Relative temporal stability of the Antarctic ice sheets during the late Neogene based on the minimum frequency of outer shelf grounding events

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Abstract

The stability of the Antarctic cryosphere involves two fundamental aspects: the magnitude of ice volume changes, and the frequency of ice volume changes. In this article, we synthesize results from three regional seismic stratigraphic studies of the continental shelf to evaluate the relative frequency of extreme advances of the ice sheets during the late Neogene for different sectors of the Antarctic ice sheet. Detailed analyses of glacial unconformities on the eastern and western Ross Sea outer continental shelf indicate that there were at least eight episodes during the late Neogene when the East Antarctic ice sheet (EAIS) and the West Antarctic ice sheet (WAIS) were significantly larger. The seismic results from the shelf do not support the conventional view that the land-based EAIS was relatively stable and that the marine-based WAIS was relatively dynamic. Glacial unconformities on the Pacific continental shelf of the Antarctic Peninsula indicate that there were at least 30 outer shelf ice sheet expansions during the late Neogene. This suggests that the small land-based Antarctic Peninsula Ice Cap (APIC) may have been the most dynamic component of the Antarctic cryosphere. Conversely, the greater number of grounding events on the Antarctic Peninsula shelf may be a result of the margin’s younger thermal age and hence greater potential to preserve units and unconformities during the late Neogene. We acknowledge that the available chronostratigraphic control from the Antarctic margin is poor, and that more chronological data are needed to confirm our late Neogene age assignments. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Antarctic ice sheet; Antarctic Peninsula; ice caps; Neogene; seismic stratigraphy

1. Introduction

Rather than being a single entity, the Antarctic cryosphere consists of many elements (Fig. 1a). The three primary elements are: (1) the East Antarctic ice sheet (EAIS); (2) the West Antarctic ice sheet (WAIS) and (3) the Antarctic Peninsula Ice Cap (APIC). The distinguishing characteristics of these glacial systems include differences in: (1) ice volume; (2) substratum elevation; (3) ice surface elevation; (4) location with respect to latitude and (5) magnitude of ice volume added/lost during the last glacial cycle (Table 1). Because of these differ-
Fig. 1. Location map. (a) Antarctica; white lines indicate pattern of ice volume drainage during the LGM [8], (b) Northern basin (i.e. northwestern Ross Sea), (c) Eastern basin, (d) Antarctic Peninsula. Light gray lines indicate seismic grids used in comparison. The bold lines on maps (b), (c) and (d) correspond to location of seismic profiles shown in Figs. 2a,b and 3–5.
ent characteristics, the ice masses presumably have evolved and responded to forcing mechanisms independently. The conventional wisdom concerning the evolution of the Antarctic ice sheets is that: (1) the EAIS, a large, land-based ice sheet, began evolving prior to the Oligocene [1], attained continental-scale proportions in the middle Miocene [2–4] and has since been a relatively stable element of the Antarctic cryosphere, experiencing only relatively small ice volume fluctuations [5] and (2) the WAIS, an intermediate-sized, marine-based ice sheet, evolved in the late Miocene [6,7] and has since been inherently unstable due its capacity to respond to changes in sea level, climate and thermal convection [8,9]. The APIC usually is considered a part of the marine-based WAIS, but the peninsula is a narrow highland volcanic arc that constitutes the northernmost extension of Antarctica. We surmise that the land-based APIC may have been particularly sensitive to climatic changes, and that its behavior during the late Neogene may have had no relationship to that of the WAIS. Other than from this semi-quantitative perspective, the frequency at which the different Antarctic ice sheets have responded to or forced climatic and/or eustatic change is not known. Addressing the issue of relative stability for the different Antarctic glacial systems is a necessary fundamental step in the effort to ascribe the likely forcing mechanisms controlling the long-term and short-term behavior of the Antarctic cryosphere. We report here the results of an ongoing investigation aimed at understanding the direct record of late Neogene (late Miocene to present) ice sheet advance and retreat for three areas of the continental shelf adjacent to the EAIS [10], the WAIS [11] and the APIC [12].

