

# West-directed flow of the West Antarctic Ice Sheet across Eastern Basin, Ross Sea during the Quaternary

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## Abstract

Detailed seismic–stratigraphic correlations and contour mapping (time–structure and time–thickness) of near-surface units in Eastern Basin, Ross Sea, outer continental shelf suggest that strata outcropping at Ross Bank were deposited as a terminal moraine in association with west-directed advance of the West Antarctic Ice Sheet grounding zone from Marie Byrd Land. During the grounding event, there was a major shift from west-directed ice sheet flow to north-directed ice stream flow. Seismic correlation to age control at DSDP Leg 28 sites 271 and 272 suggests a pre-Last Glacial Maximum Quaternary age for this major grounding event.

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## 1. Introduction

Ice-volume discharge via ice streams and iceberg calving from their downstream ice shelves constitutes the principle form of ablation (i.e., ice-volume loss) from the Antarctic cryosphere. Thus, understanding the long- and short-term evolution of ice streams is important because ice-flow dynamics ultimately exert a major control on the ability of the glacial system to

inflate or deflate, which in turn impacts global climate (e.g., thermohaline circulation, atmospheric circulation, etc.), sea-level elevation (i.e., coastline position), and ocean ecology (i.e., distribution of aquatic life). At present, six large zones of convergent ice flow, i.e., ice streams A to F, drain the Ross Sea pacific margin of the West Antarctic Ice Sheet (WAIS; Fig. 1). These long (a few hundred kilometers), wide (many tens of kilometers) streams flow at maximum rates of a few hundred meters per year [1]. The down-dip reaches of ice streams generally occupy low-lying areas separated by large banks [2–4]. In a basin-ward direction, pronounced basin and bank topography can be traced to the shelf edge. The large-scale basin/bank mor-

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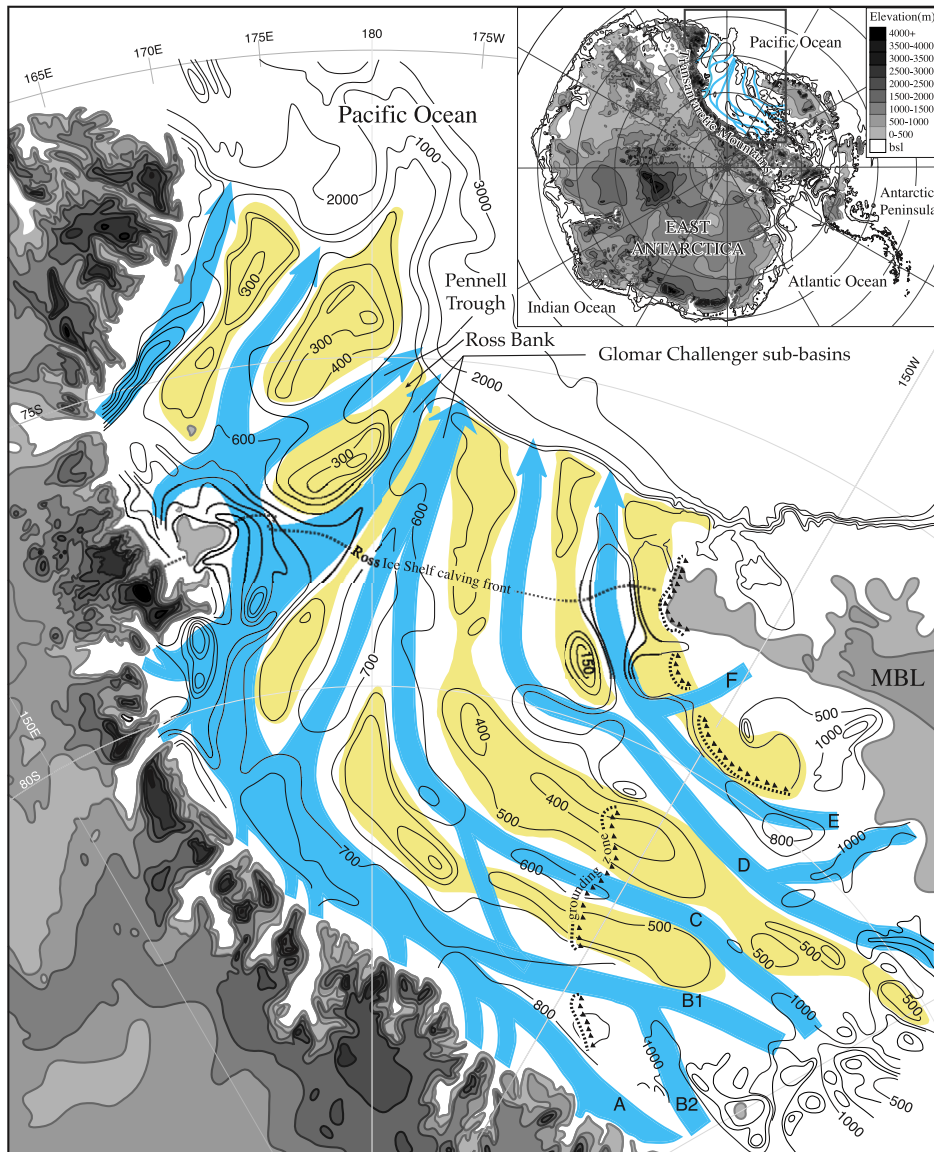


Fig. 1. Ross Sea bathymetry (contours in meters). Gray arrows show inferred positions and flow directions of ice streams during the last ice sheet advance (after Hughes et al. [5]). Ross Bank is located on the outer continental shelf between Pennell Trough and Glomar Challenger Basin. The dashed line with black triangles corresponds to the approximate position of the WAIS grounding zone in the West Antarctic rift and along Marie Byrd Land (MBL). The inset shows the position of Ross Sea with respect to entire continent. Shaded colors correspond to land-surface elevation if the land were allowed to rebound after removal of the ice load (after Drewry [3]).

phology of the Ross Sea outer continental shelf and the semicontinuous alignment with similar topographic features within the adjacent inland (i.e., subglacial) areas of the West Antarctic Rift provide strong evidence that (1) at least six paleo-ice streams

existed before grounded ice retreated from the continental shelf edge, and that (2) WAIS flow on the Ross Sea outer continental shelf was directed northward [5]. At a finer scale, seafloor lineations within basin axes also indicate north-directed ice flow

at least for the period of time immediately prior to the most recent WAIS retreat from the outer continental shelf [6].

Within the constraints of this framework (i.e., north-directed drainage via multiple ice streams), seafloor banks may have evolved in at least two ways: (1) as **erosional ridges** formed between distinct ice streams (zones of fast-flowing ice) that deeply eroded into underlying strata or (2) as **depositional ridges** (ice-stream boundary ridges) composed of subglacially accreted till below zones of relatively slow-moving ice between adjacent fast-flowing ice streams (i.e., via processes somewhat analogous to deep-sea drift evolution; see Fig. 2A, B). In either of

these two end member scenarios, ice streams may have been as much as five times longer than the modern ice streams during the periods of grounding zone advance to the Ross Sea shelf edge.

