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Seismic data from the Northern basin, Ross Sea, record extreme expansions of the East Antarctic Ice Sheet during the late Neogene

P.J. Bart[a,*], J.B. Anderson[b], F. Trincardi[c], S.S. Shipp[b]

[a]*Department of Geology and Geophysics, Louisiana State University,Baton Rouge, LA 70803 USA*
[b]*Department of Geology and Geophysics, Rice University, Houston, TX, 77251 USA*
[c]*Istituto per la Geologia Marina, Via Zamboni 65, Bologna 40127 Italy*

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Abstract

Approximately 3700 km of intermediate-resolution single-channel seismic data from the Northern basin were analyzed to investigate the late Neogene history of East Antarctic Ice Sheet (EAIS) grounding events on the shelf, and to evaluate how glacial unconformities on the shelf are manifested on the upper slope. The Northern basin was chosen as the site of this study because ice-sheet reconstructions show that the basin received sediment by ice emanating from East Antarctica. In addition, seismic correlations to DSDP Site 273 suggest that a relatively thick late Neogene section exists on the basin's outer shelf and upper slope.

On the Northern basin shelf, glacial unconformities exhibiting broad, low-angle relief, topset truncation, and cross-cutting relationships reveal a dynamic history of expansions and contractions during which the EAIS was larger than present on at least eight occasions during the late Neogene. On the upper slope, the correlative conformities of the glacial unconformities are indistinct reflections within thick trough-mouth fan (TMF) depocenters at the mouths of Drygalsky and Joides basins. The glacial unconformities and correlative conformities define TMF sequences, and each TMF sequence contains several topset-truncated prograding-slope reflectors. We infer that the correlative conformities on the continental slope correspond to the interface between prograding glaciogenic deposits (glacial maximum) and diatomaceous glacial-marine sediments (glacial minimum). The seismic–stratigraphic analysis and regional mapping indicate that the upper slope does not contain a more complete late Neogene section than that which exists on the shelf. We infer that diatomaceous glacial-marine sediments on the slope may be relatively undisturbed, and hence may provide a means of dating the TMF sequences. It is hoped that these results will stimulate efforts to core the late Neogene section in the Northern basin TMFs to investigate how these EAIS expansions and contractions relate to other records of late Neogene climate and eustasy.

Keywords: Antarctica; Ross Sea; Ice sheet; Glaciation

1. Introduction

The EAIS is the largest land-based ice sheet on Earth, and fluctuations in its volume and extent have undoubtedly had a profound influence on climate and eustasy during the late Neogene. Yet, because of the general paucity and patchy distribution of the late Neogene sediments on Antarctica (e.g. Webb et al., 1984; Marchant et al., 1993), much of what is known about the past behavior of the EAIS is inferred from the deep-sea proxy records from the Southern Ocean and beyond (e.g. Kennett and Hodell, 1993). Consequently,

* Corresponding author. Tel.: + 1-225-338-3109; fax: + 1-225-338-3109.

E-mail address: pbart@unix1.sncc.1su.edu (P.J. Bart).

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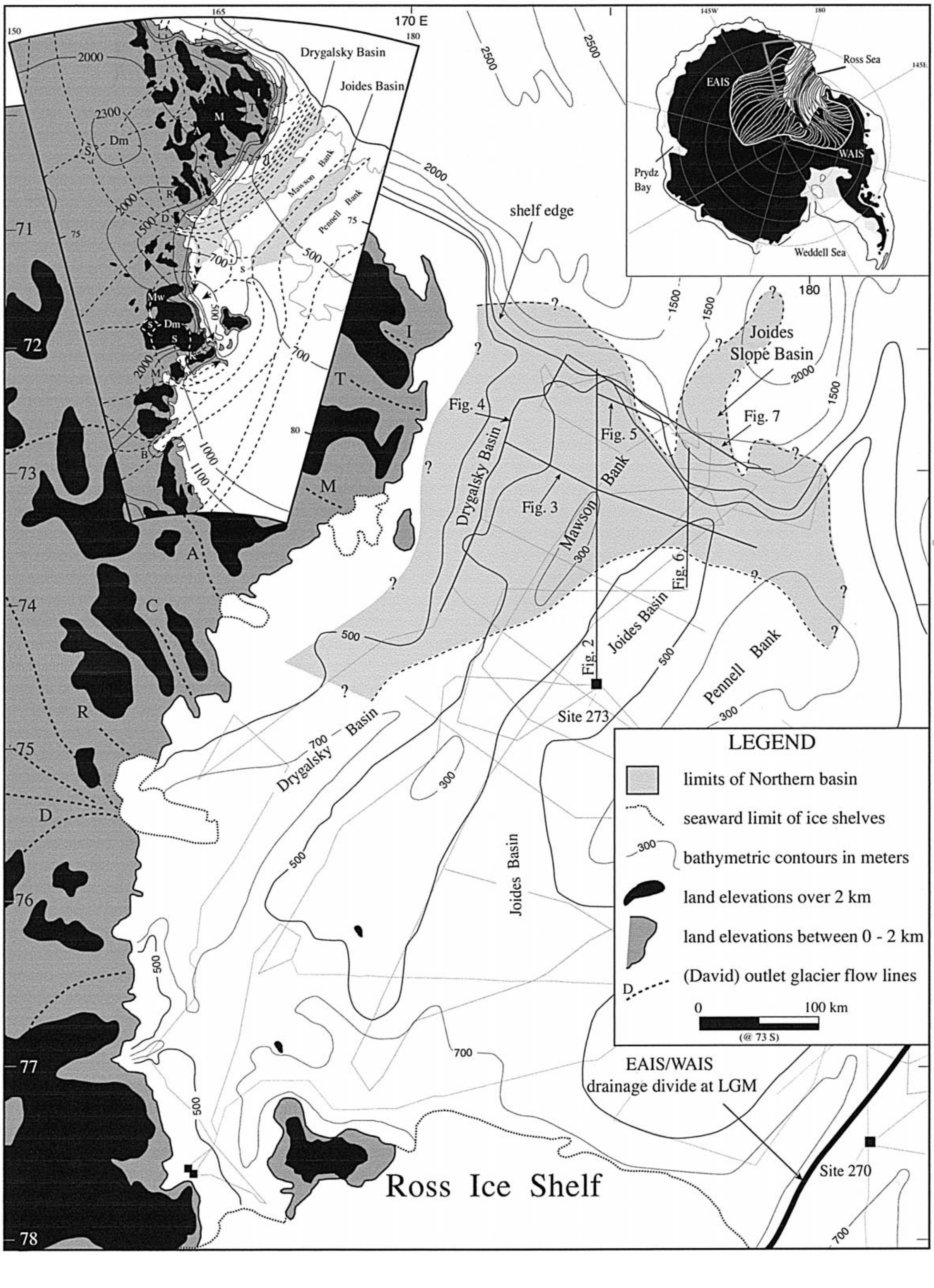
170 E
Drygalsky Basin
Joides Basin
Mawson Bank
Pennell Bank
Ross Sea
EAIS
WAIS
Prydz Bay
Weddell Sea
shelf edge
Joides Slope Basin
Fig. 2
Fig. 3
Fig. 4
Fig. 5
Fig. 6
Fig. 7
Site 273
Site 270
EAIS/WAIS drainage divide at LGM
Ross Ice Shelf
LEGEND
limits of Northern basin
seaward limit of ice shelves
bathymetric contours in meters
land elevations over 2 km
land elevations between 0 - 2 km
(David) outlet glacier flow lines
0
100 km
(@ 73 S)

many fundamental details of how EAIS fluctuations relate to late Neogene climate and eustasy remain speculative.

To date, seismic–stratigraphic investigations have demonstrated that a significant portion of material eroded from the continent and continental shelf were deposited in outer-shelf/upper-slope depocenters (e.g. Hinz and Block, 1984; Cooper et al., 1987, 1991a,b; Larter and Barker, 1989; Anderson et al., 1991; Kuvaas and Kristoffersen, 1991; Alonso et al., 1992; Anderson and Bartek, 1992; Kuvaas and Leitchenkov, 1992; Moons et al., 1992; ANTOSTRAT, 1995; Bart and Anderson, 1995, 1996; Brancolini et al., 1995; De Santis et al., 1995; Sloan et al., 1995; Bart et al., 1999). Depocenters of this type have been referred to as trough-mouth fans (TMFs) because they occur at the mouths of glacial troughs (Vorren et al., 1988). Generally speaking, the Antarctic margins are capable of maintaining steep slopes due to the poorly sorted nature of the glaciogenic sediments (Larter and Barker, 1989). Thus, because TMF strata extend onto the slope, below the limits of ice-sheet erosion and iceberg turbation, they may contain a more complete and dateable record of the late Neogene ice-sheet fluctuations. To date, Antarctic TMFs have only been drilled at Prydz Bay (Barron et al., 1991), hence their sedimentology and stratigraphy are poorly understood. For example, thick packages of topset-truncated prograding-slope foresets, typical of TMF successions, may represent the result of one ice-sheet expansion or the amalgamation of several cycles of ice-sheet expansion and contraction from the shelf.

