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SEISMIC FACIES AND GLACIAL HISTORY IN THE WESTERN ROSS SEA (ANTARCTICA)

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New multichannel and single-channel seismic data compilations are used to construct a general seismic facies model for the western Ross Sea. We also integrate offshore seismic data with onshore and offshore stratigraphic records, Ross Sea tectonic evolution models, oxygen-isotope and global sea-level curves, to describe Ross Sea depositional paleoenvironments. The evolutionary model we propose for the western Ross Sea has segmented basins of limited areal extent separated by relatively high-standing ridges in early Oligocene and older times. In the Oligocene, temperate glaciers and rivers from high-standing ridges provided sediment to marine basins that were partially open to the Southern Ocean. Regional tectonic subsidence and eustatic fluctuations in early to middle Miocene time provided mostly open marine conditions on a relatively flat and partly overdeepened shelf. Subpolar glaciers and ice sheets, intermittently grounded on the shelf, supplied sediment to offshore basins during this period. During late Miocene and Pliocene time, proglacial sediment was deposited in the structurally overdeepened basins, with a major advance of a polar ice sheet to the shelf edge at the end of this period. Since early Pliocene time, multiple advances and retreats of polar ice sheets across the western Ross Sea have further eroded the inner shelf and redeposited the sediments on the outer-shelf and continental slope, resulting in the present morphology of the continental margin. Although seismic coverage is good, the greatest weakness of the model that we propose is the lack of stratigraphic control, especially between 15 and 4 Ma.

INTRODUCTION

Sediments of the western Ross Sea record the history of the Antarctic Ice Sheet through Cenozoic time. The ice sheet entered the western Ross Sea as mountain glaciers and over-riding ice sheets from the west, and as massive ice-streams from the south [e.g., *Denton et al.*, 1991]. Yet, the history of the ice sheets that have entered the area since at least Eocene to early Oligocene time [*Barrett*, 1989; *Hannah*, 1994] is poorly understood. Sedimentary sequences in the Ross Sea have been widely recognized as recording the history of advances and retreats of ice sheets onto the continental shelf [e.g., *Cooper et al.*, 1991a; *Anderson and Bartek*, 1992], yet the debate about the types and extent of ice (i.e., floating or grounded; local or regional, temperate or polar) continues. In this paper, we examine new compilations of seismic data together with drilling data to study the geometry and acoustic characteristics of the sedimentary record, to derive a model for paleo-environments and the history of glaciation across the western Ross Sea.

The sedimentary sections of the western Ross Sea are strongly affected by tectonics and glacial erosion. The area is bounded on the west by the Transantarctic Mountains, which form a shoulder of the West Antarc-

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tic Rift System [*Behrendt et al.*, 1991; *Cooper et al.*, 1991b; *Fitzgerald*, 1992]. The evolution of the rift system since Jurassic times has greatly affected the distribution and thickness of offshore strata, which are highly variable in the western Ross Sea [*Davey*, 1981; *Davey et al.*, 1982, 1983; *Cooper and Davey*, 1987]. Widespread Cenozoic tectonic activity throughout the Ross Sea [e.g., *Cooper et al.*, 1994a,b] and particularily in the western part, with large magmatic intrusions and intense faulting, has further disrupted the sedimentary sections [e.g., *Cooper and Davey*, 1987]. Extensive glacial erosion has removed thick parts of the sedimentary section in the western Ross Sea, as we discuss below.

For this paper, we discuss three structural and depositional provinces in the western Ross Sea: the Northern basin, the Coulman high and the Victoria Land basin (Figure 1a). The Northern basin lies northeast of Coulman Island in 300 to 500 meter water depths. The basin is filled with a sedimentary section up to 5000 m thick with a broad prograding sedimentary wedge that forms the continental slope. The Coulman high is a broad basement high that lies south of Coulman Island and continues south beneath the Ross Ice Shelf east of Ross Island. Water depths over the Coulman high generally range between 500 and 700 meters, and maximum sedimentary rock thickness reaches 1500 meters. The Victoria Land basin lies south of Cape Washington and may continue below the Ross Ice Shelf south of Ross Island. Water depth reaches 1200 m and sedimentary rock thickness is greater than 12000 m [*Cooper and Davey*, 1987].

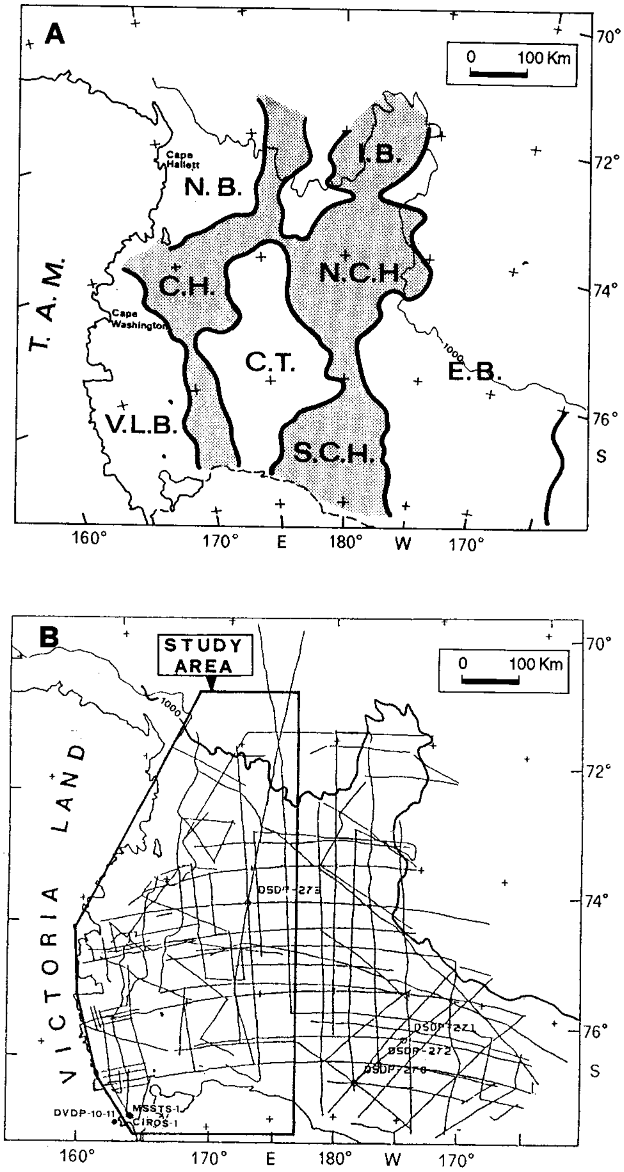

Fig. 1. Index maps of Ross Sea. (a) Main structural basins and highs. Heavy line is where sedimentary rock thickness is 1000 m. Our study area lies west of the Central high-Iselin Bank structure. NB = Northern basin, CH = Coulman high, VLB = Victoria Land basin, CT = Central trough, IB = Iselin Bank, NCH = northern Central high, SCH = southern Central high, EB = Eastern basin TAM = Transantarctic Mountains. (b) Locations of multichannel seismic profiles and DSDP and other drill sites.

METHODS

For this study, we use single-channel and multichannel seismic (MCS) reflection data compiled by the Antarctic Offshore Acoustic Stratigraphy (ANTOSTRAT) project, using the Antarctic Seismic Data Library System [*Childs et al.*, 1994]. The large MCS data set (Figure 1b) has made it possible to compile reliable three-dimensional reconstructions of the main large-scale structural and depositional features that characterize the Ross Sea [see also *Cooper et al.*, 1994a,b; *De Santis et al.*, this volume; *ANTOSTRAT*, this volume].

We define eight acoustic sequences based on the stratigraphic record in the Northern basin, where the section is more complete than in other places in the western Ross Sea. More sequences have been recognized by single-channel seismic studies across some parts of the region [e.g., *Barrett et al.*, this volume]. MCS data resolve larger-scale features, but cannot resolve layers of 10 m or less, such as may occur in many near-sea-floor Pliocene to Holocene sections.

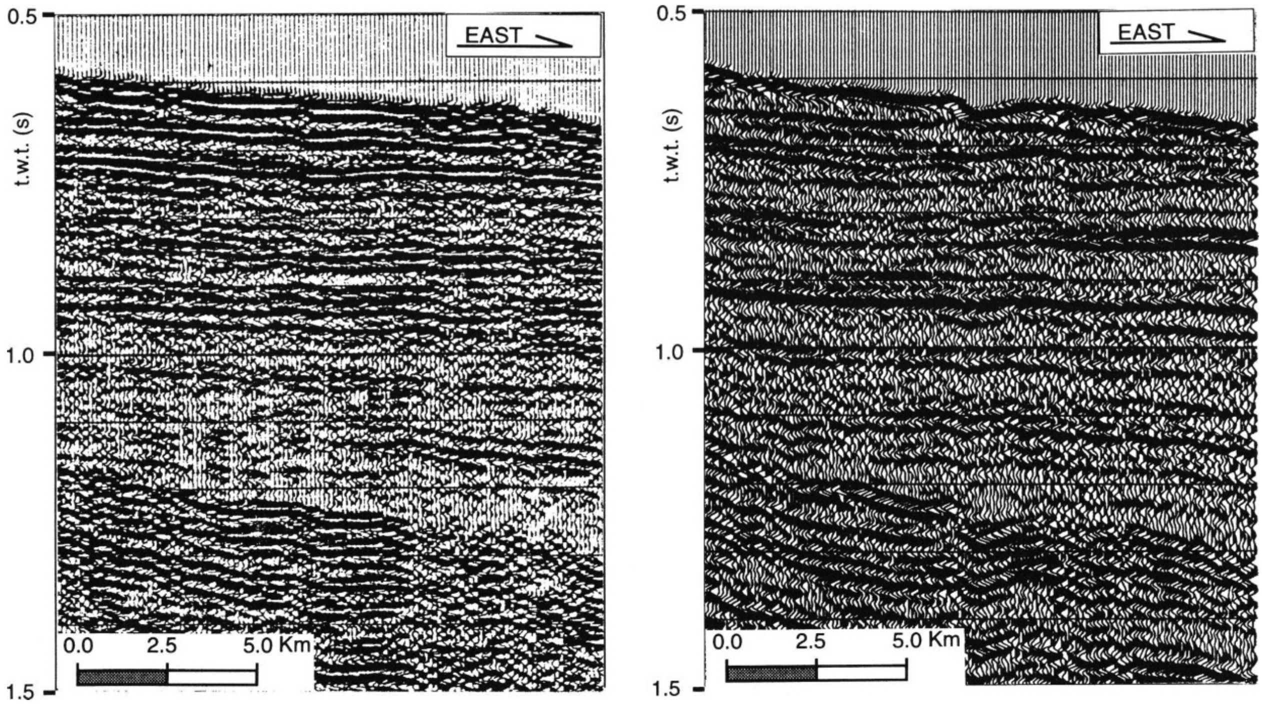

Fig. 2. Comparison of single-channel seismic data in the western Ross Sea recorded in nearly the same location. (a) Seismic profile PD-42, collected using generator-injector (GI) airgun and single-channel streamer. (b) Seismic profile It-80, recorded using tuned airgun array and near-channel of multichannel streamer. Vertical exaggeration (VE) 25:1. See Figure 5 for location.

In this study, we adduce a general glacial history: a more-detailed analysis of individual sequences is better accomplished with higher-resolution data. Where possible, single-channel and MCS data are integrated to give the best possible seismic facies and sequence characterizations. The single-channel seismic data that we used included: (1) published profiles from *Anderson and Bartek* [1992] and (2) unpublished near-channel profiles from the 1990 Italian MCS survey.

The vertical resolution of the data sets is comparable (Figure 2). With a frequency of 60 Hz and a sedimentary-rock interval velocity of 2500 m/s, the vertical resolution for the two examples is about 10 m.

We correlate seismic sequences to drill site data at the following sites: DSDP Site 273 [*Hayes and Frakes*, 1975; *Savage and Ciesielski*, 1983], MSSTS-1 [*Barrett*, 1986], and CIROS-1 [*Barrett*, 1989; *Hannah*, 1994] (Figure 1b). Reflection times are converted to depths using a weighted average of the stack velocities around the drill sites. We correlate the sequence boundaries with eustatic sea-level [*Haq et al.*, 1987] and oxygen-isotope curves [*Miller et al.*, 1991] (Figure 3). Dating of the seismic sequences is problematic due to sparse drill sites, poor recovery, and equivocal biostratigraphic and magnetostratigraphic ages. We discuss the reliability of correlations in the descriptions of the sequences.

Glacial deposits may occur in different climates. In our discussion, we use the classification of *Trewartha* [1969], adopted also by *Anderson and Ashley* [1991], in which the equilibrium line for a glacier in a "polar" climate is below sea level, in a "subpolar" climate is at sea level or just above, and in a "temperate" climate is above sea level.