This relatively straightforward view of north-directed WAIS flow during recent outer continental shelf grounding events potentially is problematic because (1) there are no large basin-ward deflections in the shelf-edge trend at the mouths of troughs (i.e., trough-mouth-fan (TMF) depocenters appear to be absent), and (2) such a configuration (i.e., multiple long avenues of ice-stream flow) is inconsistent with ice-core data [7], indicating that there probably was little change in the ice-surface elevation in the West Antarctic continental interiors at least during the last Quaternary glacial [8,9].

In an **alternate end-member view of bank/basin evolution**, bathymetric ridges may have originally formed as a series of broad semiconcentric subaqueous terminal moraines associated with, for example, east–west grounding zone migrations of the east Antarctic Ice Sheet (EAIS) [10,11] or WAIS (Fig. 2C). If this third scenario is valid, one important implication is that the dimension, number, location, and orientation of modern ice streams are strongly controlled (i.e., captured) by preexisting seafloor topography created during previous east–west migrations of the Antarctic Ice Sheet (AIS) grounding zone depositional system. Distinguishing between these three end member scenarios has important consequences for the way the past behavior of the AIS is reconstructed from the margin's stratigraphy. The specific purpose of this seismic–stratigraphic study is to address the following question: how and when did the Ross Bank (strata and morphology) on the Ross Sea Eastern Basin outer continental shelf evolve with respect to WAIS flow?

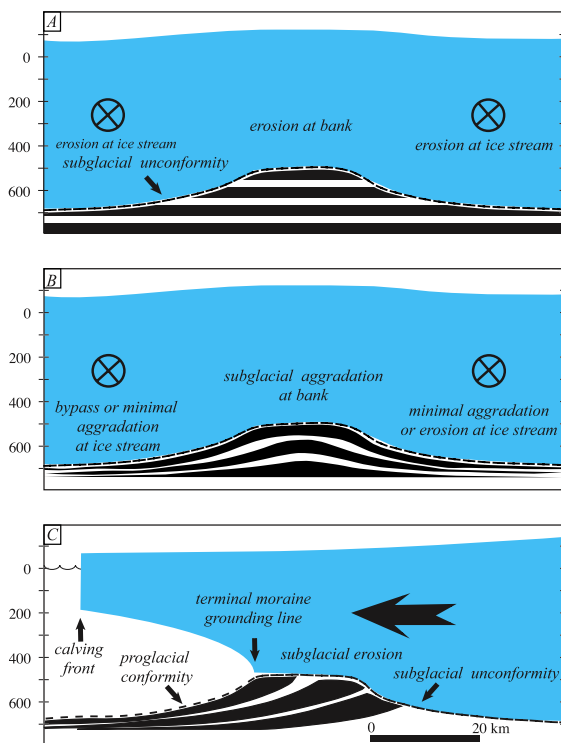


Fig. 2. Conceptual model showing three possible ways in which Ross Bank may have evolved. In this west-to-east cross-section of the outer continental shelf, north is into the page. (A) Erosional model bank formed between north-flowing ice streams (at Pennell Trough and Glomar Challenger Basins) as that deeply erode into older strata. (B) Constructional model bank formed as a depositional ridge via accretion of subglacial till from slow-moving ice between north-flowing ice streams. (C) Terminal moraine model bank formed as a subaqueous terminal moraine associated with, for example, a west-flowing WAIS. The vertical scales are in meters with respect to sea level.

## 2. Methods

The study presented here focuses on Ross Bank in Eastern Basin because a relatively dense grid of seismic data already exists in the area [12,13] and because a recent seismic investigation [6] has established that several near-surface glacial unconformities are found in the vicinity. The single-channel seismic profiles used in this study were acquired in 1990 from

the Polar Duke R/V and in 1994, 1995, and 2003 field seasons from the Nathaniel B. Palmer R/VIB (Fig. 3). Data set PD90 was acquired using a 150-in<sup>3</sup> generator–injector airgun. Data sets NBP94 and NBP95 were acquired with a 50-in<sup>3</sup> generator–injector airgun. Data set NBP0301A was acquired with a single 50-in<sup>3</sup> generator–injector airgun. Filter cut-offs were 30 to 800 Hz.

Single-channel seismic acquisition systems have the advantage that they can be towed in proximity to the vessel in the heavy sea ice that is common in Ross Sea. In addition, the dominant frequency of the single-channel seismic data was between 130 to 200 Hz, providing a theoretical stratigraphic resolution of 2 to 4 m based on the Rayleigh resolution limit criteria and

an average sediment velocity of 2 km/s. The thin-bed resolution of this data is sufficient to map the major stratal surfaces within the ridge [12,14], but, as noted by Domack et al. [15], the seismic resolution apparently is not sufficient to map the submeter scale piston-core lithofacies recovered from the top of the seismic units.

In this study, Eastern Basin till sheets described by Shipp et al. [6] were seismically mapped (time-structure and time-thickness) on the outer continental shelf in the vicinity of Ross Bank and Glomar Challenger Basin to evaluate how near-surface units (strata and morphology) evolved with respect to ice flow. Seismic correlations were performed by hand on paper copies of seismic sections plotted at a vertical