The focus of this study was to: (i) investigate the late Neogene glacial history of the EAIS recorded on the Northern basin continental shelf, and (ii) evaluate how glacial unconformities, which record ice-sheet grounding events on the shelf, are manifested on the upper slope, where a potentially more complete and dateable section may exist. The Northern basin was chosen as the site of this study because ice-sheet reconstructions (e.g. Kellogg et al., 1996; Shipp et al., 1999) show that the basin received sediment by ice emanating from East Antarctica (Fig. 1). In addition, seismic correlation of the youngest middle Miocene unit sampled at DSDP Site 273 suggests that a relatively thick late Neogene section exists on the Northern basin outer shelf and upper slope (Hinz and Block, 1984; Cooper et al., 1987, 1991a; Anderson and Bartek, 1992; ANTOSTRAT, 1995; Brancolini et al., 1995).

2. Methods

Correlating glacial unconformities from the shelf to the slope requires: (i) seismic data with sufficient stratigraphic resolution to image unconformities and relatively thin units; (ii) data grids dense enough to enable mapping of individual units; and (iii) data grids with regional extent to allow correlation from the shelf to the slope. A grid of intermediate-resolution single-channel seismic data was collected during 1990, 1994 and 1995 (Fig. 1). The seismic sources used in these studies were either a 100 or 200 cu in Generator-Injector air gun. The filter cut-offs were 30 and 800 Hz. The dominant frequency of the seismic data was between 130 and 200 Hz, providing a theoretical stratigraphic resolution of 2.5–4 m, based on the Rayleigh resolution limit criteria and an average sediment velocity equal to 2 km/s. Occasionally, severe sea ice cover limited the quality of the data, but the data quality generally is good.

In this study, approximately 3700 km of seismic data from the Northern basin outer shelf and upper slope were analyzed. The seismic data set includes several dip- and strike-oriented profiles that extend from the outer shelf to the upper slope. Indirect chronological control for the Northern basin stratigraphy was provided by seismic correlation to DSDP Site 273 (Figs. 1 and 2). A velocity of approximately 2 km/s was used to convert seismic travel time to depth because it gave the most reasonable correlation

Fig. 1. Northwestern Ross Sea location map and two inset maps. The rectilinear grid represents the seismic track lines. Seismic profiles shown in the text (Figs. 2–7) are indicated with bold lines. The gray-shaded area outlined by a dashed line indicates the general limits of the late Neogene strata in Northern basin. The inset map in the upper right hand corner shows the generalized ice-flow lines of the EAIS and WAIS drainage basins at the culmination of the last ice-sheet expansion to the shelf edge. The inset in the upper left hand corner shows the EAIS ice-flow (dashed lines) through outlet glaciers of the TAM for the maximum ice-sheet extent (from Kellogg et al., 1996). The letters along the TAM are defined as follows:; I = Ironside; T = Tucker; M = Mariner; A = Aviator; C = Campbell; D = David; R = Reeves; B = Byrd; Dm = ice-surface dome, and s = ice-surface saddle. See Legend for further explanations.

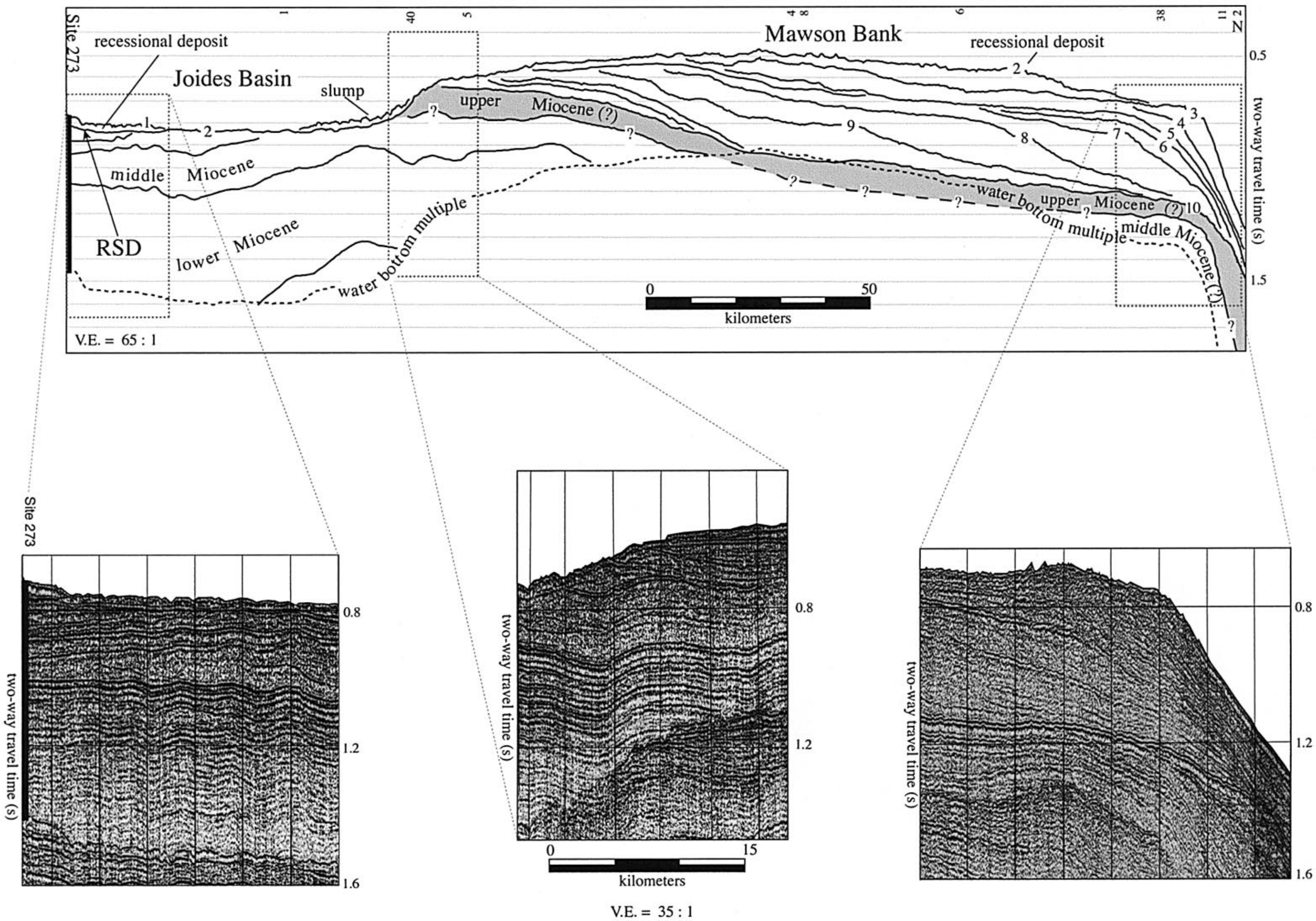

Fig. 2. Regional line drawing and uninterpreted seismic segments of dip-oriented Profile 37. At Site 273, the strata above the Ross Sea Disconformity (RSD) are Pliocene–Pleistocene in age and correspond to Unit 1. See Fig. 1 for location.

of the thin Pliocene–Pleistocene unit described by Hayes and Frakes (1975) to a seismically defined surface unit (see Plate 4 of ANTOSTRAT, 1995).

Our seismic–stratigraphic analysis used the approach described by Alonso et al. (1992), Anderson and Bartek (1992) and Bart and Anderson (1996). On the basis of the criteria outlined in these articles, reflectors exhibiting regional extent (several tens of kilometers) and cross-cutting relationships between underlying and overlying units are interpreted as glacial unconformities. Individual glacial unconformities and the units they separate on the shelf were correlated to the upper slope utilizing the seismic grid. Units and their upper-bounding unconformities are numbered from the top down. For example, the youngest unit is Unit 1, and its upper surface, Unconformity 1, corresponds to the sea-floor reflector on the outer shelf.

The seismic grid was used to construct time-structure and isopach maps, as well as to analyze seismic facies. Structure maps for each horizon were constructed using two-way travel time in milliseconds (ms) below sea level. Isopach maps of individual units were constructed using two-way travel time to trace possible changes in the location of the TMF depocenters with time.

3. Ross Sea regional setting

Extensional tectonics produced the major topographic elements of Antarctica, which includes the attenuated and rifted continental crust of West Antarctica and its elevated rift shoulder, the Transantarctic Mountains (TAM) (Cooper et al., 1991a; Lawver et al., 1992). The West Antarctic Rift includes the Weddell and Ross seas. The Northern basin is located in the northwestern corner of the Ross Sea (Fig. 1).

The TAM separate the land based EAIS and the marine based West Antarctic Ice Sheet (WAIS). These two ice sheets cover nearly all of the continent except the highest peaks of the TAM and other mountain ranges (Drewry, 1983a). Because of the locations of ice domes on the continent, and the low elevation of the West Antarctic Rift, a large percentage of ice draining from both the EAIS and WAIS converges towards the Weddell and Ross seas (Drewry, 1983a). Regions of convergent ice flow produce discrete zones of fast flowing ice streams (Hughes, 1977; Drewry et al., 1982; Drewry, 1983b). Streaming ice flows at rates of hundreds to thousands of meters per year (Lindstron and Tyler, 1984).