We distinguish subglacial and grounding-line from glacial-marine environments based on seismic facies on single-channel seismic data. Subglacial deposits are tills that, according to *Dreimanis* [1989], are "sediment that has been transported and deposited by or from glacier ice, with little or no sorting by water". This definition implies that tills are not sorted and not stratified. We define the seismic expression of a subglacial deposit as an internally non-reflective unit with an irregular external shape. Such units may range in lateral extent from a few kilometers to many tens of kilometers, and they are attributed to either large ice

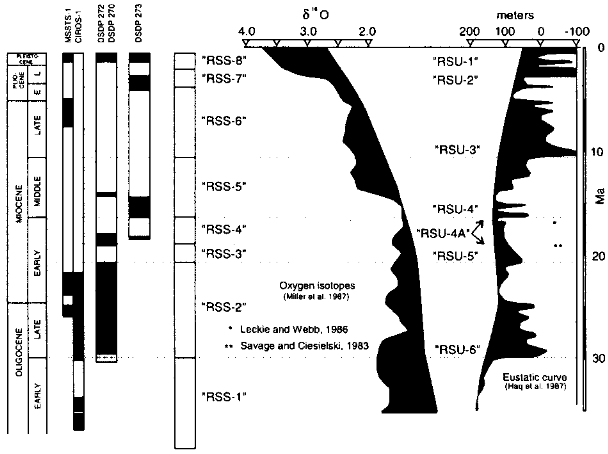

Fig. 3. Proposed correlation of the Ross Sea seismic sequences (RSS) with drill sites, eustatic sea-level curves, and oxygen-isotope curves. We assume that the boundary between RSS-6 and RSS-7 is at about 4 Ma, and hence just before a rapid increase in oxygen-isotope values (cooling). This boundary may record the first advance of a grounded ice sheet to the continental shelf edge, during full polar conditions. For drill sites, black areas show sections drilled. Core recovery is indicated in the text. See text for explanation of unconformities RSU1 to RSU6.

sheets or alpine-type glaciers. We do not believe that all the irregular and non-reflective units are the result of subglacial deposition. Many other depositional processes, for example slumps, may produce internally non-reflective and irregular units; hence, our interpretation may over-estimate the presence and extent of grounded ice. Similar non-reflective units with a wedge-like external shape are recognized on northern hemisphere polar shelves, and described as "till tongues" by *King et al.* [1991]. *Anderson and Bartek* [1992] applied the "till tongue" concept to the eastern Ross Sea seismic data evaluation.

Grounding-line deposits may be glacial fans in a temperate or subpolar environment or till deltas in a polar environment. The former have been defined as "fans that originate from subglacial and basal stream tunnels at grounding lines of glaciers terminating in a marine environment" [*Powell,* 1988]. The latter are the product of ice streams, and have been defined as comprising "basal-till topsets with minor sorted sediments, and gravity-flow foresets and bottomsets" [*Alley et al.,* 1989]. Glacial fans have been largely recognized and studied from the northern hemisphere [*Boulton,* 1990; *Powell,* 1990], whereas the presence of till deltas in front of the ice streams is still only speculative. Grounding-line deposits generally produce oblique to sigmoidal prograding clinoforms. Distribution, external shape and internal patterns can be recognized from seismic data, and may help to distinguish these deposits from subglacial or glacial-marine sediments.

Another type of grounding-line deposit is the shelf-margin delta-fan complex, described by *Larter and Barker* [1989]; *Cooper et al.* [1991a]; *Hambrey et al.* [1992]; *Anderson and Bartek* [1992]. Shelf-margin delta fans are deposited when the grounding line is close to the continental shelf edge and sedimentation occurs directly onto the slope. A steep (over 5°) and thick prograding unit with eroded topset beds at the shelf edge is considered the seismic expression of this depositional system [*Larter and Barker,* 1989; *Cooper et al.,* 1991a].

We recognize the limitations of the seismic-to-geology correlations inherent in these definitions. The value and difficulties of applying these criteria have been widely recognized and discussed [e.g., *King et al.,* 1991; *Anderson and Bartek,* 1992].

The geometries of seismic unconformities are commonly used to infer advances of grounded ice sheets [e.g., *Larter and Barker,* 1989; *Cooper et al.,* 1991a; *Bartek et al.,* 1991]. *Bartek et al.* [1991] infer the deepening of the shelf toward the continent from erosional unconformities. The criteria, however, are not unique because landward deepening of sub-surface horizons is difficult to establish, particularly with single-channel seismic data in places where only part of the unconformity can be seen above the sea-floor multiple reflection, and the unconformities themselves are subject to varied interpretations.

We recognize two types of erosional morphology that can be used to infer the presence of grounded ice:

1. Wide (up to 100 km) troughs perpendicular to the shelf edge. These troughs are similar to those that form the present sea floor morphology and are considered the product of ice stream erosion from a polar ice sheet grounded on the continental shelf.

2. Narrow (up to 5 km) U-shaped channels, which are similar in width to alpine-type glacial valleys due to glacial erosion.

The seismic criteria we adopt to distinguish different environments are not unique. Where possible, seismic facies have been integrated with drill site data. Drill site data, however, do not always unambiguously define the depositional environment, and only a small part of the Cenozoic section (i.e., 20% of that above RSU6), has been sampled.

SEISMIC FACIES IN THE WESTERN ROSS SEA

We recognize eight seismic sequences in the western Ross Sea within sedimentary sections ranging from likely Mesozoic to Holocene age. Figure 4a shows a type section for the Northern basin, and Figure 4b shows the geometric relationships for the same profile. In Figure 4b, reflectors were transformed to a pseudo-chronostratigraphic section, following the method of *Mitchum et al.* [1977], but using a time-section in lieu of depth-section to illustrate relative spatial geometries.

Seismic sequences have previously been defined for the Ross Sea by *Hinz and Block* [1984], for the Eastern basin and Central trough by *Anderson and Bartek* [1992], and for the Victoria Land basin by *Cooper and Davey* [1987]. In general, the acoustic stratigraphy of the eastern Ross Sea can be well documented because of good lateral continuity of reflectors; however, the correlation of reflectors from the eastern to western Ross Sea is less certain because of intervening erosion of seismic sequences. The general features for each seismic sequence, and correlation with previous interpretations, are summarized in Table 1.

3.1. *Seismic Sequence 1: Basement - RSU6*

Seismic sequence 1 (RSS-1) lies between acoustic basement and RSU6. In the Northern basin (Figure 4a), RSS-1 onlaps basement beneath the outer shelf and has mostly sub-parallel reflectors. The upper boundary of RSS-1 (RSU6) is a prominent unconformity characterized by a strong reflector that can be traced nearly continuously from the outer shelf, across the slope and rise. The difficulties in correlating RSS-1 between and within the different basins of the Ross Sea are discussed by *Brancolini et al.* [this volume].

Two units are recognized within RSS-1 in the Northern basin, separated by a basement high (Figure 4a). The inner unit lies below the continental shelf, and the outer below the slope and rise. In the western part of the basin, the sequence is intruded by Cenozoic magmatic rocks of the Cape Hallett volcanic province. On the Coulman high, where RSS-1 has not been deposited (Figure 5), acoustic basement is cut by channels that show V- or U-shaped profiles. Buried channels vary from about 1 km wide with 100 m relief to 15 km wide with 300 m relief (Figures 6a and b). We assume the channels to have been filled by syn- or post-RSS-1 sediment.

On the western side of the Victoria Land basin, RSS-1 has been tilted and uplifted since the earliest phases of Transantarctic Mountain uplift. The uplift has resulted in outcrop of RSS-1 at or near the sea floor. In these areas, RSS-1 can be examined using single-channel seismic data. One seismic profile (Figure 7) perpendicular to the coast shows that RSS-1 has been folded, but the seismic facies can still be resolved. Here, the sequence is well stratified, has medium-amplitude and medium-continuity internal reflections, and contains a few thin lense-shaped bodies. On a seismic profile parallel to the coast (Figure 8), the sequence is less regular and continuous. In this direction, tectonic and depositional features are more difficult to distinguish. We believe that RSS-1 may previously have extended farther west than now seen, and that the missing part was eroded following uplift of the Transantarctic Mountains and basin flank. Figures 7 and 8 show that RSS-1 is more than 2 km thick, where last seen on seismic lines approaching the coast. Assuming typical geometries for sequences that thin across a basin flank, the sequence may have continued west many tens of kilometers, with the former basin edge lying landward of the present coastline.

In South Victoria Land, RSS-1 has probably been sampled at CIROS-1 [*Barrett*, 1989], where it corresponds to part of the Lower Sequence that lies below 366 mbsf in the hole. Here, RSS-1 may be from middle Eocene [*Hannah*, 1994] to early Oligocene age. The upper boundary of RSS-1 lies within or at the top of the Lower Sequence, and could be the major hiatus between early and late Oligocene (34.5 and 30.5 Ma) at 366 mbsf or the hiatus between middle Eocene and early Oligocene at about 500 mbsf. The correlation is speculative because it is not possible to trace RSU6 from the Victoria Land basin to the CIROS-1 site, due to post-Oligocene faults and uplift, basin-flank unconformities, and deep glacially-eroded troughs (Figure 9). The Lower Sequence at CIROS-1 is fine-grained, bioturbated pro-delta mudstone, deposited below wave base at a water depth that, based on foraminifera, probably ranged between 300 and 600 m [*Webb*, 1989; *Barrett*, 1989; *Hall and Bühman*, 1989].

3.1.1. ***RSS-1 paleoenvironment.*** RSS-1 was deposited in isolated subsiding basins (Figures 4a and b), and onlaps basement highs that separate the basins [*ANTOSTRAT*, this volume, Plates 6 to 15]. Basement highs have been at least locally subaerially exposed and eroded, as demonstrated by samples recovered from the southern Central high at DSDP Site 270 (core recovery 62%). There, an Oligocene sedimentary breccia with well-developed regolith overlies early Paleozoic? metamorphic rocks [*Hayes and Frakes*, 1975]. In the

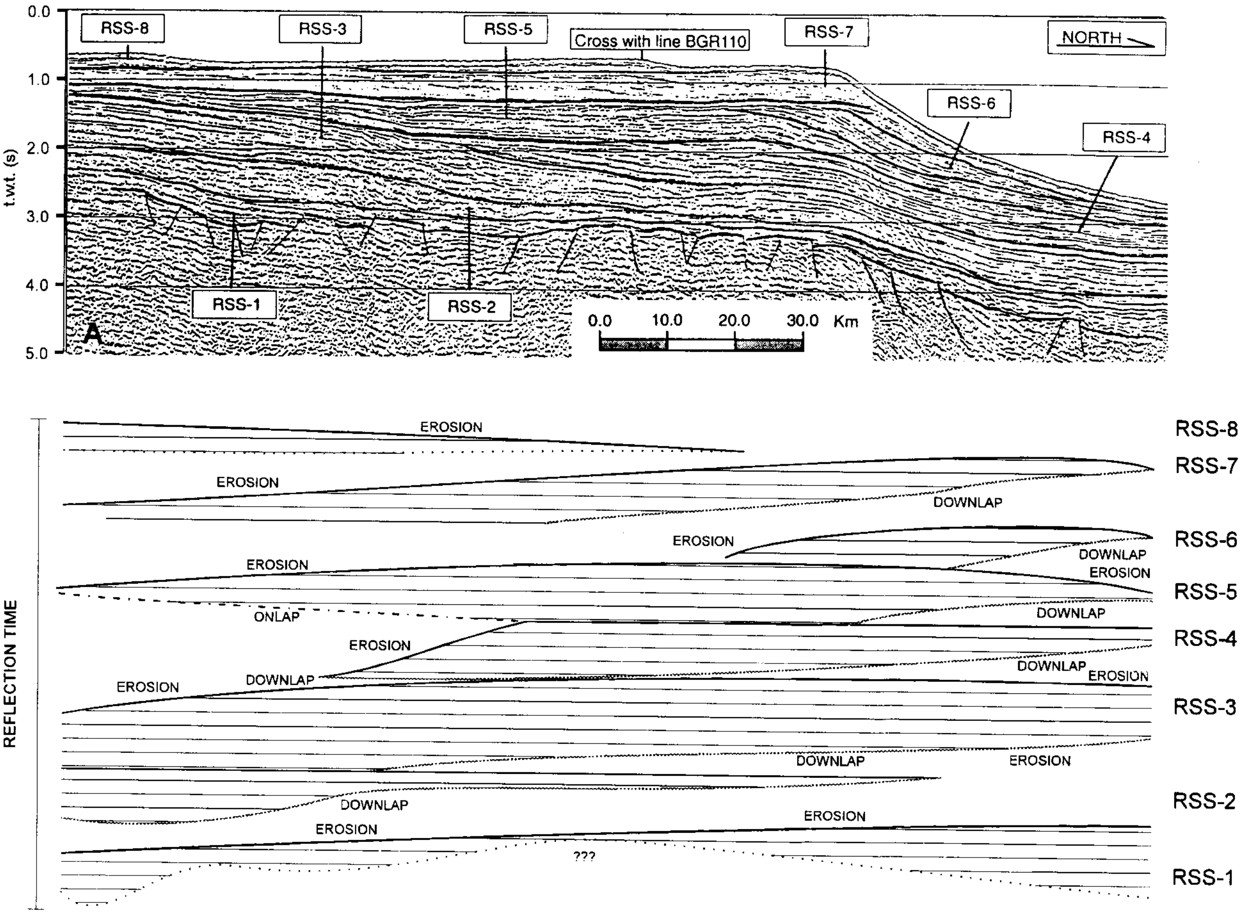

Fig. 4. (a) Type section of the Northern basin (seismic profile It-88: shot points (SP) 1500-4000, VE 14:1). Seismic sequences are same as those mapped in *ANTOSTRAT* (this volume, Plates 6 to 22). A distinct change in seismic facies and paleo-slope morphology occurs between RSS-6 and RSS-7. We believe that this change (i.e., at unconformity RSU2) marks an advance, possibly the first, of a grounded polar ice sheet to the continental shelf edge in Pliocene time. (b) Generalized pseudo-chronostratigraphic section for Figure 4a, illustrating the geometric relationships between sequences. Note the abrupt change from the prograding pattern of RSS-6 to the aggrading patterns of RSS-7 and RSS-8. See Figure 5 for location, and Table 1 for description of unconformities and facies.

