INTERGLACIAL COLLAPSE OF CRARY TROUGH-MOUTH FAN, WEDDELL SEA, ANTARCTICA: IMPLICATIONS FOR ANTARCTIC GLACIAL HISTORY

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ABSTRACT: **In this study, we investigate the stratigraphy of a trough-mouth fan in the Weddell Sea to determine possible relationships between basin-floor stratigraphy and glaciation on Antarctica. Seismic data from the basin floor show a deep, broad, and elongate erosional channel filled by thick chaotic-facies deposits, basin-floor fans, and channel-levee deposits. From seismic-stratigraphy analysis of basin-floor stratigraphy, we infer that this channel formed by large-volume mass wasting sourced from poorly sorted glacial sediments from Crary Trough-Mouth Fan and Dronning Maud Land slopes. Correlation to ODP Leg 113 Site 693 suggests that the mass wasting of the slopes occurred in the early Pliocene. We surmise that collapse occurred during an early Pliocene interglacial and was related to major drawdown of the antarctic ice volume. Collapse was probably triggered by rebound and relative sea-level fall, a mathematically predicted geoidal effect related to antarctic ice-volume reduction. The record of this major ice-volume reduction is not manifest in the trough-mouth fan but rather is manifest in the basin-floor stratigraphy as a major backfilled erosional channel, which extends far beyond the trough-mouth fan.**

INTRODUCTION

Glaciated margins can be characterized by many different depositional styles, and generally speaking, glacial depositional systems do not conform to depositional models developed for unglaciated margins. In particular, trough-mouth fans (TMFs) are shelf-edge and upper-slope depocenters adjacent to mouths of paleo–ice streams (Vorren and Laberg 1997) that existed along glaciated or formerly glaciated continental margins in high and mid-latitudes. These localized prograding-slope strata developed during glacial periods when ice sheets attained maximum thickness and extended to the shelf edge. In recent years, TMFs have been intensively studied along the margins of Canada, Greenland, Norway, and the British Isles (Piper and Normark 1982; Laberg and Vorren 1993, 1995; Hiscott and Aksu 1994; Vanneste et al. 1995; Stoker 1995; King et al. 1996; Vorren et al. 1998) and along the antarctic margins of the Ross Sea, the Antarctic Peninsula, the Weddell Sea, Prydz Bay, and Wilkes Land (Larter and Barker 1989; Bartek et al. 1991; Cooper et al. 1991; Kuvaas and Kristoffersen 1991; Moons et al. 1992; Anderson and Bartek 1992; Anderson et al. 1992; Larter and Vanneste 1995; Eittreim et al. 1995; Bart and Anderson 1996; De Batist et al. 1997).

Trough-mouth-fan strata consist of glacigenic sediment gravity flows (Damuth 1978; Vorren et al. 1988; Vorren et al. 1989) sourced from the grounding line of ice streams during glacial expansions. According to TMF models, these prograding-slope strata pinch out on the lower slope. Yet, in the antarctic, significant amounts of terrigenous clastics exist on the basin floor, far beyond the limits of TMFs. These basin-floor deposits exist either in the form of deep-sea fans (Anderson et al. 1986; Escutia et al. 1997), drift mounds (McGinnis and Hayes 1994; McGinnis et al. 1997; Rebesco et al. 1997), or distal turbidite sands (Tucholke et al. 1976; Kennett and Barker 1990). It has been suggested that these distal sediments are coeval with the deposition of the TMFs and thus with glacial expansions, but this is still a matter of debate: e.g., McGinnis and Hayes (1994) versus Rebesco et al. (1997). The stratigraphic relationships between these distal and proximal sediments have not yet been clearly established. Yet, it is important to do this before we can determine the information these deposits reveal about the glacial history on the continent.

In this paper, we investigate the stratigraphic relationships on the southeastern Weddell Sea basin floor, which we define as the region beyond the TMF (Fig. 1), via seismic correlation and contour mapping of a key unconformity surface and overlying seismic facies units. We attempt to place these results within the context of TMF stratigraphy. The results are then utilized to make preliminary inferences about the possible significance of basin-floor sediments with regard to glacial processes on Antarctica.

DATA AND METHODS

A regional grid of multichannel seismic profiles (Fig. 2) was jointly collected in the southeastern Weddell Sea by the Alfred Wegener Institute and the Renard Center of Marine Geology during the Antarktis V/4 (1986–87), Antarktis VIII/5 (1989–90), and Antarktis X/2 (1992) cruises. The bulk of the data was collected on the eastern Weddell Sea beyond the northeastern basinward limit of Crary Trough-Mouth Fan (CTMF). This grid (approximately 2000 km of seismic data) is one of the best from the basin-floor setting beyond an antarctic slope in terms of coverage and density. The data were acquired with two objectives in mind: firstly to understand the tectonic evolution of the margin (Jokat et al. 1996), and secondly to understand the stratigraphic evolution of the CTMF and basin-floor stratigraphy.

In the 1986/87 and 1989/90 surveys, seismic profiles were acquired using an 8-liter array of PRAKLA-SEISMOS airguns operated at 140 bars. The active cable length of the 24-channel PRAKLA-SEISMOS streamer was 600 m. During the 1992 survey, a 24-liter airgun array was used with a 96-channel 2400 m streamer. The digital-data acquisition system consisted of an EG&G GEOMETRICS ES 2420 seismograph with data storage on two CIPHER tape drives. Data processing (including bandpass filtering, scaling, sorting, and stacking) was carried out on the CONVEX computer with DISCO seismic software on board the R/V Polarstern and at the Alfred Wegener Institute in Bremerhaven.