2. Materials and methods

On the Antarctic shelves, upper Neogene strata are dissected by numerous cross-cutting glacial unconformities [10–14]. Thus, piecing together a complete stratigraphic section requires relatively dense grids of seismic data that yield high enough stratigraphic resolution to image individual bounding unconformities and to conduct seismic facies analyses. Because the type of data affects the ability to resolve the unconformities and units, we have restricted our investigation to three studies [10–12] for which the data acquisition was similar (Fig. 1b–d). The data acquisition for these three studies consisted of a 100 cubic inch water gun (Antarctic Peninsula data) and either a 100 or 200 cubic inch generator-injector air gun (Antarctic Peninsula and Ross Sea data) with a single-channel streamer. These acquisition systems had the advantage that they could be towed in proximity to the vessel in the heavy sea ice that is common in these regions. In addition, the frequency content and bandwidth of the single-channel seismic data used in these studies have the ability to resolve thin beds in the order of approximately 10 m. The 1988 Antarctic Peninsula data and the 1990 Ross Sea data were acquired aboard the R/V Polar Duke. In 1994 and 1995, additional seismic data were acquired on the western and eastern Ross Sea continental shelves aboard the R/V Nathaniel B. Palmer.

The seismic stratigraphic results from three previous studies were used to compare the late Neogene glacial histories of extreme advances of the EAIS [10], WAIS [11] and APIC [12]. In these studies, extreme advances of the ice sheets are manifest as regional glacial unconformities exhibiting topset truncation of prograding foresets on

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Table 1

Primary characteristics of the Antarctic ice masses summarized from Denton et al. [31]

<table>
<thead>
<tr>
<th></th>
<th>EAIS</th>
<th>WAIS</th>
<th>APIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present ice volume (km$^3$)</td>
<td>$260.3 \times 10^5$</td>
<td>$38.4 \times 10^5$</td>
<td>$2.3 \times 10^5$</td>
</tr>
<tr>
<td>Rsl equivalents (m)</td>
<td>66</td>
<td>6</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Bedrock elevation</td>
<td>mostly above Rsl</td>
<td>mostly below Rsl</td>
<td>entirely above Rsl</td>
</tr>
<tr>
<td>Ice surface elevation (m)</td>
<td>average ~ 3000</td>
<td>average ~ 1500</td>
<td>average ~ 1000</td>
</tr>
<tr>
<td>Geographic limits</td>
<td>90–65°S</td>
<td>85–72°S</td>
<td>73–60°S</td>
</tr>
<tr>
<td>Ice volume added at LGM in Rsl equivalents (m)</td>
<td>7</td>
<td>14</td>
<td>–</td>
</tr>
</tbody>
</table>

Rsl = relative sea level.
the outer shelf. Individual glacial unconformities and the units they separate on the outer shelf/upper slope were regionally correlated utilizing the seismic grids. Units and their upper bounding unconformities were numbered from the top down. For example, the youngest unit is Unit 1, and its upper surface, Unconformity 1, corresponds to the seafloor reflector on the outer shelf. The reader is referred to Bart et al. [10], Alonso et al. [11], and Bart and Anderson [12] for a complete description of the glacial grounding event interpretations for the individual study areas. In this article, the northwestern Ross Sea continental shelf, which receives drainage from the EAIS, will be referred to as the Northern basin. The eastern Ross Sea continental shelf, which receives drainage from the WAIS, will be referred to as the Eastern basin. Age constraints for the Northern and Eastern basin studies were provided via seismic correlation to DSDP sites using a time-depth conversion of 2000 m/s. Age constraints for the Antarctic Peninsula study were originally estimated using the ages of unconformities presumed to have formed during a diachronous transition of the Antarctic Peninsula from an active to a passive margin [12,15]. On the basis of the shipboard party preliminary results from ODP site 1097 on the Antarctic Peninsula continental shelf [16], we have modified our previous age estimates [12] for the Antarctic Peninsula glacial unconformities.