Site 270 area, U-shaped erosional channels are described [*De Santis et al.*, this volume]. By comparison, the Coulman high has also probably been subaerially eroded, because acoustic basement is flat and is incised by channels with V- and U-shaped profiles. We think the U shape of the channels indicates that, in at least the final stage of their evolution, they were incised by glaciers. On the western flank of the Victoria Land basin, single-channel seismic data do not show clear evidence of subglacial features. As noted above, the areas where seismic data exist may lie far from the former basin edge.

In summary, we believe that when the upper part of RSS-1 was deposited (Eocene to possibly early Oligocene), the climate was temperate with rivers and wet-based mountain glaciers eroding and transporting sediment to offshore marine basins that were isolated from the Southern Ocean or comunicated via restricted pathways. This model agrees with paleoenvironments suggested by *Barrett* [1989], based on CIROS-1 drilling and palynomorph analysis that concluded: "cool temperate soils and forests developed on land". The upper boundary of RSS-1 may correlate with a hiatus between middle Eocene and early Oligocene or a major

TABLE 1. Seismic sequences in the western Ross Sea, and correlation with previous interpretations. Seismic facies description refers to the Northern basin, where the sequences are more complete.

Seismic sequence	Bounding unconformities	Lower boundary	Upper boundary	Internal configuration	H&B*	C*	A&B*
RSS-8	Sea floor-RSU1	Undefined	Sea floor (erosion, over-bank deposits)	Partly non-reflective, chaotic	Sea floor-U1	V1	2+1
RSS-7	RSU1-RSU2	Poorly defined, downlap	Erosion	Partly non-reflective, steeply aggrading/ prograding and concordant with the slope	U1-U2	V1	5+4+3
RSS-6	RSU2-RSU3	Downlap on RSS-5	Erosion with toplap truncation	Oblique prograding, present only on the slope	U2-U3	V1	8+7+6
RSS-5	RSU3-RSU4	Onlap on RSS-4 in the inner part of the basin, low angle downlap in the outer	Erosion	Generally sub-parallel, sigmoidal prograding on the outer shelf with preserved toplap; some wedge-shaped interbedded non-reflective units	U3-U4	V1	9+8
RSS-4	RSU4-RSU4a	Mostly conformable, local downlap	Erosion	Principally sub-parallel; some non-reflective units	U4-U4a**	V2	10
RSS-3	RSU4a-RSU5	Mostly conformable with RSU2 and RSU1	Erosion in the inner part of the basin, concordant in the outer	Mainly sub-horizontal and concordant, local basinward clinoforms; some non-reflective wedges	U4a**-U5	V2,3	11
RSS-2	RSU5-RSU6	Downlap on RSS-1 in the outer shelf	Mostly conformable	Sub-horizontal and concordant, low angle basinward clinoforms in the Northern basin; some non-reflective units	U5-U6	V3,4	12
RSS-1	RSU6-Basement	Generally onlap and basin filling	Mostly conformable in the Northern basin	Highly variable: active tectonic, volcanic	U6-Acous. bas..	V4,5	13

*H&B: *Hinz and Block* [1984]; C: *Cooper et al.* [1987]; A&B: *Anderson and Bartek* [1992].
**Unconformity U4a is from *Cooper et al.* [1991a].

sea-level low stand in mid-Oligocene time (30.5 Ma, *Haq et al.*, 1987; Figure 3).

3.2. *Seismic Sequence 2: RSU6-RSU5*

Seismic sequence RSS-2 has more-continuous reflectors and is more easily identified in seismic profiles than RSS-1. Where RSS-1 is absent, the deepest part of RSS-2 onlaps basement (Figure 10), and shallower parts are mainly sub-horizontal and continuous over much of the western Ross Sea. Figure 11 shows that some parts of the offshore basement ridges may still have been high-standing sediment sources for the oldest parts of RSS-2.

In the Northern basin, RSS-2 exhibits low-angle prograding clinoforms with downlap terminations on

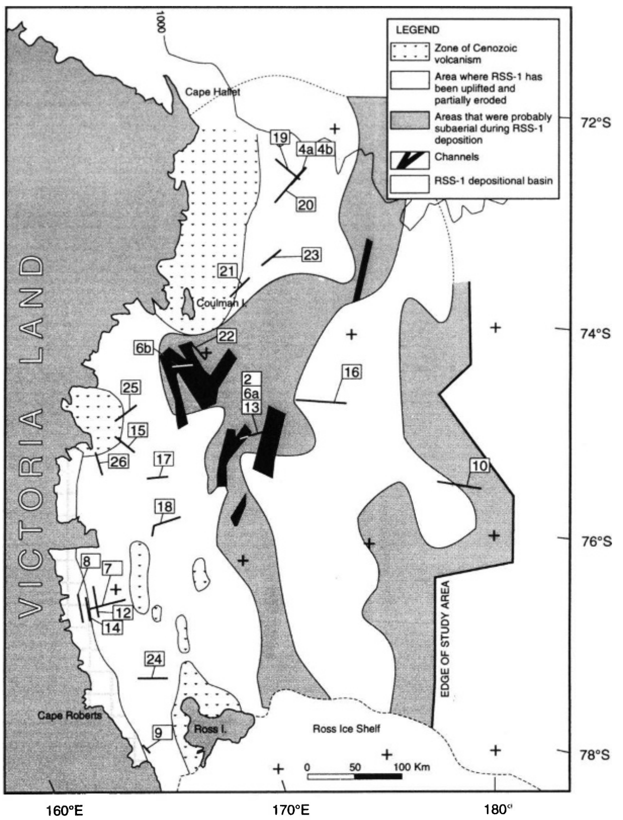

Fig. 5. Map of paleogeography of RSS-1. RSS-1 was deposited in isolated basins (white areas), with sediments probably derived from high-standing areas between the basins. Erosion and sediment transport to the basins was probably by rivers for the lower part of RSS-1, and by rivers and wet-based glaciers for the upper part of RSS-1. Seismic profiles illustrated in this paper are labeled with their figure number.

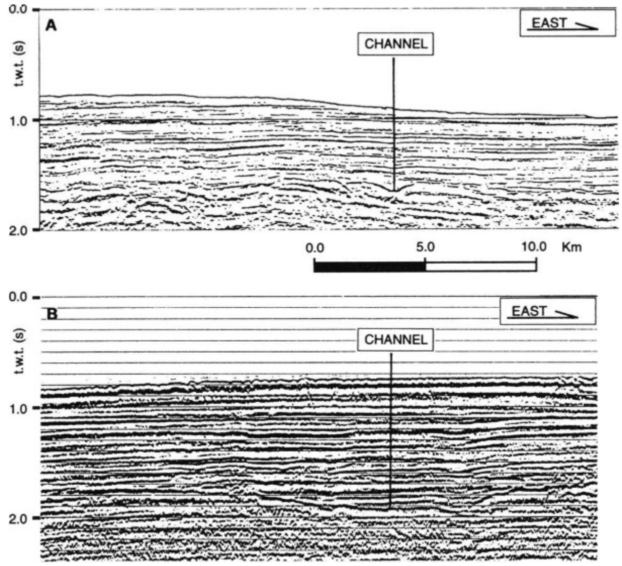

Fig. 6. V- and U-shaped channels on the Coulman high. (a) Seismic profile It-80 (SP 600-1200; VE 7:1). (b) Seismic profile USGS-411 (SP 200-600). Rivers and glaciers carved channels into the basement high, before the high was submerged as a consequence of regional subsidence and/or eustatic sea-level rise during RSS-2 time. See Figure 5 for location.

RSS-1 (Figure 4a). Towards the north, RSS-2 thins and, seaward of the paleo-depositional shelf edge, cannot be resolved unambiguously with MCS data.

On the west side of the Victoria Land basin (Figures 7 and 12), we recognize two distinct seismic facies in single-channel seismic data. One facies is well-stratified, with continuous and sub-parallel reflectors, whereas the second is non-reflective, discontinuous, and of highly variable thickness. The second facies forms the transparent wedge-shaped units of Figures 7 and 12. In the Coulman high area, the non-reflective facies is absent, and the sequence is exclusively uniformly stratified (Figure 13).

RSS-2 has been sampled at two sites in the Ross Sea. At the CIROS-1 site, RSS-2 is the Upper Sequence (30 to about 22 Ma) that consists of an alternating fossil-poor diamictite, representing glacial episodes, and fossil-rich sand and mud, representing interglacial episodes [*Barrett*, 1989]. Paleo-water depths ranged from emergent and intertidal to 50 m [*Barrett*, 1989]. At DSDP Site 270 [*Hayes and Frakes*, 1975], RSS-2 is a transgressive sequence (with glacial component) that was deposited in estuarine to 500 m water depths from late Oligocene into early Miocene times [*ANTOSTRAT*, this volume, Plate 3a; *De Santis*, this volume]. The different evolutions in water depths at CIROS 1, where RSS-2 is shallower than RSS-1 and at DSDP Site 270, where RSS-2 is deeper than RSS-1, can be explained by the different Cenozoic tectonic processes at the two sites. CIROS 1 site was uplifted with the Transantarctic Mountains during this time, whereas DSDP Site 270 has subsided.

3.2.1. *RSS-2 paleoenvironment.* We believe RSS-2 was deposited in open marine conditions. Regional subsidence continued through the early Miocene, and the entire western Ross Sea area was submerged (Figure 11). In the west, the coastline shifted eastward following Transantarctic Mountains uplift, and glaciers locally calved at sea near the coast, deeply eroding

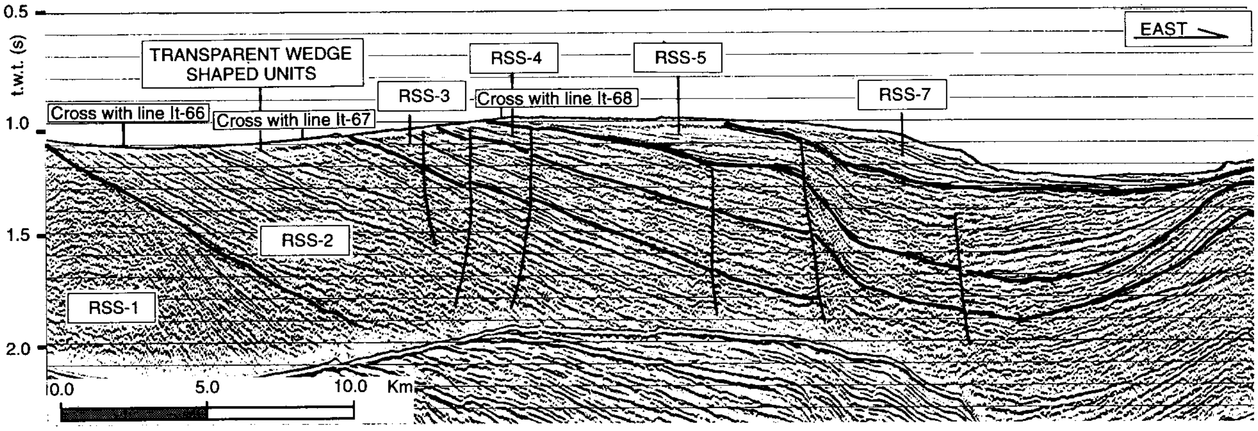

Fig. 7. Seismic profile It-63 (SP 1200-2900; VE 10:1) across, and perpendicular to, the west flank of the Victoria Land basin and showing the tilted sequences that crop out near the coast. In the west, non-reflective wedge-shaped units occur inside RSS-2 and RSS-5, whereas to the east, the non-reflective units disappear and the sequences become uniformly stratified. We interpret this as a change from subglacial or grounding-line sediments derived from Transantarctic Mountain glaciers to glacial marine strata. RSS-5 is syn-tectonic. See Figure 5 for location.

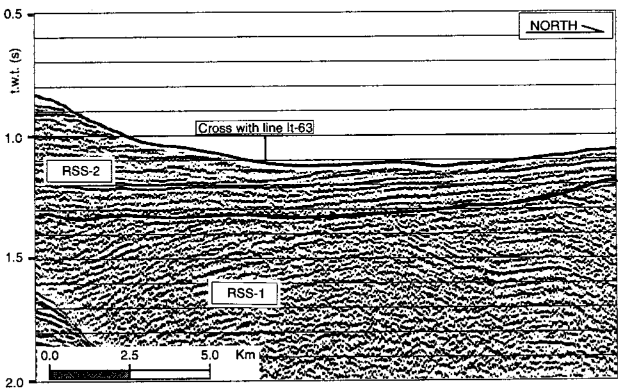

Fig. 8. Seismic profile It-66 (SP 1100-1850; VE 10:1) showing RSS-1 beneath the western flank of the Victoria Land basin. The profile is perpendicular to that in Figure 7, and shows the erosional unconformity between structurally deformed strata in RSS-1 and uniformly stratified rocks in RSS-2 in the area. See Figure 5 for location.