REGIONAL SETTING

Present Antarctic Climatic Conditions and Ice-Sheet Cover

Because of the geographical position of Antarctica, temperature and precipitation rates are very low. So arid is the current antarctic climate that a modest increase in average temperatures would increase precipitation rates (Oerlemans 1982), which might have the unexpected result of causing the antarctic ice sheets to expand (Huybrechts 1994). Today, more than 90% of Antarctica is ice covered (Fig. 1), but ice sheets are at neither their maximum extent nor volume. Contained in the extensive and thick antarctic ice sheets is an ice volume equivalent to a change of global sea level of approximately 70 m (Robin 1988). In the interior of the continent, ice reaches a maximum thickness of approximately 4000 m, overlying intercontinental subglacial basins and all but the highest peaks of mountain chains, such as the peaks of the Transantarctic Mountains.

Ice cover terminates either in the marine environment or on land very near the coast. The subfreezing temperatures result in no significant melt-

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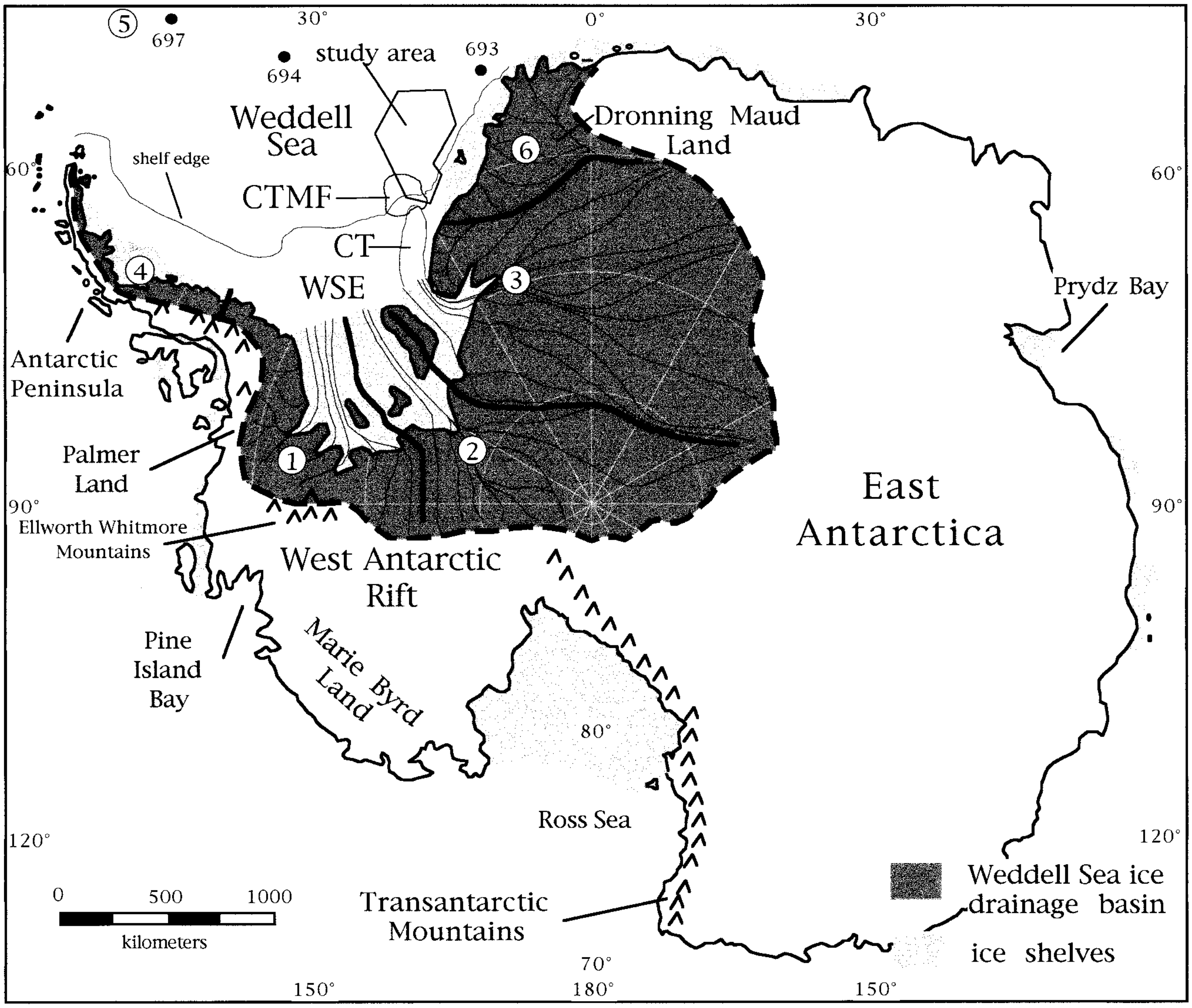


FIG. 1.—Location map showing the southeast Weddell Sea study area, ODP sites, and geographic localities mentioned in the text. The Weddell Sea drainage basin is shaded in dark gray and outlined by a heavy dashed line. The heavy solid lines separate the six (circled numbers) subregions of the Weddell Sea drainage basin. (CT = Crary Trough; CTMF = Crary Trough-Mouth Fan; WSE = Weddell Sea Embayment.)

water production except on the northernmost part of Antarctic Peninsula, during the short summer. Ice is discharged from the ice sheet primarily through wide ice streams, zones of fast moving ice. The primary form of ablation of the ice sheet in the current antarctic climatic setting is calving, whereby large icebergs break off the ice sheet and drift northward until they break up by the action of waves.

Tectonic Control on Ice-Sheet Development and Drainage into Weddell Sea

The transition from a temperate to the current polar climate in Antarctica was a consequence of separation from Gondwana and southward drift. Recent estimates indicate that drift (Antarctica-South America-Africa) started between 165 to 149 Ma (Livermore and Hunter 1996). During the Oligocene, the separation of Antarctica and South America at the Drake Passage (Barker and Burrell 1977) caused the complete opening of the Southern Ocean, which led to the establishment of a deep-marine connection, and the onset of circumpolar circulation. At about 22 Ma, deep-water circumpolar circulation was fully developed (Craddock and Hollister 1976; Ciesielski and Wise 1977). These events eventually led to the thermal isolation of Antarctica and development of continental-scale ice sheets in the mid- to late Miocene (Shackleton and Kennett 1975; Kennett 1977; Mercer 1983; Kennett and Barker 1990).

