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# West Antarctic Ice Sheet grounding events on the Ross Sea outer continental shelf during the middle Miocene

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**Abstract**

New seismic–stratigraphic analysis of the Ross Sea continental shelf suggests that there were a at least five shelf-wide grounding events of the West Antarctic Ice Sheet (WAIS) during the middle Miocene. Although the number of WAIS grounding events generally matches the number of extreme $\delta^{18}O$ enrichments and eustatic lowstands, these results do not support the long-standing assumption that West Antarctica was substantially ice-free. Instead, seismic–stratigraphic evidence from the Ross Sea shelf documents waxing and waning of a well-developed WAIS in the marine environment at least on the Pacific sector of the West Antarctic continental shelf.


*Keywords:* middle Miocene; ice sheet; West Antarctica; glaciation; Ross Sea

## 1. Introduction

During the early Miocene (∼24 Ma to ∼16 Ma), thermohaline circulation was much different than today because low-latitude inter-oceanic passages (i.e. through the Isthmus of Panama and Tethys) permitted well-developed equatorial circulation. This equatorial surface flow produced warm saline water masses (i.e. Tethyian Indian Saline Water; TISW) that sank to intermediate depths and flowed southward (Woodruff and Savin, 1989). The upwelling and subsequent refrigeration of TISW in the Southern Ocean probably was a major agent in the meridional heat transport that helped maintain relatively warm climates in Antarctica during the early Miocene (Woodruff and Savin, 1989; Wright et al., 1992; Flower and Kennett, 1995).

At the start of the middle Miocene (i.e. ∼16 Ma), closure of the Tethys at the eastern portal of the Mediterranean Sea severely interrupted equatorial circulation (Hsu and Bernoulli, 1978; Steininger et al., 1985) and resulted in reduced production of TISW (Woodruff and Savin, 1989). According to conventional interpretations of deep-sea proxy data, the reduced meridional heat transport led to climatic cooling in the Southern Ocean which thereafter fostered rapid growth of the Antarctic Ice Sheet. Indeed, the large magnitudes of $\delta^{18}O$ enrichments (Shackleton

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and Kennett, 1975; Woodruff et al., 1981; Woodruff and Savin, 1989, 1991; Wright et al., 1992) and eustatic falls (Haq et al., 1987) in the middle Miocene (∼16 Ma to ∼10 Ma) suggest significant long-term cooling and several stepped expansions of ice volume on Antarctica. Primarily on the basis of these deep-sea proxy and eustatic records, it is generally assumed that: (1) middle Miocene ice-volume increases were associated with the large land-based East Antarctic Ice Sheet (EAIS) attaining physical dimensions similar to that existing on East Antarctica today (Savin et al., 1975; Woodruff et al., 1981; Wright et al., 1992); and (2) West Antarctica, a much smaller block of low-lying continental crust and volcanic highlands, remained substantially ice-free until the latest Miocene (Kennett and Barker, 1990).

Although the view of an ice-free West Antarctica during the middle Miocene is widely accepted, eustatic and deep-sea proxy records do not uniquely define the specific locations on Antarctica where the ice-volume fluctuations occurred. Moreover, direct geologic evidence suggests that ice cover on West Antarctica may have been more extensive than has traditionally been deduced from proxy data. For example, radiometrically dated hyaloclastites (subglacially erupted volcanics) require that thick ice-covered subaerial highlands of West Antarctica at Marie Byrd Land (Fig. 1, inset) existed during this time frame (LeMasurier and Rex, 1982). In the marine environment, detailed seismic–stratigraphic studies of the Ross Sea outer continental shelf demonstrate that grounded ice (ice in contact with the seafloor) existed during several intervals in the middle Miocene (Anderson and Bartek, 1992; De Santis et al., 1995). The exact number of grounding events has not been determined and debate still exists concerning the extent of grounded ice on the Ross Sea continental shelf during the middle Miocene. Anderson and Bartek (1992) argued that the middle Miocene grounding events on the Ross Sea continental shelf (i.e. lateral advances of grounded ice into the marine environment) were shelf-wide (i.e. the entire continental shelf was covered by ice in contact with the seafloor). This line of reasoning suggested to Anderson and Bartek (1992) that a full-bodied marine-based West Antarctic Ice Sheet (WAIS) existed during middle Miocene glacial periods, because by analogy with the modern ice-sheet drainage pattern (see Fig. 1 insert), West Antarctica constitutes a major part of drainage basin for the Ross Sea continental shelf. If correct, ice-volume fluctuations on West Antarctica may have played a larger role on middle Miocene climatic and eustatic change than previously thought.

De Santis et al. (1995) also proposed that there were multiple Ross Sea grounding events, but they argued that the extent of grounded ice was relatively limited, covering only subaerial banks on the outer continental shelf. They concluded that submarine areas of West Antarctica were ice-free even during the peak of middle Miocene glacials and that the WAIS was not fully developed until the end of the late Miocene, when ice caps coalesced across the sediment-filled marine basins between the subaerial banks (De Santis et al., 1995, 1999). This view of small West Antarctic ice caps during the middle Miocene and a latest Miocene transition to extensive ice cover generally is consistent with the theme of conventional interpretations of deep-sea proxy data, i.e. that West Antarctic glaciation was not significant until the latest Miocene.

These different views on the evolution and extent of Antarctic ice volume during the middle Miocene are incompatible. Ultimately, before we can fully resolve the global-scale question concerning the meaning and cause of the dramatic climatic and eustatic shifts deduced from middle Miocene proxy records, it is necessary in the first place to redress the local debates and precisely define ice-sheet extent on West Antarctica. In this study, we used single-channel seismic data that were not available at the time of the Anderson and Bartek (1992) and De Santis et al. (1995) studies to evaluate two specific questions with respect to the nature of middle Miocene ice-volume changes on the Ross Sea outer continental shelf (i.e. West Antarctica). (1) Were Ross Sea grounding events shelf-wide or restricted to local topographic highs? and (2) How many grounding events occurred during the middle Miocene?

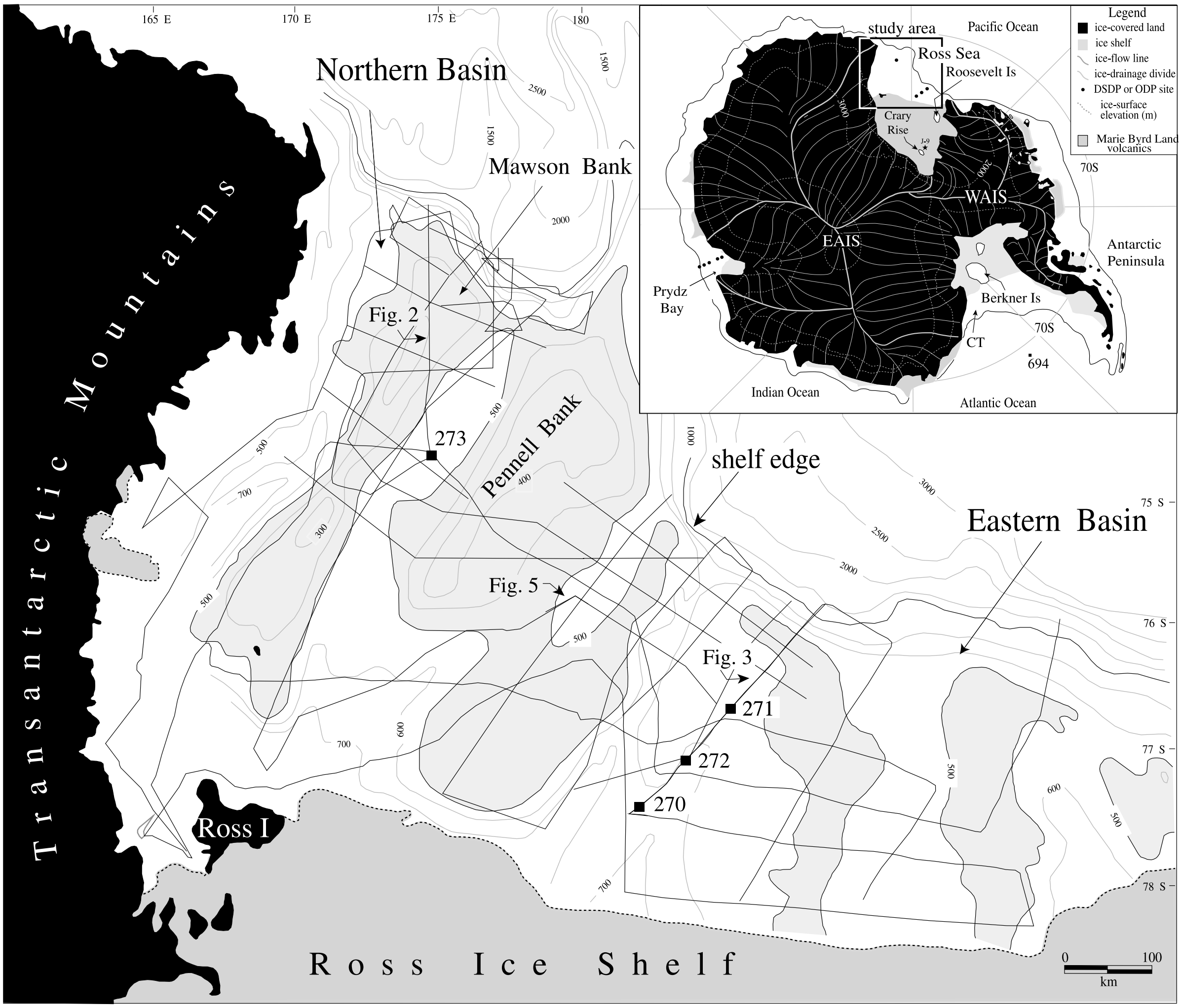


Fig. 1. Ross Sea continental shelf, showing seismic traces used in this study. Thicker lines correspond to segments of profiles shown in Figs. 2, 3 and 5. Present-day banks are highlighted in grey. The inset shows the location of hyaloclastites on Marie Byrd Land, Roosevelt, Crary, and Berkner Islands as well as the modern ice-flow patterns. CT = Crary Trough.