RSS-2 and depositing non-reflective wedge-shaped units (Figures 7 and 12). Glaciers were probably temperate to subpolar because they did not ground far from the coast line. Non-reflective facies are absent in distal areas (Figure 13). RSU5, the upper sequence boundary of RSS-2, is identified with the sea-level low stand at 21 Ma [*Haq et al.*, 1987], in accord with the age assumed by *De Santis et al.* [this volume]. The low stand concept is consistent with the nearly conformable erosion of RSU-5 observed in MCS data [*ANTOSTRAT*, this volume, Plates 10, 14 and 15].

The paleoenvironments we suggest for RSS-2 are consistent with those derived from analyses of palynomorphs from CIROS-1 [*Mildenhall*, 1989], and with texture and size of diamictite layers [*Barrett*, 1989] that indicate a humid and temperate climate, with wet-based glaciers present in the Transantarctic Mountains.

RSS-2 corresponds to Unit 12 [*Anderson and Bartek*, 1992] in the Eastern basin. Seismic facies of Unit 12 are very similar to those for RSS-2 in the western Victoria Land basin, close to the Transantarctic Mountains. We believe the similarity can be explained by land-based glaciers being present in the Transantarctic Mountains as well as on emergent parts of the Central high during this period, as is suggested by *De Santis et al.* [this volume].

3.3. *Seismic Sequence 3: RSU5-RSU4a*

RSS-3 is widespread across the western Ross Sea, and is characterized by both stratified and non-reflective units. In the Northern basin (Figure 4a), RSS-3 downlaps on RSS-2 within the southern part of the basin, and is sub-parallel to overlying and underlying units within the northern part, where it includes a set of low-angle (2°-3°) prograding clinoforms that form a depositional paleo-shelf edge.

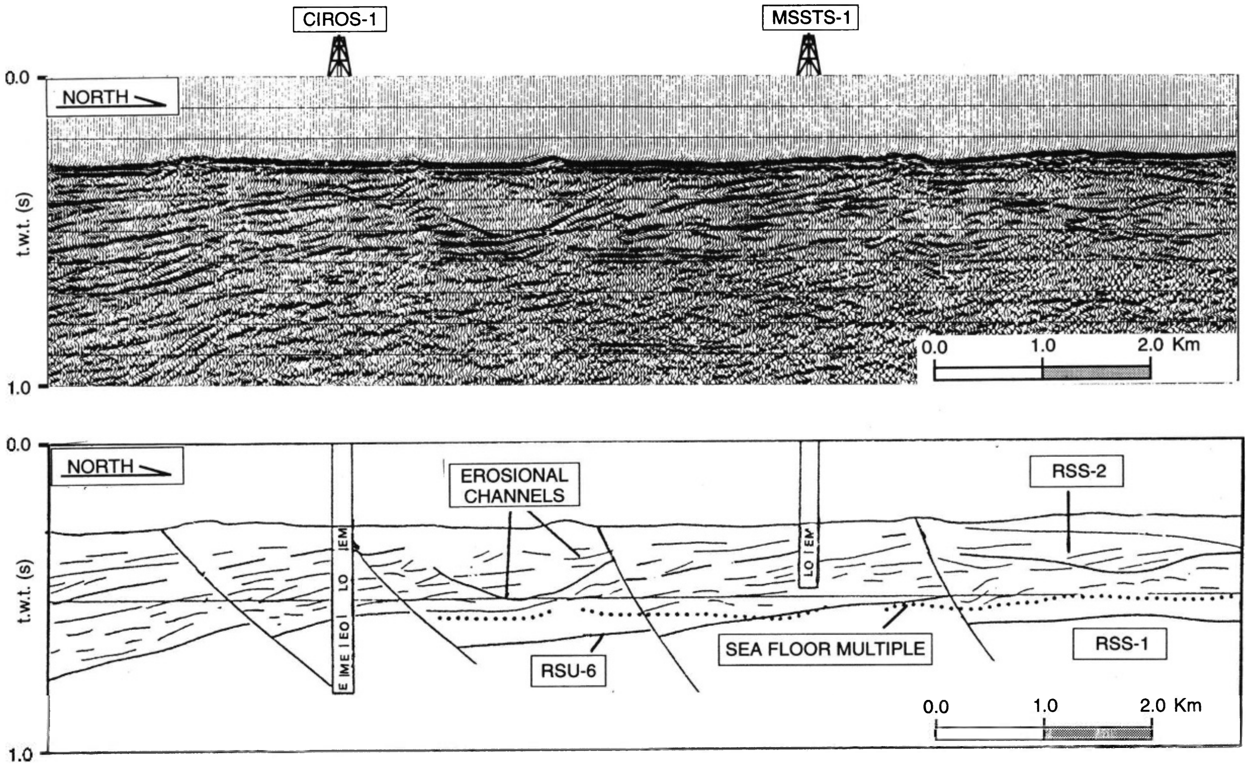

Fig. 9. Correlation between CIROS-1 and MSSTS-1 drill sites along seismic profile It-71 (SP 100-450; VE 4:1). CIROS-1 is the only site that has sampled RSS-1. RSS-2 records many advances and retreats of grounded glaciers through the Transantarctic Mountains. We believe such glaciers produced the U-shaped channels at different levels within RSS-2. See Figure 5 for location.

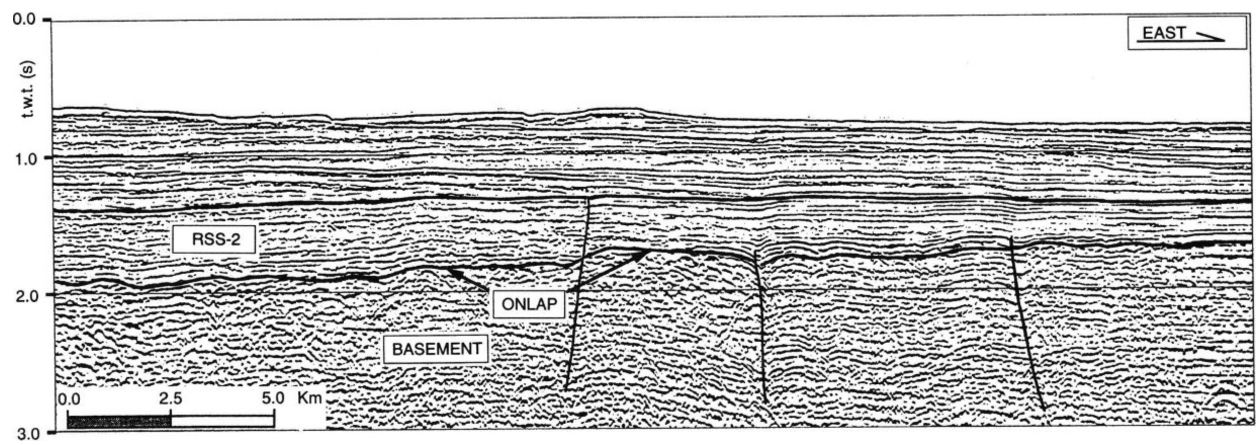

Fig. 10. Seismic profile It-02 (SP 6100-6500; VE 4:1) showing stratified sections in RSS-2 over the top of the Central high. During RSS-2 time, sea level rose, with RSS-2 onlapping and finally covering basement as the entire continental shelf subsided below sea level. When the lower part of the sequence was deposited, the northern and southern parts of the Central high were probably above sea level. See Figure 5 for location.

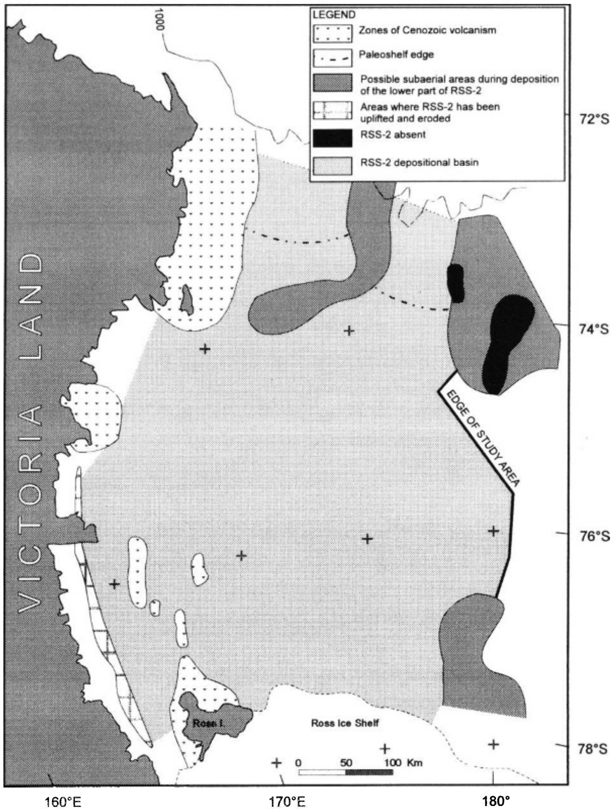

Fig. 11. RSS-2 distribution in the western Ross Sea. Emerged areas (shaded) were probably a barrier to Southern Ocean water flow between the eastern and western Ross Sea at this time. Two distinct paleo-shelf edges, separated by a north-south ridge, are seen in RSS-2.

On the western flank of the Victoria Land basin (Figure 7), RSS-3 includes some non-reflective wedges. These wedges are less evident than in RSS-2, and RSS-3 has more continuous and regular stratification than RSS-2, in both dip (Figure 7) and strike directions (Figure 14). During RSS-3 deposition, the western flank of the Victoria Land basin was incised by several high-relief (300 m) and wide (15 km) channels that are now buried (Figure 14). The channels are roughly perpendicular to the coast, and are observed only on this flank of the basin. In the center of the Victoria Land basin, RSS-3 is characterized by undeformed sub-parallel and well-stratified reflectors like the example in Figure 15, where the sequence exhibits well-stratified, low-amplitude reflectors at the base, grading upward to high-amplitude reflectors.

RSS-3 has been sampled in the eastern Ross Sea near the bottom of DSDP Site 272, below 310 mbsf [*ANTOSTRAT*, this volume, plate 3b]. At Site 272, RSS-3 mainly consists of silty claystone with rare clasts [*Hayes and Frakes*, 1975]. *Savage and Ciesielski* [1983] date these rocks as older than 18.2 Ma. We speculate that the age of RSS-3 is between 21 Ma (younger than the top of DSDP Site 270) and 18.5 Ma (derived from Savage and Ciesielski [1983]).

3.3.1. *RSS-3 paleoenvironment.* RSS-3 has not been sampled in the western Ross Sea. Due to the absence of non-reflective units in much of the western Ross Sea, we suspect that ice was not extensively grounded in the distal areas away from the coast. However, the wide east-west channel system in the western Victoria Land basin (Figure 14) is good evidence that grounded glaciers from the Transantarctic Mountains extended into the offshore areas during RSS-3 time. These glaciers were probably subpolar and may have occupied parts of the continental shelf. The morphology of the channel system (Figure 14) indicates that glaciers advanced and retreated from the Transantarctic Mountains several times. Away from the coast, the uniformly stratified units (Figure 15) are evidence that the sequence was deposited in an open marine environment. An open marine environment for RSS-3 can be also postulated for the Northern basin where the sequence aggrades on RSS-2, and the clinoforms show well-developed topset beds.

We note from sea-level curves [*Haq et al.*, 1987 and Figure 3], that significant eustatic changes do not occur about 18.5 Ma, the age that we infer for the upper boundary of RSS-3 (i.e., RSU4a). We attribute RSU4a to a regional tectonic? event, in accord with *Cooper et al.*, [1994a,b].

In the eastern Ross Sea, RSS-3 correlates with Unit 11 of *Anderson and Bartek* [1992]. They interpret Unit 11 as being high-stand glacial-marine strata. They see little seismic evidence of subglacial erosion and deposition. Our observations are consistent with their description. Similar conclusions have been reached by *De Santis et al.* [this volume].

3.4. *Seismic Sequence 4: RSU4a-RSU4*

This sequence is widespread across the Ross Sea [*ANTOSTRAT*, this volume, Plate 21a]. Single-channel and multichannel seismic data show that RSS-4 is characterized by uniformly and continuously stratified facies in the Central trough (Figure 16) and Victoria Land basin regions (Figures 17 and 18). Non-reflective units associated with irregular erosion (Figure 7) are found along the western side of the Victoria Land

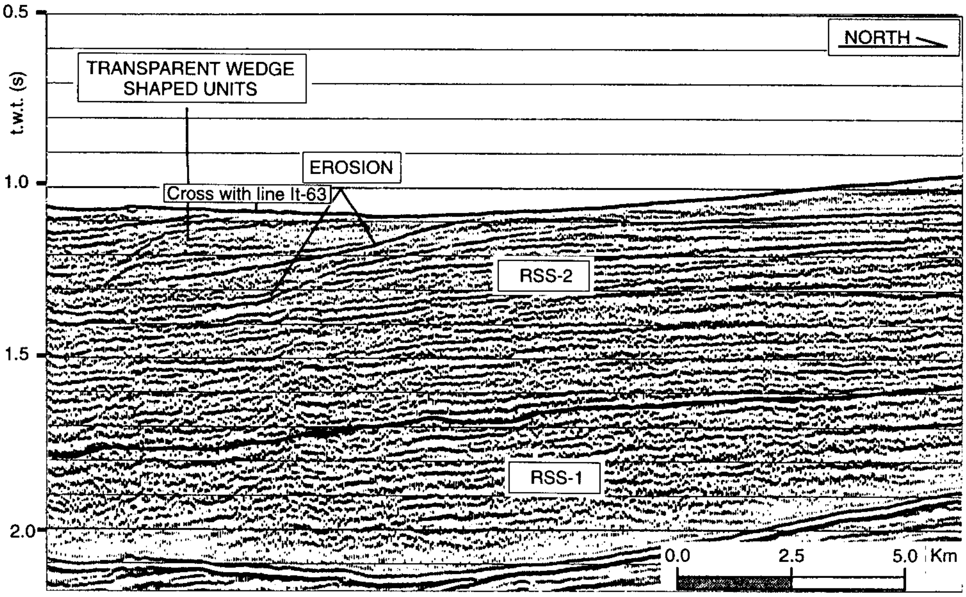

Fig. 12. Seismic profile It-67 (SP 116-900; VE 10:1) par-allel to the coast and showing RSS-2 beneath the western flank of the Victoria Land basin. The lower part of RSS-2 has uniformly stratified seismic facies unconformably overlying RSS-1, whereas the upper part of RSS-2 has deep and wide channels and units that are non-reflective and wedge-shaped. The upper part of RSS-2 was produced by erosion and deposition by grounded glaciers from the Transantarctic Mountains. See Figure 5 for location.