At the culmination of the last ice-sheet expansion, the drainage divide between the EAIS and WAIS on the Ross Sea continental shelf was located at approximately 170°E (e.g. Kellogg et al., 1996; Shipp et al., 1999) (Fig. 1). According to these reconstructions, the Northern basin was overridden by EAIS ice streams emanating mostly from outlet glaciers in the TAM (Hughes, 1975; Denton et al., 1989; Anderson et al., 1992; Kellogg et al., 1996; Shipp et al., 1999). The WAIS and its ice streams expanded and covered the central and eastern Ross Sea continental shelf. The ice-sheet drainage systems appear to have maintained this approximate pattern since at least the middle Miocene, based on seismic stratigraphic studies (Anderson and Bartek, 1992; Alonso et al., 1992; De Santis et al., 1995) and petrographic analyses of glacial and glacial-marine deposits in DSDP drill sites (Barrett, 1975; Balshaw, 1982). These interpretations support suggestions that there was no major late Cenozoic tectonic activity of the TAM (e.g. Fitzgerald and Stump, 1997) that would have significantly altered the pattern of ice-sheet drainage to the Ross Sea continental shelf.

As a consequence of glacial erosion and loading, the Antarctic shelf is overdeepened and foredeepened (ten Brink et al., 1995). On the continental shelf, large ice streams are the primary agents of erosion and deposition. The most striking physiographic features on the shelf are Drygalsky and Joides basins, and Mawson and Pennell banks, which border the basins (Fig. 1). The width and depth of the basins greatly exceed dimensions of fluvial valleys, and the basins exhibit the typical u-shaped profile of glacial troughs (Anderson, 1999). These basins reflect repeated episodes of ice-stream erosion that have preferentially cut deep into the thick sedimentary strata that fill the West Antarctic Rift (Cooper et al., 1991b; Anderson and Bartek, 1992). Materials excavated from the inner-shelf basins presumably were deposited on the outer shelf and upper slope. However, the mouths of Drygalsky and Joides basins are not associated with major convex-seaward deflections of the bathymetric contours. Instead, the trend of the shelf edge is straight to slightly concave seaward

Table 1
Seismic sequences in the Northern Basin Ross Sea and correlation with previous studies

DSDP Site 273 Savage and Cielsielski, 1983	this study	ANTOSTRAT, 1995; Brancolini et al., 1995			Anderson & Bartek, 1992		Cooper et al., 1987	Hinz and Block, 1984
		Units in Northern basin	Bounding unconformities	age assigned	Units in Northern basin	revised age assignment		
Unit 1	Unit 1 Unit 2	RSS-8	sea floor - RSU1	Pleistocene - late Pliocene	Units 1 - 8[a] (undiffer-entiated)	Pliocene - Pleistocene	V1	Seafloor - U1
Ross Sea Discon-formity	Units 3 - 9	RSS-7	RSU1 - RSU2	early- late Pliocene			V1	U1 - U2
	Unit 10 – ? – ? –	RSS-6	RSU2 - RSU3	early Pliocene - late Miocene	Unit 9 (top[a])	early Pliocene - late Miocene (?)	V1	U2 - U3
	middle Miocene	RSS-5	RSU3 - RSU4	middle Miocene	Unit 9 (base)	middle Miocene	V1	U3 -U4
Unit 2	early Miocene	RSS-4	RSU4 - RSU4a	early Miocene	Unit 10	early Miocene	V2	U4 - U4A

[a]Unit 8 and the top of the Unit 9 were not sampled at any of the DSDP Leg 28 drill sites

(Fig. 1). The upper slope generally has a smooth, seaward gradient of 1–3°.

4. The Northern basin late Neogene chronostratigraphic framework

DSDP Site 273 is located in Joides Basin (Fig. 1), and was drilled to a depth of 346.5 m below sea level (Hayes and Frakes, 1975). Sediment recovery was poor (i.e. 25%), but two units were identified: (i) a Pliocene–Pleistocene unit (0–41 m below the sea floor), and (ii) a middle to early Miocene unit (41–356 m below the sea floor). These two units are separated by the Ross Sea Disconformity (RSD), which Savage and Ciesielski (1983) estimate spans a time interval of 14.7–4.0 Ma at Site 273.

Seismic profile 37 (Fig. 2) illustrates our interpretation of the stratigraphic relationships between Site 273, the RSD and the strata at Mawson Bank (see Fig. 1 for location). In our interpretation, the RSD is equivalent to our Unconformity 2, which forms the erosional scarp of Joides Basin and the top of Mawson Bank. The strata that are the object of this study lie above Unconformity 10, a strong regionally extensive seismic reflector that provides a good basal maker for the study of the seismic units and unconformities on the outer shelf and upper slope. Fig. 2 suggests to us that Unconformity 10 is truncated at the flank of Joides Basin where it lies approximately 100 ms (i.e. approximately 100 m) above the projected top of the youngest middle Miocene strata cut by the RSD at Site 273.

On the outer shelf, there are at least nine regionally prominent reflectors (Unconformities 1–9) above Unconformity 10 (Fig. 2). These unconformities bound units with an overall topset/foreset geometry (Fig. 2). The units generally exhibit a chaotic seismic facies and contain a few poorly defined discontinuous foreset reflections. At their seaward limit, these unconformities can be traced to correlative conformities where they, and the units they bound, terminate by downlap and depositional pinch out (Fig. 2). The seismic–stratigraphic correlations show that our Units 10–2

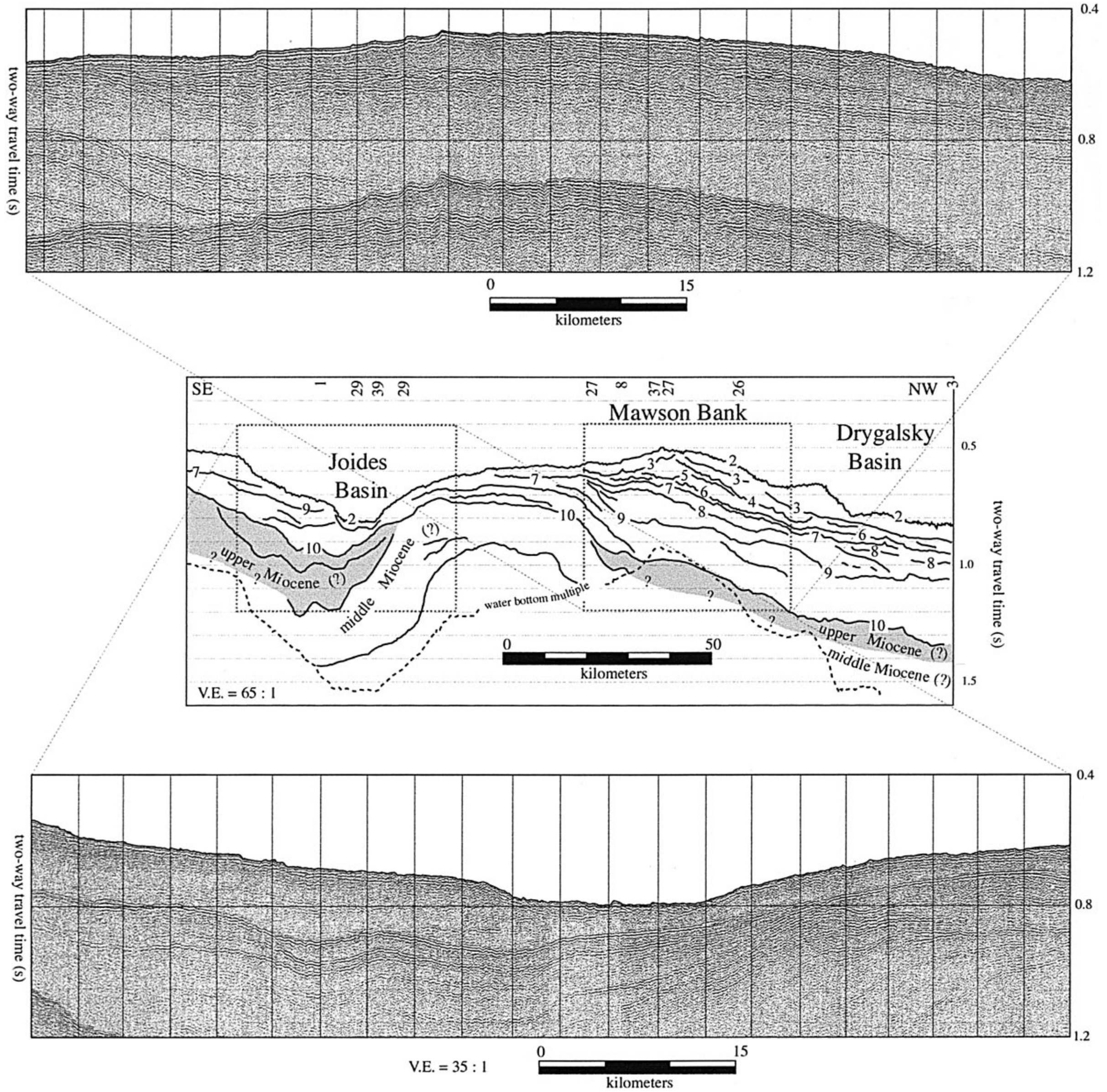

Fig. 3. Regional line-drawing and uninterpreted seismic segments of strike-oriented Profile 4 along the outer shelf extending from Joides Basin to Drygalsky Basin. A paleo-bank and two paleo-troughs at Unconformity 10 are roughly coincident with Mawson Bank, and Joides and Drygalsky basins. See Fig. 1 for location.

post-date the youngest middle Miocene strata sampled at Site 273, and that our Unit 1 is correlative to the thin Pliocene–Pleistocene unit (Hayes and Frakes, 1975) sampled at DSDP Site 273.