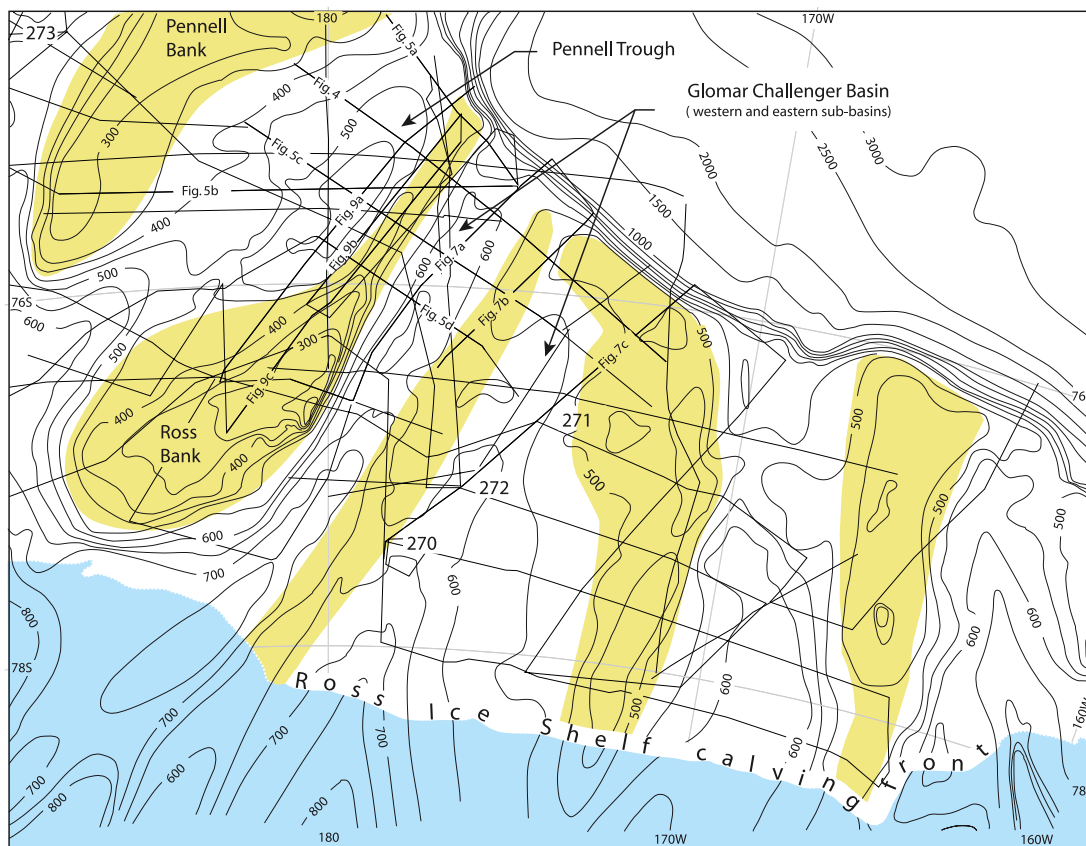


Fig. 3. Eastern Basin bathymetry (contours in meters); seismic base map (PD90, NBP94, -95, and -03); and Leg 28 DSDP sites (270, 271, 272, 273). Bold lines correspond to locations of seismic profiles shown in this article. The shaded areas north of the Ross Ice Shelf calving front correspond to seafloor banks (e.g., Pennell and Ross banks and three unnamed banks in the central and eastern part of the map). The unshaded areas correspond to seafloor basins (i.e., locations of ice streams during the last advance of grounded ice). Glomar Challenger Basin is subdivided into western and eastern subbasins separated by the unnamed bank immediately east of Ross Bank.

scale of 33:1. To show the entire regional segments, line drawing of seismic sections are shown at a vertical exaggeration of 83:1. Time-structure elevation (in two-way travel time with respect to sea level) of surfaces interpreted as subglacial unconformities was posted on a base map at every 5 km. Two-way time thickness of units bound by unconformities was posted on a base map at approximately every 5 km. These data points were contoured by hand. The till-sheet units were correlated to age control at two DSDP Leg 28 sites [16,17] on the Eastern Basin outer continental shelf (Figs. 1 and 2) to constrain the timing of these ice sheet grounding events on the outer continental shelf. Time-depth conversions from the ANTOSTRAT Atlas [18] were used to convert drill site depth below the sea floor to two-way seismic travel time.

Regional seismic correlations conducted in this study show that at least seven (7) unconformity-bound seismic units (Yellow, Gray, Brown, Red, Purple, Blue, and Green from stratigraphic top down) have significant outcrop distribution (with respect to seismic resolution, i.e., at or with 20 ms of the seafloor) in the study area. In places where the sequences are complete (i.e., no major cross-cutting of older units by erosion at younger unconformities), the unit's upper unconformity is assigned the same name as the underlying unit. For example, the top of the Yellow unit is defined as the Yellow unconformity. The base of the Yellow unit is defined as the top of the underlying Gray unit (i.e., the Gray unconformity). The upper two units (Yellow and Gray) correspond to inner-shelf till sheets described by Shipp et al. [6], whereas the older Brown, Red, and upper part of the Purple unit at Ross Bank correspond to the outer-shelf tills described by Shipp et al. [6]. The Purple, Blue, and Green units outcrop at Ross Bank.

Within this study, four criteria were considered to investigate Ross Bank evolution. (1) Ross Bank units/unconformities were seismically correlated to age control to determine whether or not there is a genetic relationship between ridge strata and ridge morphology. (2) Stratal patterns at Ross Bank were evaluated to deduce depositional setting. (3) The regional distribution and thickness of ridge strata were mapped to determine if there are coeval trough-mouth-fan depocenters. (4) The regional topography of the unconformity that defines ridge morphology was mapped to

determine the pattern of ice sheet flow at the end of the grounding end that defines bank topography.

### 3. Results

#### 3.1. Ross Bank stratigraphy: unconformities and units

From a subsurface perspective, Ross Bank strata can be subdivided into upper and lower parts (Fig. 4). The upper part consists of the Purple unit, the top of which is defined by the Purple unconformity (i.e., the seafloor reflection at Ross Bank) and the base of which is defined by the Blue unconformity. The Purple unit is exposed at the seafloor along the crest of Ross Bank on the outer continental shelf but thins and pinches out on both flanks of the ridge. The underlying Blue unconformity is a major angular unconformity truncating older east-dipping strata at or near the seafloor in Pennell Trough (to the east of Ross Bank). At Ross Bank, the Blue unconformity projects into the subsurface (i.e., below the Purple unit) and truncates the east-dipping Blue and Green units which constitute the lower part of the ridge strata.

Along Ross Bank's east flank, the Purple unconformity truncates the Blue unconformity (which dips to the west) and the stratigraphically older Blue and Green units (which dip to the east; Figs. 4 and 5). Further to the east (i.e., at Glomar Challenger Basin), the Purple unconformity projects into the subsurface where it truncates the underlying strata and is deeply buried by younger units (the Brown and Red units) on the outer continental shelf. The Red unit thins towards the west and pinches out near the thalweg of Glomar Challenger's eastern subbasin. The regional line drawing (Fig. 4B) shows that the Brown unit pinch-out approximately parallels the edge of the low ridge separating the eastern and western Glomar Challenger subbasins on the outer continental shelf. A similar stratal and outcrop pattern is noted on other strike-oriented transects on the outer continental shelf (Fig. 5). The eastern subbasin is best defined towards the inner shelf by major down-cutting at the Brown unconformity that locally exposes the underlying Red unit (Fig. 5C). The depression associated with the eastern subbasin is partially filled by the Gray unit (Fig. 5D).