## 2. Materials and methods

The middle Miocene section was identified from Deep Sea Drilling Project (DSDP) sites 273 and 272 (Hayes and Frakes, 1975; Savage and Ciesielski, 1983). From these drill sites, the top and base of the middle Miocene were directly correlated to seismic data (Table 1; Figs. 2 and 3) using the time–depth conversions from the ANTOSTRAT Project (1995). Regional correlation of the middle Miocene section was performed by hand on paper copies of seismic sections plotted at a vertical scale of 33:1. Three single-channel seismic surveys were used in this study: PD90, NBP94, and NBP95 (Fig. 1). Data set PD90 consists of nearly 6000 km of seismic data acquired aboard the R/V *Polar Duke* in the 1990 austral summer using a 150-in$^3$ generator–injector airgun. Data sets NBP94 and NBP95 were acquired aboard the R/VIB *Nathaniel B. Palmer* in 1994 and 1995 field seasons, respectively, and include more than 7000 km of single-channel data acquired with a 50-in$^3$ generator–injector airgun.

To evaluate whether grounding events were shelf-wide or were restricted to bank crests, we conducted three seismic-based experiments. If the extent of grounded ice was restricted to topographic highs on the Ross Sea shelf, then the middle Miocene section should have been primarily derived from the banks. In the first experiment, we divided the total volume of the middle Miocene strata by the area of the topographic highs to estimate a minimum reconstructed height of the banks as a way to test the De Santis et al. (1995) view of localized grounding events. Likewise, we divided the total volume by the area of the West Antarctic interior that currently drains into Ross Sea to estimate a minimum reconstructed height of the continental interior as a way to test the Anderson and Bartek (1992) view of continental-scale ice cover.

To estimate the middle Miocene sediment volume, we constructed an isopach map. The middle Miocene thickness variations were measured in milliseconds from our regional seismic correlations. These thickness variations were contoured by hand then converted to depth assuming an average velocity of 1600 m/s. The actual sediment velocities may depart greatly from this arbitrary average but at present, no existing data define velocity variations in a meaningfully precise way. To determine the volume, the Ross Sea continental shelf was divided into grid cells with dimensions of 1° longitude and 0.5° latitude. The area for each grid cell was determined using the following formula: area $= R^2(\lambda_2 - \lambda_1)(\sin \varphi_2 - \sin \varphi_1)$, where $R = 6371$ km (radius of Earth), $\lambda$ = degree longitude in radians, $\varphi$ = degree latitude in radians. Sediment volume within the grid cell was determined with the following formula: volume $= (A \times f)T$, where $A$ = area of grid cell; $f$ = fraction of grid cell area within which middle Miocene section is found; $T$ = estimated average thickness of middle Miocene section within the grid cell. The volume from each grid cell was added to obtain the volume for the entire middle Miocene section.

In addition, we calculated the volumes of the middle Miocene section using the RSS-5 isopach (pl. 20d from the ANTOSTRAT Project, 1995) and the volume of the associated proximal grounding-zone deposits (facies A and C illustrated on fig. 17 from De Santis et al., 1995). The maps from the ANTOSTRAT Project (1995) and De Santis et al. (1995) were constructed from multi-channel seismic data which allowed those authors to correlate the middle Miocene strata further across the outer continental shelf where the section projects below the water-bottom multiple.

In the second experiment, we evaluated the middle Miocene thickness distribution. If the shelf-wide grounding events culminated with ice-sheet advance to the shelf edge then large quantities of sediment should have been deposited at the mouths of ice streams (wide zones of fast flowing ice). If so, middle Miocene isopach maps should exhibit upper-slope depocenters with lateral dimensions that match the scale of ice streams.

In the third experiment, we evaluated the dip directions of grounding-zone clinoforms on the Ross Sea continental shelf. Proglacial clinoforms probably represent sediment-gravity-flow deposits at the marine-terminus of an ice sheet and there-

Table 1
Elevations and age range of middle Miocene strata sampled at DSDP sites 273 and 272 on the Ross Sea outer continental shelf

| DSDP Site 273 Northern Basin | | | DSDP Site 272 Eastern Basin | | |
|---|---|---|---|---|---|
| Depth (m bsf) | Two-way time[a] (ms bsf) | Age range[b] (Ma) | Depth[c] (m bsf) | Two-way time[a] (ms bsf) | Age range[b] (Ma) |
| 42.5 | 60 | 14.7 | 23 | 35 | 13.8 |
| 272.5 | 310 | 16.2 | 145 | 150 | 14.1 |

[a] ANTOSTRAT, 1995.
[b] Savage and Ciesielski, 1983.
[c] Hayes and Frakes, 1975.

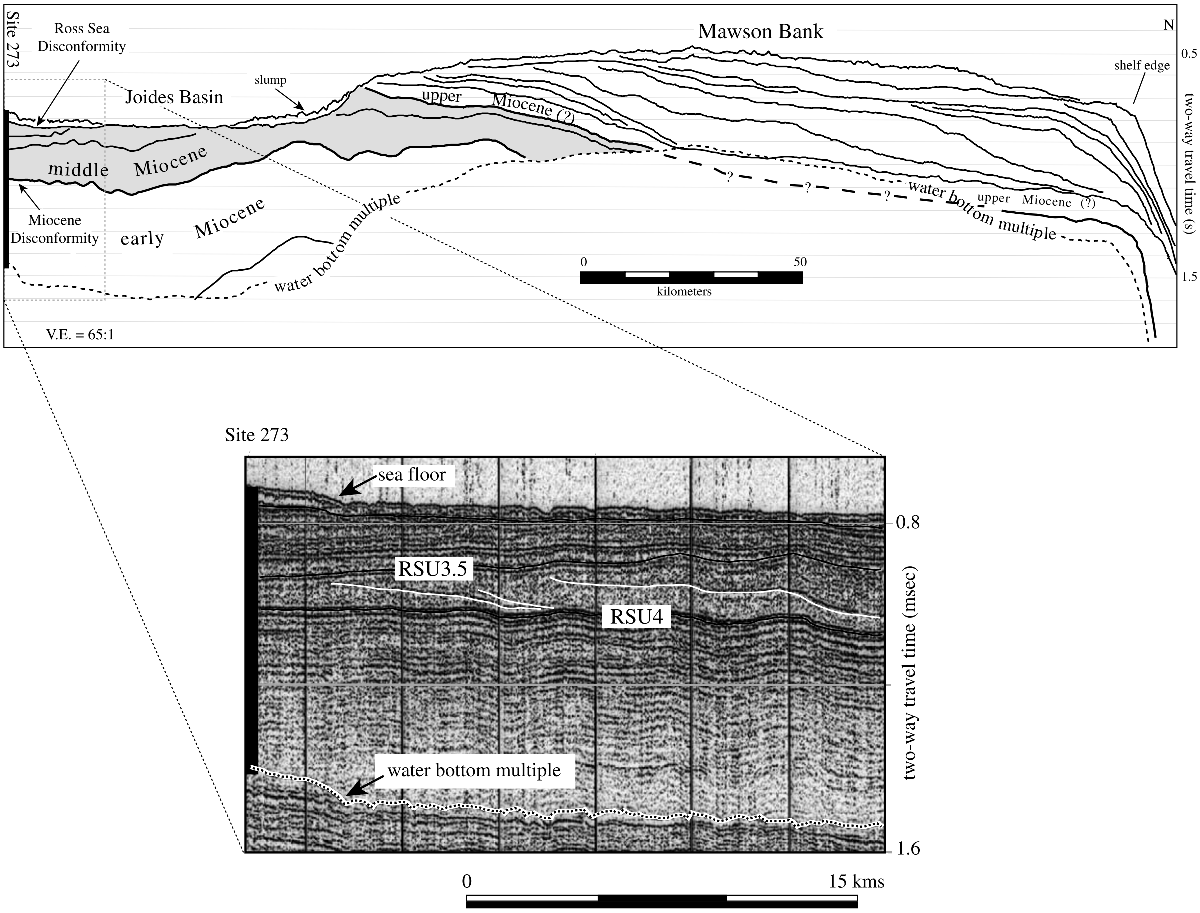


Fig. 2. Line drawing of interpreted seismic profile PD90-37 from Northern Basin, Ross Sea (see Fig. 1 for location). A segment of the seismic profile shows DSDP Site 273 and prograding foresets between the RSU4 and RSU3.5 unconformities within the middle Miocene section.

fore are the marine equivalent of terminal and lateral moraines in the terrestrial domain. We acknowledge that the proglacial-clinoform interpretation is equivocal and needs to be evaluated further. The dip directions of middle Miocene clinoforms were recorded and posted onto a seismic basemap. If the grounding events were restricted to topographic highs, then clinoforms should radiate in every direction, including landward, away from the topographic highs. If grounding events were shelf-wide, progradation should exist in the low-lying areas around the banks and should primarily be directed offshore. In addition, grounding events were shelf-wide and should exhibit glacial truncation far beyond the banks crests across the adjoining low-lying basins.