Table 1 shows our correlation of units identified in this study to DSDP Site 273 (Savage and Cielsielski, 1983) and to the seismic sequences described in previous studies (Hinz and Block, 1984; Cooper et al., 1987; Anderson and Bartek, 1992; ANTOSTRAT, 1995; Brancolini et al., 1995). Our regional correlation of the RSD in Northern basin is different from that presented in ANTOSTRAT (1995). In the

ANTOSTRAT (1995) interpretation, their RSU2 at Site 273 is equivalent to our Unconformity 2, but at Mawson Bank, RSU2 is equivalent to a strong seismic reflector, which is at the approximate stratigraphic level of our Unconformity 10. Because the RSD has eroded most of the late Neogene section at Site 273, our comparison to the units of ANTOSTRAT (1995) and Brancolini et al. (1995) was made on the basis of the seismic stratigraphy from the western part of the study area where the late Neogene section is expanded. We relied on the marked similarity of the seismic stratigraphy between Plate 6 of ANTOSTRAT (1995)and our Profile 3 (Fig. 4, to be presented later in this article). According to this comparison, our Unconformity 10 is equivalent to RSU2 (ANTOSTRAT, 1995). Our Unit 10 corresponds to at least the upper part of RSS-6, but the base of Unit 10 is not well defined in the seismic grid. Units 3–9 correspond to RSS-7, and Units 1 and 2 correspond to RSS-8. Anderson and Bartek (1992) focused on the seismic stratigraphy of the Eastern basin. In the Northern basin, they used Site 273 to demarcate lower and middle Miocene strata (i.e. their units 9–12); the overlying section was not differentiated and simply labeled as Pliocene–Pleistocene (see Figs. 2 and 5 in Anderson and Bartek, 1992). Unit 8 and top of unit 9 from Anderson and Bartek (1992) were not sampled at any of the DSDP Leg 28 drill sites. In Table 1, we subdivided the Anderson and Bartek (1992) Unit 9 into basal and upper components to reflect our view that the top of Unit 9 in Northern basin may represent the lower Pliocene/upper Miocene. We acknowledge that upper Miocene sections have only been sampled at the MSSTS-1 site in the southern Ross Sea (Barrett, 1986), and that their existence on the Northern basin outer continental shelf is inferred.

5. Unconformities on the Northern basin shelf and their correlative conformities on the slope

5.1. Interpreted seismic profiles

In this section, five seismic profiles are shown to illustrate (i) glacial unconformities and the units they bound, and (ii) the correlations of these glacial unconformities and units to the upper slope. Regional line drawings of the profiles are shown at a vertical exaggeration of 65:1 along with segments of the uninterpreted seismic data at a vertical exaggeration of 35:1. The position of the cross-lines are indicated at the top of the all line drawings. Our correlation of the middle Miocene and estimate of the stratigraphic position of the upper Miocene (Unit 10), as correlated from DSDP Site 273 (Fig. 2), is shown on all of the profiles. As noted above, upper Miocene strata have not been sampled in the Northern basin.

Profile 4 (Fig. 3) shows the correlation of units and cross-cutting relationships of amalgamated unconformities along the strike of the outer shelf from Drygalsky Basin to Joides Basin. Fig. 4 shows dip-oriented Profile 3 joined to a short segment of Profile 5 on the outer shelf, illustrating the southward extension of Units 1–10 onto the shelf at the axis of Drygalsky Basin. Profile 38 (Fig. 5), a short strike-oriented profile crossing the outermost shelf and upper slope at Mawson Bank, illustrates the abrupt lateral pinch-out of the glacial units on the outer shelf. Profile 39 (Fig. 6) is obliquely oriented at the mouth of Joides Basin and is shown to illustrate the complete erosion of Units 3–10 on the shelf and topset truncation of the prograding-slope clinoforms in this part of the study area. Finally, Profile 2 (Fig. 7) is a regional strike-oriented seismic profile showing the regional correlation of Units 10–3 on the upper slope from the mouth of Joides Basin to the mouth of Drygalsky Basin.

5.1.1. Regional strike-oriented correlations on the Northern basin outer shelf

On the outer shelf, Unconformity 10 can be correlated from Joides Basin to Drygalsky Basin on Profile 4 (Fig. 3). The erosional relief at Unconformity 10 generally matches the scale of sea-floor relief and indicates a paleo-bank roughly coincident with Mawson Bank, and paleo-troughs roughly coincident with the Drygalsky and Joides basins. The Unconformity 10 paleo-trough in Drygalsky Basin is particularly deep relative to that at Joides Basin. The overlying unconformities and units have limited lateral extent because of the cross-cutting relationships. For example, Unit 7 is truncated on the eastern flank of Joides Basin. At Mawson Bank and Drygalsky Basin, the units above Unconformity 10

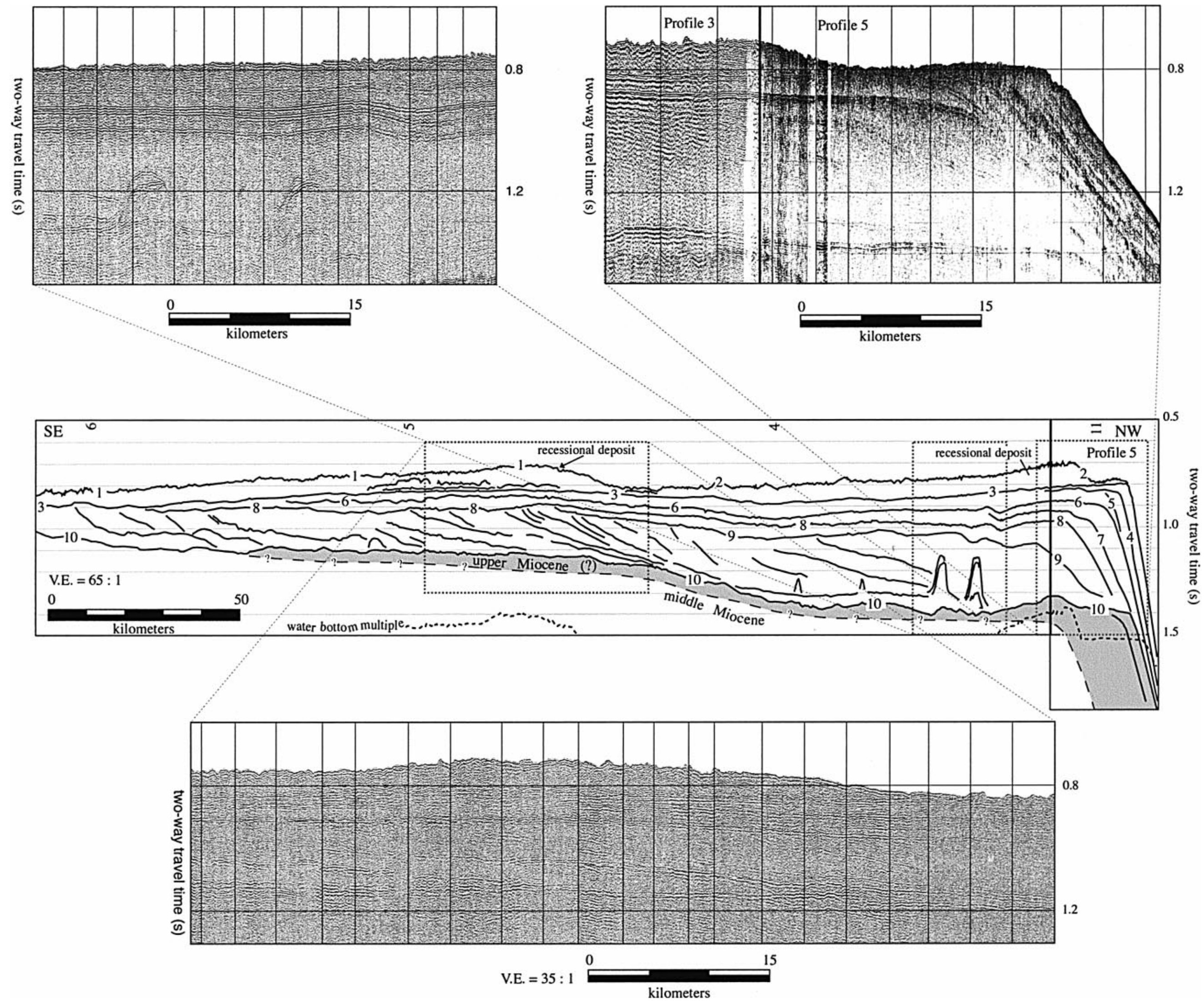

Fig. 4. Regional line drawing and uninterpreted seismic segments of dip-oriented Profile 3 joined to Profile 5 on the shelf at Drygalsky Basin. The line drawing shows the stratigraphic relationship between the deep axis of the Unconformity 10 paleo-trough and the overlying strata. Downlap and outbuilding occurred during the deposition of the upper part of Unit 9–3. Units 1 and 2 exhibit a backstepping pattern on the shelf.