3. Background

3.1. Land-based, proxy and eustatic evidence of Antarctic ice sheet fluctuations

The evolution of Antarctic ice sheets during the late Neogene is being addressed using a number of approaches, each with its own set of inherent weaknesses. Land-based studies are hampered by limited and widely scattered outcrops coupled with poor chronostratigraphic constraints, which have fueled much recent controversy [17,18]. The deep sea ‘proxy’ record of late Neogene glaciation includes variations in oxygen isotope values, icerafted debris, and open ocean microfossil assemblages [5]. These records are far more complete and datable, but there is considerable uncertainty as to how these proxy changes relate to actual build-up and changes in ice volume on the continent [19,20]. The eustatic record for the late Neogene is steadily improving, largely as a result of high resolution sequence-stratigraphic studies and improved biostratigraphic zonation of Plio-Pleistocene strata in the northern Gulf of Mexico and other regions where expanded Plio-Pleistocene strata exist. However, uncertainty exists as to the actual magnitude of these eustatic events, and there is no way of knowing from which glaciated or formerly glaciated region the contributions to eustasy were being made [20,21].

3.2. Evidence of extreme ice sheet expansions from Antarctica’s outer shelves and upper slopes

Unlike low latitude continental shelves, the Antarctic shelves are severely overdeepened and foredeepened as a consequence of isostatic depression from the thick ice sheets centered over the continental interiors, as well as the result of glacial erosion and deposition in the marine realm [22]. Each time the ice sheet advances across the shelf it erodes sediment from the continent and inner continental shelf. The primary agents of erosion are large ice streams (discrete zones of fast flowing ice within an ice sheet). During successive glacial advances, ice streams preferentially carve large troughs on the shelf (Fig. 2A). Alley et al. [23] illustrated that transport of subglacially eroded detritus primarily occurs in a conveyor-belt fashion within a meter-scale thick layer of deforming fluidized sediment at the base of ice streams. At the grounding zone (zone where grounded ice is loosely coupled to the seafloor), the debouching of fluidized sediments creates sediment-gravity flows which construct proglacial till delta foresets (i.e. till deltas). When ice sheets advance to the shelf edge, deposition from ice streams construct thick till delta foresets that prograde across the outer shelf and upper slope, well below the level of subglacial erosion. Therefore, although Antarctica’s inner shelves are regions of net erosion, the outer shelves and upper slopes are regions of net deposition [22]. Indeed, the most direct and stratigraphically complete record of
late Neogene ice volume expansions in Antarctica may exist in the form of these thick stratigraphic packages that occur in outer shelf/upper slope depocenters. We use the term glacial unconformity in the way that it is defined in previous articles [10–12]. On the basis of the criteria outlined in these articles [10–12], seismic reflectors exhibiting topset geometry, foreset truncation, regional extent (several tens of kilometers) and cross-cutting relationships between underlying and overlying units are interpreted as glacial unconformities. These glacial unconformities essentially reflect episodes when the ice sheets advanced onto the outer shelf, and therefore were larger than at present. Chaotic seismic facies and truncated foreset reflections directly below these unconformities are interpreted as proglacial strata that were truncated as the ice sheet advanced across the continental shelf. Stratified seismic facies draping the topset/foreset reflections are interpreted as glacial marine (glacial minimum) sediments presumably accumulated after ice sheet decoupling and rapid retreat [12,24]. These seismic facies interpretations for the intermediate resolution seismic data are supported by high resolution (chirp and minisparker) seismic data, swath bathymetry images and sediment cores from the youngest deposits on the shelf which record the last glacial maximum and minimum [24,25] (Fig. 2B).

3.3. WAIS, EAIS and APIC: last glacial maximum (LGM) reconstructions as an approximation of late Neogene drainage patterns

Marine geological studies conducted during the past 10 years have utilized swath bathymetry, side-scan sonar and high resolution seismic data, along with sedimentologic and petrographic analyses of sediment cores, to develop LGM (i.e. oxygen isotope stage 2) ice sheet reconstructions for the Ross Sea and Antarctic Peninsula regions [26–30]. The generalized LGM ice sheet drainage patterns for these areas [8] are shown in Fig. 1a.
According to Denton et al. [31], Antarctic ice sheet expansion during the LGM contributed approximately 21 m to the total (∼120 m) global relative sea level fall (Table 1). The LGM reconstructions indicate that the EAIS was grounded (i.e. coupled to the sea floor) approximately 100 km from the shelf break in the Northern basin, whereas the WAIS was grounded at the shelf break in the Eastern basin [25,30]. On average, this is 800 km seaward of the present grounding line. The ice sheet may have been greater than 1200 m thick, based on maximum depths of grounding on the shelf and on extrapolation from ice elevations derived from land-based geomorphic studies [30,31]. In the Antarctic Peninsula region, the exact location of the LGM grounding line remains problematic, but prominent glacial unconformities extend to the shelf margin on both the Pacific and Weddell Sea side of the peninsula [12,24]. On the Pacific margin, the principal outlet for the expanded APIC was Marguerite Trough (Figs. 1d and 2a).