Finally, to determine the minimum number of grounding events, we assumed that seismic reflectors exhibiting regional extent, trough topography, and truncation of the underlying strata are glacial unconformities. Following the ANTOSTRAT Project (1995) nomenclature, we refer to the base of middle Miocene unconformity as RSU4. We refer to the top of middle Miocene (defined as RSU3 by ANTOSTRAT, 1995) as RSU3.1 and the underlying intra middle Miocene unconformities are numbered RSU3.2, RSU3.3, etc. from the top down.

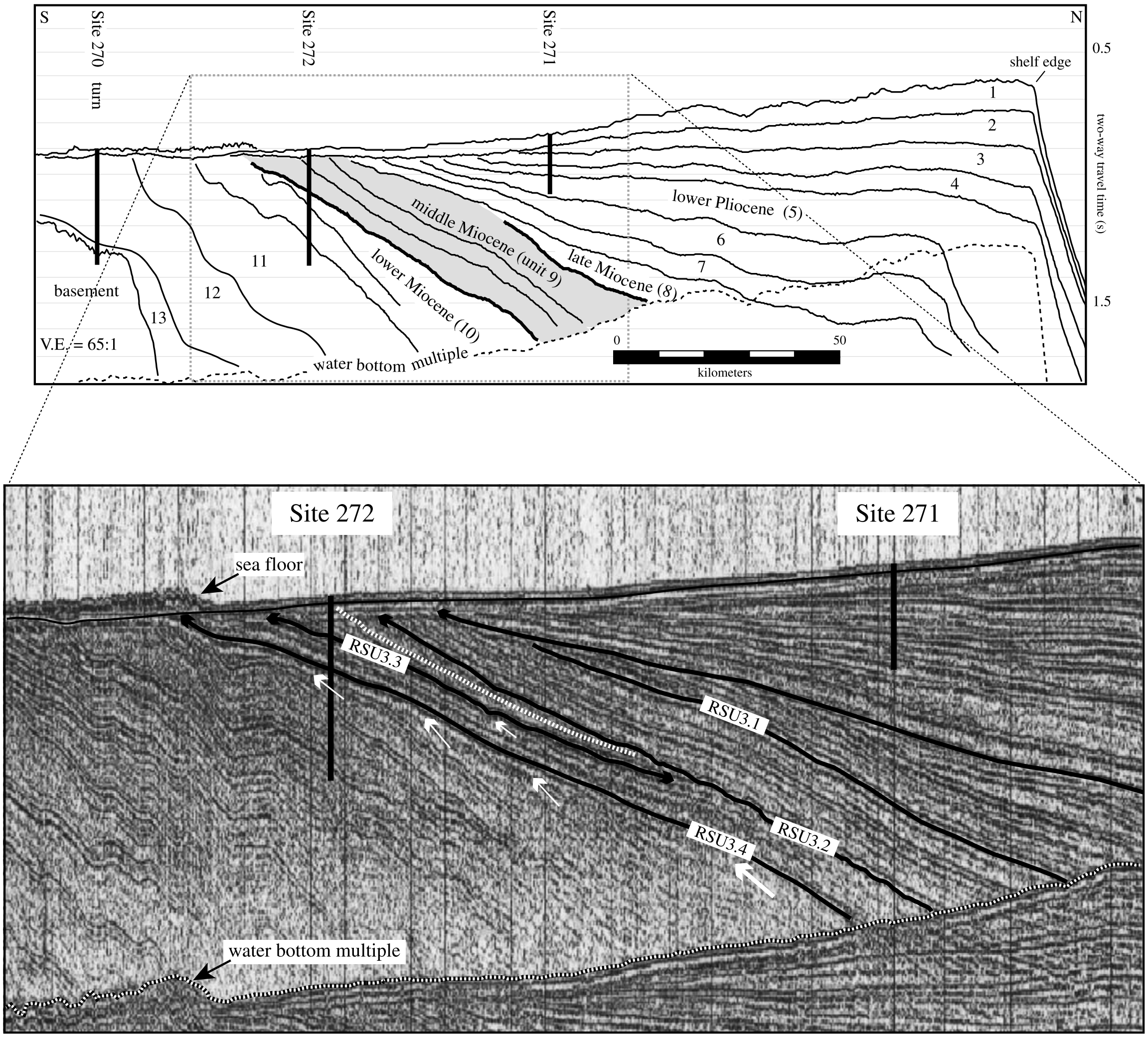


Fig. 3. Interpreted seismic profile PD90-30 from Eastern Basin, Ross Sea (see Fig. 1 for location). Units posted on the line drawing are from Anderson and Bartek (1992). A segment of the seismic profile shows DSDP Site 272 and truncation of underlying strata at RSU3.4, RSU3.3, RSU3.2 and RSU3.1. The white dashed line corresponds to the top of middle Miocene sampled at Site 272.

## 3. Results

### 3.1. *Middle Miocene strata at DSDP sites on the Ross Sea outer continental shelf*

In the Northern and Eastern basins, middle Miocene strata are part of a basinward-tilted offlapping succession (Figs. 2 and 3, respectively). In the landward direction, strata are truncated near the seafloor by angular unconformities eroded during recent glacial advances. According to the location of the shelf-edge trend at the onset (RSU4) and termination (RSU3) of the middle Miocene (De Santis et al., 1995), we infer that these tilted strata are topsets. On the outer shelf, the basinward thickening middle Miocene strata project below the water-bottom multiple.

According to the Savage and Ciesielski (1983) age model (Table 1), the stratal contact between the top of the middle Miocene and the late Mio-

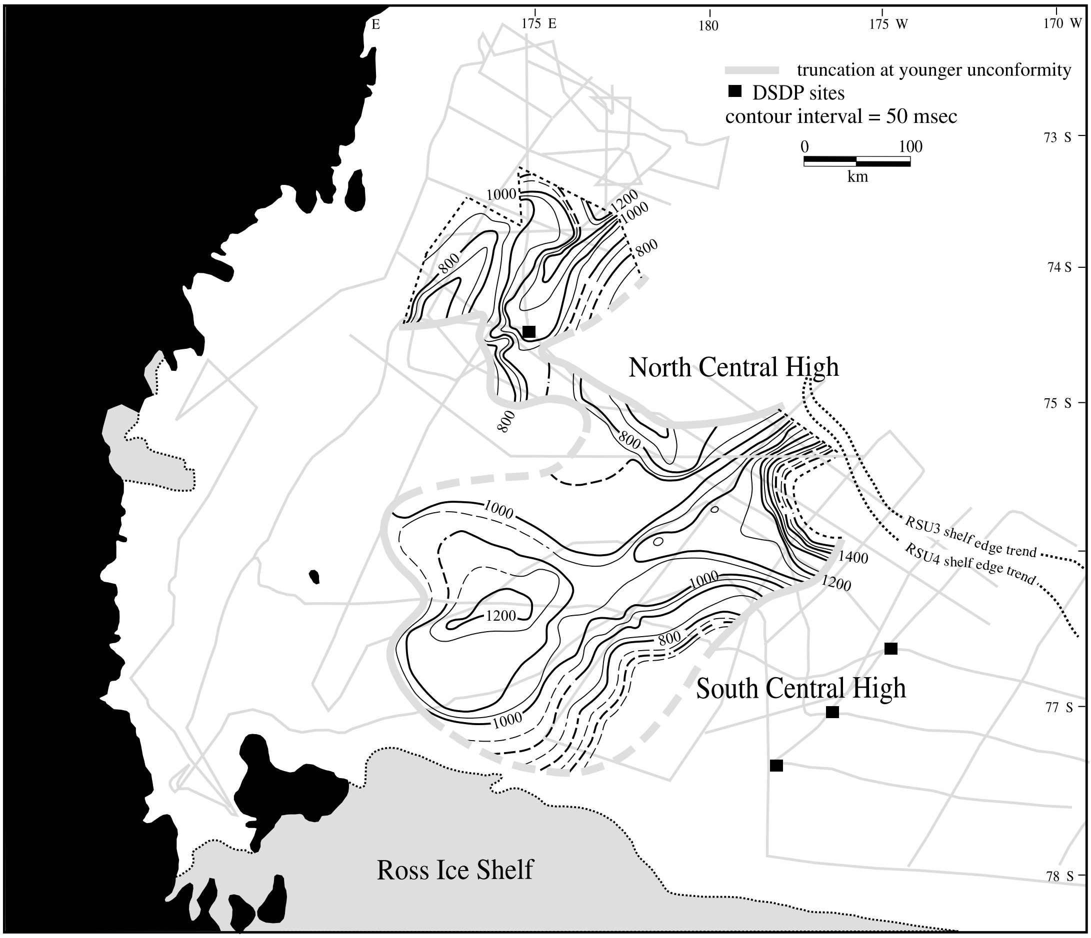


Fig. 4. Isopach map of middle Miocene section derived from this study. Arrows represent the position and orientation of dipping reflectors interpreted (from the single-channel seismic data) as grounding-zone proximal foresets. The inset is a rose diagram showing the orientations of the 39 clinoform progradations.

cene is not sampled at the DSDP drill sites on the outer continental shelf. We used the top of RSS-5 (i.e. RSU3 from ANTOSTRAT Project, 1995) as the top of the middle Miocene. Although this choice is arbitrary, this datum is a prominent angular unconformity below lower Pliocene sampled at DSDP Site 271 in Eastern Basin (Fig. 3).