Extensional fragmentation also produced the major topographic elements on the continent, which include the attenuated continental crust of the West Antarctic Rift and its elevated rift shoulder, the Transantarctic Mountains (Fig. 1). These and other tectonic features control the overall physiography of the continental areas bordering the Weddell Sea and hence control ice-sheet drainage from the continent to the marine margins. Because of its low elevation, a high percentage of ice-volume drainage converges towards the West Antarctic Rift. Convergent ice-volume drainage (and hence sediment supply) into the Weddell Sea Embayment, a subdivision of the West Antarctic Rift, is derived from three areas, numbered 1 to 3 in Fig. 1. Drainage area 3 is the largest and sources Crary Trough (Fig. 1). The Crary Trough receives approximately 25% of the ice-volume drainage from the continent. Drainage basins 4, 5 (South Orkney Microcontinents of the discontinuous South Scotia Ridge), and 6 are small drainage areas with divergent ice-volume drainage. Hence, submarine margins adjacent to areas

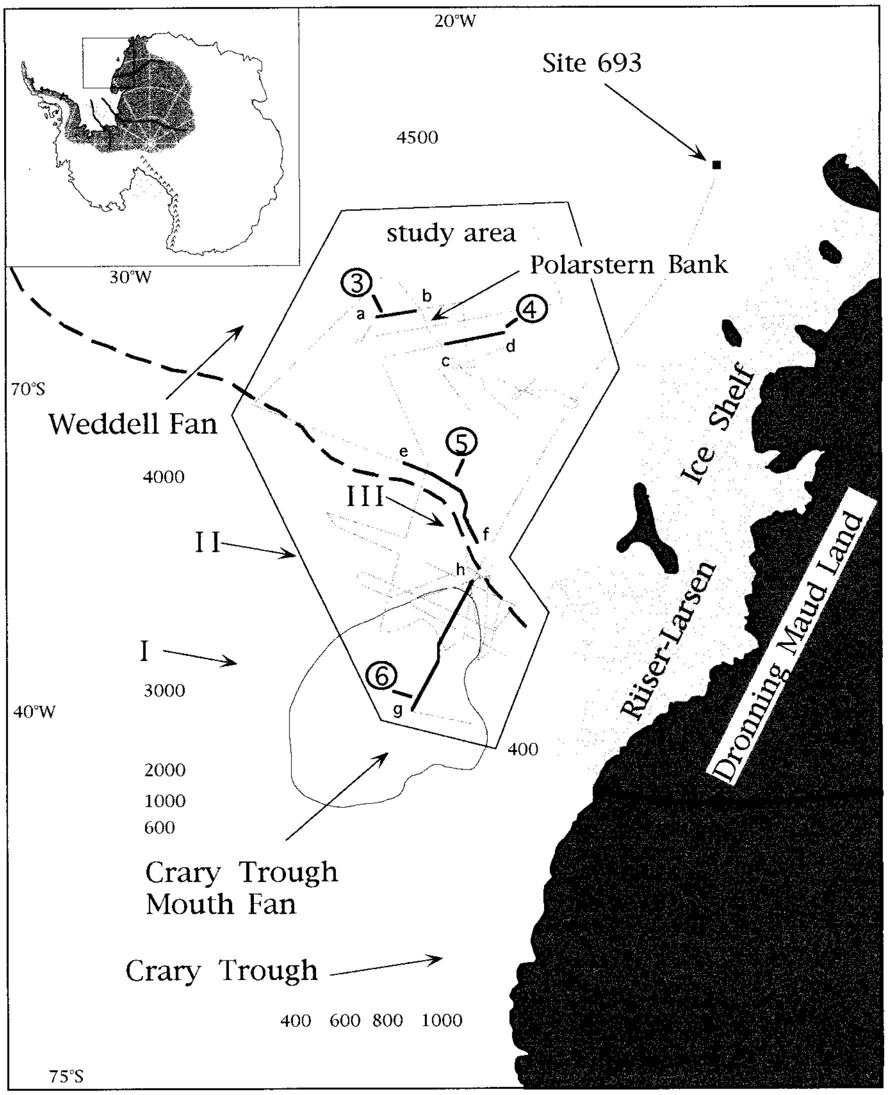


FIG. 2.—Weddell Sea study area, bathymetry, and seismic grid. Crary Trough-Mouth Fan is indicated by stippled pattern bordered by a thin solid line. The western limit of the Weddell Fan is indicated by a heavy dashed line. The circled numbers (3 through 6) refer to figure numbers of seismic profiles presented in this article. Segments of seismic profiles presented are indicated with a solid bold line marked with letters (a–h). (Symbols I, II, and III = Channel-levee systems I, II, and III)

4, 5, and 6 receive relatively little sediment input. The study area receives drainage from areas 3 and 6.

Weddell Sea Physiography

Bathymetry in the Weddell Sea study area (Fig. 2) is fairly well known. The bathymetry shown in Fig. 2 is the most recent version constructed at the Alfred Wegener Institute from a compilation of seismic and sounding information. Crary Trough is the most conspicuous feature on the wide continental shelf of the southeastern Weddell Sea. Crary Trough exhibits a broad and foredeepened topography with a maximum observed axial depth of 1140 m (Haugland et al. 1985) and a sill depth of 630 m at the shelf edge. Overdeepening and foredeepening is a consequence of ice-stream glacial erosion and isostatic depression by thick ice sheets (Anderson 1991). The upper continental slope in front of the Crary Trough is characterized by oceanward-convex bathymetric contours (Fig. 2) outlining the general extent of the CTMF depocenter. The morphology of the CTMF is smooth and without major canyons. The average upper slope gradient is 1.5°. On the lower slope, this relatively smooth morphology changes to one dominated by large elongate ridges numbered I, II, and III (Fig. 2). Polarstern Bank, a chain of volcanic sea mounts (Jokat et al. 1996), forms a series of major positive elements on the basin floor. Along the Dronning Maud Land (DML) margin, the relatively narrow continental shelf is covered by the Riiser/Larsen Ice Shelf. DML slopes are steep (15° on average), and submarine canyons are numerous (Fig. 2).