The Transantarctic Mountains (TAM) are the principal physiographic features controlling ice sheet drainage into the Ross Sea. Since there has been no major tectonic activity on the TAM in the Plio-Pleistocene [32], we assume that the LGM ice sheet reconstruction (Fig. 1a) provides a good approximation of the Ross Sea paleo-drainage patterns for the late Neogene ice sheet expansions. Likewise, the physiographic setting of the southeastern Pacific margin of the Antarctic Peninsula is not believed to have been significantly altered by tectonic activity during the late Neogene [15]. Therefore, the late Neogene drainage of the APIC probably was similar to that existing at the LGM.

4. Antarctic seismic stratigraphy and correlations to ODP/DSDP drill sites

4.1. Northern basin and DSDP site 273

On the Northern basin continental shelf, DSDP site 273 was located on the eastern flank of Joides Basin, a large paleo-trough (Figs. 1b and 3). According to LGM ice sheet reconstructions, the overdeepened paleo-trough at Joides Basin probably was eroded by ice streams flowing from the Byrd glacial drainage system; ice streams flowing from the David outlet glacier, probably eroded the Drygalsky Basin [8].

Seismic profile 9037 (Fig. 3) is oriented north-south and obliquely crosses Joides Basin and Mawson Bank. The profile extends from site 273 to the upper slope where a thick wedge of strata exhibits foreset/topset geometry. On the basis of its great relief, widespread extent across Northern basin, and occurrence above the middle Miocene section, Bart et al. [10] surmised that Unconformity 10 is correlative with the previously recognized upper Miocene (?) glacial unconformity (i.e. RSU2) that overdeepened the shelf in Northern basin [13,33]. The thick units overlying Unconformity 10 on the outer shelf/upper slope are believed to comprise a reasonably complete upper Neogene section [10]. Admittedly, the age control for the Northern basin is poor, but age constraints from site 273 clearly provide useable information and certainly constitute the best basis for comparing stratigraphic packages from different sectors of the Antarctic shelf, where age control of any kind usually is lacking. In spite of the cross-cutting relationships in Northern basin, the units bound by grounding event unconformities are thick (tens of meters) over broad areas of the study area. According to detailed regional seismic correlation and mapping in Northern basin, Bart et al. [10] argued that Units 3 through 10 (Fig. 3) and their bounding glacial unconformities were formed during outer shelf grounding events of the EAIS. These units are thickest on the outer shelf at the mouths of the troughs (Joides and Drygalsky basins), but are also present at Mawson Bank [10].

On the basis of radiocarbon age dates of piston core samples from the Northern basin, Shipp et al. [25] 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. The stratal geometries of Units 1 and 2 (see Fig. 3) suggested to Bart et al. [10] that these units represent minor grounding events (i.e. submarine recessional moraines) deposited during pauses of
an overall EAIS retreat since the Unconformity 3 grounding event at the shelf edge.

4.2. Eastern basin and DSDP sites 270, 272 and 271

In the Eastern basin, three DSDP drill sites (270, 272 and 271) are located along the axis of a major unnamed glacial trough (Fig. 1c). Seismic profile 9030 (Fig. 4) crosses these three drill sites. Glacial erosion has truncated the offshore dipping strata within the trough. DSDP site 271 sampled approximately 250 m of Plio–Pleistocene strata on the outer shelf [31]; the lower 100 m are assigned an early Pliocene age. The recovery at DSDP site 271 is low (7%), and the biostratigraphic resolution permitted by the radiolarian and diatom zonations is poor [34].