### *3.2. Middle Miocene thickness variations on the Ross Sea outer continental shelf*

The middle Miocene strata are widespread on the outer continental shelf but have been eroded over the crests of the North and South Central Highs (N- and SCHs) (Fig. 4). At the landward limit, the middle Miocene section is truncated by an unconformity at a younger stratigraphic level. The basinward limit represents the location where middle Miocene strata project below the water-bottom multiple and are thus obscured on single-channel seismic data. The thickest section is within a basin along the northern flank of the SCH that trends northeast–southwest to the north of Ross Island. The maximum thickness is ∼400 m. Within this basin, the middle Miocene is also thick within an elongate basin oriented northwest–southeast along the southwest flank of the NCH, where maximum thickness reaches ∼200 m.

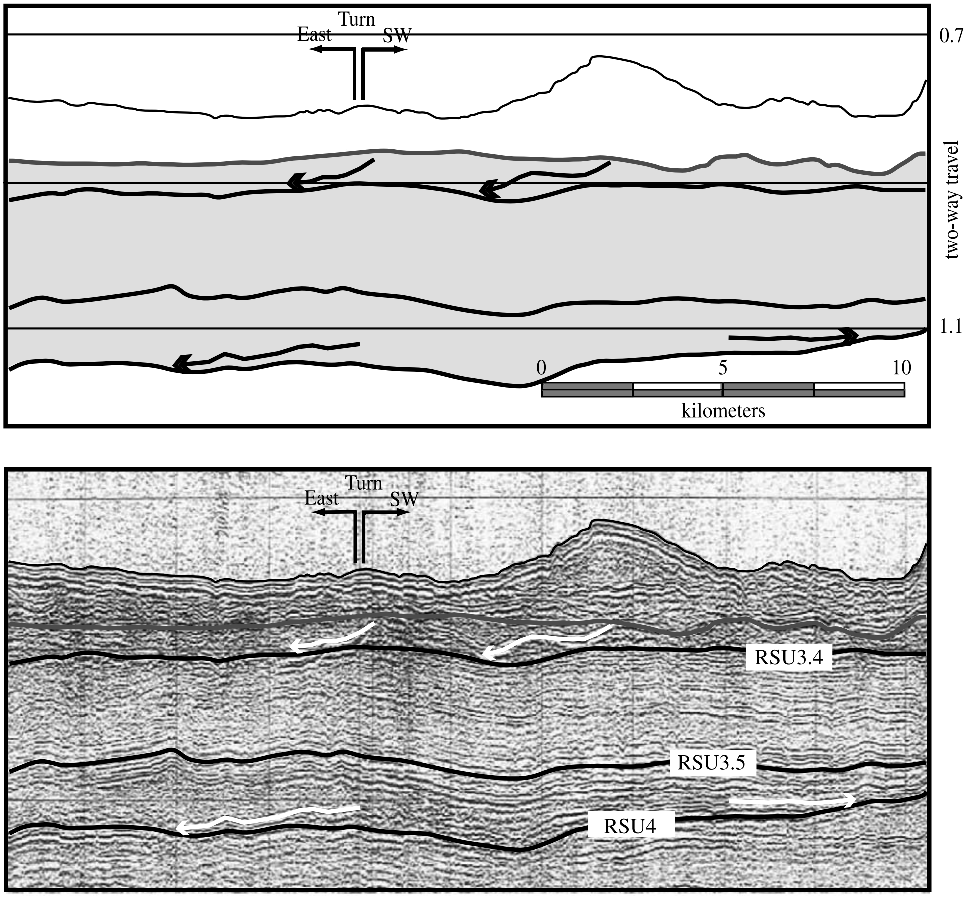


Fig. 5. Interpreted seismic profile NBP95-19-20 showing landward prograding foresets within the axis of an elongate basin between N- and SCHs. On the southern end of the profile, foresets dip landwards.

### 3.3. *Middle Miocene sediment-volume estimates from the Ross Sea outer continental shelf*

We estimate that the middle Miocene section identified in our study (Fig. 4) has a volume of ~20 000 km$^3$, and an average thickness of 170 m, covering a surface area of ~107 000 km$^2$ (Table 2). This obviously is a minimum volume because the section dips below the water-bottom multiple on the outer shelf. The ANTOSTRAT Project (1995) map of the middle Miocene (i.e. RSS-5) provides a more accurate estimate of the total volume for the middle Miocene section because the water-bottom multiple was successfully suppressed in seismic processing. We estimate that the RSS-5 middle Miocene section has a volume of ~90 600 km$^3$, an average thickness of ~450 m, and a surface area covering ~200 500 km$^2$ (Table 2). We estimate that the volume of grounding-zone proximal facies (facies A and C from De Santis et al., 1995) is ~7000 km$^3$ (Table 2).

### 3.4. *Middle Miocene grounding-zone progradation: distribution and orientations*

Within the middle Miocene section, we observed relatively few (39) clinoform reflections between topsets. The arrows posted on the thickness map (Fig. 4) are the apparent-dip directions observed from single-channel seismic profiles. Apparent dips of clinoforms range from 1° to 2°. Clinoform progradation was found at several dif-

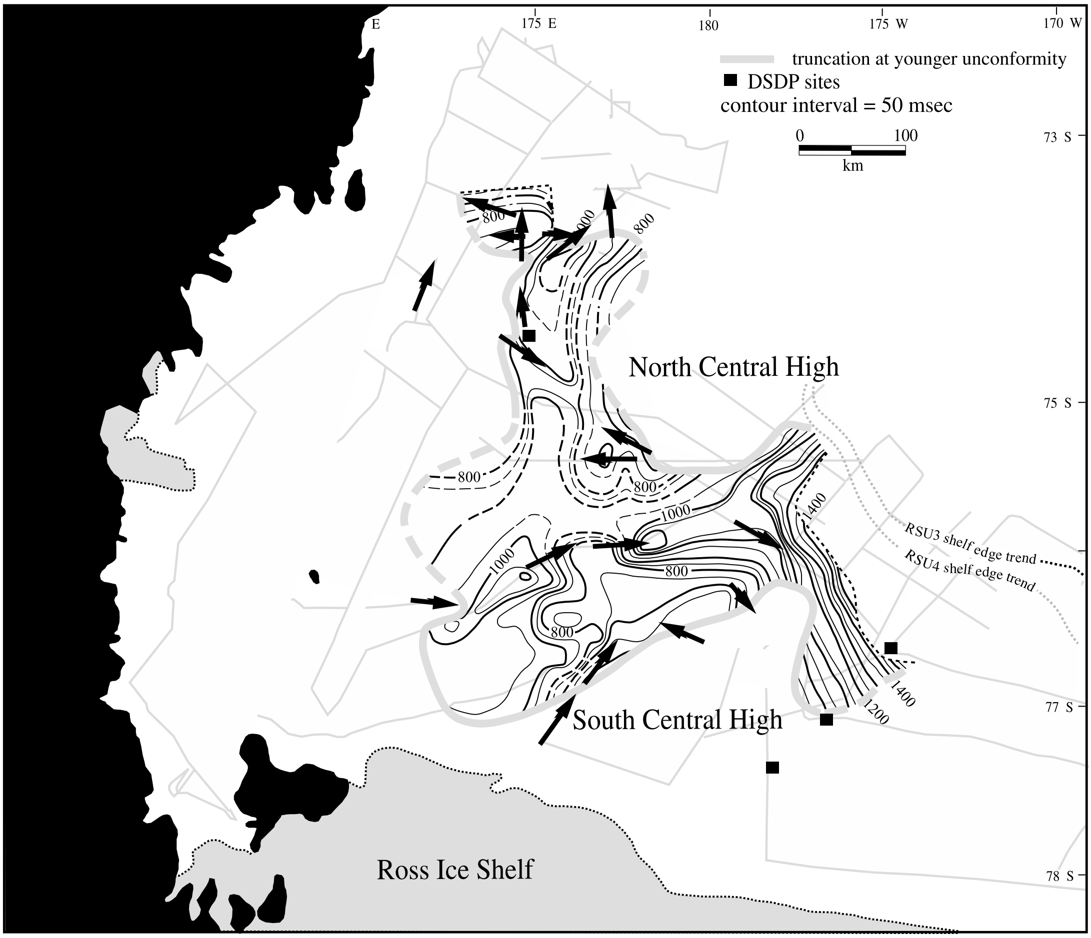


Fig. 6. Time–structure contour map at RSU4 (base of middle Miocene). The landward limit represents truncation of the surface at a younger stratigraphic level. The basinward limit represents where this horizon projects below the water-bottom multiple.

ferent stratigraphic levels. The clinoforms were found in the areas flanking the banks, and beyond the limits of the grounding-zone facies A and C delimited by De Santis et al. (1995). Clinoforms were also observed in the low-lying areas adjacent to the N/SCHs (Fig. 4).

The observed clinoform progradation directions primarily are oriented to the northeast, but in general, the range is from northwest to southeast (see inset on Fig. 4). In the areas rimming the N/SCHs, apparent dips of clinoforms primarily are oriented perpendicular to the bank crest. On the southern half of the NCH only a few landward (i.e. southwestward) oriented clinoforms were observed (Figs. 4 and 5). Within the low-lying areas adjacent to the bank crests, clinoforms primarily are directed offshore (i.e. towards the north-northeast).