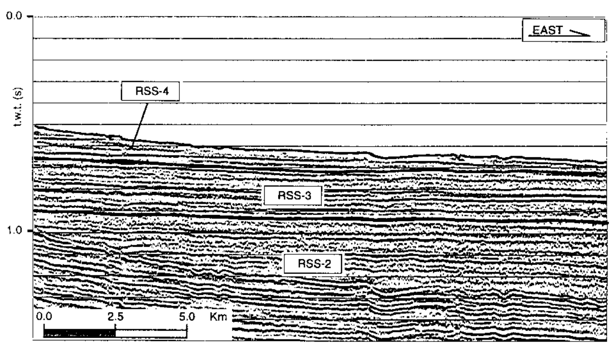

Fig. 13. Seismic profile It-80 (SP 100-900; VE 10:1) showing RSS-2 and RSS-3 over the Coulman high. Going away from the coast, across the Coulman high area, the deep scours and wedge-shaped, non-reflective units disappear. RSS-2 becomes uniformly stratified, indicating that grounded ice did not reach this area during RSS-2 time. RSS-3 is separated from RSS-2 by a nearly flat-lying unconformity. RSS-3 seismic facies are similar to RSS-2. See Figure 5 for location.

basin, and are the only acoustic evidence, by our criteria, for subglacial sedimentary rocks in RSS-4.

In the Northern basin (Figure 4a), low-angle prograding clinoforms that are eroded across their tops are seen in RSS-4, downlapping at relatively low dip onto RSS-3. On the outer shelf toward the north (Figures 4a and b), RSS-4 has uniformly thick and sub-parallel strata. Its upper boundary is a prominent angular unconformity that reached the shelf edge, and near the shelf edge formed an erosional channel that cut into the uppermost part of the sequence. Landward, on the middle and inner continental shelf, the strata above RSS-4 are thin or absent due to erosion and non-deposition, so that much of the sequence now outcrops at or near the sea floor.

RSS-4 has been sampled at DSDP Site 272 (RSS-4 recovery 30%) and Site 273 (RSS-4 recovery 17%) [*Hayes and Frakes*, 1975; *ANTOSTRAT*, this volume, Plates 3b and 4d]. It is composed of diatomaceous silt/clay with rare ice-rafted debris, shell fragments and some bioturbation. The top of the sampled interval was dated at 18.2 Ma at both sites [*Savage and Ciesielski*, 1983]. Considering that erosion removed large parts of the sequence from these two sites, the upper boundary of the sequence should be younger than 18.2 Ma. We tentatively assign the boundary an age of 16.5 Ma, when a major sea-level drop is shown by the eustatic curve [*Haq et al.*, 1987]. RSS-4 at the base of Site 272

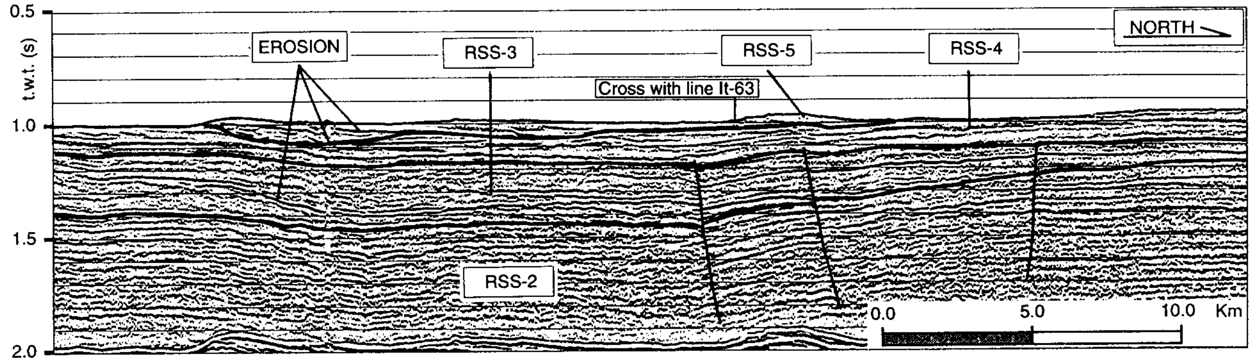

Fig. 14. Seismic profile It-68 (SP 400-2200; VE 10:1) across the western flank of the Victoria Land basin. The profile parallels the coast and crosses the profile illustrated in Figure 7. RSS-2 is uniformly stratified and does not have the non-reflective and wedge-shaped units that characterize RSS-2 where affected by subglacial deposition near the coast. RSS-3 has wide east-west channels that we believe were eroded by grounded glaciers from the Transantarctic Mountains, and were then filled by glacial-marine sediment. The thin remnants of RSS-4 and RSS-5 suggest that glaciers were grounded in this area many times since RSS-2 was deposited. See Figure 5 for location.

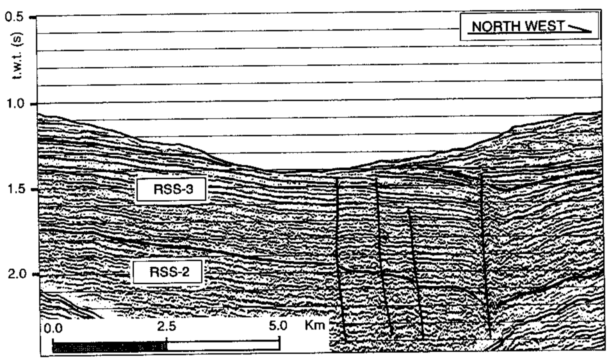

Fig. 15. Seismic profile It-77 (SP 6500-7000; VE 10:1) showing RSS-2 and RSS-3 south of Cape Washington. During the Pliocene and younger glacial advances and retreats, the Antarctic ice sheet eroded wide and deep troughs into the continental shelf. One of these troughs is parallel to the NE-SW trend of the Transantarctic Mountains in this area. The profile crosses the deepest part of the trough, which. post-dates RSS-3. Northwest is to the right. See Figure 5 for location.

has been dated as 19.2 Ma and at Site 273 as 18.34 Ma [*Savage and Ciesielski,* 1983]. Younger ages (16.5 Ma) have been derived from foraminifera by *Leckie and Webb* [1986]. Figure 3 illustrates the difference between the two interpretations for the base of RSS-4.

3.4.1. *RSS-4 paleoenvironment.* RSS-4 was probably deposited in an open-water environment, like that established by regional subsidence of the Ross Sea and likely initial tectonic overdeepening of the outer shelf when RSS-3 was deposited. It is important to note that the upper boundary of RSS-4 (RSU4) has been sampled at Site 273, Core 21a [*Hayes and Frakes,* 1975]. It consists almost entirely of fine sand that may be the product of sea-floor currents [*Savage and Ciesielski,* 1983] or possibly wave-base winnowing [P. Barrett, personal communication, 1995]. Texture and composition of Core 21a excludes a subglacial origin. It seems therefore more reasonable to attribute RSU4 to a change in ocean circulation or to a relative sea-level low stand, rather than to a major advance of a grounded ice sheet. We cannot however exclude the presence of ice sheets and glaciers on the subaerially exposed areas of the shelf during the possible low stand at the end of the sequence. Such an ice sheet would probably have been subpolar, because it calved at sea and deposited ice-rafted debris in RSS-4 at DSDP site 272, but was not able to ground below sea level during high-stand periods.

In summary, glaciers from East Antarctica may have existed in deep cross-mountain fjords, and calved icebergs into the Ross Sea, and at times subpolar ice sheets may have extended across parts of the shelf. Relative sea level apparently dropped again at the end of the sequence, between 15.5 and 16.5 Ma, as shown by the pronounced erosional character of RSU4 across most of the outer continental shelf in the Northern basin (Figures 4a and b).

RSS-4 corresponds to Unit 10 of *Anderson and Bartek* [1992]. *De Santis et al.* [this volume], in a

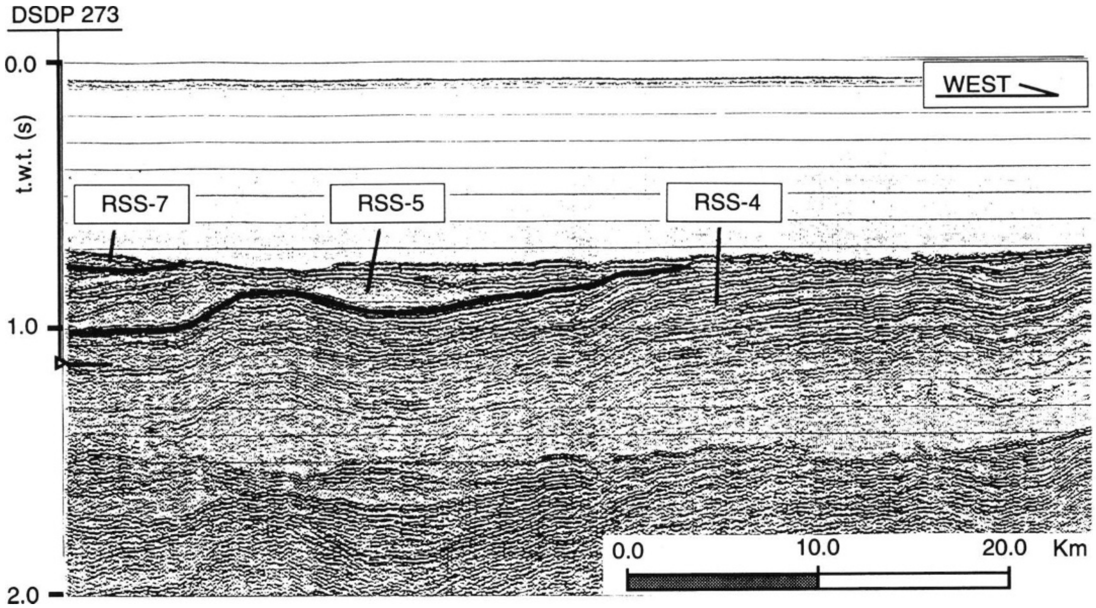

Fig. 16. Seismic profile PD 43 (VE 20:1) [*Anderson and Bartek,* 1992] across DSDP Site 273, where RSS-5 is irregularly stratified with interlayered wedge-shaped units that unconformably overlie stratified units of RSS-4. Here, we interpret RSS-5 as sub-ice deposition and RSS-4 as open-water deposition, in agreement with *Savage and Ciesielski's* [1983] paleo-environmental reconstruction for DSDP 273. The grounded ice here, at a large distance from East Antarctica, may have developed following large drops in sea level at 15 and 16 Ma, thereby exposed wide areas of the continental shelf to temperate glaciers. West is to the right. See Figure 5 for location.

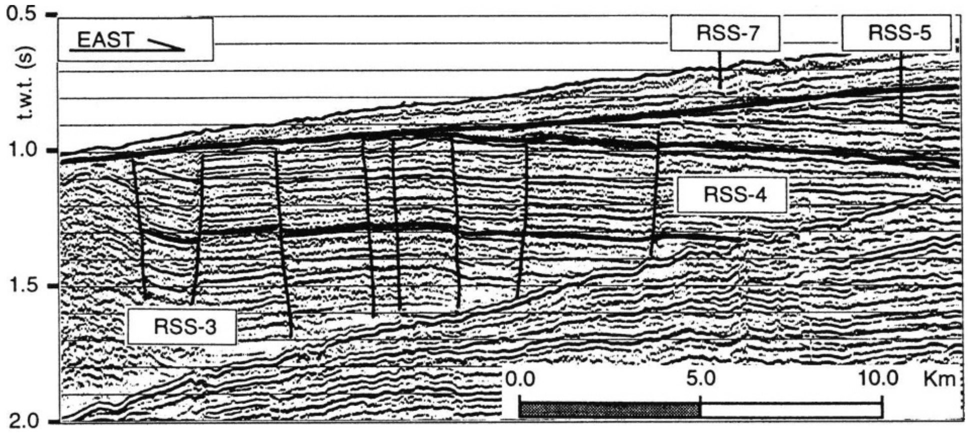

Fig. 17. Seismic profile It-61 (SP 1000-1800; VE 10:1) south of Cape Washington. RSS-4 is uniformly stratified across the western Ross Sea, except near the Transantarctic Mountain front. Morphology of the un-conformity between RSS-5 and RSS-7 (i.e., RSU2 and RSU-3) here mimics the sea floor. We believe RSU2 marks the first grounded polar ice sheet to reach the shelf edge. See Figure 5 for loca-tion.

