve confidence in seismic facies identification. Success in work of this sort on near-surface sequences is promising.

The chronology established here and the extension of McMurdo Sound stratigraphy to the area off Cape Roberts, has identified strata of early Cenozoic and possible late Mesozoic age cropping out on the sea floor. Coring of these strata, which are from an extremely high southern latitude position, may also provide insight into the question of whether early Paleogene and/or late Mesozoic climates were warm and equable. Which in turn may radically change the way we interpret the meaning of either isotopic data as indicators of sea water temperature/ocean volume, or revise our interpretation of coastal onlap variations as a measure of eustatic variation. All of this will have an impact of setting boundary conditions for paleoclimate models and models of future climate evolution. Finally our entire understanding of the ranges of climatic tolerance of various organisms to broader or narrower ranges of climatic boundary conditions may alter our understanding of the causes for evolution and extinctions as well.

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