Results of ODP Leg 113, Sites 693 and 694

Drill sites from ODP Leg 113 provide the only deep subsurface chronostratigraphic and lithostratigraphic control in the region. Leg 113, Site 693, is located in the eastern Weddell Sea on a middle-slope bench off DML (Fig. 2). Seismic coverage extends to ODP Leg 113 Site 693 to the east of the study area. Albian to Aptian organic-rich sediments are overlain by terrigenous silty and clayey sediments separated by a major unconformity spanning approximately 60 My (Kennett and Barker 1990), i.e., early Cretaceous to Oligocene. Miller et al. (1990) referred to this as the W4 unconformity. Another major unconformity, W5, separates lower Middle Miocene nannofossil-bearing clayey mud and diatomaceous silt to clay with some slumps, from Upper Miocene silty and clayey mud.

ODP Site 694, located on the central Weddell Sea abyssal plain (Fig. 1), sampled Upper Miocene distal hemipelagics, pelagics, and fine-grained turbidites overlain by a thick package (90 m) of Lower Pliocene coarse-grained turbidites. Site 694 lithostratigraphy has not been correlated to seismic-stratigraphic results on the adjacent margins (Kuvaas and Kristof-

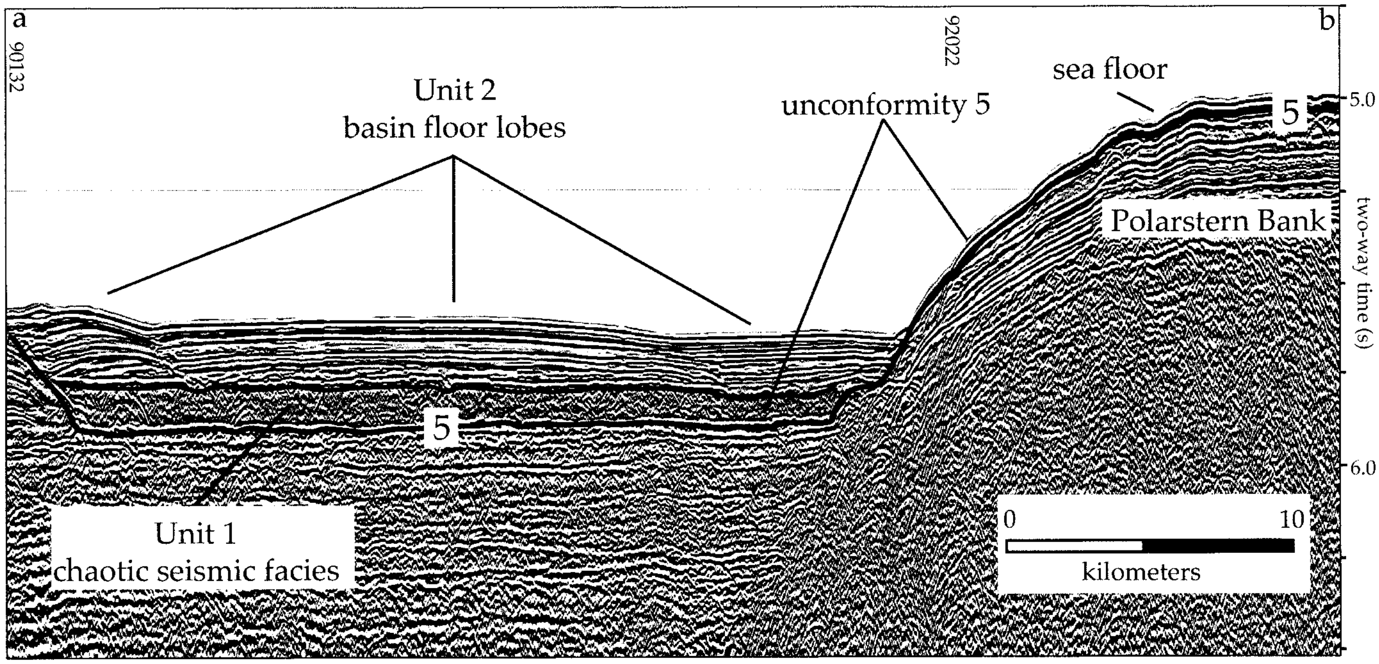


FIG. 3.—Seismic profile 90133 on the basin floor on the western flank of Polarstern Bank distant from Crary Trough-Mouth Fan. Unit 1, the chaotic seismic facies unit, infills Unconformity 5 topography and is believed to be derived from the body of large-volume turbidity currents sourced from TMF strata. Subsequent shedding from the upper slopes produced the basin-floor-fan strata (Unit 3).

fersen 1991; Anderson et al. 1986; Moons et al. 1992; De Batist et al. 1997) because of a lack of seismic control.

Previous Studies of Weddell Sea Stratigraphy

Anderson et al. (1986) defined the limits of the large (0.75 million km^2) Weddell Fan using piston cores and high-resolution seismic data. The southwestern limit of Weddell Fan is shown in Fig. 2. From petrographic analysis of sand-size sediment, they concluded that this region was sourced primarily from DML (drainage area 6; Fig. 1). Using multichannel seismic data, Kuvaas and Kristoffersen (1991) investigated the stratigraphy off Crary Trough and found that the elongate bathymetric ridges on the basin floor (Fig. 2) are major channel-levee systems (I, II, and III). The updip limits of these systems are buried below the distal limits of CTMF. Channel-levee system III is located within the study area (Fig. 2). These channel-levee systems are believed to have formed during a temperate glacial climate when copious meltwater existed.