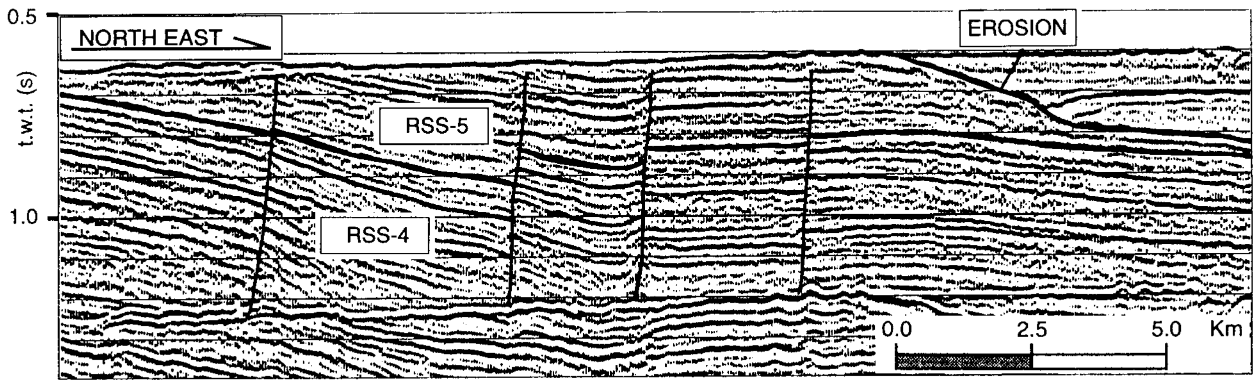

Fig. 18. Seismic profile It 77 (SP 1500-2500; VE 10:1) across the central Victoria Land basin. We believe that during deposition of RSS-4 and RSS-5, the basin had subsided enough to maintain marine environments during the 15 and 16 Ma low stands, thereby explaining the uniform stratification of these sequences (see also Figure 7). See Figure 5 for location.

detailed study of Unit 10 in the eastern and central Ross Sea, show that non-reflective subglacial sediments were deposited on two uplifted areas along the Central high, and deduce that the subglacial features noted by *Anderson and Bartek* [1992] are restricted to former high-standing basement areas along the Central high. These are areas where nearby land glaciers locally grounded and calved into the ocean during deposition of RSS-4. Elsewhere in the Ross Sea, such as at DSDP Site 273, RSS-4 is regular and well-stratified, and there is no indication of grounded ice sheets (Figure 16). The interpretation by *Savage and Ciesielski* [1983] of the cores from DSDP Site 273: "an open ocean environment, where rapidly calving debris-laden outlet glaciers apparently dumped huge quantities of sediment into the Ross Sea" is consistent with our model for the western Ross Sea.

Cochrane et al. [this volume] use sonobuoy seismic refraction data to suggest that sedimentary rocks below RSU4 to RSU5 on the inner and middle shelf areas of the western Ross Sea have linear velocity gradients typical of deposition in an open-water shelf environment. Above these unconformities, sedimentary rocks have thin layers with variable and higher-than-normal velocities and some velocity reversals. The variable velocities are more typical of changing environments with periods of erosion and over-compaction from episodically grounded ice sheets. We note, as do they, that multiple unconformities can be caused by sea-level changes, without grounded ice sheets. Regionally higher-than-normal sedimentary rock velocities, with overcompaction of thin layers, are not found with sea-level unconformities, and are strong, but not conclusive, evidence of episodic grounding of ice sheets since RSU5 to RSU4 times on parts of the inner and middle shelf.

3.5. *Seismic Sequence 5 (RSU4-RSU3)*

RSS-5 is a basin-filling and aggrading sequence found in the Northern basin and central part of the Victoria Land basin. Later erosion has removed nearly the entire sequence from the rest of the western Ross Sea. RSS-5 is uniformly stratified in the eastern and central parts of the Victoria Land basin (Figure 18), whereas at the western side, where it outcrops at the sea floor (Figure 7), it is mostly discontinuous and disrupted, with thick wedge-shaped interbedded non-reflective units. In the northern Central basin at DSDP Site 273, RSS-5 is non-reflective, with irregular and cross-cutting reflections (Figure 16). In the Northern basin, the paleo-shelf edge and associated sigmoidal-clinoform foreset beds of RSS-5 (Figure 4a) are nearly coincident with the present geographic position of the shelf edge and continental slope. In a profile parallel to the shelf edge (Figure 19), RSS-5 shows reflectors gently dipping onto RSS-4 toward the northwest. These reflectors can be interpreted as either erosional features or clinoforms within RSS-5. The dipping reflectors are overlain by a mostly disrupted, sub-horizontal or gently dipping sequence. Because seismic lines do not intersect in this area, we are not able to identify this sequence. It may represent the uppermost part of RSS-6. In the Victoria Land basin, (Figure 7) RSS-5 appears to be syntectonic, because it unconformably overlies RSS-4

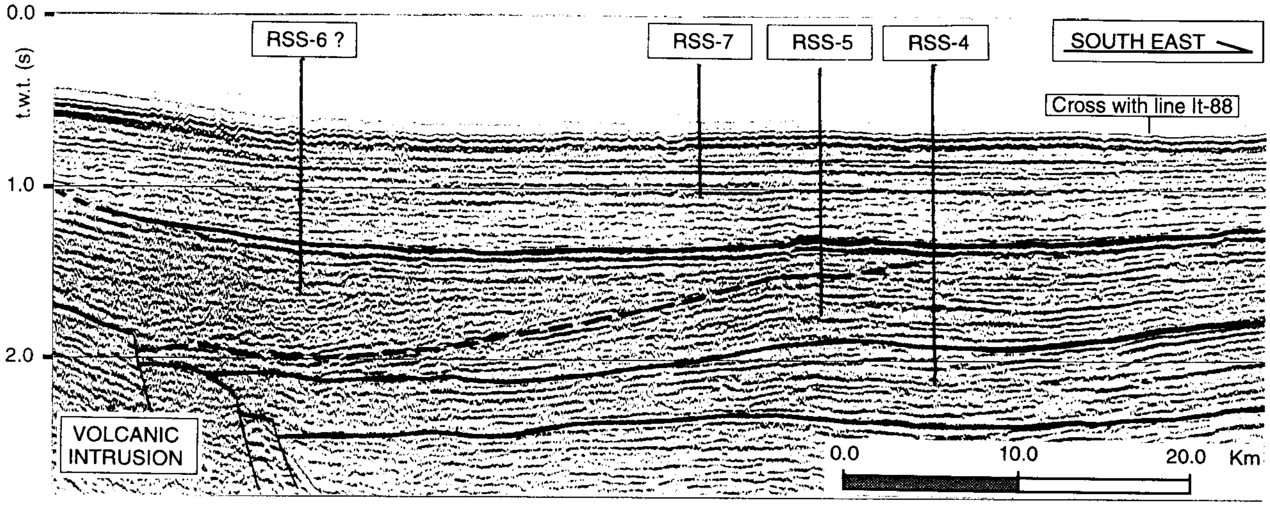

Fig. 19. Seismic profile BGR-110 (SP 1000-2000; VE 14:1) lying perpendicular to Figure 4a and parallel to the shelf edge in the Northern basin. Seismic sequence RSS-5 shows internal reflections that can be interpreted as either an erosional feature (glacial trough?) or the boundary with RSS-6. See Figure 5 for location.

which has been tilted and faulted during the late-rift phase of *Cooper and Davey* [1987].

RSS-5 has been sampled in Unit 2a at DSDP Site 273, in which it is semi-lithified, pebbly silty clay that has diatoms and is sparsely bedded. The top of Unit 2a is about 14.7 Ma, but the age of the upper boundary of RSS-5 is not defined, due to the hiatus at site 273 between 14.7 and 4.0 Ma (Figure 3).

3.5.1. ***RSS-5 paleoenvironment.*** We interpret RSS-5 as a transgressive glacial-marine sequence. We suggest that the base of RSS-5 corresponds to a relative low-stand of sea-level at 15.5-16.5 Ma [*Haq et al.*, 1987], which resulted in exposure of a large part of the continental shelf seaward to the shelf edge (see RSS-4 description). The subaerial environment, a proposed cooling at about 15 Ma [*Miller et al.*, 1991] and ice growth on East and West Antarctica [*Denton et al.*, 1991] may have caused land-based glaciers to coalesce, covering large exposed areas. The absence of non-reflective units and subglacial features in the central part of the Victoria Land basin is the likely combined result of few ice sheets grounding far from the shore line, and continued tectonic subsidence of the basin during this period, thereby preserving a marine setting during the 15.5-16.5 Ma low-stands.

As mentioned in the previous section, the dipping reflectors in RSS-5 in the Northern basin (Figure 19) may represent an erosional episode at the shelf edge. It is not possible with a single seismic line to determine direction and extent of this possible erosion, and we cannot exclude its subglacial origin. The erosion may have occurred at the upper boundary of the sequence (i.e., RSU3) during the 10.5 low-stand [*Haq et al.*, 1987] and inferred subaerial exposure of the shelf margin.

RSS-5 corresponds to *Anderson and Bartek* [1992] Units 9 and 8, which they interpret as acoustically laminated (Unit 9) and having in addition small till tongues (Unit 8). They suggest both units are glacial marine and deposited in open waters. Our interpretation (above) is consistent with *Anderson and Bartek* [1992].

3.6. *Seismic Sequence 6 (RSU3-RSU2)*

We believe, considering seismic sections from the Northern basin (Figure 4), that RSS-6 has been deposited there. RSS-6 also exists in the eastern Ross Sea [*ANTOSTRAT*, this volume, Plate 14] and, as we discuss below, RSS-6 in the Northern basin appears to be a shelf-edge deposit that we tentatively correlate with the sea-level low-stand periods between 10.5 and 4 Ma (Figure 3).

The identification of RSS-6 is speculative in the western Ross Sea, where we suspect it is almost entirely confined to the Northern basin: a small prograding wedge is observed there beneath the shelf edge (Figures 4a and 20). The RSS-6 wedge is regressive, thinning

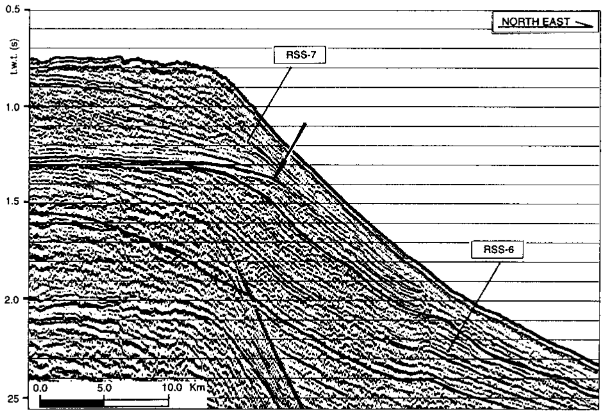

Fig. 20. Seismic profile It-88 (SP 3100-4000; VE 10:1) across a small progradational prism (i.e., RSS-6) beneath the outer shelf of the Northern basin. Prograding clinoforms of RSS-6 are steep, and thin northward. We believe RSS-6 was deposited during lower sea levels. RSS-7 is the oldest sequence that meets our acoustic criteria for subglacial or grounding-line deposits beneath the continental slope in the Northern basin. The arrow indicates a reflection that we interpret as an erosional surface produced by ice sheet advance on its own grounding-line deposits. See Figure 5 for location.

towards and with downlap terminations at the base of the slope. The topset beds have been partly eroded. Foreset beds dip about 2° seaward beneath the inner part of the wedge, and up to 4° beneath the outer part. The seismic facies is uniformly stratified with minor slumps and debris flows. Seaward, in deep water, the sequence is too thin to be resolved by MCS data.

We tentatively assign an age range to RSS-6 of between 10.5 Ma and 4.0 Ma (Figure 3), which correspond to a general low-stand period (10.5 to 5.5 Ma) followed by a sea-level rise (5.5 to 4 Ma)[*Haq et al.*, 1987]. The unconformity at the upper boundary of RSS-6 shows the first strong evidence for a grounded polar ice sheet at the continental edge. Later groundings of polar ice sheets to the shelf edge in the western Ross Sea, after the deposition of RSS-6, may have deeply eroded RSS-6 and removed large parts of the sequence. In the Northern basin, within the offshore part of the Cape Hallett Volcanic Province, magma intruded into RSS-6, before RSS-7 was deposited (Figure 21). Onshore, the volcanics are dated at 13-2.5 Ma [*McIntosh and Gamble*, 1987]. The oldest age for sedimentary rock sampled at DSDP Site 273 above RSU2 is 4.0 Ma [*Savage and Ciesielski*, 1983]. Hence, we believe our postulated age range of 10.5-4.0 Ma for RSS-6 is reasonable.

The ages that we assume for RSS-6 make it coeval with rocks sampled by the deepest cores in the Dry Valley Drilling Project (DVDP) Sites 10 and 11 and by MSSTS-1 at the southern end of the Victoria Land basin. Ages for the DVDP and MSSTS-1 rocks are also uncertain [*Powell*, 1981; *Barrett*, 1986; *McKelvey*, 1991], so correlation with the offshore acoustic stratigraphy is speculative. Cores from these drill sites, which may have sampled RSS-6, consist of late Miocene and early Pliocene glacial-marine muddy sandstone interlayered with diamictites, and interpreted as lodgement till [*Powell*, 1981; *Barrett*, 1986].