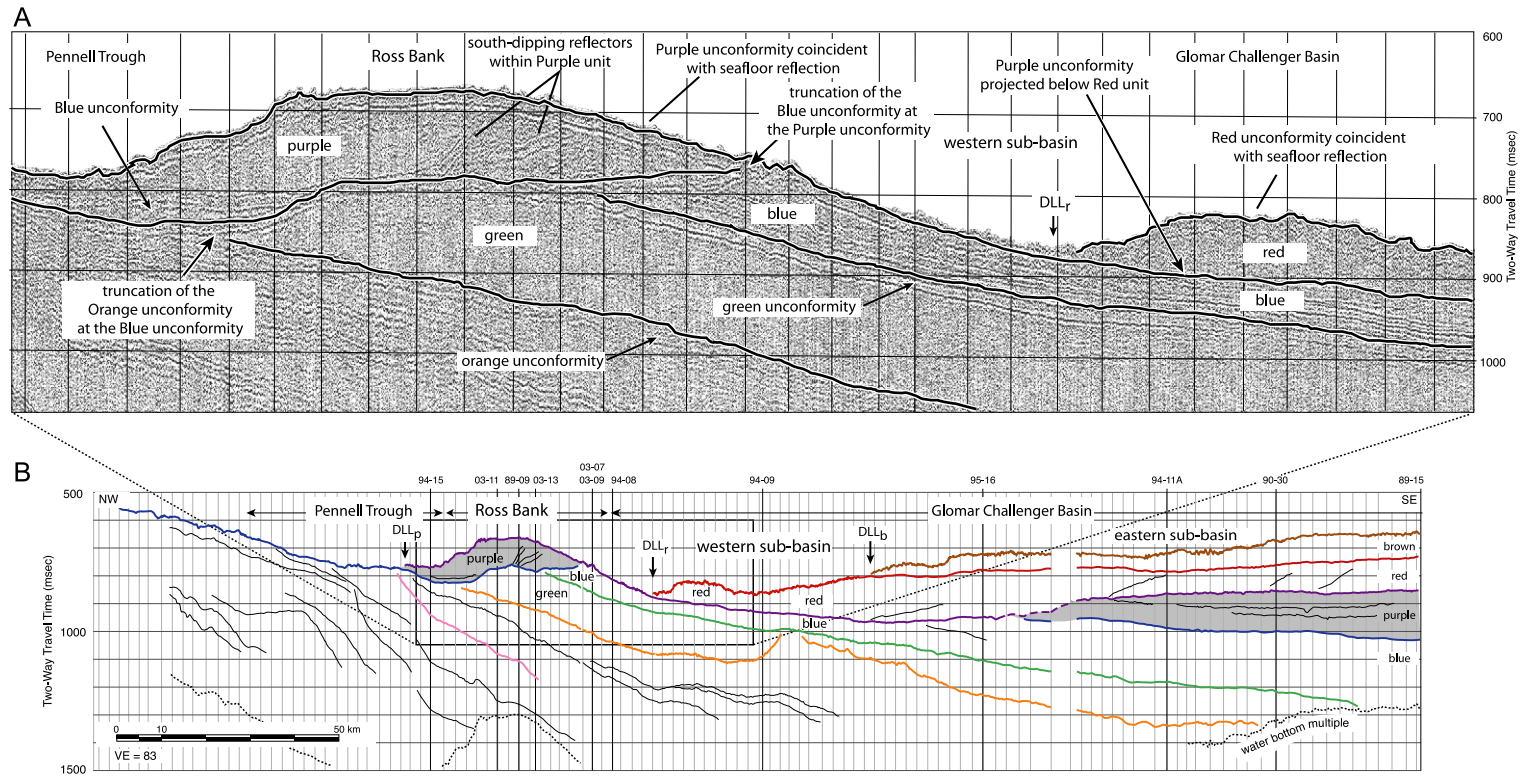


Fig. 4. (A) Segment of uninterpreted seismic profile NBP94-14 crossing Ross Bank on the outer continental shelf between Pennell Trough and Glomar Challenger Basin. The upper part of Ross Bank is defined by the Purple unit, which is bound by the Purple and Blue unconformities (above and below, respectively). West-dipping seismic reflections within the Purple unit suggest accretion towards the west and depositional downlap into Pennell Trough. In terms of stratigraphy, this stratal pattern is most consistent with the terminal moraine model (see Fig. 2C). The Purple unconformity projects into the subsurface and is deeply buried by the Red (and Brown units) at Glomar Challenger Basin. (B) Regional line-drawing interpretation of seismic profile NBP94-14. The Purple unit is shaded gray. DLL—downlap limit (stratal termination interpreted as a depositional limit) for the unit designated by the subscript. The subscripts p, r, b stand for the purple, red, and brown units, respectively. The numbers at the top of the profile show the locations of seismic cross lines. The names of seismic units are posted on the profile and line drawing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