On the basis of truncation and onlap relationships, Moons et al. (1992) subdivided the strata of the channel-levee systems into 20 fan units. Using different seismic data sets, Kuvaas and Kristoffersen (1991) and Moons et al. (1992) independently correlated unconformities W4 and W5 from ODP Site 693 (Miller et al. 1990) to the area of our study. The correlation distance is approximately 500 km, but despite this long distance, both correlations are in agreement. At present, these correlations provide the best subsurface age constraints in the study area. Using these age constraints, Moons et al. (1992) tentatively correlated the 20 fan units with the Haq et al. (1987) eustatic cycles and established the overall sequence stratigraphy of the fan.

SEISMIC STRATIGRAPHIC ANALYSIS

Interpreted Seismic Profiles

Four seismic profiles have been selected to illustrate the specific stratal relationships between the basin-floor deposits in the southeastern Weddell Sea and the prograding-slope strata of the CTMF. Profiles 90133 and 90137 (Figs. 3, 4) are lines obliquely oriented across the basin floor in water depths of about 4000 m and approximately 150 km beyond the downlap limits of the CTMF strata (Fig. 2). Profile 92020 (Fig. 5) is an oblique line at the distal end of the CTMF prograding-slope strata. Profile 90060 (Fig. 6) is a dip line over the northeastern sector of CTMF.

Profiles 90133 and 90137 (Figs. 3, 4) show the primary stratal relationships observed on this sector of the Weddell Sea basin floor. The most conspicuous feature is an erosional unconformity, Unconformity 5, which is overlain by a chaotic seismic facies unit, Unit 1. Seismic Profile 90133 (Fig. 3) crosses to the west of Polarstern Bank (Fig. 2) where Unconformity 5 defines a broad channel. On the western flank, the channel cuts approximately 300 ms into the underlying strata. The eastern flank of the channel is defined by Polarstern Bank. The channel is 30 km wide at this location. Unit 1 blankets and partially infills the base of the channel. This unit has a uniform thickness of about 100 ms at this cross section. The top of Unit 1 is even and horizontal. Above Unit 1, a major change in seismic facies type occurs. The overlying unit, Unit 2, is a stratified seismic facies characterized by parallel to subparallel reflection patterns that exhibit bidirectional downlap onto the upper surface of Unit 1. Unit 2 has several large lobes which have convex-up geometry. Lobes have widths of 10 km and thicknesses of 200 ms.

Fig. 4 is a segment of Profile 90137 from the eastern side of Polarstern Bank. Seismic coverage does not permit direct correlation around the flanks of Polarstern Bank. However, as on the western side of Polarstern Bank, an erosional unconformity is overlain by a chaotic seismic facies unit. On the basis of the similarity of stratal relationships observed to the west and on the similarity of its subsurface position, the erosional unconformity is tentatively correlated with Unconformity 5 and the chaotic seismic facies unit is regarded as correlative with Unit 1 to the west of Polarstern Bank. On the eastern side of Polarstern Bank, Unit 1 is overlain by a stratified seismic facies unit, Unit 3. Unlike the lobes of Unit 2, Unit 3 has the general morphology of a one-sided channel-levee system. Unit 3 has a maximum thickness of 500 ms, and thins towards and away from Polarstern

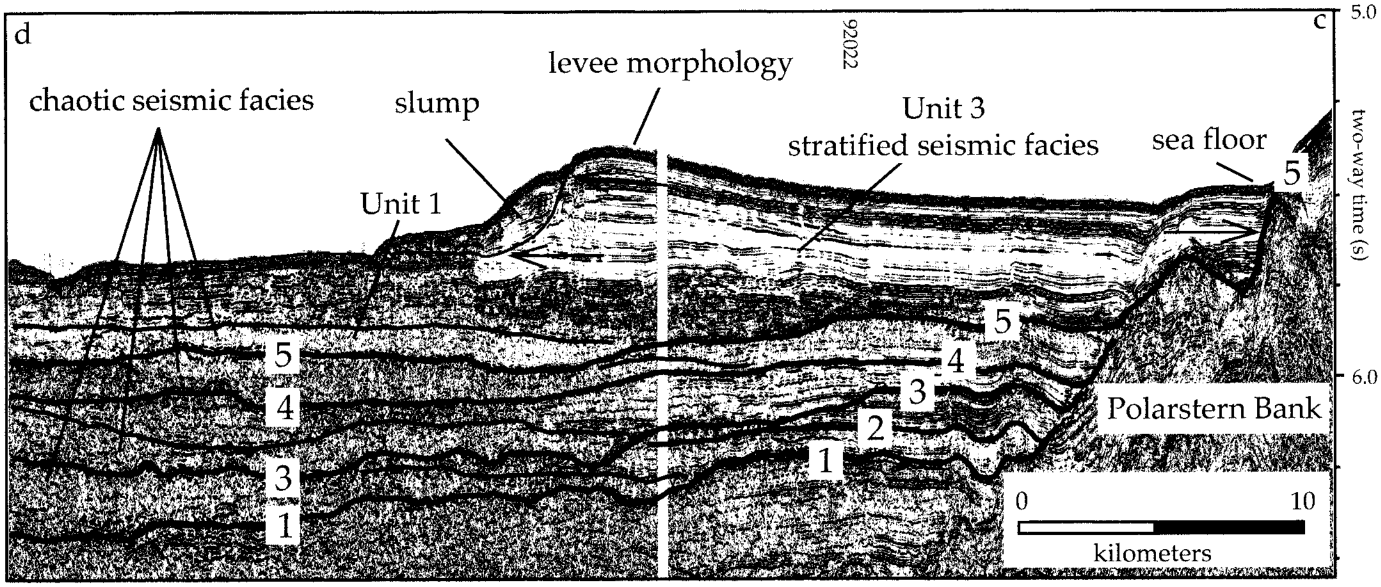


FIG. 4.—Seismic profile 90137 on the basin floor on the eastern flank of Polarstern Bank distant from Crary Trough Mouth Fan. The chaotic seismic facies unit (Unit 1) is overlain by a stratified seismic facies unit (Unit 3) that has the morphology of a levee.