3.6.1. *RSS-6 paleoenvironment.* The steep slopes and rapid downlap of RSS-6 near the base of the slope in the Northern basin, suggest that the sequence was deposited during a sea-level low stand. We offer two conflicting hypotheses for RSS-6 that are consistent with lowered sea levels: (a) RSS-6 is a type Ia [*Cooper et al.*, 1991a] grounding-line sequence, deposited directly on the slope, seaward of a grounded ice sheet, and (b) RSS-6 is a pro-delta deposit comparable in size and geometry to those of the low-latitude passive margins, as illustrated by *Bally* [1988].

There are no samples from RSS-6 on the outer shelf, so we cannot eliminate either hypothesis. If RSS-6 was deposited from a grounded ice sheet, then we suspect the ice sheet was subpolar because: (1) cores from DVDP and MSSTS drill sites in the southern Victoria Land basin area indicate that were deposited by subpolar glaciers and floating ice tongues [*Powell*, 1981; *Barrett*, 1986; *McKelvey*, 1991] and (2) *McIntosh and Gamble* [1987] concluded that ice was of limited extent in the Hallett Volcanic Province, adjacent to the Northern basin, where volcanics range in age from 2.5 to 13 Ma (i.e., postulated RSS-6 time): "The predominance of subaerial volcanic rocks shows that a fully expanded Ross Ice Sheet was absent during most of the emplacement of the Hallett Coast volcanoes". These reconstructions seem to exclude the presence of polar conditions for ice sheets that may have been grounded near the shelf break during deposition of RSS-6.

In the eastern Ross Sea, RSS-6 corresponds to Units 6, 7 and 8 (partly) of *Anderson and Bartek* [1992]. They note that these units strongly prograde the shelf. They suggest that in the eastern Ross Sea there were few groundings of the Antarctic Ice Sheet during the late Miocene, whereas their inferred Miocene-Pliocene boundary (between Units 8 and 7), marks a sudden change of the sequence geometries from strongly progradational to strongly aggradational with a large

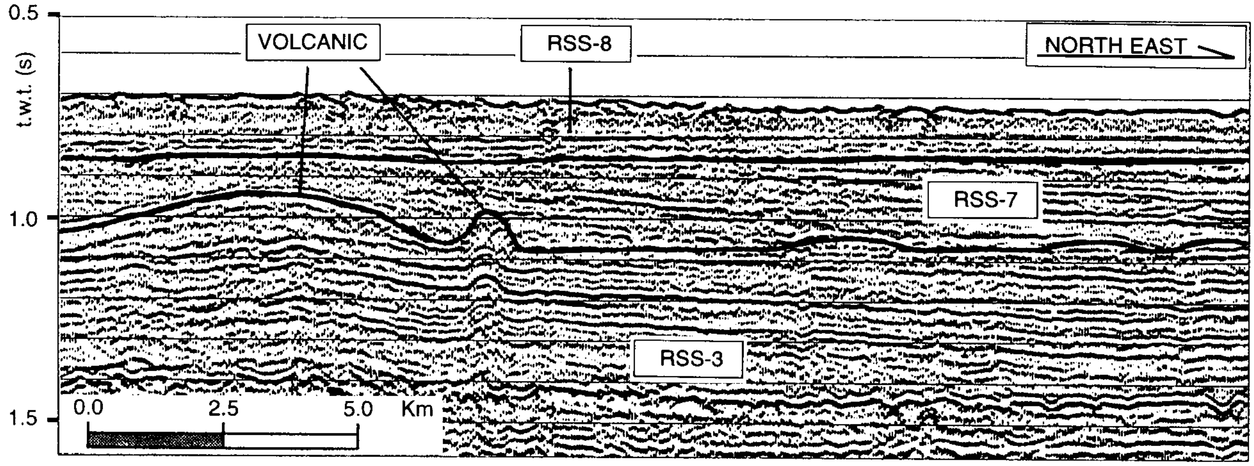

Fig. 21. Seismic profile It 55 (SP 2250-2650; VE 5:1) across the west flank of the Northern basin, where RSS-7 onlaps Cape Hallett-Coulman Island volcanics. We interpret the smooth dome shape of the volcanics as due to subglacial erosion during a major glacial advance. The volcanics were then buried by deposition of RSS-7 during the glacial retreat phase. See Figure 5 for location.

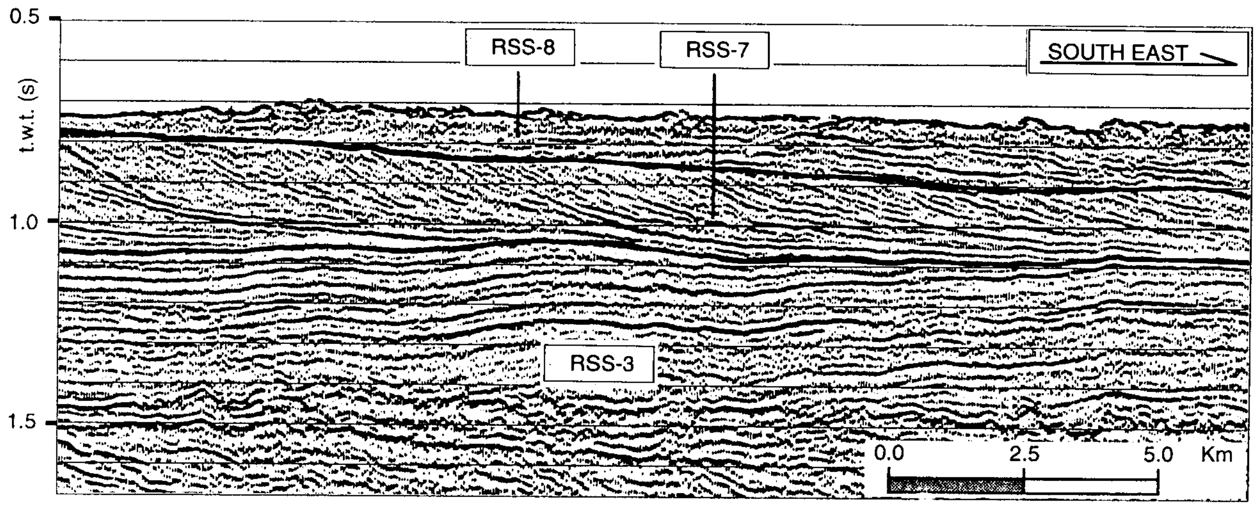

Fig. 22. Seismic profile It-56 (SP 1350-450; VE 5:1) south of Coulman Island. Near the coast of North Victoria Land, RSS-7 commonly has steeply dipping clinoforms, with eroded topset beds, that prograde seaward from the coast. We believe these were deposited as a subglacial delta by glaciers originating in the Transantarctic Mountains. See Figure 5 for location.

increase in the frequency of grounding events. The Miocene-Pliocene boundary inferred by *Anderson and Bartek* [1992] corresponds to the top of RSS-6 (i.e., RSU2). Stratigraphic control for RSS-6 in the eastern Ross Sea is from DSDP Site 271, at which recovery was poor (7%). Therefore, ages and environments for RSS-6 in this area are also mostly speculative.

3.7. *Seismic Sequence 7 (RSU2-RSU1)*

RSS-7 exhibits a wide range of seismic units, from non-reflective to uniformly and continuously stratified. In places, RSS-7 has sigmoidal and oblique geometries that prograde and aggrade the sequence. As mentioned in the previous section, in the Northern basin the

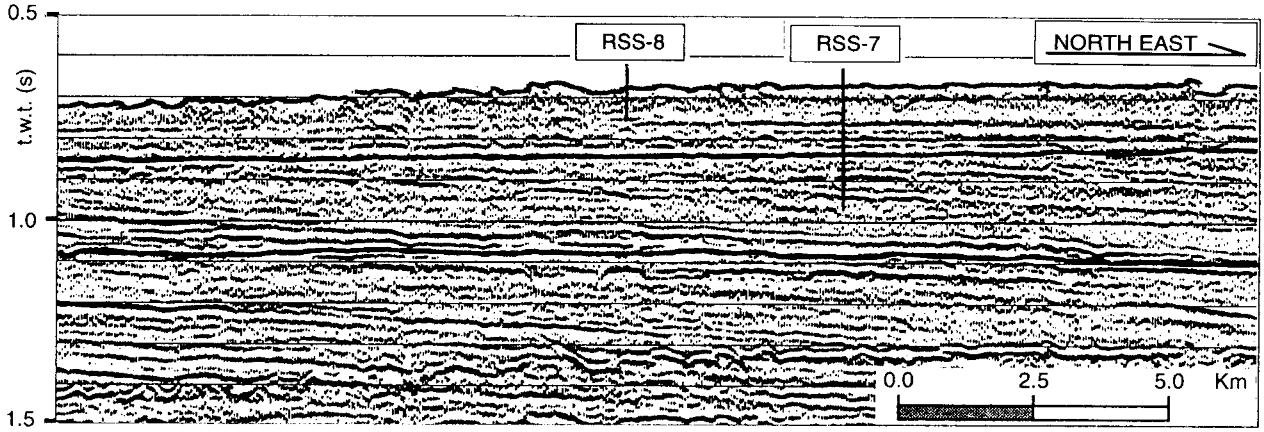

Fig. 23. Seismic profile It-55 (SP 650-1050; VE 5:1) in the Northern basin. Away from the coast, prograding clinoforms in RSS-7 become sub-horizontal. See Figure 5 for location.

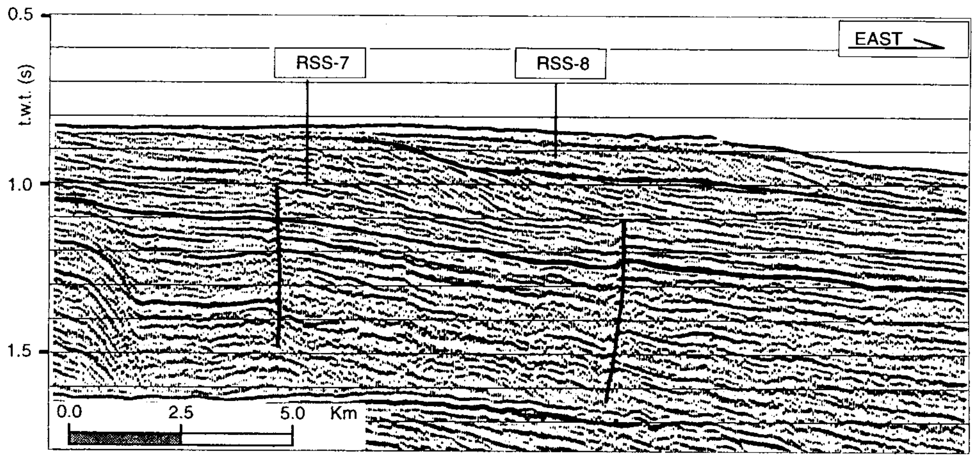

Fig. 24. Seismic profile It-76 (SP 2000-2800; VE 10:1) north of Ross Island. Here, strata in RSS-7 and RSS-8 prograde eastward, with apparent sediment sources from likely grounded ice sheets in the Cape Roberts area. See Figure 5 for location.

boundary between RSS-6 and RSS-7 marks an abrupt change in seismic character from regularly stratified to non-reflective (Figure 4a). Near the coast, RSS-7 generally has steeply-dipping (between 7° and 10°) and oblique and sigmoidal reflectors (Figures 22 and 24). These units are shaped like fans, and occur in front of some major Transantarctic Mountain glaciers. Away from the coast in basinal areas, reflectors are sub-horizontal, medium to low amplitude and mostly discontinuous (Figure 23). In the Northern basin, RSS-7 onlaps and covers intrusive structures and likely lava flows (Figure 21), and beneath the outer shelf RSS-7 forms a non-reflective unit with rare low-angle oblique clinoforms that downlap on RSS-6 (Figure 4a). Beneath the continental slope, RSS-7 is stratified with prograding clinoforms that have eroded topsets and foresets dipping at up to 10° (Figures 4a and 20). RSS-7 was sampled at DSDP Site 273, and included a basal glacial till dated at 4.0 Ma overlain by glacial-marine strata [*Savage and Ciesielski*, 1983]. Above this is marine sediment that was deposited under sea ice until 2.8 Ma. We put the lower boundary for RSS-7 at 4.0 Ma and the upper boundary at 2.5 Ma, to correspond to a major sea-level low-stand that was followed by an increased amplitude of short-term sea-level changes [*Haq et al.*, 1987].

3.7.1. *RSS-7 paleoenvironment.* The base of RSS-7 (i.e., RSU2) marks an abrupt change in erosional

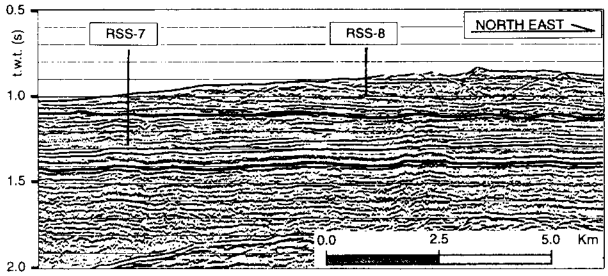

Fig. 25. Seismic profile It-57b (SP 3100-3600; VE 5:1) north of Cape Washington, where RSS-8 unconformably overlies RSS-7. RSS-8 is an eroded bank in which some oblique clinoforms and sub-horizontal reflectors can be observed. See Figure 5 for location.

patterns across the western Ross Sea (Figures 4a and Figure 19). The morphology of sedimentary units above RSU2 is similar to that of the present sea floor, which is a series of wide and deep erosional troughs and depositional banks that have been cut and deposited during multiple advances of the Antarctic Ice Sheet [*Cooper et al.*, 1991a; *Anderson et al.*, 1992; *Anderson and Bartek*, 1992]. We believe that the extensive erosion of RSU2 is the first unequivocal evidence of full polar conditions and grounding of the Antarctic Ice Sheet to the continental shelf edge; however, earlier advances of grounded ice are possible. At full extent, the grounded ice sheet deposited sediments directly on the continental slope to create a prograding wedge (Figures 4a and 20). The construction of the prograding wedge allowed the ice sheet to advance further, as recorded by the erosion of prograding clinoforms within RSS-7 (arrow in Figure 20).