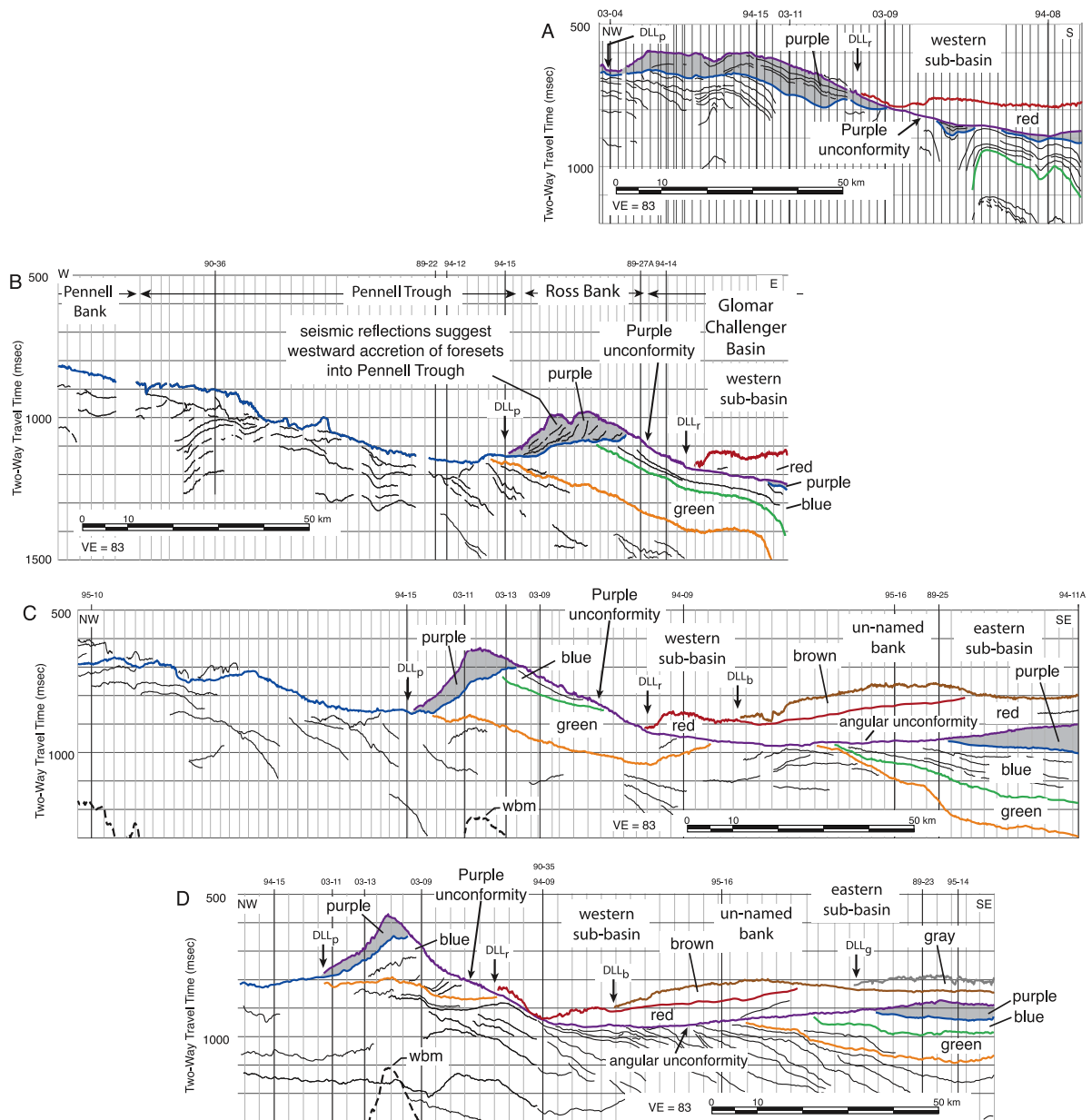


Fig. 5. Line drawings of four strike-oriented seismic profiles across Ross Bank. (A) Profile NBP03-08; (B) Profile NBP94-8; (C) Profile NBP94-12; and (D) NBP95-19. These profiles show stratigraphy similar to that observed on NBP94-14 (see Fig. 4). At each transect, the Purple unit is exposed at Ross Bank and pinches out by depositional downlap in Pennell Trough. The unit's upper surface, the Purple unconformity projects into the subsurface, buried below thick units (Red, Brown, and Gray) in Glomar Challenger subbasins. The Purple unconformity is a major angular unconformity throughout the area of Ross Bank and Glomar Challenger Basin (see C and D). Above the Purple unconformity, the Red and Brown units thin towards the west and abruptly pinch out by depositional downlap near the thalweg of Glomar Challenger's western subbasin. The unnamed bank separating the western and eastern subbasins is seen on C and D. The eastern subbasin is partially filled by the Gray unit (D). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

### 3.2. Topography of the Purple unconformity

Ross Bank morphology is defined by the topography of the Purple unconformity (Fig. 6). The western flank is slightly concave up, whereas the eastern flank generally has a more convex up shape in most cross-sections (Figs. 4 and 5). On the outermost continental shelf, the east and west flanks of Ross Bank dip at low angles (averages of  $0.75^\circ$  and  $0.35^\circ$ , respectively, as measured from the time-structure map, Fig. 6). The exception is for the area east of the high crest of Ross Bank (toward the inner shelf) where the seafloor dips at a relatively high angle ( $\sim 2.5^\circ$ ; Figs. 1 and 7A). The crest elevation of Ross Bank generally deepens in an offshore direction from 300 to 600 ms below sea floor (ms bsf).

The west limit of the Purple unconformity (Fig. 6) corresponds to the area where the Purple unit

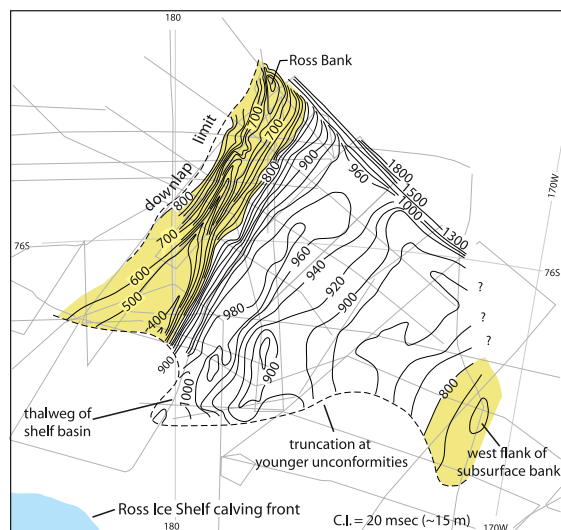


Fig. 6. Time-structure elevation contour maps (in milliseconds below sea level) of the Purple unconformity (i.e., the top of the Purple unit) constructed from regional grid of interpreted seismic profiles. Ross Bank is shown in a light-shade pattern. The dashed line to west of Ross Bank corresponds to the downlap limit of the Purple unit in Pennell Trough noted on seismic profiles (see Figs. 4 and 5). The shelf basin to the east of Ross Bank corresponds to the area where the Purple unconformity projects into the subsurface. This shelf basin exhibits slight foredeepening (i.e., landward dip). The light-shaded area to the east of the basin may correspond to second bank at the Purple unconformity, but it is not possible to map the feature with the existing data. The landward limit of the Purple unconformity corresponds to truncation at the younger unconformities.

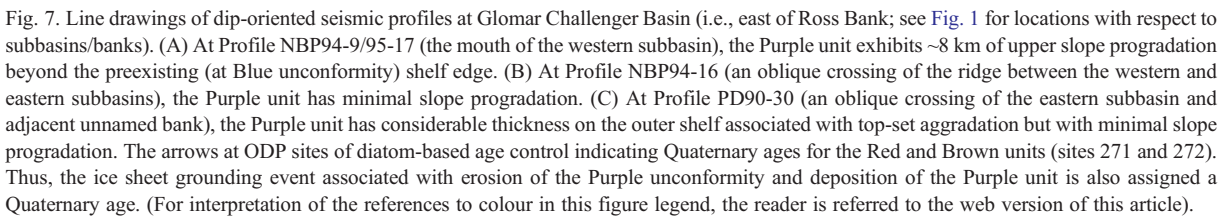
pinches out along the west flank of Ross Bank (Figs. 4 and 5). At this point, the Purple unconformity amalgamates with (downlaps against) the underlying Blue unconformity at/or near the sea floor in Pennell Trough. The landward limit of the Purple unconformity corresponds to truncation at the younger unconformities (i.e., at the Brown or Gray unconformities; Fig. 7).