Alonso et al. [11] identified several glacial unconformities in the Eastern basin. These strata consist of alternating massive and layered seismic facies bounded by glacial unconformities. Alonso et al. [11] demonstrated, through careful seismic stratigraphic mapping, that these units are widespread on the Eastern basin continental shelf. Their glacial unconformities are shown in the line drawing (Fig. 4). We have renumbered their unconformities based on our interpretation of a small unit manifest at the sea floor on the middle shelf. On the basis of its backstepped position, we infer that this unit (herein labeled Unit 1) may be correlative to the Unit 1 described for the North-
ern basin [10]. Using the age constraints provided by the drill site biostratigraphy, Alonso et al. [11] inferred a late Miocene (?) age to Unconformity 10 (Fig. 4). Alonso et al. [11] identified nine glacial unconformities within the Plio-Pleistocene section above the upper Miocene (?) unconformity.

4.3. Pacific margin of the Antarctic Peninsula and ODP site 1097

On the Antarctic Peninsula shelf, ODP site 1097 is located within the axis of Marguerite Trough (Figs. 1d and 2a). Site 1097 penetrated 436 m of late Neogene section at the outer shelf. Seismic profile 8804 (Fig. 5) obliquely crosses a large inner shelf bank and Marguerite Trough on the outer shelf. Seismic data from the area show that Plio-Pleistocene strata essentially are confined to the outer shelf [12]. Basement rocks and folded forearc strata are exposed on the inner shelf (Fig. 5). Bart and Anderson [12] identified 31 glacial unconformities on the Antarctic Peninsula shelf using a regional seismic grid (Fig. 1d). On the basis of its position above the 16.5 and 14.5 Ma ridge-trench collision unconformities [12,22], Bart and Anderson [12] assigned a middle Miocene age to Unconformity 31. Unconformity 31, the oldest glacial unconformity identified by Bart and Anderson [12], was not penetrated at the site 1097 (Figs. 2a and 5). Preliminary information provided via general shipboard party announcement from ODP site 1097 [16] suggests that the section containing Unconformity 28
may be as old late Miocene or as young as early Pliocene. Utilizing the preliminary biostratigraphic results from site 1097, we infer that the 31 glacial unconformities represent the minimum number of late Neogene outer shelf grounding events. The youngest glacial unit in the area is confined to the inner shelf and we assume that it represents a recessional deposit of the last ice sheet retreat from the outer shelf.

5. Discussion

5.1. Composite stratigraphic records of ice volume changes from the perspective of the outer continental shelf: minimum estimate of extreme advances of the ice sheets

Because the seismic stratigraphic approach used in the three studies [10–12] was to map regional glacial unconformities and units, it is not likely that the outer shelf grounding events proposed by Alonso et al. [11], Bart and Anderson [12] and Bart et al. [10] reflect multiple decoupling/coupling events occurring during a single cycle of ice sheet advance. In addition, laterally discontinuous stratigraphic sections were incorporated, hence the glacial units and unconformities on the outer shelves should represent reasonable composite stratigraphic records of the grounding events preserved in the individual regions. However, because of mass wasting, tectonic effects, successive episodes of ice sheet advance (i.e. subglacial erosion), etc., the preserved record may far underestimate the actual number of grounding events. Before comparing the composite records from the different areas, we address the question: how complete is the stratigraphic record of extreme

Fig. 5. Line drawing of seismic profile 8804 from the southern Antarctic Peninsula shelf showing the location of ODP site 1097. Numbers correspond to APIC grounding events at the outer shelf from Bart and Anderson [12]. All of the unconformities are not present at this location. Profile B (Fig. 2A) crosses profile 8804 at site 1097. CU stands for the collision unconformity related to the ridge–trench collision that occurred at 16.5 Ma for this segment of the margin.
grounding events in the outer shelf/upper slope depocenters?

The available seismic data at the outer shelf shows generally conformable offlapping stratal patterns, yet multibeam images from the Antarctic Peninsula and Ross Sea provide clear evidence that mass wasting occurs on these slopes [30,35]. Mass wasting may have allowed significant quantities of sediment to escape the upper slope [36], but other than Unconformity 10 in Northern basin, there is no seismic evidence that large-scale (relative to the size of a glacial unit) mass wasting was sufficient to remove the stratigraphic evidence of the late Neogene outer shelf grounding events. On the basis of the available data, we surmise that upper slope depocenters were essentially intact during the late Neogene, and that mass wasting probably has not reduced the number of grounding events preserved at the outer shelf depocenters. However, because the available seismic data essentially are confined to the uppermost slope, it is not possible to fully explore the possibility that upper slope mass wasting may have reduced the number of grounding events preserved in the outer shelf/upper slope depocenters evaluated from the three study areas.