### 3.5. Middle Miocene seismic unconformities on Ross Sea outer continental shelf

We identified six seismic unconformities (RSU4, RSU3.5, RSU3.4, RSU3.3, RSU3.2 and RSU3.1; from the bottom up) located within and/or bounding the middle Miocene section. Table 3 shows the relationship between these unconformities and previous nomenclature for the Ross Sea continental shelf stratigraphy. The lowest unconformity, RSU4, defines the base of the middle

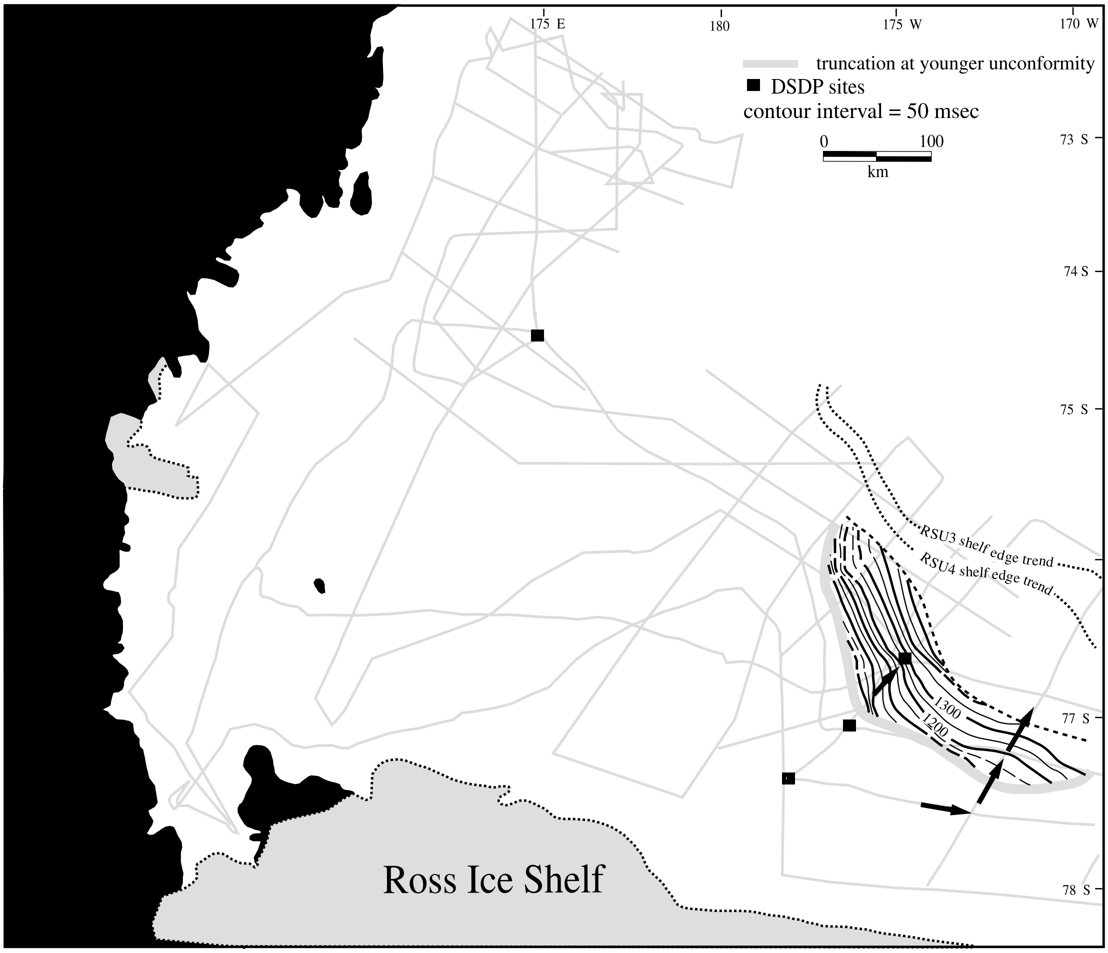


Fig. 7. Time–structure contour map at RSU3.5 within the middle Miocene. The surface is penetrated at DSDP Site 273 but not at Site 272.

Miocene at DSDP Site 273 (Fig. 2). Seismic correlation and time–structure contour mapping of the RSU4 shows that this horizon exhibits substantial topographic relief in Northern Basin and in the western part of Eastern Basin (Fig. 6). The topography resembles the bank/trough features at the seafloor, but it also is similar to the horst/graben topography of basement (pl. 19d from the ANTOSTRAT Project, 1995). In Northern Basin, a north–south oriented trough is located west of the NCH. A larger trough oriented northeast–southwest is located between the NCH and SCH and essentially defines a saddle structure (Fig. 6). The RSU4 unconformity exhibits ∼400–500 ms (300–375 m) maximum topographic relief from bank crest to trough axis. Towards the SCH, the unconformity is truncated by younger stratigraphic levels within and above the middle Miocene section.

In Northern Basin, the RSU3.5 unconformity truncates low-angle clinoforms that prograde down the axis of the RSU4 unconformity trough (Figs. 2 and 6). The time–structure contour map of RSU3.5 (Fig. 7) shows that troughs and banks at this horizon are coincident with those existing at the RSU4 unconformity. The RSU3.5 unconformity can be correlated towards Eastern Basin but is truncated by the overlying unconformity, RSU3.4.

In Eastern Basin, RSU3.4 defines the base of

Table 2
Volume and areal distribution of middle Miocene strata and N/SCH topographic banks on the Ross Sea outer continental shelf

| | Figure 4[a] | RSS-5[b] | Facies A and C[c] | NCH and SCH[c] |
|---|---|---|---|---|
| Volume ($km^3$) | 20 000 | 90 600 | 7 000 | NA |
| Area ($km^2$) | 10 700 | 20 0500 | | 55 000 |

The estimated areas of the NCH and SCH include only that part of the features to the north of the Ross Ice Shelf but these features probably are more extensive to the south.
[a] This study, 2002.
[b] ANTOSTRAT Atlas, 1995.
[c] De Santis et al., 1995.

the middle Miocene at DSDP Site 272 (Fig. 3 and Table 1). This unconformity shows a trough and flanks of a saddle between NCH and SCH. The extent of the horizon is more restricted than at RSU4 and RSU3.5 unconformities because of truncation at higher stratigraphic levels and because only a small area of the surface can be traced across the study area before the surface projects below the water-bottom multiple.

The map extent of the three upper unconformities (RSU3.3, RSU3.2, and RSU3.1) is limited to Eastern Basin and could not be confidently correlated with the existing seismic grid to Northern Basin. The RSU3.3 is within the middle Miocene section sampled at DSDP Site 272 but is truncated by RSU3.2 in a basinward direction. RSU3.2 shows irregular erosional relief before projecting below the water-bottom multiple. RSU3.1 (Fig. 8) is equivalent to RSU3 (i.e. the top of RSS-5; ANTOSTRAT Project, 1995) and the top of Unit 9 (Anderson and Bartek, 1992) (see Table 3).

## 4. Discussion

### 4.1. *Were Ross Sea grounding events localized or shelf-wide?*

#### 4.1.1. *Experiment 1: reconstructed height of the middle Miocene drainage basin*

The fundamental difference between the Anderson and Bartek (1992) and De Santis et al. (1995) models concerns the area of the middle Miocene drainage basins that provided sediments to the Ross Sea outer continental shelf. If the middle Miocene volume (Table 2) was exclusively derived by local shedding of glacial detritus from the N- and SCHs (estimated minimum surface areas of ~20 000 $km^2$ and 35 000 $km^2$, respectively), then these banks would have been ~1.6 km higher at the beginning of the middle Miocene compared to their present-day heights. The total volume of the middle Miocene section may contain a significant volume of biogenic sediments as well as clastic sediments derived from catchment other than

Table 3
Middle Miocene units and bounding unconformities identified on the Ross Sea continental shelf

| ANTOSTRAT, 1995 | | Anderson and Bartek, 1992 | Hinz and Block, 1984 | Cooper et al., 1987 | This study | |
|---|---|---|---|---|---|---|
| Seismic unit | Top–base bounding unconformities | Seismic unit | Top–base bounding unconformities | Seismic unit | Top–base bounding unconformities | Intra middle Miocene unconformities |
| RSS-5 | RSU3–RSU4 | Unit 9 | U3–U4 | V1 | RSU3.1–RSU4 | RSU3.2<br>RSU3.3<br>RSU3.4<br>RSU3.5 |

