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Were West Antarctic Ice Sheet grounding events in the Ross Sea a consequence of East Antarctic Ice Sheet expansion during the middle Miocene?

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Abstract

Seismic correlation of glacial unconformities from the Ross Sea outer continental shelf to chronostratigraphic control at DSDP sites 272 and 273 indicates that at least two West Antarctic Ice Sheet (WAIS) expansions occurred during the early part of the middle Miocene (i.e. well before completion of continental-scale expansion of the East Antarctic Ice Sheet (EAIS) inferred from $\delta^{18}O$ and eustatic shifts). Therefore, if the volume of the EAIS was indeed relatively low, and if the Ross Sea age model is valid, then these WAIS expansions/contractions were not a direct consequence of EAIS expansion over the Transantarctic Mountains onto West Antarctica. An in-situ development of the WAIS during the middle Miocene suggests that either West Antarctic land elevations were above sea level and/or that air and water temperatures were sufficiently cold to support a marine-based ice sheet. Additional chronostratigraphic and lithologic data are needed from Antarctic margins to test these speculations.

Keywords: West Antarctic Ice Sheet; East Antarctic Ice Sheet; middle Miocene shift; seismic stratigraphy

1. Introduction

Numerous lines of geologic evidence from deep-sea proxy records indicate an important transition from global warmth in the early Miocene to progressively colder climates in the middle Miocene [1–6]. In particular, the large-amplitude shifts on $\delta^{18}O$ and eustatic records strongly suggest cooling and major expansion of global ice volume via a series of steps, i.e. the middle Miocene shift (MMS). These proxy records provide a powerful means to reconstruct high-resolution changes in global ice volume and water-mass temperature. However, they do not provide evidence as to the specific distribution of ice on Earth. Many investigators infer that the global ice-volume increases during the MMS were associated with East Antarctic Ice Sheet (EAIS) expansion to continental scale [1,3,7,8]. It is usually assumed that the smaller West Antarctic Ice Sheet (WAIS) evolved into a full-bodied system several million years later, in the late Miocene [9,10] or early Pliocene [11] resulting from either overgrowth of a robust EAIS

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over the Transantarctic Mountains onto West Antarctica [11] and/or progressive climate change that sufficiently cooled the ocean water and thus eventually permitted in-situ development of a marine ice sheet from progressive thickening of shelf ice (floating ice connected to an ice sheet) originating from highlands of the West Antarctic archipelago [10,12].

What assumptions and reasoning led to these conclusions concerning East- and West-Antarctic glacial history? The conceptual framework within which deep-sea proxy records usually are interpreted appears to rely on at least three tacit assumptions regarding land elevation and climatic conditions in Antarctica during the middle Miocene: (1) geomorphology and elevation of Antarctica was similar to that existing today (i.e. the large East Antarctic continental block had several high-elevation areas and an average land elevation above sea level, whereas the relatively small

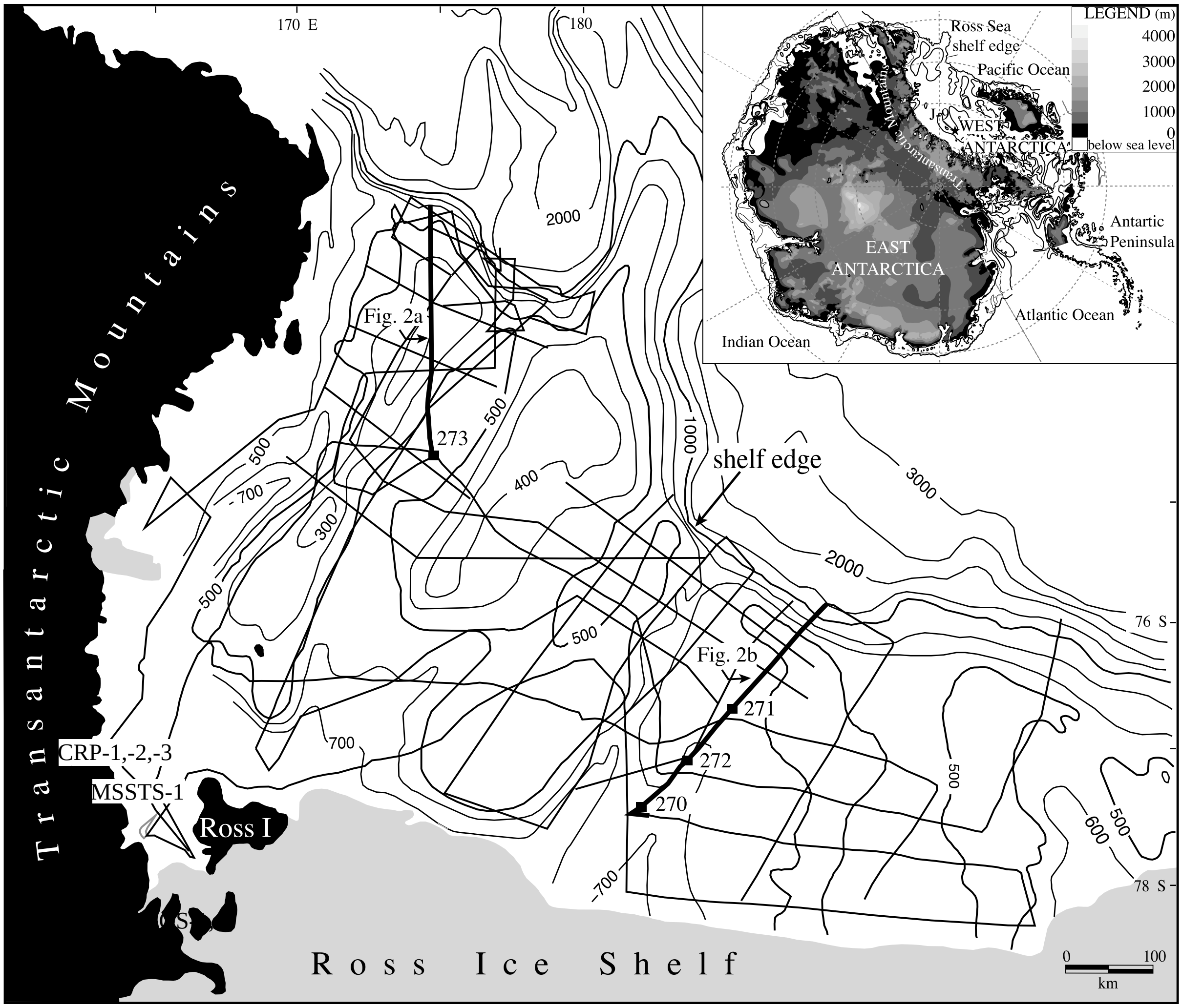

Fig. 1. Antarctic location map and Ross Sea study area. Inset: Antarctic land-surface elevation if ice volume were removed and land allowed to isostatically rebound [13].