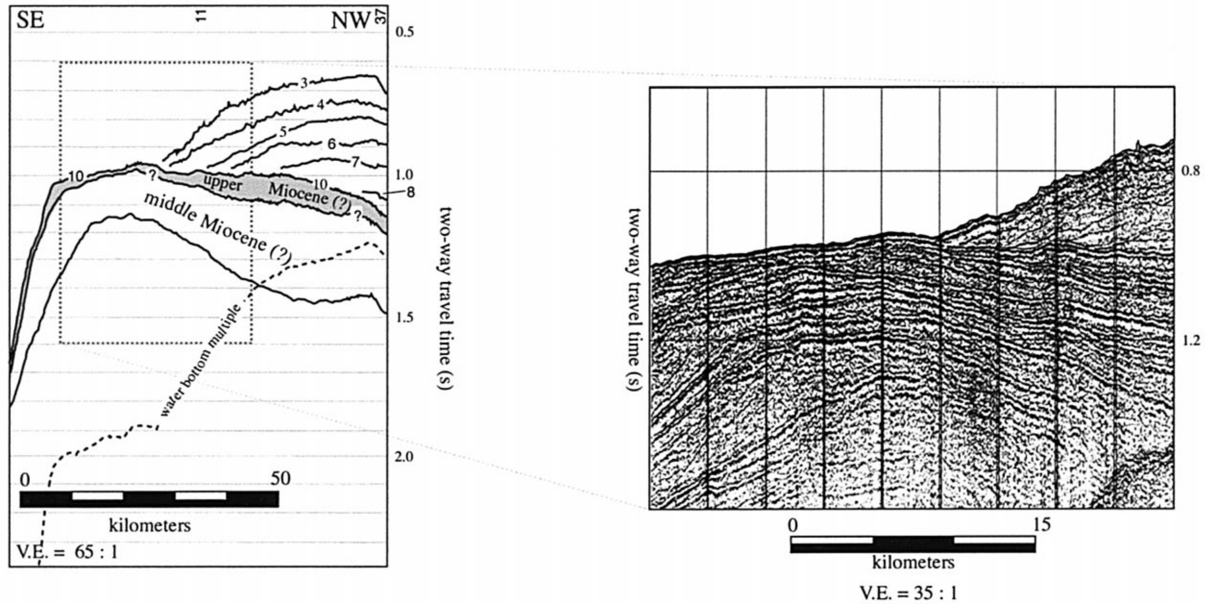

Fig. 5. Line drawing and uninterpreted seismic segment of Profile 38 which crosses the Mawson Bank outer shelf and the western flank of the Joides Slope Basin. The stratal patterns indicate to us that during the Unconformity 10 grounding-event, the ice sheet expanded to the shelf edge whereas subsequent expansions did not prograde this segment of the margin. See Fig. 1 for location.

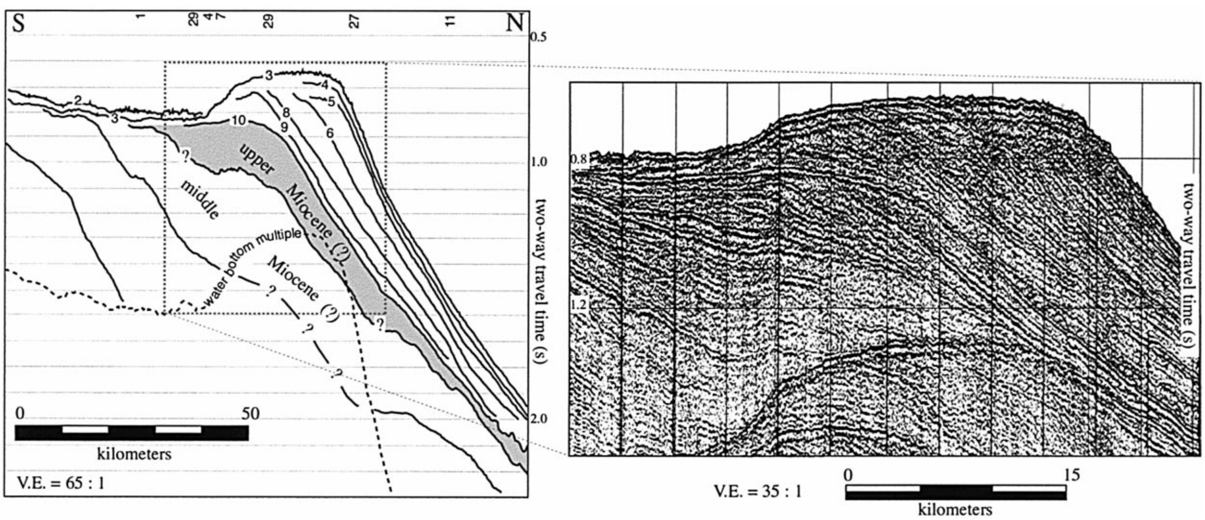

Fig. 6. Line drawing and uninterpreted seismic segment of dip-oriented Profile 39 crossing from the mouth of Joides Basin to the Joides Slope Basin. This profile shows a thick wedge of prograding-slope strata at the mouth of Joides Basin. Unconformities 4, 5, 6, 8, 9 and 10 are truncated at Unconformity 3. See Fig. 1 for location.

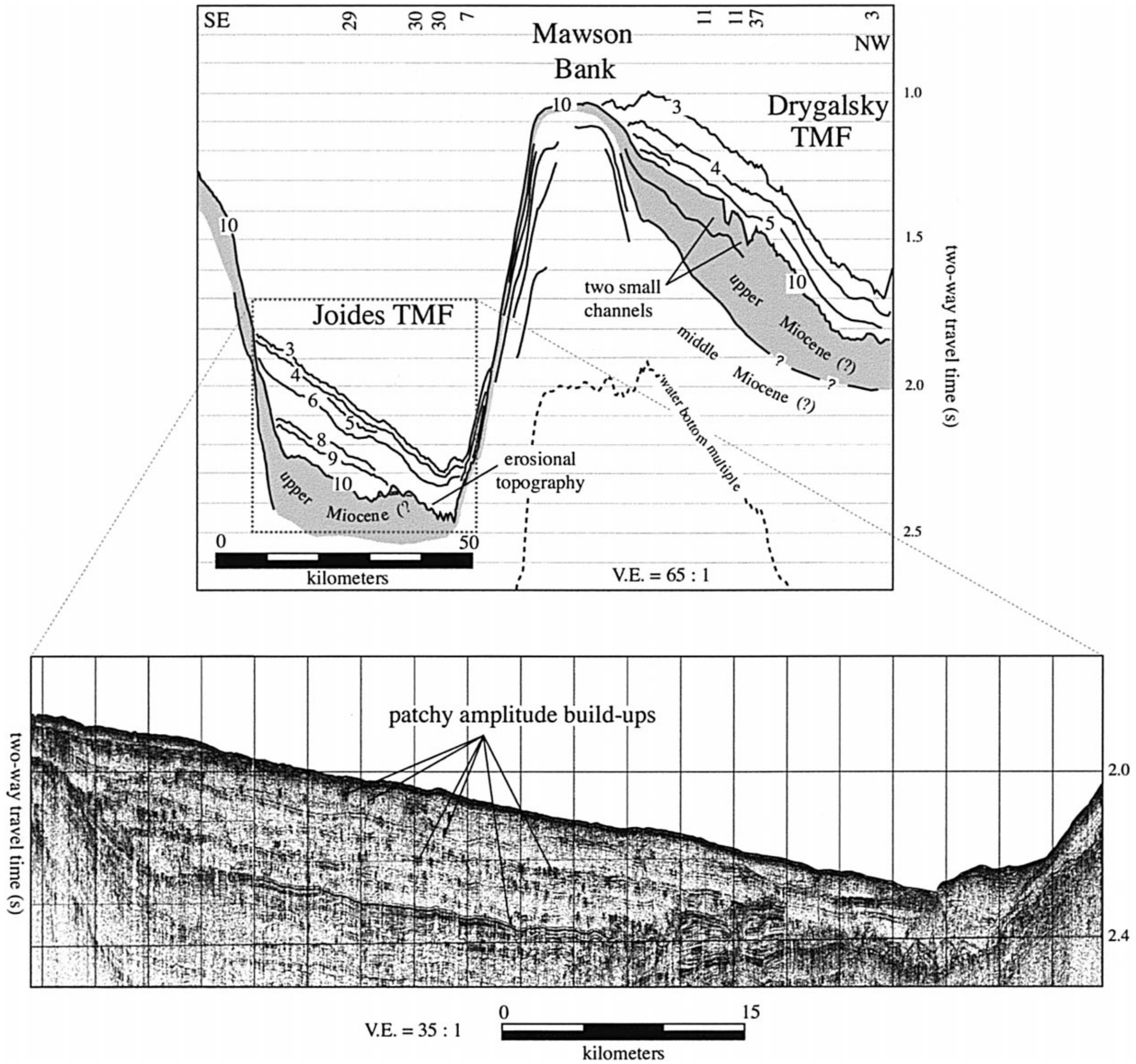

Fig. 7. Line drawing and uninterpreted seismic segment of strike-oriented Profile 2 on the upper slope beyond the mouths of Joides and Drygalsky basins. Unconformity 10 has erosional morphology at the axis of the Joides Slope Basin and at two small channels on the eastern flank of the Drygalsky Basin. See Fig. 1 for location.

are thick, whereas at the mouth of Joides Basin, Unconformity 10 is overlain by a thinner section containing Units 9 and 2.