Advances and retreats of the ice sheet are likely during subsequent glacial and interglacial periods, based on the geometry of thin aggrading topset beds and on the model proposed by *Larter and Barker* [1989]. While deposition on the slope according to *Larter and Barker* [1989] has probably occurred during glacial maximum, we suspect that the fans in front of many Transantarctic Mountain glaciers were deposited during the interglacial periods. We suspect also that interglacial climate during RSS-7 was more temperate than today because, unlike today [*Powell,* 1994], glaciers from the Transantarctic Mountains deposited large subglacial deltas in the western Ross Sea, as documented by the clinoforms in Figures 22 and 24.

In summary, we relate RSU2 to the development of polar conditions in the Antarctic, with a full-scale polar ice sheet grounded across the Ross Sea. Interglacials were probably marked by open-water marine conditions and wet-based glaciers in the Transantarctic Mountains.

RSS-7 corresponds to Units 5, 4 and 3 of *Anderson and Bartek* [1992]. In Unit 5, they describe chaotic to uniformly stratified sub-units, with U-shaped channels that are similar to subglacial valleys described by *Armentrout* [1983] and *Ashley et al.* [1985]. They interpret the units as showing increased frequency of ice-sheet grounding during Pliocene and Pleistocene times, with warmer than present interglacial conditions. Our assessment of paleoenvironments for the western Ross Sea concurs with that of *Anderson and Bartek* [1992] for the central and eastern Ross Sea.

3.8. *Seismic Sequence 8 (RSU1-Sea floor)*

RSS-8 is a thin, highly eroded, and regionally isolated set of sequences in the western Ross Sea. Because the isolated segments have geometric similarities, we attribute them to one sequence (i.e., RSS-8). In the Northern basin, RSS-8 is generally nonreflective, with sporadic sub-horizontal reflections, and lies above a highly eroded surface (Figure 4a). Directly north of Cape Washington, RSS-8 also has a nonreflective character, but oblique clinoforms and some sub-horizontal reflectors are occasionally observed (Figure 25). South of Cape Washington, RSS-8 has isolated segments with high-angle clinoforms (up to 13°) that overlie a distinct erosion surface (Figure 26). Northwest of Ross Island, the sequence shows a small prograding delta complex that consists of irregularly stratified sigmoidal reflectors that prograde from west to east (Figure 24).

We believe that only the uppermost part of RSS-8 has been sampled in many piston cores and gravity cores [*Anderson et al.*, 1984] and at DSDP Site 273, where it consists of 80 centimeters of marine diatomaceous sediment of Pleistocene age [*Savage and Ciesielski,* 1983]. Existing MCS data cannot resolve units as thin, hence the unit we believe is RSS-8 in the western Ross Sea cannot be traced to the drill site. The best record of RSS-8 is probably in coeval DVDP samples, but seismic data do not cross the DVDP sites and definitive correlation is not possible. We suggest that the oldest strata in RSS-8 are younger than the major low stand at 2.5 Ma, as noted also in discussion of RSS-7.

3.8.1. ***RSS-8 paleoenvironment.*** During RSS-8 time, we believe that a polar ice sheet advanced and retreated across the shelf many times, deeply eroding sediment from the older sequences on the inner parts of

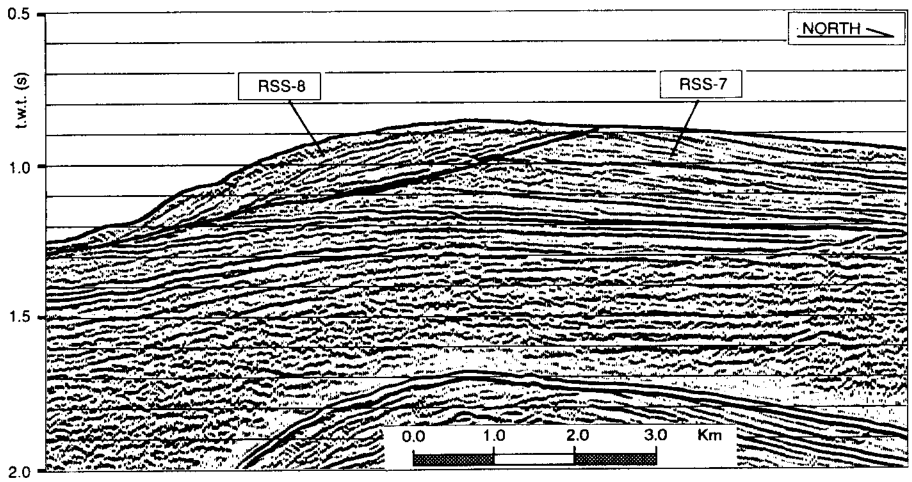

Fig. 26. Seismic profile It-59 (SP 500-1000; VE 5:1) south of Cape Washington. In this area, RSS-8 has steeply dip-ping clinoforms that partly cover the flank of a wide erosion channel, which is deeply eroded into RSS-7. We interpret RSS-8 as being deposited near the grounding-line of a local glacier originating in the Transantarctic Mountains, following a major advance of the Antarctic Ice Sheet. See Figure 5 for loca-and tion.

the continental shelf. Advances and retreats of the ice sheet have probably been controlled by short-term sea-level changes, as proposed by *Anderson and Bartek* [1992], but currently, age control and seismic resolution are inadequate to resolve separate ice-sheet fluctuations in RSS-8 in the western Ross Sea. During interglacial periods, we suspect that temperatures were low, like today, and the climate was polar.

DISCUSSION

Previous seismic studies of the Ross Sea shelf [*Hinz and Block*, 1984; *Karl et al.*, 1987; *Karl*, 1989; *Anderson and Bartek*, 1992; *Bartek et al.*, 1991; *Cooper and Davey*, 1987; *Cooper et al.*, 1991a,b; *Alonso et al.*, 1992] and new ones [*DeSantis et al.*, this volume; Barrett et al., this volume] have proposed acoustic stratigraphic histories that include tectonic uplift and subsidence, changes in sea-level, periods of grounded ice, and times of open marine conditions for Oligocene and younger times. As with previous assessments, we see good evidence in pre-Pliocene sequences (RSS-1 to RSS-6) for stratified deposits of likely marine origin. These stratified deposits are more common in mid-basin sedimentary sections than along the margins of the basins, where non-reflective and massive deposits of likely subglacial and grounding-line origin occur. We also see acoustic evidence of ice grounding (e.g., broad erosional troughs) that is more common in post mid-Pliocene sedimentary sequences (RSS-7 and RSS-8) than in pre mid-Pliocene sequences (RSS-1 to RSS-6), for mid-basin and outer-shelf areas.

A significant but not surprising observation we make is that areas around the western Ross Sea that we suspect have been close to, or above, sea level since late Eocene times, due to sea-level and tectonic movements, are prone to extensive erosion. We believe that, in places such as along the Transantarctic Mountain front and the Central high, the erosion may be due to grounded wet-based glaciers that episodically discharged sediments into the western Ross Sea during temperate glacial and interglacial periods (i.e., prior to 4.0 to 2.5 Ma). The eroded sediments fill the shelf basins. The intensive pre-Pliocene erosion elsewhere in the western Ross Sea, such as over basement ridges and across large sections of the shelf (i.e., the regional unconformities) is the likely result of sea-level change and near wave-base erosion. Sediments from this erosion fill the structurally overdeepened parts of the inner- and outer-shelf basins. In pre-Pliocene times, some erosion may also have been effected by extensive grounded ice sheets, the records of which lie in the major sequence boundary unconformities and regional changes in styles and amounts of sediment deposition at the paleo-depositional shelf edges. We believe, however, that pre-Pliocene ice sheets were mainly subpolar, and did not ground far below sea level. The extent of grounded ice across the shelf was greater for relative sea-level low stands than for high-stands, during which ice-sheets were less stable and retreated rapidly [e.g., *Larter and Barker,* 1989]. We see unequivocal acoustic evidence of massive erosion by polar ice sheets at the shelf edge since early Pliocene time (i.e., since RSU2 time), as was also noted by *Cooper et al.* [1991a].

The evolution of the shelf basins of the western Ross Sea, and the creation of accommodation space for glacial-marine sediments is clearly recorded in the stratigraphic maps and distribution of acoustic sequences [e.g., *ANTOSTRAT*, this volume, Plates 16a to 23d; *De Santis et al.*, this volume]. The evolution progresses from segmented basins of limited extent, separated by relatively high-standing ridges in pre-Oligocene times, to an open-marine, relatively flat shelf environment in early Miocene time, to a series of basins and highs with pronounced structural relief in the western Ross Sea by Pliocene time, to the present ice-carved bathymetry of the shelf today.

The new data compilations suggest to us that eustatic changes, as well as regional structural subsidence and uplift, have strongly controlled locations and types of sequence geometries in the western Ross Sea. All sequences since early Oligocene time (i.e., RSS-2 to RSS-8) show some evidence for subglacial deposition, indicating that grounded ice has been present regionally in the Transantarctic Mountains and on basement highs in the western Ross Sea, albeit commonly in confined zones (e.g., fjord-ice, ice-tongues), throughout this time. Because the major sequence boundaries can be reasonably explained by the eustatic history of *Haq et al.* [1987], we believe that sea-level changes have controlled depositional environments, including the distribution of subglacial deposits (i.e., grounded ice), in the Ross Sea, even though the geologic cores and drill-site data are too sparse to establish this correlation definitively. Indirect evidence are the regional unconformities, the prevalence of uniformly stratified glacial marine deposits, the systematic distribution of subglacial deposits (e.g., Figures 5 and 11) and prior correlations of drilling results with eustatic curves [e.g., *Barrett,* 1989; *Bartek et al.,* 1991]. Further, we see general similarities between the sequence boundaries of the outer shelf of the Northern basin (Figures 4a and b) and those of low latitude margins [e.g., *Bally,* 1988] suggesting to us a connection to eustatic curves (Figure 3). However, we cannot make a one-to-one correlation of western Ross Sea sequence boundaries to global seismic data, as has been attempted by *Bartek et al.* [1991] for the eastern Ross Sea.

Sea-level changes have partly controlled western Ross Sea stratigraphy, but a large part of Cenozoic history is not represented in the stratigraphic section. Large hiatuses exist at drill sites and they correlate with regional unconformities [e.g., *ANTOSTRAT,* this volume, Plates 3a to 5). Parts of the hiatuses are from erosion and parts from non-deposition. Hence, much of the record of sea-level and grounded-ice fluctuations in the western Ross Sea is missing, and our model does not give a complete picture of Cenozoic depositional and glaciological paleo-environments. At least part of such a record should exist below the outer shelf and the slope, because most unconformities are time-transgressive and rocks for the entire Cenozoic are likely in places in the Ross Sea area. Additional seismic-reflection and drilling data are needed to locate and classify these deposits.

CONCLUSIONS

The seismic facies in the western Ross Sea hold a varied record of tectonic, eustatic, and glaciologic changes during Cenozoic times, but the stratigraphic record is discontinuous and changes are difficult to verify. We draw the following conclusions:

1. Grounded ice has existed in the western Ross Sea region since at least early Oligocene time. Distribution of inferred subglacial deposits indicates that paleo-environments have varied from mostly temperate in early Oligocene time to variable (episodic temperate and subpolar) in Oligocene to late Miocene time, to polar since mid-Pliocene time.

2. The first unequivocal evidence for massive erosion by a grounded ice sheet to the paleo-shelf edge of the western Ross Sea is in Pliocene time (i.e., RSU2 time). However, earlier advances of grounded ice to the shelf edge, with less dramatic erosion but with thick sediment deposition, are likely since early Miocene time. Grounded ice may have covered large areas of the continental shelf that were high-standing during periods of lower sea level, since late Oligocene time, especially along the Transantarctic Mountain front and the Central high in the middle of the Ross Sea [see also *DeSantis et al.*, this volume].

3. Geometries and internal acoustic facies of seismic sequences for large parts, but not all, of the western Ross Sea appear to be directly related to sea-level changes through most of the Cenozoic, until Pliocene times when polar conditions like today's were fully established.

4. Parts of the western Ross Sea shelf (e.g., the Victoria Land basin, outer part of shelf) appear to have

been permanently over-deepened in early to middle Miocene time by subsidence during a regional structural event [*Cooper et al.*, 1994a,b]. The subsided areas provided accommodation space for sediment eroded from surrounding high-standing areas onshore and offshore. Since late Miocene time and the transition to a "polar" configuration, other parts of the western Ross Sea shelf were permanently overdeepened by massive glacial erosion to depths below wave base, thereby ending the direct influence of sea-level change on depositional processes.

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