West Antarctic block had few high-elevation areas and an average land elevation below sea level[1], see Fig. 1, inset); (2) a large EAIS did not exist at the onset of the middle Miocene[2]; and (3) water temperatures in West Antarctic interior basins were too warm to allow the existence of a marine ice sheet[3]. Given the large magnitude of the MMS ($>$1.0 per mil), it is quite logical to focus attention on ice-volume changes associated with the larger/higher land mass (i.e. East Antarctica) whereas, in contrast, the maximum volume of ice that might accumulate on West Antarctica is (according to the late Pleistocene calibration of $\delta^{18}O$ to sea-level change) relatively small. In other words, the small magnitudes of $\delta^{18}O$ and eustatic shift that would be caused by major changes in the volume of the WAIS are too close to the analytical precision of these techniques to be meaningful.

The purpose of this paper is to re-examine these conclusions concerning East and West Antarctic glacial history interpretations from Miocene deep-sea proxy records [1–6] in light of lithologic and seismic–stratigraphic evidence from Ross Sea, West Antarctica (Fig. 1), that suggest significant glaciation at sea level during the middle Miocene [16–25]. On the Ross Sea outer continental shelf, middle Miocene strata have sigmoidal and oblique offlap geometries [19,25] and where sampled these prograding sequences consist of glaciomarine strata [16] deposited either near or directly in front of an ice sheet in the marine environment [17,19–21]. Seismic-stratigraphic evidence from the Ross Sea shows that the WAIS apparently experienced multiple expansions/contractions on the outer shelf during the middle Miocene [20,21]. A recent regional seismic–stratigraphic study of glacial unconformities and strata on the Ross Sea outer continental shelf [26] shows that there were at least six WAIS grounding events (major advance and retreat of ice in contact with the seafloor). The absence of middle Miocene strata at drill sites adjacent to the Transantarctic Mountains in the western Ross Sea [27] (see Fig. 1 for drill site locations) is consistent with major ice-sheet advance to the Ross Sea paleo-shelf edge and widespread erosion on the inner shelf [18–21]. Waxing and waning of grounded ice during these middle Miocene glacial/interglacial cycles may have also involved substantial retreat of the WAIS from the Ross Sea outer continental shelf [21] as at least one diatomite clast from Site J9 (see Fig. 1, inset) contains middle Miocene marine diatoms, the presence of which suggests that some inner parts of Ross Sea may have periodically been ice free [28].

These inconsistencies between the conventional interpretations of proxy data (e.g. [1–8,10]) and the direct records from the Ross Sea margin (e.g. [16–26]) requires that the conceptual models concerning when and how the WAIS evolved during the late Neogene with respect to the larger EAIS be reevaluated and refined. The specific purpose of this ongoing study is to evaluate if middle Miocene expansions of the WAIS inferred from glacial unconformities (grounding events) on the Ross Sea outer continental shelf [26] pre- or postdate the continental-scale expansion of the EAIS inferred from the $\delta^{18}O$/eustatic shift (i.e. the MMS). Determining the relationships between EAIS and WAIS evolution are critical to address fundamental questions concerning how the WAIS formed and what forcing mechanisms caused this important part of Antarctic cryosphere to fluctuate.

[1] The earliest images of Antarctic subglacial topography were obtained via seismic experiments conducted in the 1950s by Soviet and American scientist traversing the ice sheet with over-snow vehicles. The first comprehensive compilation of airborne radio echo soundings was prepared in 1983 by D.J. Drewry and S.R. Jordan [13].

[2] Schnitker [14] proposes that upwelling of relatively warm North Atlantic deepwater in the 'pre-cooled' South Ocean supplied the moisture that led to EAIS expansion during the MMS. In contrast, Woodruff and Savin [3] propose that reduced production of Warm Saline Deepwater from equatorial regions greatly decreased meridional transport of warmth to the Southern Ocean which led to Southern Ocean cooling and EAIS expansion during the MMS.

[3] The term 'marine ice sheet' was defined in 1970 by Mercer [15] to describe a glacial system, such as the WAIS, for which the base is in contact with the seafloor so far below sea level that it must contain cold ice (i.e. a polar as opposed to a temperate ice sheet). A marine-based glacial system requires water and summer-air temperatures to be low.