There is no evidence of late Neogene tectonic uplift of the Ross Sea or southern-most Antarctic Peninsula margins, and therefore shoaling or subaerial exposure of the outer shelves would not have contributed to the ability of the ice sheets to advance across the shelf. Therefore, we exclude local tectonic uplift as an important mechanism contributing to the formation and/or amalgamation of glacial unconformities and units on the Ross Sea and Antarctic Peninsula outer continental shelves.

Subsidence rates and hence preservation potential of units and unconformities on the continental shelves were partly related to the thermal age of the basin to a first order approximation [37]. The Eastern and Northern basin study areas are both part of the West Antarctic Rift which began rifting in the Jurassic [38]. Because both sub-basins have the same thermal age and similar sediment thickness, variations in subsidence rates between the two sub-basins are an unlikely mechanism to have produced differences in the degree of amalgamation [37]. Because the southwestern Antarctic Peninsula has been a passive margin since the middle Miocene [15], the late Neogene subsidence rates probably were higher than those for the Eastern and Northern basin regions. Higher subsidence on the Antarctic Peninsula margin may have been an important mechanism contributing to higher preservation of glacial units and unconformities on the Antarctic Peninsula shelf.

If an individual glacial unit and its bounding unconformities at the outer shelf/upper slope represent an amalgamation of multiple outer shelf grounding events, then the sediment volume of the individual unit should probably exceed the volume of the units that were deposited during the last ice sheet retreat from the outer shelf [10]. This is because recessional units are at least partially eroded during the subsequent ice sheet advance to the shelf edge [22,27]. The eroded detritus is transported basinward in a basal debris zone and may ultimately be re-deposited in a proglacial environment at the outer shelf/upper slope as a stratigraphically younger grounding event unit. Indeed, the only clear seismic stratigraphic evidence of deposition during an overall ice sheet retreat is at the sea floor (i.e. Units 1 and 2 on Figs. 3 and 4). Thus far, sediment volumes have only been calculated for the individual units in the Northern basin [10]. In Northern basin, the combined sediment volumes of the recessional units (Units 1 and 2) generally exceed the average volume of the individual shelf edge grounding units (Units 3 to 8; see Table 2). On the basis of the volume calculations from Northern basin, we infer that some large volume units and the bounding unconformities may represent amalgams of multiple advances (i.e. Unit 9, see Table 2). We surmise that in general, an individual glacial unconformity and unit from the outer shelf depocenters probably does not represent amalgamation from multiple grounding events to the shelf edge.

The seismic-based observations from the individual study areas do not conclusively require or preclude that ice sheet advances to the shelf edge were more frequent than has been reported by Alonso et al. [11], Bart and Anderson [12], and Bart et al. [10]. Given the arguments presented
above, we surmise that the grounding events preserved in the outer shelf/upper slope depocenters represent a reasonable composite of the actual number of grounding events. Because the available evidence does not definitively support our view, we take a conservative approach and conclude that the grounding event unconformities described from the individual study areas [10^12] represent the minimum number of late Neogene ice sheet advances for each region.

5.2. Comparison of the late Neogene grounding events of the EAIS, WAIS and APIC

Table 3 compares the minimum number of late Neogene grounding events from the EAIS [10], the WAIS [11] and the APIC [12]. We infer that the minimum average frequency of extreme advances of the EAIS and WAIS was approximately 1.39 grounding events/Ma (see Table 3). Unfortunately, it has not been possible to correlate the late Neogene unconformities between the outer continental shelves of the Eastern and Northern basins because of cross-cutting stratigraphic relationships and the limited seismic data coverage between these two areas. We infer that Unconformity 10 in the Eastern basin is correlative with Unconformity 10 in the Northern basin on the basis of (1) the age constraints provided by the DSDP sites from both areas and (2) the pronounced erosion occurring at this stratigraphic level in both the Northern and Eastern basin study areas [11,10]. Using multi-channel seismic data sets, ANTOSTRAT [33] independently made a similar correlation of an upper Miocene (?) unconformity (RSU2) between Eastern and Northern basins. We infer that the minimum average frequency of the APIC expansions to the outer shelf was approximately 5.2 grounding events/Ma (Table 3).