Bank. The thinning and internal stratal patterns in Unit 3 indicate aggradational onlap of Unit 3 against Polarstern Bank. In the direction away from Polarstern Bank, thinning of Unit 3 is more abrupt, and reflector terminations indicate slumping and erosional truncation at or near the sea floor. The top of Unit 3 defines a sea-floor channel that has no appreciable fill. Other unconformities (Unconformities 4, 3, 2, and 1) exist below Unconformity 5. Chaotic seismic facies units are found above Unconformities 4, 3, and 1.

Unconformity 5 was correlated towards the CTMF to determine the stratigraphic relationship of this erosional surface with the TMF strata. On Profile 92020 (Fig. 5), one flank of the Unconformity 5 channel is observed to deeply erode (approximately 1000 ms) into underlying strata of channel-levee system III. Four other major erosional unconformities, each directly overlain by a chaotic seismic facies (Unconformities 4, 3, 2, and 1), also are found within strata of channel-levee system III (Fig. 5). These unconformities and the overlying units are tentatively correlated to those observed on Profile 90137 (Fig. 4) in the Polarstern Bank area. On Profile 92020 (Fig. 5), the basal fill of the Unconformity 5 channel is a thick (250 ms) chaotic seismic facies. Judging from seismic mapping and correlation, this chaotic seismic facies unit is regarded as correlative with Unit 1 observed on Profiles 90133 and 90137 (Figs. 3, 4). The basal infill (Unit 1), is overlain by a stratified seismic facies, Unit 4. Seismic correlation and mapping suggest that Unit 4 is not contiguous with either Unit 2 or Unit 3 on the basin floor but rather corresponds to the thinning distal edges of CTMF.

Unconformity 5, Unit 4, and Unit 1 are correlated to Profile 90060 (Fig. 6). Seismic correlation to Profile 90060 indicates that Unit 1 does not extend up the slope. Profile 90060 shows Unconformity 5 and the typical prograding-slope strata of the CTMF (Unit 4). Low-angle downlap of these prograding-slope strata completely bury the Unconformity 5 erosional topography. Seismic correlation to the east (along the continuation of Profile 90060; Fig. 2) indicates that Unconformity 5 is correlative with the major canyons manifest at the sea floor on the DML lower slope.

Contour Maps of Unconformity 5 and the Units 1, 2, 3, and 4

Contour maps were constructed from the seismic grid to investigate the relationship of Unconformity 5 and its overlying units (Units 1 to 3) to the development of the CTMF (Unit 4). The maps (Figs. 7, 8) are described below. Figure 7 shows the contour map at Unconformity 5. Contours are in two-way travel time (seconds). A broad amphitheater-shaped depression is evident on the unconformity-5 lower slope. The location of this feature is coincident with the northeastern flank of the modern CTMF (Unit 4). The amphitheater-shaped depression and several DML slope canyons converge at the base of slope. This erosional feature extends basinward, where it bifurcates around Polarstern Bank. The contour map of this depression suggests an elongate mini-basin on the lower continental margin. A prominent ridge defines the western edge of the mini-basin. This ridge corresponds with the crest of the channel-levee system III. Subsequent deposition was confined to the mini-basin and included the four major units illustrated on the seismic profiles:

Unit 1: a chaotic seismic facies unit partially infilling the base of the mini-basin;

Unit 2: a stratified seismic facies unit with mounded morphology, overlying the chaotic seismic facies to the west of Polarstern Bank;

Unit 3: a stratified seismic facies unit with levee morphology, overlying the chaotic seismic facies to the east of Polarstern Bank; and

Unit 4: a stratified seismic facies unit of the CTMF.

The extent and thickness (in two-way travel time) of these different units are shown in Figure 8 (A to D). The time-thickness contour map (Fig. 8A) of the chaotic seismic facies unit (Unit 1) shows that it is extensive but confined to the Unconformity 5 mini-basin to the west and east of Polarstern Bank and pinches out on the lower slope. The maximum thickness is 250 ms, and the unit extends over an area of approximately 28,000 km^2. Using an average thickness of 100 ms and a velocity of 1500 m/s, we estimate that in the study area the volume of Unit 1 is approximately 2100 km^3.

The time-thickness contour map of the Unit 2 stratified seismic facies shows that it is confined within the Unconformity 5 mini-basin to the west of Polarstern Bank (Fig. 8B). Unit 2 has average thickness of approximately 100 ms over an area of approximately 12,500 km^2. The estimated volume of Unit 2 is approximately 950 km^3. Unit 3, the stratified seismic facies unit, overlies the mini-basin to the east of Polarstern Bank (Fig. 8C). The unit has an average thickness of 200 ms, an approximate area of 17,500 km^2 and an approximate volume of 2600 km^3. CTMF strata (Unit 4) show basinward thinning and downlap onto the base and flanks of the mini-basin