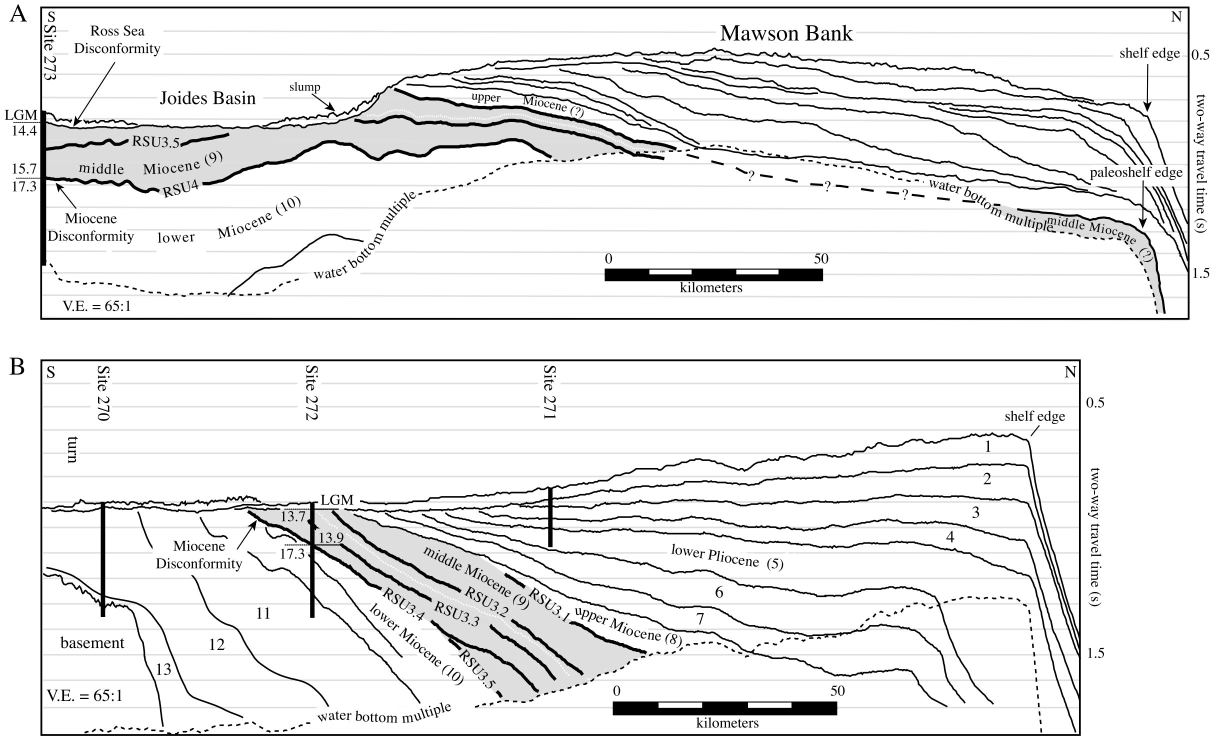

Fig. 2. (A) Line drawing of seismic profile 90-37 and correlation of RSU4, RSU3.5 to DSDP Site 273. (B) Line drawing of seismic profile 90-30 and correlation of RSU3.5 RSU3.4, RSU3.3, RSU3.2, and RSU3.1 to DSDP Site 272.

2. Methods

In this study, the six Ross Sea unconformities (RSU4, RSU3.5, RSU3.4, RSU3.3, RSU3.2, and RSU3.1) described by Chow and Bart [26] were seismically correlated to age control at two DSDP Leg 28 sites (272 and 273) on the Ross Sea outer continental shelf (Figs. 1 and 2) to estimate the timing of these grounding events. These are the only two West Antarctic shelf sites where middle Miocene strata are drilled. The seismic profiles used in this study were acquired in 1990 from R/V *Polar Duke*, and in the 1994 and 1995 field seasons from the R/VIB *Nathaniel B. Palmer*. The age model for DSDP sites 272 and 273 [29] is based on diatom zonations from DSDP Leg 28 sites 266 and 278 in the South Pacific/Indian Ocean sector of the Southern Ocean [30]. Correlation of the diatom zonations to standard epoch boundaries and ages [31] was subjective because the stratigraphically important planktonic calcareous microfossils [32,33] are rare in Neogene sediments of the Southern Ocean region [30]. Neither Weaver and Gumbos [30] nor Savage and Ciesielski [29] provide an assessment of the age uncertainties. On the basis of the durations of the magnetic chrons (within which Savage and Ciesielski [29] presume the sites 273 and 272 diatom-biozone boundaries occur), the maximum temporal resolution for the Miocene ranges from 0.06 to 0.51 Ma. Censarek and Gersonde [34] provide an update to Miocene diatom biostratigraphy for sub-Antarctic sites (DSDP Leg 113 sites 689 and 690, and ODP Leg 177 sites 1088 and 1092) in the Atlantic sector of the Southern Ocean but this new scheme has not yet been applied to DSDP sites 272 and 273. These recent biozonations [34] are distinctly different from that developed by Weaver and Gumbos [30], and it is not possible to update the Ross Sea age model based on the information reported by Savage and Ciesielski [29]. Table 1 shows the depths, time–depth con-

Table 1
Depth, two-way time, age and corrected age of middle Miocene at DSDP sites 273 (A) and 272 (B)

(A) DSDP Site 273, Northern Basin				(B) DSDP Site 272, Eastern Basin			
Depth[a] (m bsf)	Two-way time[b] (msec bsf)	Age range[c] (Ma)	Corrected age range[d] (Ma)	Depth[a] (m bsf)	Two-way time[b] (msec bsf)	Age range[c] (Ma)	Corrected age range[d] (Ma)
42.5	60	14.7	14.4	23	35	13.8	13.7
272.5	310	16.2	15.7	145	150	14.1	13.9

[a] Depth ranges from Hayes and Frakes [16].
[b] Two-way time conversions based on time-depth charts from ANTOSTRAT Atlas [24].
[c] Age range estimates from Savage and Ciesielski [29].
[d] Conversion of Savage and Ciesielski [29] age ranges to Berggren et al. [35] in this study.

versions and age ranges of the middle Miocene strata sampled at DSDP sites 273 and 272. In Table 1 the first set of age ranges for sites 273 (column A) and 272 (column B) are from Savage and Ciesielski [29] with respect to the time scale of Ryan et al. [32]. The second set of age ranges were calculated in this study and are with respect to the time scale of Berggren et al. [35].

The Haq et al. [36] eustatic curve was selected because it is the only global-scale evaluation of eustatic fluctuations and thus errors associated with local climate, sediment supply, tectonics, etc. presumably are minimized. The sequence boundaries are assumed to be formed by eustatic falls [36]. The uncertainty of age assignments may be as high as ±1.0 Ma [37]. Despite the controversy surrounding the sequence-stratigraphic methodology and reliance on unpublished data (e.g. Christie-Blick et al. [38]), a recent detailed comparison shows that the number and timing of middle Miocene sequence boundaries [36] agrees remarkably well with that observed on the New Jersey margin [37]. Table 2 shows sequence boundary ages from Haq et al. [36] (i.e. with respect to the Haq et al. [40] paleomagnetic time scale) and the sequence-boundary ages corrected to Berggren et al. [35]. The corrected sequence-boundary ages (Table 2A) were estimated in this study by linear extrapolation between age dates for the tops of magnetic chrons reported by Haq et al. [40] and the equivalent chron boundaries on the time scale of Berggren et al. [35].