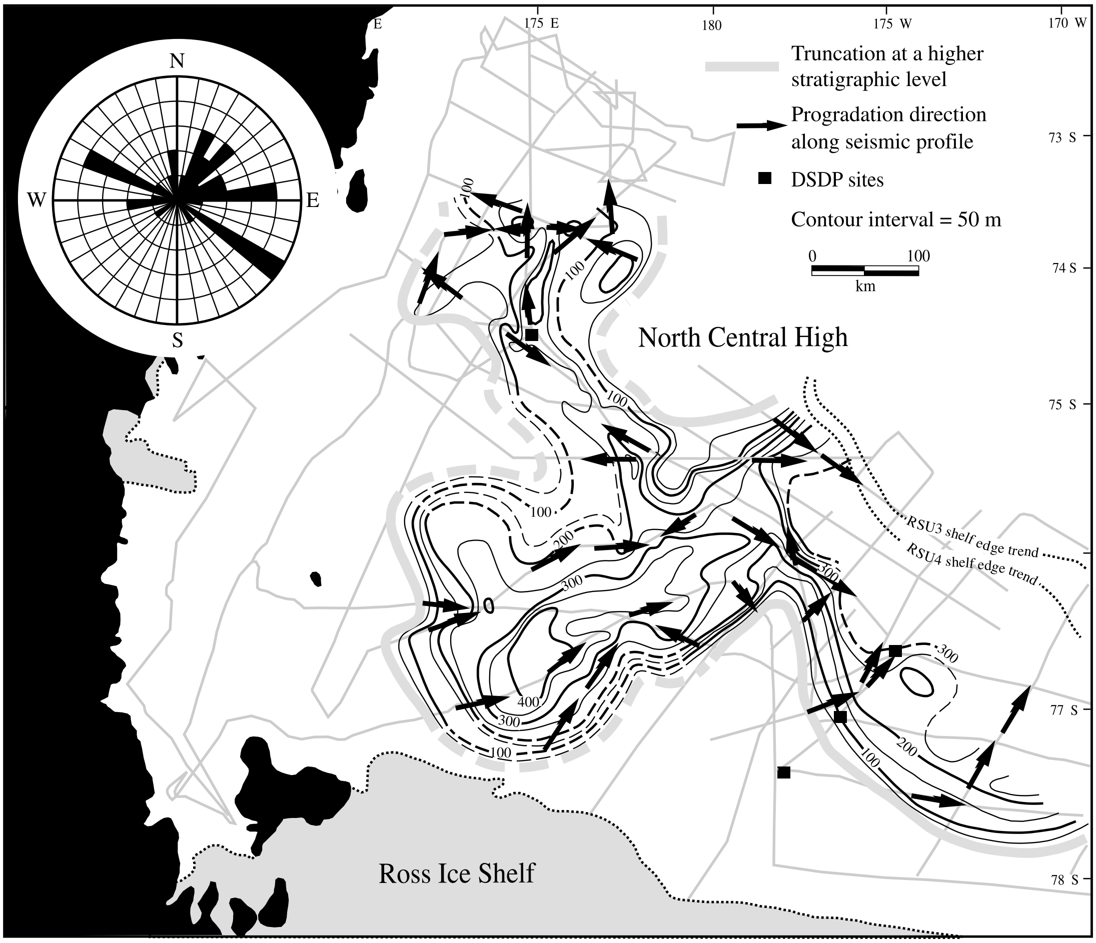


Fig. 8. Time–structure contour map at RSU3.1 which defines the top of the middle Miocene section and also corresponds to the top of Unit 9 defined by Anderson and Bartek (1992). The surface is confined to Eastern Basin but is not penetrated at DSDP Site 272.

the N/SCHs. In today's polar climate with low terrigenous flux to the Ross Sea outer continental shelf, biogenic sediments constitute ~35% of open-marine sediments (Leventer and Dunbar, 1987). If we reduce the middle Miocene volume by this extreme percentage (i.e. 35%), then the reconstructed height of the N/SCHs would still have been unusually high, i.e. ~1.1 km higher than present-day height.

We stress that these are simple reconstructed heights based only on sediment volume. Factors such as regional subsidence and isostatic adjustments have not been included in our calculations. Regional subsidence of the continental shelf that has occurred since middle Miocene time (due to crustal extension, sediment loading, etc.) would result in higher reconstructed heights for banks and intra-bank areas than we calculate. Conversely, isostatic uplift due to bank-crest erosion over the same period would result in lower reconstructed heights than we calculate. The magnitude of regional subsidence is not known and the amount of isostatic uplift would depend upon factors such as the density of the material eroded (e.g. sediment or basement), and if the N/SCHs were above or below sea level.

The middle Miocene section may contain a significant volume of clastic sediments derived from non-N/SCH catchment in either West Antarctica or East Antarctica, particularly if the mean middle Miocene climate was temperate because then, terrigenous flux including rock flour (e.g. seismic facies B of De Santis et al., 1995) could have been transported long distances from the original source area. On West Antarctica, free-air gravity data suggest that tectonic horst exists below the Ross Ice Shelf (ANTOSTRAT pl. 1b, 1995) and therefore, these topographic features might have also supplied sediments to the Ross Sea outer continental shelf.

The Dry Valleys sector of the TAM probably experienced relatively little denudation and through-put from the EAIS since the latest early Miocene (Sugden et al., 1995; Marchant et al., 1993; Stroeven and Kleman, 1999) but ice-rafted pebbles found within the upper part of the middle Miocene section at DSDP Site 272 (Eastern Basin) have a lithology (diabase) that suggests a TAM provenance (Barrett, 1975a). If these diabase pebbles were derived from the TAM, then EAIS outlet glaciers may have provided significant volumes of sediment to the Ross Sea shelf. Ultimately, since the area of non-N/SCH catchment for the Ross Sea continental shelf cannot be reliably determined, the two reconstructions (∼1.6 and 1.1 km higher than today) may significantly over-estimate the height of the N/SCHs at the beginning of the middle Miocene.

To minimize the above-mentioned problems associated with precisely defining the catchment area, we conducted a third sediment-volume reconstruction using only the grounding-zone facies surrounding the N/SCHs. Grounded ice restricted to shelf banks would require that the volume of the grounding-zone proximal seismic facies A and C (De Santis et al., 1995) was directly derived by glacial shedding from the N- and SCHs bank crests. In a proximal setting, sedimentation rates would be much higher than biogenic production, and therefore, facies A and C would be dominated by clastic sediment reworked from the bank tops. If the volume of facies A and C (Table 2) was derived solely by shedding of glacial debris from these two bank crests, then the N/SCHs would have been ∼125 m higher (assuming a simple layer-cake configuration and non-isostatically adjusted reconstruction) at the beginning of the middle Miocene compared to present-day heights. If the facies A and C volume was configured as inverted right circular cones, then the apex of the cones would have been ∼385 m higher at the beginning of the middle Miocene compared to present-day heights. The low height (∼125 m) required by this volume reconstruction is not unusual with respect to the large dimensions of the N/SCHs. Thus, the constraint provided by this reconstruction shows that the De Santis et al. (1995) ice-cap grounding model is feasible.

If the deposition of the entire middle Miocene section was associated with shelf-wide grounding events, the catchment area presumably would have included a large part of West Antarctica (Anderson and Bartek, 1992). The area of West Antarctica that currently drains into Ross Sea is ∼1 000 000 $km^2$. If this provides a reasonable estimate of the middle Miocene drainage area, then the land surface would have been lowered by ∼90 m on average during the middle Miocene. If correct, the minimum average denudation rate for the entire drainage basin during the middle Miocene would have been 0.015 mm/a. This drainage basin-wide denudation rate is lower than the estimated Quaternary polar climate interglacial erosion rate for the relatively small catchment area for ice stream B (Alley et al., 1989) but as the other ice streams (B, C, D, and E) are essentially stagnant, the Quaternary denudation rate for the entire West Antarctic drainage basin must be much lower. Moreover, given that sedimentary basins on the West Antarctic interior (Behrendt, 1999) may sequester middle Miocene sediments (Harwood et al., 1989), and that the relatively thick middle Miocene section drilled on the Ross Sea lower slope at DSDP Site 274 (Hayes and Frakes, 1975) requires sediment bypass of the Ross Sea continental shelf, the middle Miocene denudation rate probably was significantly higher than the low estimate we calculated. Because significant quantities of middle Miocene sediment might be sequestered in interior basins or have bypassed the shelf, we do not deem the minimum reconstructed height (∼90 m higher than today) of the West

Antarctic interior drainage basin to be unusually low. Therefore, we surmise that the shelf-wide grounding events might have been associated with substantial ice cover in the West Antarctic continental interior.

*4.1.2. Experiment 2: thickness trends on the outer-shelf/upper-slope depocenters in Northern and Eastern basins*

If grounded ice was restricted to isolated shelf banks, then the middle Miocene section should be relatively condensed in areas far removed from the banks (i.e. at the shelf edge and upper slope). Our time–thickness contour map (Fig. 4) as well as the RSS-5 isopach (ANTOSTRAT Project, 1995) show that the middle Miocene section thickens basinward. Because our observations are restricted to those places where the middle Miocene strata are above the water-bottom multiple, we cannot use our single-channel seismic mapping results to determine if depocenters are located at the paleo-shelf edge. However, the RSS-5 isopach map shows that two outer continental shelf depocenters in Northern Basin are roughly coincident with the mouths of Drygalski and Joides basins, two glacial troughs eroded during the last several glacial advances. In Eastern Basin, the RSS-5 isopach map also shows an elongate outer continental shelf depocenter that is far larger than the dimensions of modern ice streams. Deposition at the Northern Basin shelf-edge depocenters is more consistent with two distinct point sources delivering sediment directly to the upper slope. Either a line source or laterally shifting point source could have produced the elongate depocenter along the Eastern Basin shelf edge. Because these three outer-shelf depocenters are not proximal to middle Miocene banks, direct shedding of facies A and C from the bank tops could not have been the ultimate source of sedimentary material. This leaves the following question: could processes other than an ice sheet grounded at the shelf edge (i.e. fluvial deltaic sedimentation during eustatic lowstands, robust discharge of sediment-charge meltwater across the shelf, open-marine ravinement, etc.) have created the upper-slope depocenters observed on the RSS-5 isopach map (ANTOSTRAT, 1995)?

Sedimentologic and faunal data from DSDP Site 270 suggest glacially influenced sedimentation on a deep-water (i.e. ~500 m) Ross Sea continental shelf during the early Miocene (Barrett, 1975a; McDougall, 1977; Leckie and Webb, 1983; Hambrey and Barrett, 1993). On the basis of backstripping analysis of regional seismic profiles in Eastern Basin, De Santis et al. (1999) concluded that the Ross Sea outer continental shelf was not yet foredeepened (landward dip due to glacial erosion and isostatic loading by the ice sheets) but water depths increased basinward and at least locally, the shelf-edge depths approached 1000 m. If the deep-water interpretation is correct, the relatively small glacioeustatic fluctuations ($\leq 60$ m average magnitude of middle Miocene eustatic falls according to the Haq et al. (1987) eustatic curve) could not have caused subaerial exposure or significant shoaling at the Ross Sea paleo-shelf edge. Thus, it is unlikely that fluvial deltaic sedimentation constructed the RSS-5 upper-slope depocenters (ANTOSTRAT, 1995).