From the perspective of the continental shelf stratigraphy, our summary of previous seismic stratigraphic studies [10^12] suggests to us that at least portions of all three major elements of the Antarctic cryosphere periodically experienced extreme advances during the late Neogene. Since the stratigraphy from the Ross Sea outer shelf suggests that the EAIS and WAIS experienced the same number of extreme advances, the seismic results do not support the conventional view that the land-based EAIS was a relatively stable glacial system and that the marine-based WAIS was a relatively dynamic glacial system. Because the subsidence rates in the Eastern and Northern basins probably were similar, it is unlikely that this mechanism contributed to a significant differential

<table>
<thead>
<tr>
<th>Unit number</th>
<th>Estimated volume (km$^3$)</th>
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<tbody>
<tr>
<td>1</td>
<td>633</td>
</tr>
<tr>
<td>2</td>
<td>728</td>
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<tr>
<td>3</td>
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<tr>
<td>8</td>
<td>1286</td>
</tr>
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<td>9</td>
<td>4344</td>
</tr>
</tbody>
</table>

Units 3 through 8 have an average volume of 748 km$^3$. Since the Unit 3 grounding event, the ice sheet retreat from the outer shelf occurred in at least two steps (i.e. Units 1 and 2) and deposited 1361 km$^3$.

Table 2
Sediment volumes of Units 1 through 9 in Northern basin [10]

Table 3
Minimum number and inferred frequency of late Neogene ice sheet grounding events to the outer shelf for EAIS [10], WAIS [11] and APIC [12]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of grounding events</td>
<td>8</td>
<td>8</td>
<td>30</td>
</tr>
<tr>
<td>Frequency (grounding events/Ma)</td>
<td>1.39</td>
<td>1.39</td>
<td>1.39</td>
</tr>
</tbody>
</table>

Frequency was calculated using 5.77 Ma for approximate duration of late Neogene. This approximate duration was arbitrarily chosen on the basis of the assumption that a peak $80^{\text{th}}$ event, TG20/22, corresponds to a significant Antarctic ice volume expansion in the late Miocene [39].
in the relative degree of preservation of glacial unconformities and units. In terms of the minimum number of extreme advances across the outer shelf, the comparison shown on Table 3 suggests that the APIC may have been an order of magnitude more dynamic than the EAIS and WAIS. We acknowledge that the higher number of grounding events may be due to higher subsidence rates on the Antarctic Peninsula during the late Neogene; a detailed evaluation of this possibility is beyond the scope of this article.

Due to the poor chronostratigraphic constraints, it is not yet possible to directly determine whether the Antarctic ice sheet grounding events were synchronous or whether they were correlative with late Neogene climatic/eustatic events indicated from oxygen isotope and eustatic records. It is hoped that these preliminary comparisons will stimulate efforts to obtain better estimates as to when the grounding events occurred, to determine if grounding events were synchronous, and to investigate the cause(s) of these extreme glacial events.

6. Conclusions

Our comparison of the seismic stratigraphic records from receiving basins of the land-based EAIS [10] and marine-based WAIS [11] suggests that these two very different glacial systems experienced at least eight extreme expansions across the continental shelf during the late Neogene. In contrast, the APIC experienced at least 30 extreme expansions to the shelf edge during approximately the same time interval [12]. In terms of the minimum number of outer shelf grounding events, our comparison suggests that the marine-based WAIS was not inherently more dynamic than the land-based EAIS. The small land-based APIC may have been the most dynamic element of the Antarctic cryosphere, but the greater number of grounding events on the Antarctic Peninsula shelf may also be a result of the margin’s younger thermal age and hence greater potential to preserve glacial units and unconformities during the late Neogene. Because of generally poor chronostratigraphic constraints, direct correlation of grounding events between the different sectors of the Antarctic continental shelf is not yet possible.

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