The ODP Site 747 benthic foram $\delta^{18}O$ record from the Kerguelen Plateau in the Indian Ocean sector of the Southern Ocean was selected because

Table 2
Timing of middle Miocene sequence boundaries (A), Mi events at ODP Site 747 (B), and Ross Sea grounding events (C)

(A) Eustatic curve		(B) ODP Site 747 $\delta^{18}O$		(C) Ross Sea stratigraphy	
3rd order sequence cycle	Sequence-boundary age/ corrected age[a] (Ma)	Enrichment event	Mi event age/ corrected age[b] (Ma)	Seismic unconformity[c]	Grounding event inferred time range[d] (Ma)
TB3.2	8.2/9.1	Mi7	8.5/8.7	RSU3.1	e Plio $< t_1 <$ 13.7
TB3.1	10.5/11.0	Mi6	10.2/10.3	RSU3.2	e Plio $< t_2 <$ 13.7
TB2.6	12.5/12.6	Mi5	11.7/11.7	RSU3.3	$13.7 < t_3 < 13.9$
TB2.5	13.8/13.8	Mi4	12.8/12.9	RSU3.4	$13.9 < t_4 < 14.4$
TB2.4	15.5/15.4	Mi3b	13.6/13.7	RSU3.5	$14.4 < t_5 < 15.7$
TB2.3	16.5/16.4	Mi3a	14.1/14.2	RSU4	$15.7 < t_6 < 17.3$
TB2.2	17.5/17.3	Mi2	15.9/16.2		
TB2.1	21.0/21.2	Mi1c	17.8/17.9		

[a] Sequence-boundary ages from Haq et al. [36]/corrected ages (i.e. converted to Berggren et al. [35] in this study).
[b] Enrichment event ages from [39]/corrected ages (i.e. converted to Berggren et al. [35] by Miller et al. [37]).
[c] Ross Sea unconformities (RSU) defined by Chow and Bart [26].
[d] Inferred time ranges of Ross Sea grounding events converted (this study) to the Berggren et al. [35] time scale.

it spans the entire middle Miocene and in addition it may ultimately be possible to directly relate the sedimentology and isotope/biostratigraphy at this high-latitude (54°48.68′S) site to stratigraphy on Antarctic continental shelves. The Miocene shifts (Mi events) shown on the ODP Site 747 $\delta^{18}O$ record are sharp shifts to higher values that are observed at several sites [3,4,8,39,41]. The age uncertainty for Mi events is ±0.25 Ma [37]. Table 2 shows Mi-event ages as reported in 1991 by Miller et al. [39] with respect to the time scale of Berggren et al. [42] and as reported in 1998 by Miller et al. [37] updated to the time scale of Berggren et al. [35]. A second benthic $\delta^{18}O$ record from ODP Site 588, Tasman Sea [5], was evaluated because of the high-resolution (average temporal sampling of 9.7 ka) available from an expanded section of the lower middle Miocene drilled at this location (26°06.7′S).

The timing of the six grounding events (estimated by seismic correlation to DSDP sites 272 and 273) was compared to the timing of eustatic lowstands [36] and ^{18}O enrichments at ODP Site 747 [4]. All ages mentioned in this study are approximate and reported with respect to the Berggren et al. [35] time scale. For the purpose of this study, four fundamental assumptions were made: (1) the glacial-unconformity interpretations [26] are valid; (2) the eustatic [36], $\delta^{18}O$ [37], and Ross Sea [29] age models are reliable; (3) the middle Miocene ^{18}O enrichments/eustatic lowstands primarily are representative of global ice-volume increases on Antarctica; (4) because of the much larger land area of East Antarctica (Fig. 1, inset), EAIS fluctuations probably constituted the largest contribution to first-order global ice-volume change. Therefore, major shifts on $\delta^{18}O$ and/or eustatic records should primarily be a consequence of ice-volume change on East Antarctica. If these assumptions are valid, then a comparison of the ages of the WAIS grounding events in Ross Sea (this study) to the timing of ^{18}O enrichments [37] and eustatic lowstands [36] should indicate whether the Ross Sea (West Antarctic) grounding events during the middle Miocene significantly pre-date or post-date the expansion of the EAIS to continental scale during the MMS (i.e. from 17.5 to 14.5 Ma).

3. Background

3.1. WAIS grounding events on the Ross Sea outer continental shelf

During major glacial periods, an ice sheet may advance from land far into the marine realm as grounded ice (Fig. 3A). During these times, the ice-covered inner continental shelf becomes a zone of net erosion as sediments are transported via subglacial debris zones to the outer-continental shelf [43,44]. Most sediments probably are eroded and transported by ice streams (broad zones of fast flowing ice). At the ice-sheet grounding line (the terminus of grounded ice), subglacial debris is released subaqueously as sediment gravity flows constructing either chaotic mass flows and/or dis-

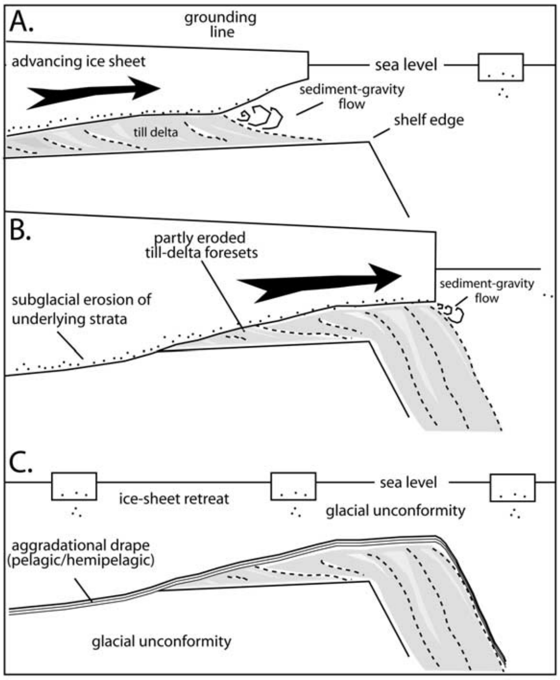

Fig. 3. Conceptual model of ice-sheet erosion and deposition on the Antarctic outer continental shelf during a glacial/interglacial cycle. (A) Initial advance of the ice sheet from land onto inner shelf and deposition of a till delta at the grounding zone. (B) Subglacial erosion of till delta and underlying strata on the inner shelf and deposition of till delta on outer continental shelf. (C) Rapid ice-sheet retreat from the continental shelf and aggradation of open-marine hemipelagics/pelagics.