If the middle Miocene was a time of wet-based glaciation (Barrett, 1975b), then robust sediment-charged melt-water discharge from either a shelf-wide grounded ice sheet (on the inner continental shelf) or local ice cap on an outer continental shelf bank could have been topographically steered long distances across an open continental shelf (i.e. funneled through low-lying basins). There is no lithologic or seismic evidence of fluvial/glaciofluvial processes and thus, the possibility that sediment-charged meltwater was a major factor transporting sediment long distances across the shelf within middle Miocene depositional systems is discounted.

Several open-marine ravinement processes (e.g. transgressive and/or regressive erosion at wave-base, storms, impinging Circumpolar Deep Currents, High Salinity Shelf Water, etc.) potentially could transport large volumes of sediment basinward to the shelf edge/upper slope. However, on the Antarctic shelves, open-marine ravinement probably would not produce a substantial volume of sediment because the seafloor would become armored with pebbles as fines are winnowed from glacial deposits (Dunbar et al., 1985). Therefore, it is unlikely that the extremely large volume in the upper-slope depocenters was derived by open-marine ravinement. Of the two possible grounding scenarios evaluated in this study (shelf-wide vs bank-crest grounding events), it is more likely that shelf-wide advance of thick grounded ice to the shelf edge constructed upper-slope depocenters.

#### *4.1.3. Experiment 3: distribution and orientation of grounding-zone clinoforms*

If grounded ice was restricted to bank crests, sediments should have been shed radially off the banks. East-southeast and west-northwest progradation observed in this study (Fig. 4) generally matches that shown by De Santis et al. (1995) and confirms a significant component of off-bank flow. However, the general absence of landward-directed clinoforms around the N- and SCHs suggests that if an ice cap existed on the banks, then a fully radial ice-volume/sediment discharge from the banks was poorly developed. We acknowledge that the configuration of topography on the subaerial banks might predispose ice-volume drainage to one side or another of the bank.

In contrast to the ice-cap model, the observed clinoform pattern of off-bank shedding could also have been produced by a sinuous trend of a shelf-wide grounding zone on the outer shelf as is the case for the WAIS grounding zone today on the Ross Sea inner continental shelf (see Fig. 1, inset). We propose that the rare landward-directed clinoforms rimming the N- and SCHs may have formed by glacial erosion and deposition at an ice rise (i.e. a localized elevation of an ice shelf because of pinning on an underlying subaqueous bank). An ice shelf, as opposed to sea ice, is thick floating ice attached to an ice sheet. The ice shelf begins at the grounding zone, the zone where an ice sheet decouples from the seafloor. The free end of the ice shelf corresponds to the calving front. Development of an ice shelf is favored by rapid flow of cold ice into a protected embayment with high banks (Alley et al., 1986). The primary flow direction in an ice shelf is controlled by the pattern of discharge from the ice sheet. If a thick ice shelf comes in contact with a shallow bank, the basinward flow of ice decelerates because of friction with the seabed. Ice-flow deceleration causes a localized three-dimensional (3-D) buildup of ice over the bank, the ice rise. The creation of a 3-D ice rise (e.g. Roosevelt Island on the Ross Ice Shelf; Berkner Island on the Ronne/Filchner Ice Shelf) should create a local discharge regime at the subaqueous bank but the primary flow should still be towards the ice shelf's calving front. To our knowledge, there are no modern or ancient examples describing the sedimentary/erosional processes and resulting stratigraphy that should be associated with ice-rise features. We surmise that prograding directions around an ice rise should include significant off-bank shedding in a semi-radial pattern. Because the primary ice-sheet/ice-shelf flow would always be directed basinward, we infer that landward-directed discharge should be minimal. If the ice-rise interpretation of the facies rimming the N/SCHs is correct, the middle Miocene ice rise was larger than the dimensions of the Roosevelt Island ice rise on the Ross Ice Shelf and similar to dimensions of Berkner Island ice rise on the Ronne/Filchner Ice Shelf (see Fig. 1, inset).

The overall distribution of dipping reflectors could not have been produced by an ice cap or an ice rise because clinoforms prograde parallel to the elongate axes of low-lying basins (Figs. 2 and 4). This demonstrates that, at several times during the middle Miocene, thick grounded ice was more widespread on the Ross Sea outer continental shelf than shown by the distribution of facies A and C illustrated by De Santis et al. (1995). As the majority of observed clinoforms exhibit offshore-directed apparent dip (Fig. 4, inset), a significant component of ice discharge on the continental shelf must have been directed towards the shelf edge. Thus, the data suggest that ice cover was shelf-wide. Because the middle Miocene section could not be traced below the water-bottom multiple on single-channel seismic data, we cannot directly determine if a shelf-wide grounding event culminated at the paleo-shelf edge. As the RSS-5 middle Miocene thickness map (ANTOSTRAT Project, 1995) shows shelf-edge depocenters, we infer that at least some of the shelf-wide grounding events must have culminated in ice-sheet advance to the shelf edge.

### *4.2. How many grounding events occurred on the Ross Sea shelf during the middle Miocene?*

Within the middle Miocene, six unconformities (from base to top: RSU4, RSU3.5, RSU3.4, RSU3.3, RSU3.2, and RSU3.1) exhibit truncation of the underlying strata and are thus angular unconformities. However, truncation is not ubiquitous and over large areas, the unconformities are essentially disconformities.

Although clinoforms are not common within the middle Miocene section, at least a few are found associated with five of the six regional seismic unconformities defined in this study. Because the unconformities truncate the prograding clinoforms and because the topography of the individual unconformities generally mimics the scale of banks and troughs at the seafloor, we interpret these unconformities as erosional surfaces formed during a shelf-wide grounding event as the ice sheet advanced over its proglacial grounding-zone foresets. We refer to the truncation of foresets by RSU3.5 as the RUS3.5 grounding event (Fig. 2). If the glacial interpretation of these unconformities is correct, then there were a minimum of five advances (RSU3.5, RSU3.4, RSU3.3, RSU3.2 and RSU3.1 grounding events) of the ice sheet during the middle Miocene assuming that the Savage and Ciesielski (1983) age model is correct (see Table 1), and that the top of RSS-5/Unit 9 defines the top of the middle Miocene section (see Table 3). According to the available age constraints, RSU4 may have occurred at the beginning of the middle Miocene or in the latter part of the early Miocene. This minimum number of WAIS grounding events on the Ross Sea outer continental shelf therefore generally matches the number of middle Miocene $\delta^{18}O$ enrichments (i.e. four Mi-enrichment events from Wright et al., 1992) and eustatic lowstands (i.e. four sequence boundaries from Haq et al., 1987). We can exclude the possibility that there were many more major grounding events but if so, the stratigraphic evidence of such on the Ross Sea outer continental shelf has been removed.

The widespread occurrence of aggrading stratal patterns on the outer continental shelf between grounding-event unconformities suggests that major interglacial periods with minimal ice cover on the outer shelf probably were also important in the middle Miocene. Our Ross Sea results suggest waxing and waning of a well-developed WAIS at least on the Pacific sector of the Antarctic continental shelf and do not support to the conventional view (developed from oceanic records) of a substantially ice-free West Antarctica during the middle Miocene. Thus, middle Miocene oxygen-isotope and eustatic shifts were in part due to WAIS fluctuations. As East Antarctica is the much larger landmass, expansions of the EAIS probably were volumetrically more significant than those of the WAIS document here.

### *4.3. Do shelf-wide grounding events during the middle Miocene require a full-bodied marine-based WAIS?*

The shelf-wide grounding events of the Ross Sea outer continental shelf could have been associated with either a large WAIS covering the interiors of West Antarctica (Anderson and Bartek, 1992) or a small marine-based WAIS centered on the Ross Sea continental shelf. Combined with the results from previous studies, five lines of reasoning suggest to us that these Ross Sea grounding events probably were associated with substantial ice cover on the interiors of West Antarctica. (1) The large volume of the middle Miocene strata on the Ross Sea outer continental shelf (Table 2) suggests that sediments probably were derived from a large drainage basin. (2) The shelf-wide extent of thick grounded ice on the deep-water Ross Sea outer continental shelf suggests a large inland reservoir of ice. (3) The primary geomorphologic features that currently direct WAIS drainage towards the Ross Sea outer continental shelf (i.e. the TAM, Marie Bryd Land, and attenuated, but not necessarily subaqueous, continental crust of West Antarctica) were in existence well prior to the middle Miocene (Cooper et al., 1991; Behrendt and Cooper, 1991; ten Brink et al., 1993; Behrendt, 1999; Dalziel and Lawver, 2001). Dalziel and Lawver (2001) conclude that existence of the WAIS would not have been possible without the lithospheric ‘cradle’ that these features provide. (4) Subglacially erupted volcanics indicate thick ice cover on West Antarctic highlands at Marie Byrd Land during the middle Miocene (LeMasurier and Rex, 1982). (5) The dominant basinward-directed flow of ice on the Ross outer shelf inferred for middle Miocene grounding events (Fig. 4, inset) closely matches the WAIS drainage pattern that existed on the Ross continental shelf at the peak of the last glacial maximum (Shipp et al., 1999).

Although we favor the view of major ice cover on West Antarctica, the seismic-based results from the Ross shelf do not require that large areas of the West Antarctic continental interiors were below sea level in the middle Miocene. The strongest evidence for glacially influenced sedimentation in middle Miocene marine basins on the West Antarctic interiors comes from a single diatomite clast that contains a few rare occurrences of age diagnostic diatoms recovered from Ross Ice Shelf Project (RISP) Site J-9 (Harwood et al., 1989) (see Fig. 1, inset for location). Unless confirmed by additional data, this evidence is tenuous because the single clast cannot be used to argue that interior basins were widespread.