To the east of Ross Bank, where the Purple unconformity projects into the subsurface (Figs. 4 and 5), the topography of the Purple unconformity defines a broad ( $\sim 75$  km at the 900-ms contour) basin (Fig. 6). The shelf basin's thalweg is  $\sim 80$  km east of Ross Bank's crest. In contrast to the basin-ward dip of Ross Bank's crest, the thalweg is foredeepened, shallowing from  $>1000$  ms (in a landward direction) to 960 ms (at the shelf edge) (Fig. 6). The basin's east flank exhibits gentle dip ( $\gg 1^\circ$ ) towards the thalweg before rising to a possible bank crest (subsurface topography) towards the east. It is not possible to determine if this major subsurface basin is delimited on its eastern side by a continuous buried ridge with the existing seismic data grids. The paleo shelf edge at the Purple unconformity has a northwest–southeast trend, and there does not appear to be a major basin-ward deflection of the paleo shelf edge at either Ross Bank or Glomar Challenger Basin. Seismic correlations basin-ward of the paleo shelf edge (i.e., onto the slope) is equivocal because no regional upper slope strike-oriented profile is available to confirm the correlations from adjacent dip-oriented profiles.

### 3.3. Thickness distribution of the Purple unit

Along the axis of Ross Bank, the Purple unit has a maximum thickness of 120 ms (90 m; Fig. 8). To the east of this Ross Bank depocenter, the Purple unit is eroded from a broad swath corresponding to where erosion at the Purple unconformity carved a deep basin on the outer continental shelf (Figs. 4–6). The Blue unconformity (the base of the Purple unit) cannot be correlated across this subsurface basin on either the continental shelf or the upper slope with the seismic grids used in this study. On the basis of the stratal superposition at Ross Bank (Figs. 4 and 5), the Blue unconformity is constrained to be stratigraphically above the Green horizon and stratigraphically below or amalgamated with the Purple





is tentatively placed at the youngest major reflection horizon below the Purple unconformity. Given the uncertainty associated with the stratigraphic position of the Blue unconformity, the Purple unit thickness from this part of the study area may not accurately depict the absolute thickness of the Purple unit

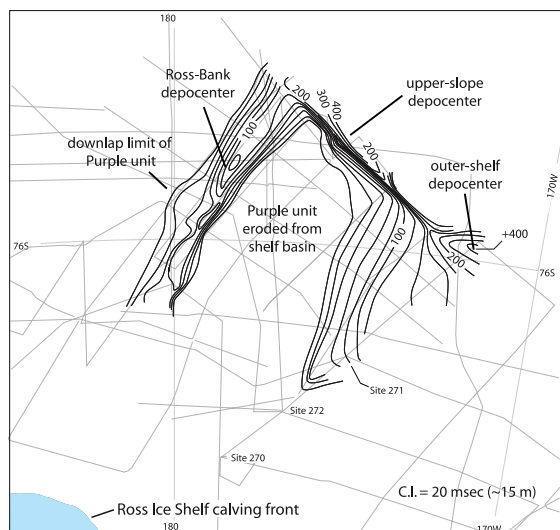


Fig. 8. Time-thickness contour map of the Purple unit. Along the axis of Ross Bank, the Purple unit has a maximum thickness of 120 ms (~90 m) on the outer shelf. The downlap limit is interpreted to represent the maximum westward expansion of a WAIS terminal moraine. To the east of Ross Bank, the Purple unit is absent from a broad swath corresponding to shelf basin eroded at the Purple unconformity on the outer continental shelf. The upper slope depocenter adjacent to shelf basin suggests there was a shift to north-directed flow after the terminal moraine (Ross Bank) was constructed. The outer shelf depocenter (to the east of the shelf basin) primarily consists of aggrading top-sets (i.e., minimal upper slope progradation).

coeval with that represented at Ross Bank. As mapped, the upper slope depocenter is adjacent to deepest part of the broad shelf basin eroded at the Purple unconformity (Figs. 7A and 8). Towards the southeast along the strike of the upper slope/outer shelf, the unit thins to <150 m (110 m) before thickening to what appears to be the west flank of a second major depocenter consisting of aggrading top sets with minimal progradation (Figs. 7C and 8).

### 3.4. Internal stratification within the Purple unit

At Ross Bank, the Purple unit contains only a few poorly defined discontinuous reflection horizons. Stratal surfaces exhibit low-angle ( $\ll 1^\circ$ ) but definite west-directed lateral accretion on strike-oriented profiles (Figs. 4 and 5). The dip angles of internal surfaces within the middle of the unit generally are

higher than the dip of the west flank of the Ross Bank (Figs. 4 and 5C). At the outermost strike-oriented profile crossing Ross Bank (Fig. 5A), internal horizons within the Purple unit generally parallel the seafloor but also exhibit downlap termination against the underlying Blue unconformity. On ridge-parallel transects (i.e., dip-oriented profiles at Ross Bank; Fig. 9B), stratal surfaces exhibit definite south-directed dip. In both strike- and dip-oriented sections, stratal surfaces within the Purple unit terminate above at the seafloor on the east flank and crest of Ross Bank (i.e., at the Purple unconformity) and terminate below against the underlying Blue unconformity. East of Ross Bank, stratal surfaces within the Purple unit generally exhibit basin-ward dips concordant with the topography of the underlying Blue unconformity (Figs. 4, 5 and 7C).

### 3.5. Age constraints on the Purple unit and unconformity at Leg 28 DSDP sites

The regional seismic correlation of the Purple unconformity from Ross Bank (Fig. 4) to the seismic transect crossing Leg 28 DSDP sites (Fig. 7C) is straightforward, but as mentioned in Section 3.2, the correlation of the Purple unit strata exposed at Ross Bank to the Leg 28 seismic transect must be considered tentative because the Purple unit is eroded across the outer continental shelf in the broad basin to the east of Ross Bank (Figs. 4 and 5). The Red and Purple units are penetrated at DSDP Site 271 on the outermost shelf (Fig. 7C). At this location, the two-way travel time between the seafloor and the base of the Red unit is ~50 ms (i.e., 0 to 23 m below sea floor (mbsf) using the ANTOSTRAT [18] time-depth conversion chart for Site 271). The time-thickness of the Purple unit at this site is ~80 m which corresponds to the 23 to 82 mbsf. The first downhole recovery at Site 271 is a 1.5-m section and core catcher from the 21.0 to 30.5 m below sea floor (mbsf) cored interval. According to the convention used on DSDP Leg 28 for cored sections with incomplete recovery, the 1.5-m section from this cored interval is assigned to the top of the cored interval, whereas the core catcher is assumed to come from the bottom of the cored interval. If correct, the 1.5-m section comes from near the base of the Red unit (i.e., 21.0 to 22.5 mbsf), whereas the core catcher comes from the top 1/4 of the