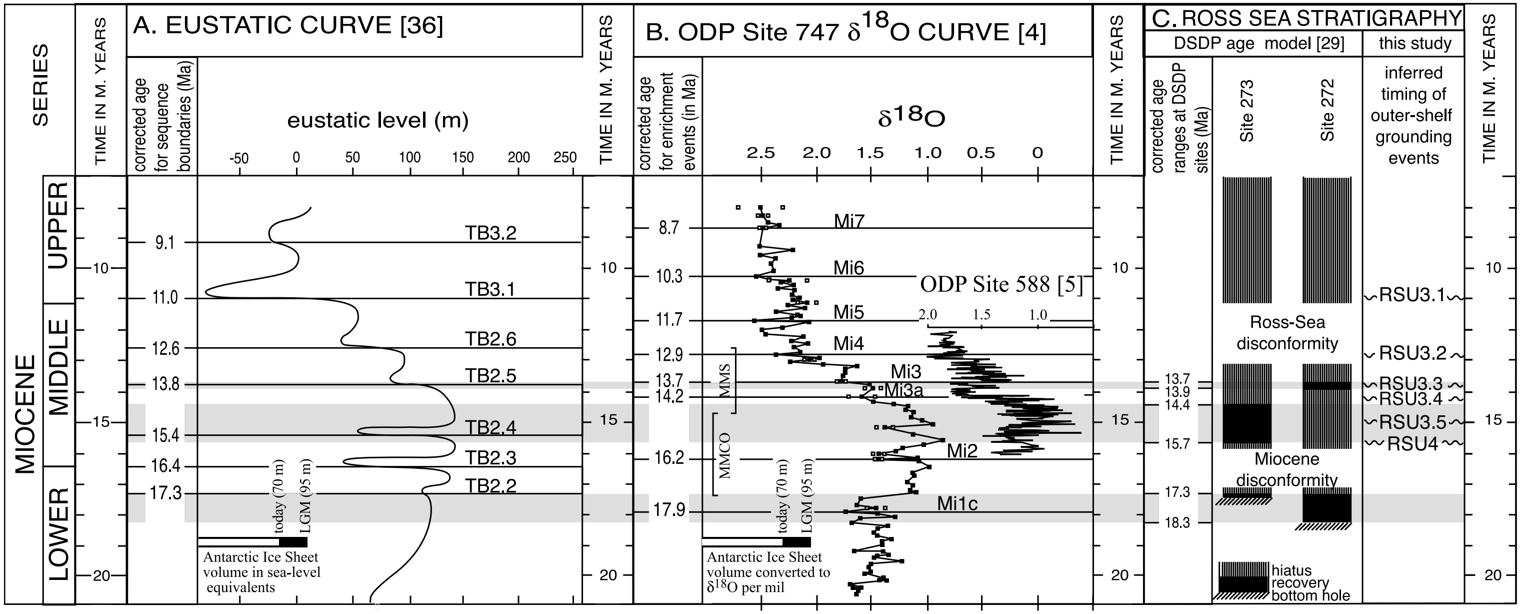

Fig. 4. Chronostratigraphic chart. (A) Eustatic record [36]. (B) Sites 747 [4] and 588 [5] $\delta^{18}O$ records with ages corrected to Berggren et al. [35] by Miller et al. [37]. (C) Ross Sea grounding events ([26], this study). On the Site 747 $\delta^{18}O$ record, open boxes represent stratigraphic levels where multiple samples where obtained. At those levels, the black represents the average of the multiple values. The scale on the lower left of the eustatic and $\delta^{18}O$ records (A and B, respectively) shows the volumes of the Antarctic ice sheet for the modern and for the maximum configuration at the last glacial maximum [50] converted to sea-level equivalents.

continuous low-angle prograding foresets, i.e. till deltas [45]. As the glacial period proceeds, the grounding line and the coeval grounding-zone till deltas may continue to advance basinward. Thus, till deltas deposited early during the ice-sheet advance are over run and are at least partly eroded by grounded ice [46]. Consequently, subglacially-eroded unconformities may deeply erode into older strata. In this way, eroded detritus is continually recycled and redeposited forward to the new grounding zone (Fig. 3B). Ice-sheet retreat from the marine realm is relatively rapid and thus subglacially eroded unconformities are draped by open-marine sediments (Fig. 3C). The grounding event (an advance and retreat of grounded ice into the marine realm) is seismically manifest as a regional unconformity that truncates the underlying strata (Fig. 2A,B).

3.2. Middle Miocene sequence boundaries

The Haq et al. [36] eustatic curve was derived from sequence-stratigraphic principles and represents a composite of stratal relationships from many tectonically passive low-latitude continental margins [47]. The sequence boundary, a major erosion surface on the continental shelf and upper slope, is an easily recognizable stratal discontinuity on seismic and/or lithologic data believed to be formed during the time of most rapid eustatic fall. Of mechanisms known to change sea-level elevation, only expansion of global ice volume is sufficiently rapid and of sufficient magnitude to cause subaerial exposure of the outer continental shelf and thus produce sequence boundaries [48].