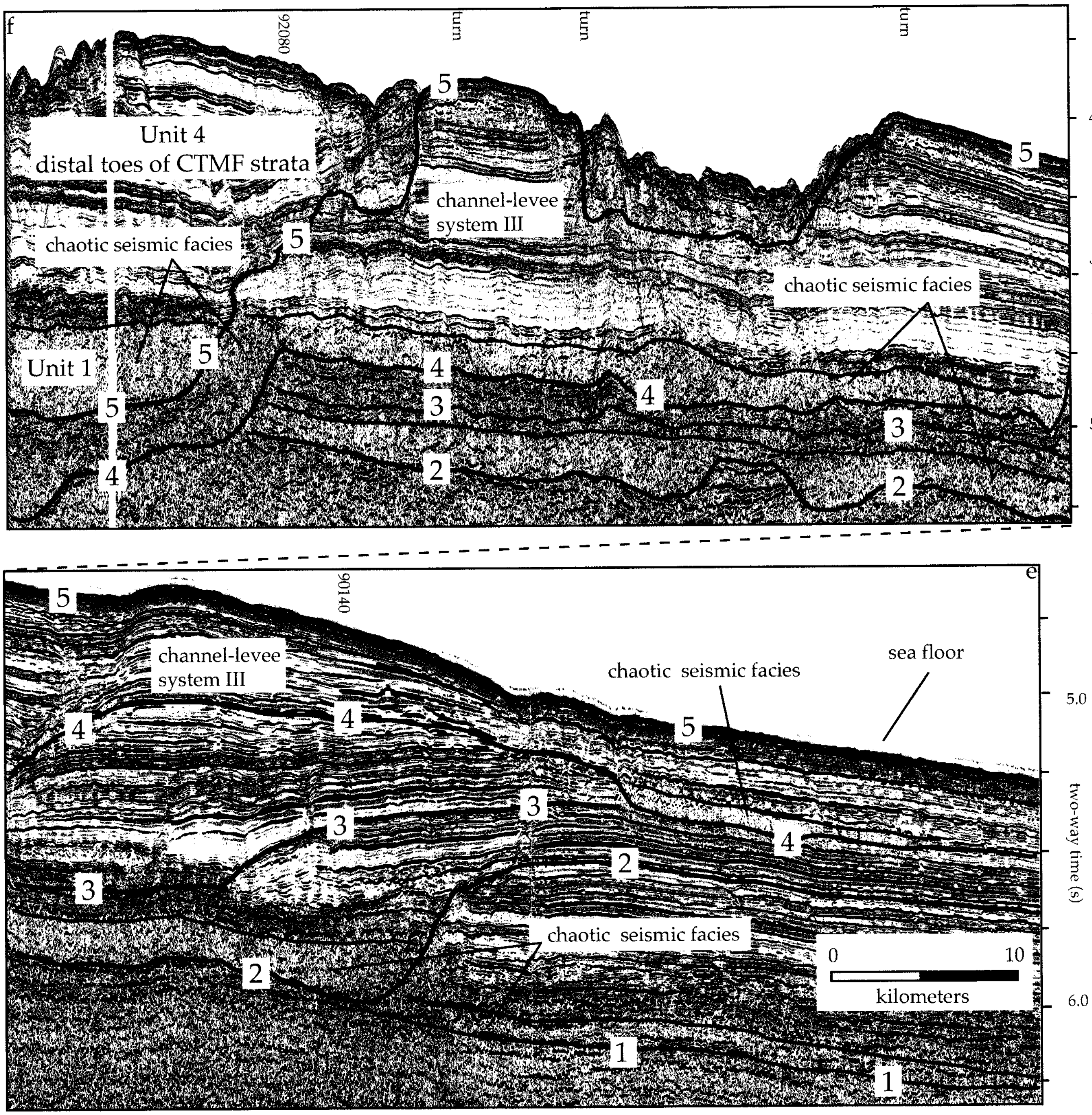


FIG. 5.—Seismic profile 92020 at the basinward limit of Crary Trough Mouth Fan on the lowermost slope. At the left-hand side of the upper panel, the base of Unconformity 5 erosional topography is filled with Unit 1 (chaotic seismic facies). Unit 1 is overlain by the distal toes of Crary Trough Mouth Fan strata. In the subsurface, Unconformities 4, 3, 2, and 1 are each overlain with a chaotic seismic facies unit and a stratified seismic facies unit.

(Fig. 8D). On the lower slope, the CTMF strata bury the chaotic seismic facies unit (Unit 1) and the Unconformity 5 mini-basin.

DISCUSSION

Stratigraphic Relationships between Weddell Sea Basin-Floor and Trough-Mouth-Fan Units

Seismic-stratigraphic analysis and contour mapping indicate that a major episode of deep channelized erosion (Unconformity 5) affected the southern Weddell Sea slope and basin-floor area. The great depth and length of the Unconformity 5 erosional scour into channel-levee system III suggest that the Unconformity 5 mini-basin should be regarded as an erosionally enhanced preexisting channel. From the observed pattern of erosion, we propose that erosion at Unconformity 5 extended far up the slopes of CTMF and DML. However, upper-slope topography of Unconformity 5 is not well constrained because of the lack of data in that area. On the basin floor, the chaotic seismic facies type of Unit 1 suggests that it is composed of poorly sorted material. The large volume of Unit 1, its confinement to the Un-