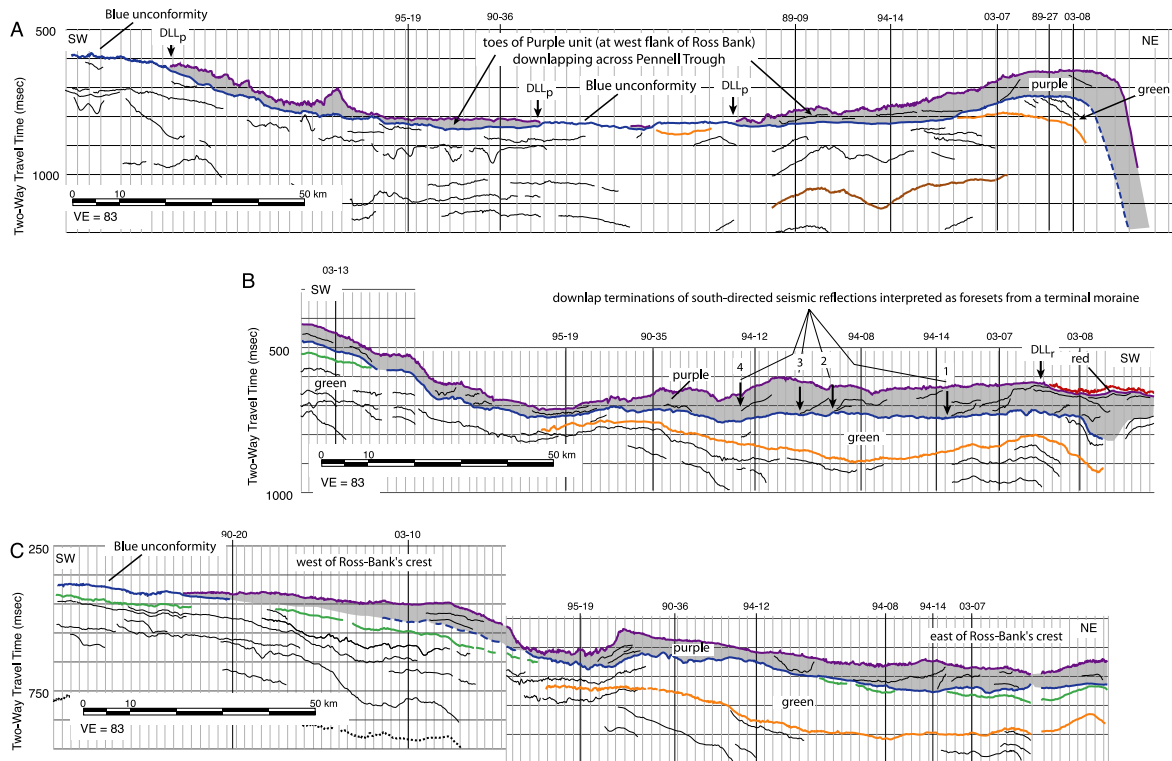


Fig. 9. (A) Line drawing of dip-oriented seismic profile NBP03-13 in Pennell Trough showing the thin edge of the Purple unit near its western downlap limit. (B) Line drawing of seismic profile NBP03-9 across the west flank of Ross Bank showing several seismic reflections within the Purple unit interpreted as poorly defined grounding zone foresets (i.e., proglacial surfaces) downlapping onto the underlying Blue unconformity. The progression of downlap terminations from northwest to southeast (see arrows numbered 1 to 4) suggests that the terminal moraine probably was not parallel with the present-day orientation of Ross Bank. (C) Line drawing of seismic profile NBP03-11 obliquely crossing the crest of Ross Bank (the relatively uniform offshore dip of the seafloor is due to the fact that the crest of the Ross Bank decreases elevation in an offshore direction).

Purple unit (i.e., at 30.5 mbsf). This section (base of Red and top of Purple) is assigned a Quaternary age by Hayes and Frakes [16] primarily on the basis of diatom biozones.

An additional 9 m of cored section are recovered within the remainder of the depth range that corresponds to the Purple unit at DSDP Site 271 (i.e., core 2 (40 to 49.5 mbsf), core 3 (i.e., 49.5 to 59 mbsf), core 4 (i.e., 59.0 to 68.5 mbsf), core 5 (i.e., 68.6 to 78.0 mbsf), and the upper part of core 6 (i.e., 78.0 to 87.5 mbsf). The longest continuous core, 5.5 m, is from core 5. No age is assigned for the depth range that corresponds to the lower 3/4 of the Purple unit. Below the Purple unit, the youngest down-hole age (Pliocene) reported by Hayes and Frakes [16] comes from the core catcher of core 16 (i.e., at 184.5 mbsf). This

stratigraphic level is close to the base of the Blue unit. The dominant lithology is silty clay with pebbles throughout.

The Red unit is also sampled at DSDP Site 272. At this location, the unit has a time thickness of ~22 ms, which corresponds to a depth range of 0 to 23.5 mbsf (using the ANTOSTRAT [18] time-depth conversion for Site 272). Within this depth range (core 1, i.e., 4 to 13.5 mbsf, and core 2, i.e., 13.5 to 23 m), recovery was 52%. The dominant lithology is silty clay with pebbles throughout. In a postcruise evaluation of this site, Cielski and Savage [17] assigned an age range of 0 to 0.62 Ma to the depth interval that corresponds to the Red unit. Seismic data indicate that a major angular unconformity is coincident with the base of the Red unit, and indeed,

core 3 (23 to 32.5 mbsf) recovered middle-Miocene claystone [17] below the Red unit.

## 4. Discussion

### 4.1. Absolute age control: when did Ross Bank (strata versus morphology) form?

If Ross Bank morphology is a consequence of deep incision into older strata at the axes of paleo ice streams (i.e., localized incision into strata that originally had regional extent), then the ridge strata should be significantly older than the unconformity. In contrast, if ridge strata were deposited in genetic association with the erosion of Ross Bank morphology (Fig. 2B or C), then there should be no significant hiatus between the age of section immediately above and below the Purple unconformity. Since the base of the Red unit and top of the Purple unit are both assigned a Quaternary age [16], then the Purple unconformity, the surface separating these two units, must also be of Quaternary age. The resolution of the age control reported from DSDP Leg 28 drill sites [16,17] is insufficient to more precisely define the age of either the Purple unit or to determine whether there is a significant hiatus at the Purple unconformity. Therefore, it is not possible to use reported ages to quantitatively assess the degree to which erosion of the Purple unconformity at Ross Bank morphology was or was not be coeval with the deposition of the underlying strata (i.e., Purple unit). Despite the imprecision of the age control, the Purple unit clearly is older than the seismic units that Shipp et al. [6] and Domack et al. [15] attribute to the Last Glacial Maximum (LGM; i.e., oxygen isotope stage 2).

### 4.2. Stratal criteria: how did Ross Bank form?

If Ross Bank is an eroded ridge, stratal surfaces should be truncated on both flanks (Fig. 2A). If the ridge was constructed by subglacial aggradation (Fig. 2B), stratal surfaces should be convex up, and stratal units within the ridge should thicken near the crest of the ridge and thin towards the axes of the ice streams, i.e., the flank of the ridge. Conversely, if Ross Bank formed as a terminal moraine (Fig. 2C), stratal surfaces should show unidirectional progradation in

the direction of grounding zone migration. On the basis of stratal relationships at Ross Bank, the erosional model (Fig. 2A) probably does not apply to the evolution of the ridge on the outer continental shelf because terminations are only observed on one flank of the ridge (Figs. 4 and 5). Likewise, the stratal terminations at the ridge's east flank are not consistent with the subglacial aggradation of till (Fig. 2B). In addition, the Purple unit stratal surfaces do not conform to the external morphology of the ridge except possible at the outermost shelf strike-oriented transect (Fig. 5A).