## 5. Conclusion

Our analysis of single-channel seismic data synthesized with results from the ANTOSTRAT Project (1995) suggests that there were a minimum of five shelf-wide grounding events of the WAIS on the Ross Sea outer continental shelf during the middle Miocene. As the WAIS grounding line advanced towards the shelf edge, thick ice shelves probably pinned on the N- and SCHs. Sediments eroded at the ice rise were shed into the adjacent open-marine basins. The number of WAIS grounding events at Ross Sea is consistent with that which could be deduced from $\delta^{18}O$ and eustatic records. However, in contrast with the traditional views developed from oceanic records, the seismic evidence from Ross Sea shows that the WAIS periodically contained significant ice volume during the middle Miocene at least on the Pacific margin of West Antarctica.

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## References

Alley, R.B., Blankenship, D.D., Bentley, C.R., Rooney, S.T., 1986. Deformation of till beneath ice stream B, West Antarctica. Nature 322, 57–59.

Alley, R.B., Blankenship, D.D., Rooney, S.T., Bentley, C.R., 1989. Sedimentation beneath ice shelves – The view from ice stream B. Mar. Geol. 85, 101–120.

Anderson, J.B., Bartek, L.R., 1992. Cenozoic glacial history of the Ross Sea revealed by intermediate resolution seismic reflection data combined with drill site information. Antarctic Research Series, 56 (The Antarctic Paleoenvironment: A Perspective on Global Change), 231–263.

ANTOSTRAT Project, 1995. Geology and Seismic Stratigraphy of the Antarctic Margin. Antarctic Research Series, 68.

Barrett, P.J., 1975a. Textural characteristics of Cenozoic preglacial and glacial sediments at Site 270 Ross Sea, Antarctica. Init. Rep. Deep Sea Drill. Proj. 28, 757–766.

Barrett, P.J., 1975b. Characteristics of pebbles from Cenozoic marine glacial sediments in the Ross Sea (DSDP Sites 270–274) and the South Indian Ocean (Site 268). Init. Rep. Deep Sea Drill. Proj. 28, 769–784.

Behrendt, J.C., Cooper, A., 1991. Evidence of rapid Cenozoic uplift of the shoulder escarpment of the Cenozoic West Antarctic rift system and a speculation on a possible climate forcing. Geology 19, 315–319.

Behrendt, J.C., 1999. Crustal and lithospheric structure of the West Antarctic Rift System from geophysical investigations – a review. Glob. Planet. Change 23, 25–44.

Cooper, A.K., Davey, F.J., Behrendt, J.C., 1987. Seismic stratigraphy and structure of the Victoria Land basin, western Ross Sea, Antarctica. In: Cooper, A.K., Davey, F.J. (Eds.), The Antarctic Continental Margin; Geology and geophysics of the western Ross Sea, Earth Science Series, vol. 5(B), pp. 279–283.

Cooper, A.K., Davey, F.J., Hinz, K., 1991. Crustal extension and origin of sedimentary basins beneath the Ross Sea and Ross Ice Shelf, Antarctica. In: Thomson, M.R.A., Crame, J.A., Thomson, J.W. (Eds.), Geological Evolution of Antarctica. Cambridge University Press, New York, pp. 285–291.

Dalziel, I.W.D., Lawver, L.A., 2001. The lithospheric setting of the West Antarctic Ice Sheet. Antarctic Research Series,

77 (The West Antarctic Ice Sheet: Behavior and Environment), 29–44.
De Santis, L., Anderson, J.B., Brancolini, G., Zayatz, I., 1995. Seismic record of late Oligocene through Miocene glaciation on the central and eastern continental shelf of the Ross Sea. Antarctic Research Series, 68 (Geology and Seismic Stratigraphy of the Antarctic Margin), 235–260.
De Santis, L., Prato, S., Brancolini, G., Lovo, M., Torelli, L., 1999. The eastern Ross Sea continental shelf during the Cenozoic: implications for the West Antarctic Ice Sheet development. Glob. Planet. Change 23, 173–196.
Dunbar, R.B., Anderson, J.B., Domack, E., 1985. Oceanic influences on sedimentation along the Antarctic continental shelf. Antarctic Research Series, 43 (Oceanology of the Antarctic Continental Shelf), 291–312.
Flower, B.P., Kennett, J.P., 1995. Middle Miocene deepwater paleoceanography in the southwest Pacific: Relations with East Antarctic Ice Sheet development. Paleoceanography 10, 1095–1112.
Hambrey, M.J., Barrett, P.J., 1993. Cenozoic sedimentary and climatic record, Ross Sea region, Antarctica. In: Kennett, J.P., Warnke, D.A. (Eds.), The Antarctic Paleoenvironment: A Perspective on Global Change, Part 2. AGU, Washington, DC, pp. 91–124.
Haq, B.U., Hardenbol, J., Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. Science 235, 1156–1167.
Harwood, D.M., Scherer, R.P., Webb, P.N., 1989. Multiple Miocene marine productivity events in West Antarctica as recorded in Upper Miocene sediments beneath the Ross Sea shelf (Site J-9). Mar. Micropaleontol. 15, 91–115.
Hayes, D.E., Frakes, L.A., 1975. General synthesis. Init. Rep. Deep Sea Drill. Proj. 28, 919–942.
Hinz, K., Block, M., 1984. Results of geophysical investigations in the Weddell Sea and in the Ross Sea, Antarctica. Proceedings of the World Petrol. Congress, London, 1983, vol. 2, pp. 79–91.
Hsu, K.J., Bernoulli, D., 1978. Genesis of the Tethys and the Mediterranean. Init. Rep. Deep Sea Drill. Proj. 42, 943–950.
Kennett, J.P., Barker, P.F., 1990. Latest Cretaceous to Cenozoic climate and oceanographic developments in the Weddell Sea, Antarctica: an Ocean-Drilling perspective. In: Barker, P.F., Kennett, J.P. et al. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, College Station, TX, Ocean Drilling Program, 113, pp. 937–960.
Leckie, R.M., Webb, P.N., 1983. Late Oligocene-early Miocene glacial record of the Ross Sea, Antarctica: Evidence from DSDP Site 270. Geology 11, 578–582.
LeMasurier, W.E., Rex, D.C., 1982. Volcanic Record of Cenozoic glacial history in Marie Byrd Land and western Ellsworth Land: revised chronology and evaluation of tectonic factors. Antarctic Geoscience Series B – Number 4. In: Craddock, C. (Ed.), The University of Wisconsin Press, Madison, WI, pp. 725–734.
Leventer, A., Dunbar, R.B., 1987. Diatom flux in McMurdo Sound. Mar. Micropaleontol. 112, 49–64.
Marchant, D.R., Denton, G.H., Swisher, C.C., III, 1993. Miocene-Pliocene-Pleistocene glacial history of Arena Valley, Quartermain Mountains, Antarctica. Geogr. Ann. 75A, 269–302.
McDougall, I., 1977. Potassium-argon dating of glauconite from a greensand drilled at Site 270 in the Ross Sea, DSDP Leg 28.
Savage, M.L., Ciesielski, P.F., 1983. A revised history of glacial sedimentation in the Ross Sea region. In: Oliver, R.L., Jago, J.B. (Eds.), Antarctic Earth Science. Australian Academy of Science, Canberra, pp. 555–559.
Savin, S.M., Douglas, R.G., Stehli, F.G., 1975. Tertiary marine paleotemperatures. Geol. Soc. Am. Bull. 86, 1499–1510.
Shackleton, N.J., Kennett, J.P., 1975. Paleotemperature history of the Cainozoic and the initiation of Antarctic glaciation: oxygen and carbon analysis in DSDP sites 277, 279 and 281. Init. Rep. Deep Sea Drill. Proj. 29, 743–755.
Shipp, S., Anderson, J.B., Domack, E.W., 1999. Seismic signature of the Late Pleistocene fluctuation of the West Antarctic Ice Sheet. GSA Bull. 111, 1486–1516.
Steininger, F.F., Rabeder, G., Rogl, F., 1985. Land Mammal distribution in the Mediterranean Neogene: A consequence of geokinematics and climatic events. In: Stanley, D.J., Wezel, D.J. (Eds.), Geological Evolution of the Mediterranean Basin. Springer-Verlag, New York, pp. 559–571.
Stroeven, A.P., Kleman, J., 1999. Age of Sirius Group on Mount Feather, McMurdo Dry Valleys, Antarctica, based on glaciological inferences from the overridden mountain range of Scandinavia. Glob. Planet. Change 23, 231–247.
Sugden, D.E., Denton, G.H., Marchant, D.R., 1995. Landscape evolution of the Dry Valleys, Transantarctic Mountains: Tectonic implications. J. Geophys. Res. 100, 9449–9967.
ten Brink, U.S., Bannister, S., Beaudoin, B.C., Stern, T.A., 1993. Geophysical investigations of the tectonic boundary between East and West Antarctica. Science 261, 45–50.
Woodruff, F., Savin, S.M., Douglas, R.G., 1981. Miocene stable isotope record: A detailed deep Pacific Ocean study and its paleoclimatic implications. Science 212, 665–668.
Woodruff, F., Savin, S.M., 1989. Miocene deepwater oceanography. Paleoceanography 4, 87–140.
Woodruff, F., Savin, S.M., 1991. Mid-Miocene isotope stratigraphy in the deep sea: high-resolution correlations, paleoclimatic cycles, and sediment preservation. Paleoceanography 6, 755–806.
Wright, J.D., Miller, K.G., Fairbanks, R.G., 1992. Early and middle Miocene stable isotopes: Implications for deepwater circulation and climate. Paleoceanography 7, 357–389.