The high eustatic levels that characterized the end of the early Miocene and the start of the middle Miocene were temporarily interrupted by two brief lowstands beginning at the 16.4-Ma and 15.4-Ma sequence boundaries (Fig. 4A; Table 2A). The permanent shift towards lower eustatic levels began after the sequence TB2.4 highstand at 14.5 Ma. Subsequently, rapid eustatic falls (i.e. sequence boundaries) occurred at 13.8 Ma, 12.6 Ma and 11.0 Ma. Sequence boundaries also occurred just prior to and immediately after the middle Miocene (e.g. 17.3 Ma and 9.1 Ma). The eustatic lowstands were brief (i.e. <0.5 Ma) and although only about 10% of the middle Miocene is defined as 3rd order eustatic-lowstand systems tracts, there was progressive net fall. The estimated magnitudes of middle Miocene eustatic falls are extremely large (60, 60, 60, and 140 m, respectively) and an unusually high net fall of 220 m is indicated (Fig. 4A). This large magnitude of net eustatic fall is unrealistic with respect to a glacioeustatic cause [49] because it far exceeds that which could be attributed to the maximum possible configuration of ice volume on Antarctica (e.g. the Antarctic Ice Sheet configuration at the peak of the last glacial maximum contained a volume of ice equivalent to $\sim$95 m of sea-level change [50]). Because the sequence-stratigraphic technique may not accurately estimate the magnitudes of eustatic change [36–38], the Haq et al. [36] eustatic record cannot be objectively used to define the onset and termination of the middle Miocene Climatic Optimum (MMCO) and the subsequent MMS.

3.3. Middle Miocene oxygen-isotope enrichments

The primary factors affecting $\delta^{18}O$ of diagenetically-unaltered benthic foram shells are $\delta^{18}O$ of sea water and water-mass temperature which is then inferred to reflect ice volume assuming that regional water-mass salinity does not change. Composite and individual ODP/DSDP $\delta^{18}O$ records show that the end of the early Miocene and start of the middle Miocene (i.e. the MMCO) were characterized by low values followed by abrupt shifts to high values [3–5,51]. According to the ODP Site 747 $\delta^{18}O$ record [4], the MMCO ranged from 17.5 to 14.5 Ma. The subsequent MMS began at 14.5 Ma and was essentially completed by 12.5 Ma (Fig. 4B).

The middle Miocene $\delta^{18}O$ zones observed at ODP Site 747 were originally defined from various DSDP sites by Miller et al. [39] on the basis of maximum observed enrichments exhibiting shifts of >0.5‰. At ODP Site 747, the low $\delta^{18}O$ values that characterized the later half of the MMCO were temporarily interrupted by ^{18}O enrichments at 16.2 Ma (Mi2) and 15.1 Ma (probably Mi2a as described in Miller et al. [37]). In addition to Mi2 and Mi2a, four major ^{18}O enrichment events (Mi3a, Mi3, Mi4, and Mi5) were defined [39] for the middle Miocene (at 14.2, 13.7, 12.9, and 11.7 Ma, respectively [37]). At ODP Site 747, the absolute magnitudes of ^{18}O enrichment were 0.5‰, 0.6‰, 0.4‰, and 0.5‰ and there was a net ^{18}O enrichment of ~1.7‰. If the late Pleistocene calibration scheme (0.11‰ ~10 m sea-level equivalent [52]) is valid for the middle Miocene, the large magnitude of ^{18}O enrichment suggests an unrealistic ice-volume increase of ~170 m relative sea-level equivalent. This indicates that substantial deepwater cooling probably accompanied the ice-volume expansion [5,6,39]. Indeed, in a paired study of Mg/Ca and $^{18}O/^{16}O$ measurements on benthic foraminifera from Southern Ocean ODP Site 747, Billups and Schrag [53] demonstrate that Southern Ocean water temperatures cooled by ~3°C during the MMS.

4. Results

4.1. Age constraints on WAIS grounding events on the Ross Sea outer continental shelf

The stratigraphic positions of the major glacial unconformities on the Ross Sea shelf (RSU4, RSU3.5, RSU3.4, RSU3.3, RSU3.2 and RSU3.1) with respect to the corrected ages from DSDP sites 273 and 272 (Table 1) are shown on two line drawings constructed from regional seismic profiles [26] (Fig. 2A,B). The oldest middle Miocene section was sampled in the western Ross Sea (Northern Basin) and has an estimated age range from 15.7 to 14.4 Ma (Table 1A). A younger middle Miocene section was sampled in the eastern Ross Sea (Eastern Basin) and has an estimated-age range from 13.9 to 13.7 Ma (Table 1B). Regional seismic correlation shows the existence of a stratigraphic section younger than the middle Miocene strata sampled at DSDP Site 273 and older than the middle Miocene strata sampled at DSDP Site 272 [26]. On the basis of its stratigraphic position, this section has a maximum estimated age range from 14.4 to 13.9 Ma. The seismically defined top of the middle Miocene section [20,24] corresponds to a major glacial unconformity that occurs ~200 m stratigraphically below the oldest lower Pliocene section sampled at DSDP Site 271 in the Eastern Basin and ~200 m stratigraphically above the youngest middle Miocene sampled at DSDP Site 272 (Fig. 2B).

The age of RSU4, the oldest glacial unconformity, is defined by seismic correlation of this surface to DSDP Site 273 (Fig. 2A). At Site 273, RSU4 is coincident with the Miocene Disconformity [29], a 2-Ma hiatus that separates the lower and middle Miocene sections. Below RSU4, the youngest lower Miocene strata have an age of 17.3 Ma [29]. Above RSU4, the oldest middle Miocene strata have an age of 15.7 Ma [29] (Fig. 2A). Therefore, the glacial advance that produced unconformity RSU4 at Site 273 could have formed anytime between 17.3 and 15.7 Ma (Table 2C). RSU3.5 can also be seismically correlated to DSDP Site 273 where it is located within the middle Miocene section interpreted to have an estimated age range between 15.7 to 14.4 Ma [29] (Fig. 4A). On this basis, the ice sheet that eroded grounding event RSU3.5 advanced and retreated sometime after 15.7 Ma and before 14.4 Ma (Table 2C).

RSU3.4 defines the base of the middle Miocene strata at DSDP Site 272 (Fig. 2B) where it corresponds to the Miocene Disconformity [29], a 3.4-Ma hiatus separating the lower and middle Miocene sections. At Site 272, the youngest lower Miocene section below RSU3.4 has an estimated age of 17.3 Ma, whereas above RSU3.4 the oldest middle Miocene section has an estimated age of 13.9 Ma (Figs. 2B and 4C). On the basis of the regional seismic–stratigraphic analysis [26], RSU3.4 is stratigraphically higher than the youngest middle Miocene strata sampled at DSDP Site 273 (i.e. <15.7 Ma). Therefore, the glacial advance that eroded RSU3.4 occurred after 14.4 Ma and before 13.9 Ma (Table 2C).