5.1.2. Regional dip-oriented correlations on the outer shelf at Drygalsky Basin

Fig. 4 (Profile 3/5) shows that the thick fill that covers the Unconformity 10 paleo-trough extends more than 250 km along the axis of Drygalsky Basin. The basal part of our Unit 9 contains several flat-based, concave-up mounds that are a few kilometers in width and approximately 100 ms in height. Brancolini et al. (1995) interpreted the relatively small mounded features above RSU2/Unconformity

10 as extrusive volcanics. There is no clear evidence of seismic velocity pull-up structures underlying the mounds on Fig. 4 to definitively support a volcanic interpretation although admittedly, the data quality at these locations is poor. The upper part of our Unit 9 consists of north-directed mega-foresets, which downlap the mounds and Unconformity 10. Unit 9 and the overlying units (Units 3–8) prograde and progressively filled the deep paleo-trough at Drygalsky Basin. At this location, the topset/foreset geometry of Unit 3 defines a morphologic shelf edge, and the upper two units (Units 1 and 2) are confined to the shelf, i.e. they do not prograde the slope. The internal geometry of Units 1 and 2 is not well imaged. The upper surfaces are slightly foredeepened; the basinward terminations have a steeper seaward dip and more abrupt taper. Unit 2 pinches out on the outermost shelf and Unit 1 pinches out near Coulman Island. Shelf-confined units of this type are not detected in the subsurface.

5.1.3. Seismic–stratigraphic pinchouts on the outer shelf at Mawson Bank

Along the strike of the outer shelf and upper slope, Units 3–8 do not uniformly prograde the margin. Profile 38 (Fig. 5) crosses Profile 37 (Fig. 2) on the outermost shelf and illustrates the abrupt lateral pinchout of the units overlying Unconformity 10 (Units 8, 7, 6, 5, 4 and 3) on the outer shelf at Mawson Bank. Unconformity 10 coincides with the sea floor over a broad region (approximately 1500 km^2) of the outermost shelf and upper slope (see Fig. 8, to be presented later in this article).

5.1.4. Topset truncation of prograding-foresets at Joides Basin and Joides Slope Basin

The distal end of Unit 2 is seen to downlap and pinchout at the mouth of Joides Basin (Fig. 6), and Unit 1 is confined to the inner portion of Joides Basin (i.e. at DSDP Site 273 on Fig. 2, Profile 37). At the mouth of Joides Basin, Unconformity 3 truncates a thick wedge of prograding, parallel to sub-parallel, and semi-continuous clinoforms (Fig. 6). This seismic-facies package contains numerous prograding-slope reflections. The offlapping reflectors above Unconformity 10 extend seaward into the Joides Slope Basin and are more numerous than the nine unconformities (Unconformities 1–9) observed on the shelf (i.e. at Profile 37, Fig. 2). Unconformity 7 could not be correlated to the mouth of Joides Basin because of its limited distribution on the continental shelf relative to the seismic data coverage (Fig. 6), but probably occurs between units 6 and 8. Reflectors that are demonstrably correlative conformities of the unconformities defined at Mawson Bank (Fig. 2) are labeled on the line drawing (i.e. Unconformities 9, 8, 6, 5, 4 and 3 on Fig. 6). However, other than by direct seismic correlation to the shelf, the correlative conformity slope reflectors do not appear to have a seismic signature (i.e. amplitude, continuity, etc.) that differs from other prograding-slope reflectors within the TMF.

5.1.5. Regional strike-oriented correlation of correlative conformities on the Northern basin upper-slope

Profile 2 (Fig. 7) is a regional strike-oriented profile on the upper slope showing that Unconformity 10 exhibits considerable erosional relief (approximately 75 m) near the axis of Joides Slope Basin. On the upper slope adjacent to Drygalsky Basin, Unconformity 10 exhibits two erosional channels. The overlying stratigraphic levels do not exhibit seismic evidence of significant erosional downcutting of the type seen on Unconformity 10. Fig. 7 also shows that deposition was not spatially uniform across the upper slope. Instead, Units 10–3 are confined to the slope areas adjacent to Drygalsky and Joides basins. The seismic segment of Profile 2 (Fig. 7) illustrates that the stratigraphic section is dominated by semi-continuous and faint subparallel-laminated seismic facies with medium and low amplitudes separating thin chaotic seismic facies. Patchy and relatively small-scale amplitude buildups (500 m average width) occur at several stratigraphic levels within the laminated seismic facies and indicate that the local channelized flow (slope gullies) existed during the outbuilding of these seismic sequences.

5.2. Time–structure and isopach maps of the Northern basin TMF sequences

Time–structure contour maps were constructed for each of the ten stratigraphic levels to evaluate the formation of the unconformity-bound seismic sequences. Because of the cross-cutting relationships

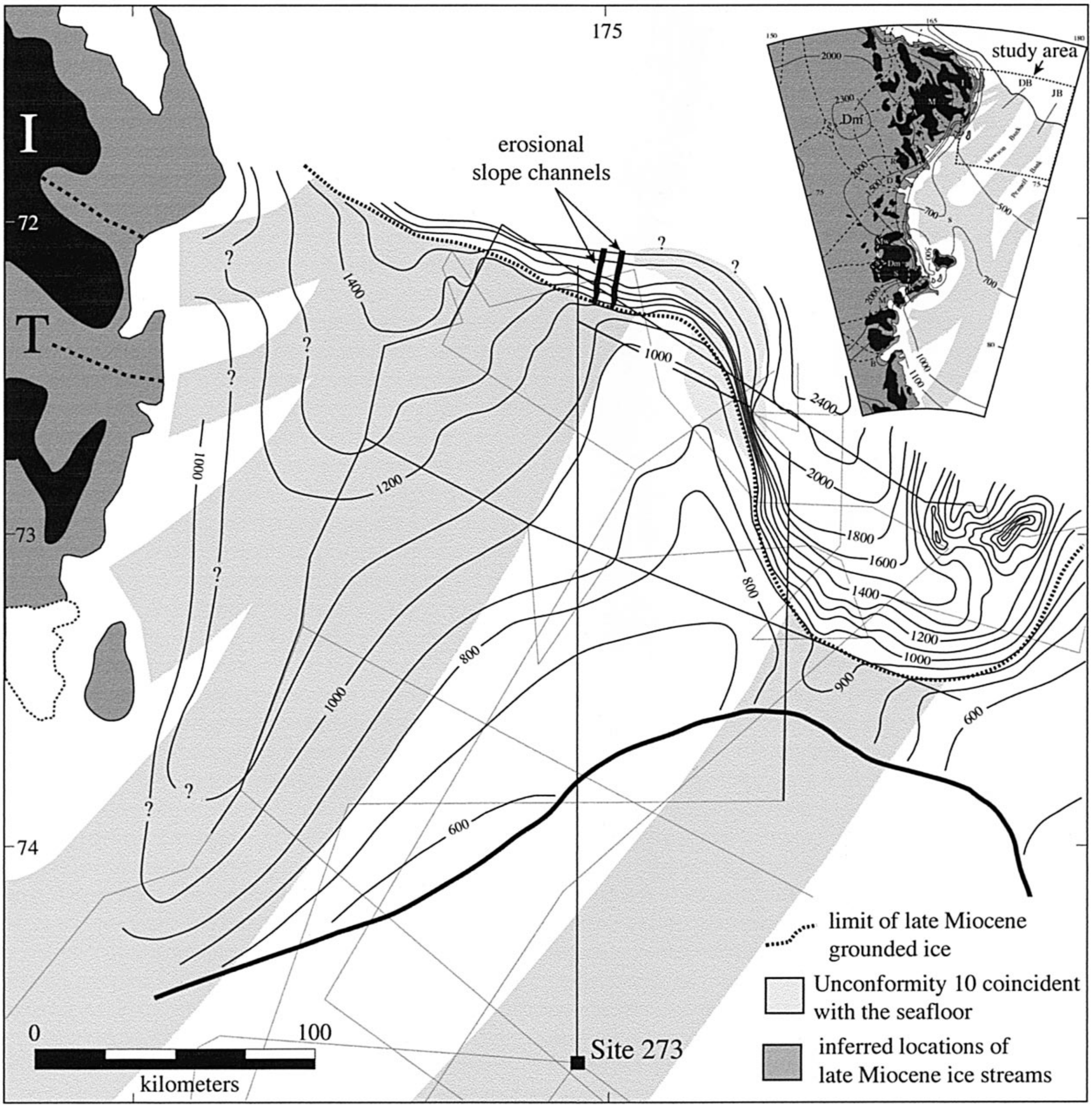

Fig. 8. Time–structure contour map at Unconformity 10. Contours are in two-way travel time below sea level. The dashed line shows the seaward extent of topset truncation of the underlying strata. The heavy solid line indicates the landward limit of Unconformity 10. The light-shaded area on the outer shelf and upper slope correspond to the area where Unconformity 10 coincides with the sea floor. The inset shows our inference on the location of late Miocene ice streams emanating from the TAM.