From the perspective of 2-D strike-oriented transects (Figs. 4 and 5), Ross Bank stratigraphy most closely resembles that expected for a terminal moraine (Fig. 2C). Within the framework of the terminal moraine model, dipping stratal surfaces are interpreted to be proglacial grounding zone foresets deposited into open water. East flow of the EAIS onto the western Ross Sea continental shelf [10,11,19,20] may have existed during the Purple unconformity grounding event, but stratigraphic evidence at Ross Bank shows that the zone of east-flowing grounded ice from east Antarctica did not encroach into Eastern Basin during the deposition of the Purple unit. For example, if east-flowing grounded ice of the EAIS was in contact with the west flank of Ross Bank, Purple unit stratal surfaces would dip towards the east as opposed to the observed westward dip on strike-oriented profiles (Figs. 4 and 5). The down-dip terminations of these surfaces on the underlying Blue unconformity are interpreted as depositional downlap at a line-sourced grounding zone system of the WAIS as it advanced from the east towards the west from a Marie Byrd Land accumulation zone. Terminations of west-dipping surfaces at the seafloor are interpreted as truncation of grounding zone foresets at a major subglacial eroded unconformity on the west flank and crest of Ross Bank, whereas the east flank is interpreted as the correlative conformity associated with the foreset progradation of the terminal moraine constructing into open water. The poor continuity and general paucity of internal reflections in the Purple unit is consistent with terminal moraine deposition within a proximal grounding zone setting dominated by sediment gravity flow processes.



#### 4.3. What is the stratigraphic relationship between Purple unit strata at Ross Bank and the adjacent TMF?

If Ross Bank morphology is a consequence of deep incision into older strata at the axes of paleo ice streams (Fig. 2A), then large upper slope depocenters constructed by the ice streams should be stratigraphically younger than the youngest Purple unit strata at the Ross Bank ridge. If the Ross Bank was constructed via subglacial accretion contemporaneous with erosion and sediment bypass at the adjacent ice streams (Fig. 2B), then TMF depocenters should be coeval with the age of ridge strata. Conversely, if Ross Bank was constructed as a terminal moraine associated with east–west directed ice sheet flow, then TMF development should be minimal.

From the local perspective of the Purple unit's thickness and distribution at Ross Bank, the pinch-out of Purple unit along ridge flanks is consistent with all three conceptual models considered in this study (Fig. 6). Unfortunately, as neither the base of the Purple unit (the Blue unconformity at Ross Bank) nor Purple unit stratal surfaces at the Ross Bank depocenter can be seismically correlated to Purple unit TMF depocenter (Fig. 8), it is not possible to evaluate whether the Purple unit strata at Ross Bank are older, younger, or coeval with TMF strata on the adjacent upper slope.

#### 4.4. Topographic criteria: what was the direction of ice flow at the time of ridge formation?

If north-flowing ice streams existed at the time of Ross Bank evolution (Fig. 2A, B), trough axes should be foredeepened to the south. Conversely, if the ridge formed as a terminal moraine (Fig. 2C) associated with either eastward flow of the EAIS or westward flow of the WAIS, the Purple unconformity might be foredeepened toward either the Transantarctic Mountains or Marie Byrd Land, respectively. The Purple unconformity exhibits downlap termination in Pennell Trough, and therefore, its map extent west of this zone was not investigated further. To the east, the Purple unconformity projects into the subsurface (Figs. 4 and 5), and thus, the adjacent unnamed ridges are constructed from seismic units (Red, Brown, Gray, and Yellow units) that are stratigraphically younger than the Purple unit outcropping at Ross Bank. The eastward

projection into the subsurface and the overlying stratigraphy suggest a regional-scale eastward foredeepening of the Purple unconformity associated with west-directed ice sheet flow from Marie Byrd Land. At a more local scale, the shelf basin to the immediate east of Ross Bank (Fig. 6) has the general form of a glacial trough. The slight southward dip of the shelf basin's thalweg suggests that ice stream flow through the trough was north directed. The landward termination of the Purple unit also suggests north-directed ice sheet flow. It is not possible to accurately estimate the volume of material eroded by the glacial trough, but a visual inspection of strike-oriented transects (Figs. 4 and 5) suggests that the volume removed exceeds that contained within the Purple unit at Ross Bank. Therefore, the end of the Purple unconformity grounding event probably was characterized by north-directed ice stream flow through a trough to the east of Ross Bank and, thus, delivery of sediment to the adjacent TMF depocenter (Fig. 8).

## 5. Conclusions

The west-directed accretion at Ross Bank (Figs. 4 and 5) is most consistent with the evolution of the ridge as a terminal moraine (Fig. 2C) associated with westward flow of the WAIS. The north–south oriented shelf basin (i.e., glacial trough) to the east of Ross Bank (Fig. 6) clearly requires north-directed ice flow, but this (north-directed flow) need only existed during the period of time prior to end of the grounding event (i.e., the direction and mode of grounding zone advance need not have been the same as ice flow existing during the latter part of the grounding event). On the basis of the available data, I tentatively propose that the upper part of Ross Bank strata on the outer continental shelf (i.e., the Purple unit) was deposited in open water as a terminal moraine associated with a major west-directed flow of the WAIS grounding zone in the initial phase of a Quaternary grounding event. If correct, perhaps this unusual flow pattern represents the first major reoccupation of Eastern Basin Ross Sea continental shelf by grounded ice after the Quaternary retreat of grounded ice from the West Antarctic Rift, as deduced by Scherer et al. [21]. The timing for both the major retreat [21] and the Purple unit grounding event

described here are too poorly constrained to either require or preclude linkage of these events. Given the configuration of the West Antarctic land surface, WAIS flow into Eastern Basin probably originated from elevated areas of Marie Byrd Land. I hypothesize that a shift from west-directed sheet flow to north-directed ice stream flow occurred during the later phase of this grounding event perhaps after the inner parts of the West Antarctic Rift became occluded similar to today. In this scenario, shift to north-directed ice stream flow produced the large erosional shelf basin (i.e., glacial trough) to the east of Ross Bank (Fig. 6) and the point source TMF depocenter on the adjacent slope (Fig. 8). I acknowledge that additional lithologic and chronologic data are needed to test this hypothesis for Ross Bank evolution, as well as to determine the degree to which the terminal moraine model may apply for other bathymetric banks in Eastern Basin Ross Sea.

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