RSU3.3 is located within the middle Miocene section sampled at DSDP Site 272 (Figs. 2B and 4C). Because the section has an estimated age range from 13.9 to 13.7 Ma [29] (Table 1B), the glacial advance that eroded RSU3.3 and the subsequent retreat must have been relatively brief (Table 2C). The overlying unconformities, RSU3.2 and RSU3.1, are stratigraphically above the youngest middle Miocene section sampled at Site 272 and below the oldest lower Pliocene section sampled at DSDP Site 271 (Fig. 2B). Therefore, RSU3.2 and RSU3.1 are younger than 13.7 Ma (Table 2C) but could also be much younger (i.e. late Miocene or early Pliocene).

Thus, if the age model is accepted at face value, of the six grounding events [26], only three (RSU3.5, RSU3.4 and RSU3.3) are required to be of middle Miocene age (Table 2C). Moreover, these three grounding events were within the earliest part of the middle Miocene (between 15.7 and 13.7 Ma). RSU4 could be latest early Miocene and/or earliest middle Miocene in age (Fig. 4A) and within the confines of the existing age model, RSU3.2 and RSU3.1 could be during the latest part of the middle Miocene or considerably younger than middle Miocene (Table 2C).

4.2. *Correlation of grounding events to eustatic curve*

The chronostratigraphic position of the middle Miocene strata sampled at the DSDP sites 272 and 273 is shown shaded in gray to highlight the correlation with the eustatic and $\delta^{18}O$ records (Fig. 4). The correlation of the Ross Sea stratigraphy to the eustatic curve illustrates that Ross Sea grounding events are not well constrained with respect to 3rd order eustatic cycles (Fig. 4A,C). Grounding event RSU4 could have been eroded anytime within sequence TB2.2, or the lowstand, transgression or early highstand of sequence TB2.3. Erosion of grounding event RSU3.5 could have formed within the highstand of sequence TB2.3 or the lowstand, transgression or early highstand of the following sequence, TB2.4.

In contrast to the poor constraints on grounding events RSU4 and RSU3.5, the DSDP age model suggests that grounding event RSU3.4 occurred during the middle highstand of sequence TB2.4, and that grounding event RSU3.3 occurred sometime between the latest highstand of sequence TB2.4 or the earliest lowstand of sequence TB2.5 (Fig. 4A,C). The poor age constraint on RSU3.2 and RSU3.1 preclude meaningful correlation of these grounding events to eustatic events. For example, even if the glacial advances that eroded RSU3.2 and RSU3.1 definitely were middle Miocene events, the correlation to the eustatic curve illustrates that these two Ross Sea unconformities could have formed any time in sequence TB2.5 or sequence TB2.6 (Fig. 4A,C).

4.3. *Correlation of grounding events to ODP Site 747 $\delta^{18}O$ curve*

The correlation of Ross Sea stratigraphy to the ODP Site 747 $\delta^{18}O$ record shows that the erosion of grounding events is not well constrained with respect to discrete ^{18}O fluctuations. Grounding event RSU4 occurred within the upper two-thirds of oxygen-isotope zone Mi1c and the lower-third of oxygen-isotope zone Mi2[4]. Although the $\delta^{18}O$ values are low through most of this stratigraphic interval, the section also contains significant ^{18}O enrichments which are observed near the base of oxygen-isotope zone Mi2 (Fig. 4B,C). The next grounding event, RSU3.5, occurred sometime within the middle two-thirds of zone Mi2 whereas RSU3.4 occurred during the uppermost part of zone Mi2 or the lowermost part of zone Mi3a. The $\delta^{18}O$ values within this stratigraphic interval are higher than the low values that characterize most of zone Mi2. Grounding event RSU3.3 occurred during the upper part of zone Mi3a within which there are only a few $\delta^{18}O$ values at ODP Site 747. The ODP Site 588 $\delta^{18}O$ record [5] shows high-frequency fluctuations in this interval, but the $\delta^{18}O$ values are higher than the low $\delta^{18}O$ values within the underlying zone, Mi2. Assuming that RSU3.2 and RSU3.1 were eroded during the middle Miocene, the grounding events occurred sometime during zones Mi3, Mi4, or during the lower part of zone Mi5. Although the age constraints on the Ross Sea grounding events are too coarse to make specific correlations to discrete events, the correlations do suggest that RSU4 occurred during the MMCO

[4] The Mi events define the base of the zone – the top of the zone is defined by the next Mi event upsection.

whereas grounding event RSU3.5 occurred during the later part of the MMCO or earliest part of the MMS. RSU3.4 and RSU3.3 ice advances were during the early part of the MMS, i.e. before 13.7 Ma.

5. Discussion

5.1. *WAIS expansions during the MMCO and early part of the MMS (i.e. between 17.5 and 13.7 Ma)*

The low resolution of chronostratigraphic control of the Ross Sea grounding events provided by the DSDP age model [29] highlights the critical need for additional age control on the Antarctic outer continental shelves before fundamental linkages between ice-sheet fluctuations and events on the proxy records can be comprehensively evaluated. For example, although the WAIS fluctuations associated with RSU3.2 and RSU3.1 post-date 13.7 Ma, additional chronostratigraphic data are needed to confirm whether these two glacial unconformities are indeed middle Miocene in age (as opposed to late Miocene or early Pliocene). As RSU3.2 and RSU3.1 occurred within or after the later part of the MMS, it is possible that these groundings were associated with EAIS overgrowth onto West Antarctica. However, due to the chronostratigraphic uncertainties associated with these two grounding events, the following discussion focuses on the older grounding events (i.e. RSU4 through RSU3.3) constrained to be middle Miocene age.