(Fig. 3), the unconformities are limited in lateral extent, and thus only partially reflect the original bathymetry. Since Unconformity 10 is the most extensive, it is shown to illustrate several of the key geomorphic features for these unconformities: (1) paleo-bank morphology roughly coincident with the location of the modern Mawson Bank; (2) partially truncated paleo-trough morphology coincident with

Drygalsky and Joides basins; and (3) a distinct slope-basin morphology adjacent to the mouth of Joides Basin (Fig. 8). A similar map of RSU2 (equivalent to Unconformity 10) is given in Plate 16 of ANTOSTRAT (1995). Our interpretation of the locations of the paleo-ice streams that presumably created the Unconformity 10 trough/bank morphology is shown in the gray-shaded pattern.

Isopach maps were constructed for each seismic sequence above Unconformity 10 (i.e. Units 1–9) to evaluate the evolution of the TMF depocenters. Every unit has a different distribution, but each shows a depocenter coincident with the Drygalsky and Joides basins on the outer shelf and/or upper slope. Our mapping shows that the location of the two TMF depocenters did not shift (along strike) during successive outbuilding events (Fig. 9). The composite thickness map (Fig. 9) shows that depocenters with thicknesses of approximately 650 ms lie at the mouths of Drygalsky and Joides basins. Our comparison with ANTOSTRAT (1995) indicates that this stratigraphic section is equivalent to the interval mapped on Plate 22. Units 1–9 do not extend across a broad area of the outer shelf and upper slope (Fig. 9), and in this region, Unconformity 10 essentially coincides with the seafloor (Fig. 9).

6. Discussion

6.1. Glacial interpretation of the late Neogene unconformities on the Northern basin shelf

Sedimentologic and biostratigraphic analyses of DSDP Leg 28 drill sites suggested to Hayes and Frakes (1975) that the Ross Sea continental shelf had uninterrupted glacial conditions since the late Oligocene. Brancolini et al. (1995) showed that the first episode of ice-sheet expansion to the paleo-shelf edge and major erosional overdeepening of Northern basin continental shelf occurred much later at RSU2 (i.e. equivalent to our Unconformity 10). After the RSU2/Unconformity 10 overdeepening of the shelf, relative sea-level falls in the late Neogene probably did not cause significant shoaling or subaerial exposure. Indeed, we found no evidence of fluvial incision above RSU2/Unconformity 10 in the Northern basin. Although the overdeepened Northern basin shelf was likely affected by bottom currents, the winnowing of fines from glacial-marine sediments probably produced a coarse lag deposit, which would protect the surface from extensive erosional deflation (Anderson et al., 1984; Dunbar et al., 1985). In addition, we do not find it likely that oceanic currents would produce the regional-scale cross-cutting observed at Unconformities 1–10. For these reasons, we exclude subaerial exposure and erosive bottom currents as important mechanisms in the formation of regional unconformities in the Northern basin. Rather, the overall topset/foreset geometries, the extensive cross-cutting relationships, and trough/bank morphology are most consistent with the view that ice-sheet overriding events produced the late Neogene unconformities (Bartek et al., 1991; Cooper et al., 1991b). The wide extent, great thickness and locations of the upper-slope depocenters at the mouths of paleo-troughs indicate that Units 3–10 were deposited by EAIS ice streams with dimensions similar to the scale of the paleo-troughs (Fig. 9). For the two units confined to the shelf (Units 1 and 2), we infer that their respective grounding lines correspond to the seaward limit of their foredeepened upper surfaces (see Fig. 4). The seismic data indicate to us that all ten unconformities are the result of glacial erosion at times when the EAIS was significantly larger than present.

6.2. Evaluation of EAIS glacial history from the perspective of the Northern basin shelf

Using the maximum ice-sheet reconstruction of Kellogg et al. (1996) as a guide, the overdeepened paleo-trough at Drygalsky Basin probably was eroded by ice flowing from the David outlet glacier; ice flowing from the Byrd glacial drainage system, probably eroded Joides Basin (Fig. 8). Unconformity 10 represents widespread and deep erosion of the outer shelf (Brancolini et al., 1995; De Santis et al., 1999). The mounded features above Unconformity 10/RSU2 probably are subaqueous extrusive volcanics within the Drygalsky paleo-trough (Brancolini et al., 1995). The overall northward outbuilding of the late Neogene units at Drygalsky Basin (Fig. 4) and Joides/Joides Slope Basin (Fig. 6) indicates that the dominant direction of ice flow was along the trough axes.

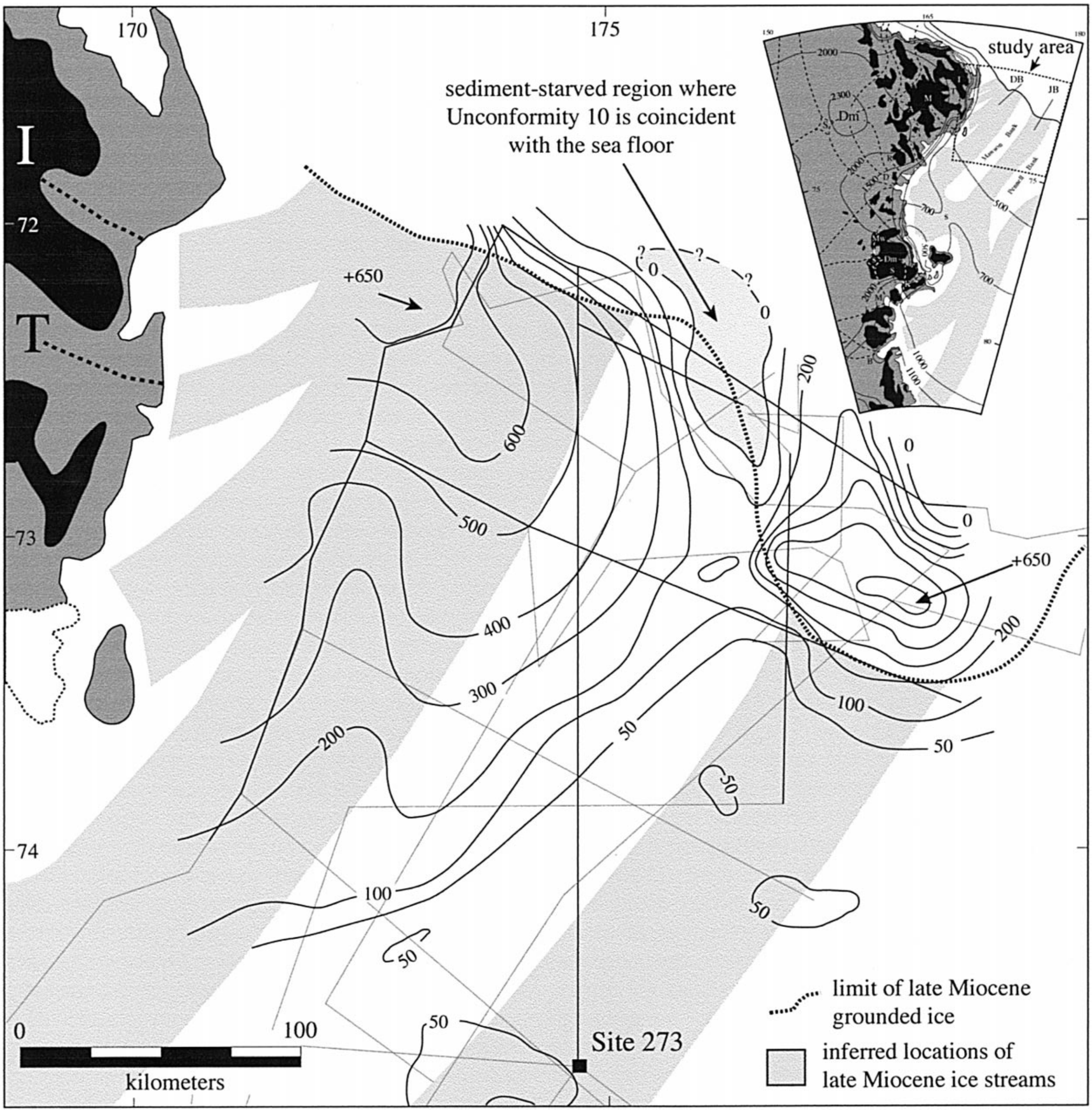

Fig. 9. Composite isopach map of Units 1–9 above Unconformity 10. The map shows a western and an eastern depocenter coincident with the locations of ice streams (gray shading) inferred from the Unconformity 10 structure map (see Fig. 8). The light-gray shaded area on the outer shelf and upper slope between Drygalsky and Joides paleo-troughs corresponds to the region where Unconformity 10 essentially coincides with the sea floor (i.e. Fig. 5). The inset shows our inference on the location of late Miocene ice streams emanating from the TAM.

Fig. 4 shows that Unit 9 was deposited principally on the paleo-shelf and filled the paleo-trough of Unconformity 10/RSU2, and that later units prograded the shelf/slope. The pattern of topset truncation at Unconformities 3–10 indicates that the EAIS advanced to a morphologic shelf edge during each of the grounding events. We interpret the absence of the units from the outer shelf and upper slope (Figs. 5, 8

Table 2
Approximate volumes of TMF sequences in the Northern Basin

Unit #	1	2	3	4	5	6	7	8	9
Unit volume (km^3)	633	728	646	340	1107	565	565	1286	4344

and 9) to be a result of along strike and seaward pinchout of units on the shelf and slope. We acknowledge that this region probably has experienced erosion from bottom currents (Dunbar et al., 1984), but the gradual seaward dip and taper of the late Neogene units above Unconformity 10 suggests to us that a broad region of the outer shelf (and upper slope) has been sediment starved since the erosion of Unconformity 10/RSU2 (Figs. 8 and 9).