Generally speaking, neither the timing nor duration of the middle Miocene Ross Sea grounding events is precisely constrained by the age model. For example, correlation of RSU4 to DSDP Site 273 indicates either that the WAIS may have advanced at 17.3 Ma and remained grounded on the outer shelf, thus precluding sedimentation until ice-sheet retreat at 15.7 Ma, or that the continental shelf may have experienced open-marine sedimentation until ice-sheet advance at 15.7 Ma deeply excavated the underlying strata. Two lines of reasoning suggest that the later scenario (ice-sheet advance and retreat at 15.7 Ma) is most likely. Firstly, at Site 273, the distal glacial-marine character of lower Miocene sediments directly below RSU4 [17] suggests that these strata were not deposited in genetic association with the subglacial erosion of RSU4. Therefore, the 17.3-Ma age of the strata underlying RSU4 at DSDP Site 273 cannot explicitly indicate the timing of ice-sheet advance on the continental shelf during the RSU4 grounding event but reflects, at least to some degree, post-17.3-Ma excavation of the underlying strata. Proglacial deposits genetically associated with erosion of RSU4 presumably are located further basinward, i.e. at the paleo-shelf edge (Fig. 2A). Secondly, the inferred age of the youngest sediments above RSU4 provides an approximate time for the resumption of open-marine sedimentation that could occur only after ice-sheet retreat at the end of the RSU4 grounding event. Following these lines of reasoning suggests that RSU4 probably was eroded in the later part of this 2-Ma hiatus (i.e. closer to 15.7 Ma than to 17.3 Ma). However, given that the relatively small WAIS may or may not have expanded/contracted in phase with expansions of the larger EAIS, there is no a priori reason to correlate the Ross Sea grounding events to the 'nearest' sequence boundary or Mi event. Despite this limitation, the data suggest that grounding event RSU4 occurred during the early part of the MMCO whereas RSU3.5 was during the later part of the MMCO or the earliest part of the MMS. Grounding events RSU3.4 and RSU3.3 post-date the MMCO but occur relatively early during the MMS.

Ice volumes on East Antarctica probably experienced significant fluctuations and net positive mass balance throughout the entire middle Miocene [21], but five lines of reasoning suggest that the EAIS was not large enough to overtop the Transantarctic Mountains even during the peak glaciations of the MMCO and earliest part of the MMS (i.e. before 14.4 Ma). Firstly, the lithology of ice-rafted pebbles found at DSDP Site 273 (the older part of the middle Miocene – estimated age range of 15.7 to 14.4 Ma) suggest that these clasts probably were derived from the West Antarctic interior basins [17] as opposed to a Transantarctic–Mountains source eroded by an overriding EAIS. Secondly, progradation directions of grounding-zone till deltas on the Ross Sea outer continental shelf primarily are basinward directed, i.e. towards the north [26] rather than towards the east as would be expected had an inflated EAIS advanced from the west over the Transantarctic Mountains at Northern Victoria Land[5]. Thirdly, ice-volume fluctuations within this timeframe included that volume attributable to WAIS advance and retreat into Ross Sea [26]. Fourthly, positive shifts from extreme depletions to enriched ^{18}O values (e.g. at 15.6 Ma) may include pronounced temperature effects associated with Southern Ocean cooling as the upwelling of Warm Saline Deep Water diminished [5]. If parts of the shifts to higher $\delta^{18}O$ values were associated with deepwater cooling, then the amount that could be attributed to ice volume added to East Antarctica would have to be less. (Schnitker [14] and Billups et al. [54] provide two alternate views on Southern Ocean deepwater temperate history.) Fifthly, at ODP Site 747, the highest $\delta^{18}O$ values during this timeframe (i.e. between 17.3 and 14.4 Ma) were $\sim$1.4‰ which is $\sim$40% of the maximum $\delta^{18}O$ values reached by the end of the middle Miocene (see Fig. 4B). Together, this information suggests that an inflated EAIS or alpine glaciers of the Transantarctic Mountains did not provide substantial ice volume to West Antarctica [17] during the MMCO and earliest part of the MMS (between 17.3 and 15.7 Ma).

If the volume of the EAIS was relatively low during this timeframe [1,10], then grounding events RSU4 and RSU3.5 on the Ross Sea outer continental shelf were not directly due to EAIS overgrowth onto and retreat from West Antarctica. These two WAIS grounding events probably were a result of in-situ processes. In-situ development of the WAIS during the MMCO suggests that either West Antarctic land areas were significantly higher than today (i.e. subaerial) and/or if not, that air and water temperatures in the low-lying West Antarctic interior basins were sufficiently cold to permit existence of an extensive marine ice sheet.

The presence of ice-rafted diabase pebbles within the middle Miocene strata at DSDP Site 272 (from 34 to 52 m below the seafloor) suggests that the EAIS may have become sufficiently large and robust sometime between 13.9 and 13.7 Ma to overtop and/or breach the Transantarctic Mountains (the only known source of diabase). Conversely, the ice-rafted debris could have been derived from alpine glacial systems restricted to the Transantarctic Mountains. The ice-rafted mode of deposition [17] indicates that these pebbles probably were transported across the Ross Sea outer continental shelf at times when the WAIS retreated at least from the outer continental shelf. WAIS grounding events RSU3.4 and RSU3.3 may have been related to EAIS expansions but additional geologic data from East Antarctic margins are needed to determine to what degree if any that the EAIS over-rode the Transantarctic Mountains within the earliest part of the MMS (i.e. between 14.4 and 13.7 Ma).

6. Conclusions

Seismic correlation of glacial unconformities to age control at DSDP sites 272 and 273 suggests that at least two WAIS grounding events (RSU4 and RSU3.5) occurred in Ross Sea during the early part of the middle Miocene and thus predate the major expansions of the EAIS. If indeed the EAIS had not yet expanded to continental scale, the evolution of the WAIS probably was not a consequence of EAIS expansion and advance over the Transantarctic Mountains onto West Antarctica. In-situ expansions of the WAIS during the early part of the middle Miocene suggest that either West Antarctic land areas were higher than today (i.e. above sea-level) and/or that air and water temperatures in West Antarctic interior basins were sufficiently cold to permit the existence of a marine-based ice sheet. Additional data are needed from the Antarctic margins to test these hypotheses.

[5] Seismic and lithologic data from the Ross Sea outer continental shelf cannot be directly used to evaluate the ice-flow directions over the West Antarctic interior basins. Therefore, it is possible that the EAIS over-topped the Transantarctic Mountains south of the Ross Sea outer continental shelf before advancing northward towards the Ross Sea shelf edge.

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