The stratal geometries of Units 1 and 2 (see Fig. 4) suggest to us that these units are backstepping grounding-events associated with an overall EAIS retreat since the Unconformity 3 grounding event at the shelf edge. In terms of evaluating the EAIS glacial history from the perspective of the Northern basin shelf, our two-step recessional model is the most conservative interpretation because it requires the least amount of EAIS grounding-line migration. We acknowledge that the seismic stratigraphy also allows at least one alternative interpretation, i.e., that both Units 1 and 2 correspond to major ice-sheet grounding events that were separated in time by a major ice-sheet retreat before the EAIS re-advanced to the outer shelf. From the perspective of the seismic signature, both these alternatives are viable because in our view, the seismic stratigraphy would be the same. On the basis of radiocarbon age dates of piston core samples from the Northern basin, Shipp et al. (1999) interpret Unit 2 (their seismic facies 4b) as a pre-oxygen-isotope 2 (i.e. $>$20,000 years) grounding-event, and Unit 1 (their seismic facies 4a) as an oxygen-isotope stage 2 grounding-event. In terms of our two possible interpretations of Units 1 and 2, the age-dating results from Shipp et al. (1999) are inconclusive because the absolute ages of Units 2 and 3 are not known. Nonetheless, from the perspective of the Northern basin continental shelf, our seismic analysis suggests to us a dynamic glacial history including extreme expansions of the EAIS on at least eight occasions (Unconformities 3 through 10) in the late Neogene.

6.3. Stratigraphic manifestation of EAIS grounding-events within the TMF upper-slope depocenters, and implications of topset-truncated prograding-slope foresets

The erosional slope topography at Unconformity 10 suggests to us that a major re-mobilization of sediment partially excavated the axis of Joides Slope Basin with at least isolated channelized erosion occurring near the mouth of Drygalsky Basin (Fig. 7). Above Unconformity 10, the thick accumulations of the late Neogene TMF strata discretely located along the axis of, or at the mouths of Drygalsky and Joides basins (Fig. 9) indicates that the individual grounding events are not manifested as significant along strike shifts in the location of the TMF depocenter. Consequently, the late Neogene stratigraphic record of the EAIS glacial history is not equally well represented along the strike of the upper slope. Moreover, the absence of a distinct bathymetric bulge at the mouths of the Drygalsky and Joides basins, in spite of the thick TMF depocenters located there, shows that the sea-floor bathymetry is not always a good criterion for locating TMFs.

Because the reflection character (i.e. amplitude, continuity, etc.) of the correlative conformities does not differ from that of other prograding slope foresets within the TMF depocenters (i.e. Fig. 5), these important surfaces can only be distinguished from the other topset-truncated foresets by direct seismic correlation to a glacial unconformity on the continental shelf. The near complete erosion of the late Neogene sediments from Joides Basin, the major topset truncation of Units 9–3 at the mouth of Joides Basin, and our inability to correlate Unconformity 7 to the topset-truncated prograding-slope foresets in Joides Slope Basin (see Fig. 6), highlights the potential for TMF depocenters to represent an extreme amalgamation of several ice-sheet expansion/contraction cycles (i.e. more grounding events than are indicated from the regional study of the continental shelf). To evaluate whether every prograding-slope reflection truncated by a topset unconformity within a TMF sequence results from an EAIS grounding-event, we compared the volume of the shelf-confined units (Units 1 and 2) to the volumes of the individual TMF sequences (Table 2). If a TMF sequence containing many topset-truncated prograding-slope reflections is an amalgamation of several glacial cycles, then the volume of that TMF sequence might be expected to far exceed the volume of the shelf-confined units. This is because the units on the shelf provide at least part of the sediment supplied to the TMF during the subsequent expansion of the ice sheet to the shelf edge (Bart and Anderson, 1996). Indeed, the absence of back-stepped units in the Northern basin subsurface indicates to us that any previously existing shelf-confined units were eroded during subsequent expansions of the EAIS to the shelf edge.

The large volume of Unit 9 is anomalous compared to the other TMF units, and hence Unit 9 may indeed represent an amalgamation of several glacial cycles (Table 2). The average volume for the TMF sequences (Units 3–8) is 748 km^3. Units 1 and 2 have a combined volume of 1361 km^3. Hence, the volume of the shelf-confined units exceeds the average volume of the TMF sequences. We acknowledge that this comparison is imperfect because: (1) the slope gullies (i.e. Fig. 7) clearly indicate that a percentage of sediment escapes the upper slope; and (2) the downdip and lateral extents of the TMF depocenters are not defined whereas the distribution of Units 1 and 2 on the shelf are fairly well defined. In light of the fact that there is no evidence for major downslope mass movement above Unconformity 10, the small volume of the average TMF sequence relative to the volume of the shelf-confined units (Table 2) suggests to us that the topset-truncated foresets within the Northern basin TMF sequences (i.e. Units 10–3) probably are not an amalgamation of several ice-sheet grounding events. Therefore, the TMF depocenters on the slope do not appear to contain a more complete record of EAIS glacial history than that which is evident from our regional study of the Northern basin shelf.

6.4. Northern basin TMF sedimentology and chronostratigraphic implications

The prograding-slope reflectors that are not correlative conformities of glacial unconformities on the shelf may be related to the normal lithologic variability of the TMF depositional environment (Stoker, 1990). For example, the patchy pattern of amplitude build-ups within the laminated seismic facies (Fig. 7) is interpreted as a network of small aggradational gullies and adjacent overbank deposits from small-scale channelized, sediment-charged underflows emanating from the grounding line of ice streams. The gullies on Fig. 7 are similar to the width and depth of those that exist on the upper slope in the central Ross Sea (Shipp et al., 1999). Semi-continuous laminated seismic facies are interpreted as sheet-flow and/or channel-overbank deposits (Fig. 7). Thin chaotic facies within the TMF sequences are interpreted as small-volume mass flows. The distribution of seismic facies on Profile 2 (Fig. 7) indicates that numerous gullies probably were active at any one time and that these gullies shifted location during the outbuilding of the TMF. This suggests wet-based glaciers, unlike those in the Antarctic today.

Detailed sedimentologic studies of the Antarctic shelves have shown that during glacial expansions, terrigenous deposition primarily occurs by subglacial and proglacial processes (Anderson et al., 1980; Anderson et al. 1984, 1992; Jahns, 1994; Shipp et al., 1999). Studies of the modern Antarctic shelf suggest that ice-sheet retreat after the Unit 1 grounding event was relatively rapid (Shipp et al., 1999), and that during the current interglacial, diatomaceous glacial-marine sediments drape the sea floor (Anderson et al., 1984). Even on the overdeepened shelf, these sea-floor sediments are reworked by bioturbation, marine currents, and iceberg turbation (Dunbar et al., 1985). Since the TMF sequences extend into deeper water on the slope, it is unlikely that the glacial-marine sediments would be affected by subglacial erosion or by iceberg turbation. In addition, the absence of seismic evidence of major mass wasting above Unconformity 10 favors a generally constructive outbuilding of the TMF sequences during glacial maximum. The TMF sequences evidently remained intact during the ice-retreat and glacial minimum. Thus, there is a good likelihood that relatively undisturbed diatomaceous glacial-marine sediments comprise a key component of the TMF depocenters on the Northern basin upper slope. The thickness of the interglacial drape would depend on the duration of the glacial minimum, and probably would be thin compared to the glaciogenic deposits (glacial maxima). In addition to the expected high abundances of diatoms, these glacial-marine drapes may contain ash layers from volcanic centers on North Victoria Land. Therefore, although the upper slope does not appear to contain a more complete record of the EAIS grounding events (i.e. compared to the shelf), the diatomaceous glacial-marine sediments draping the correlative conformities may prove to be more dateable than the equivalent sections on the continental shelf.

7. Conclusions

Glacial unconformities on the shelf in the Northern basin of Ross Sea indicate a dynamic history of expansions and contractions during which the EAIS was larger than present on at least eight occasions in the late Neogene. The two upper-most units on the outer shelf may have been deposited during the overall retreat of the ice sheet after the last EAIS expansion to the shelf edge. Our seismic analysis shows that the glacial unconformities and their correlative conformities on the upper slope define at least eight TMF sequences. The TMF sequences do not ubiquitously prograde the margin, and no significant along strike shifts in the location of the TMF depocenters occurred during the successive grounding events. On the upper slope, the seismic reflections for the correlative conformities are not different than other prograding slope reflectors within the TMF. Therefore, without direct correlation of the slope reflections to glacial unconformities on the shelf, isolated reflectors within prograding-slope stratigraphy of the TMF cannot be used to establish the history of grounding events on the continental shelf. The average volume of the outbuilding TMF sequences (Units 3–10) is less than the volume of the two shelf-confined units (Units 1 and 2). On the basis of this comparison, we infer that the eight TMF sequences defined in this study probably are not an amalgamation of several TMF sequences deposited during many glacial cycles. On the basis of sedimentologic studies of the Antarctic continental shelf (see Anderson, 1999 for review), we infer that the correlative conformities within the TMF correspond to the interface between thick prograding glaciogenic deposits (glacial maximum) below and thin diatomaceous glacial-marine units (glacial minimum) above.

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