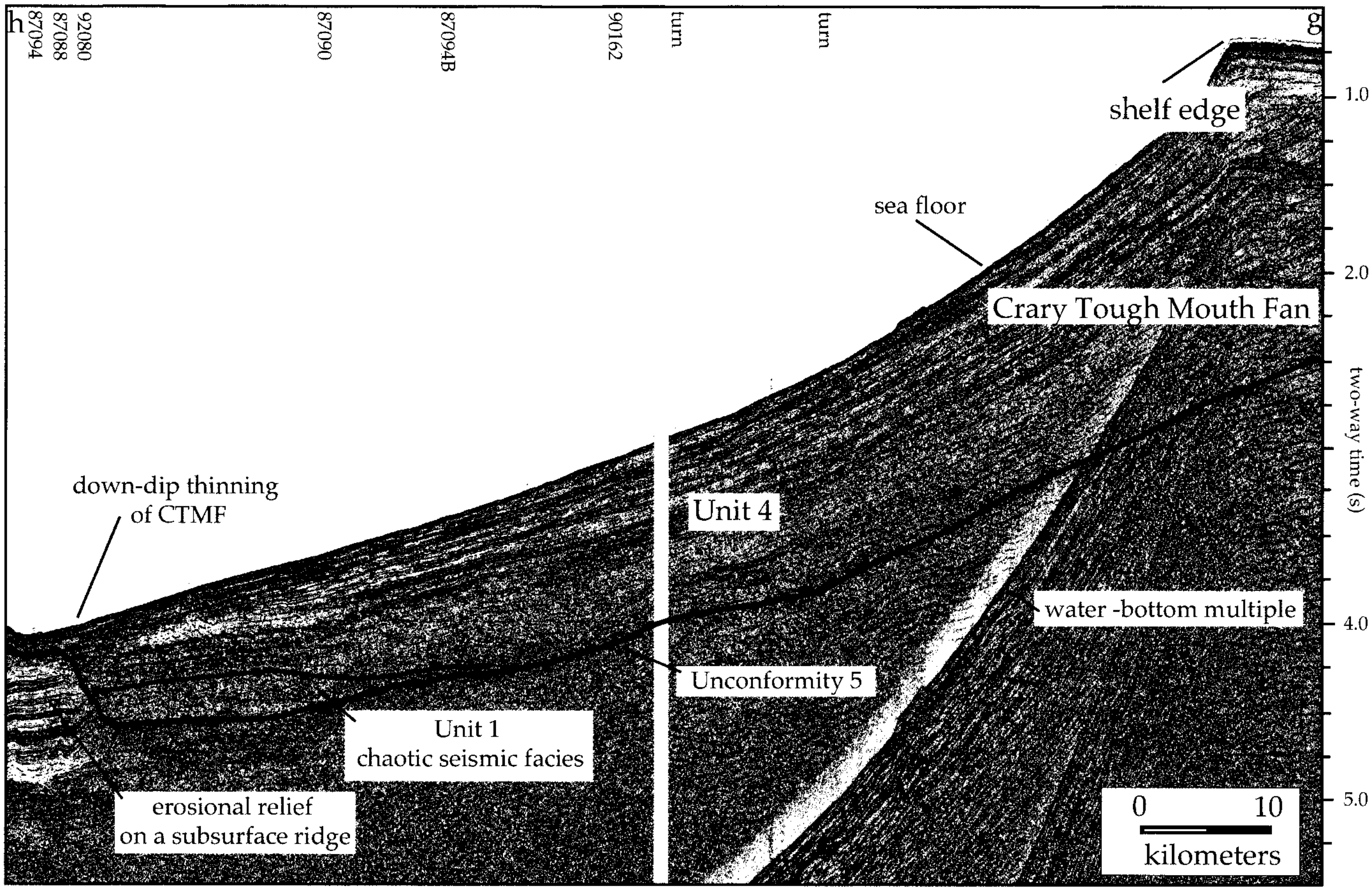


FIG. 6.—Seismic profile 90060 is dip-oriented on the eastern flank of Crary Trough-Mouth Fan. The projection of Unconformity 5 into Crary Trough Mouth Fan is indicated. At the left hand side of the figure, the subsurface ridge corresponds to the updip limits of channel-levee III.

conformity 5 mini-basin, and the style of mini-basin infill on the basin floor reflect a dip-aligned evolution of this stratigraphy. We infer that Unit 1 is a poorly sorted deposit resulting from large-scale upper-slope mass wasting. The shelf-derived poorly sorted and texturally immature glacial sediments (Wright and Anderson 1982; Anderson et al. 1983) are the source material for the upper-slope depocenters. Large-scale remobilization of these glacial sediments probably produced sediment-gravity-flow transitions including large-volume mass flows and faster-flowing high-density turbidity currents. The turbidity currents probably excavated a preexisting channel during their downslope passage, and the slower-moving mass flows partially infilled the excavated channel.

Stratal patterns indicate that the Unconformity 5 erosional channel was only partially filled after the deposition of Unit 1, and thus, the mini-basin continued to act as a depocenter. From the observed bidirectional downlap and the mounded morphology in (oblique) strike view, we infer that the Unit 2 lobes are basin-floor fans. The observed seismic stratal pattern of Unit 2 could alternatively be interpreted as migrating sediment waves, suggesting a drift or contourite origin. However, because Unit 2 is restricted to the mini-basin, we discount a contour-current origin and regard these mounds as reflecting primary basin-floor-fan depositional morphology associated with relatively small-volume mass wasting originated on the continental slope. Juxtaposition of the basin-floor fan deposits (Unit 2) overlying the mass-flow deposits (Unit 1) indicates a backfilling stratal pattern, which we infer reflects conditions of diminishing sediment supply from the slope.

To the east of Polarstern Bank, the morphological and seismic facies characteristics of Unit 3 suggest that it is a levee that aggraded above the Unit 1 mass-flow deposit. The channel-levee system is highly asymmetrical, with a well-developed western levee and an eastern levee that is virtually absent. Levee asymmetry is attributed to Coriolis force (Moons et al. 1992) and the westward-flowing Weddell Sea Gyre currents. The fact that the stratified levee strata (Unit 3) overlie the chaotic seismic facies unit (Unit 1) is a very important observation because it shows that the Unit-1 deposit is not the channel fill of the overlying aggrading levee.

On the basis of their existence directly above the mass-flow deposit, Unit 2 (basin-floor fans) and Unit 3 (channel-levee) are regarded as essentially coeval. The difference in overall form (fan versus levee) on either side of Polarstern Bank may be related to a difference in sediment type supplied from the up-dip margins. To the west of Polarstern Bank, the mini-basin was probably sourced by mass wasting from the CTMF slope, whereas to the east of Polarstern Bank, the mini-basin probably received sediment supply from both the CTMF and DML slopes. Perhaps the sediment supplied by the DML slopes was dominantly fine-grained and hence resulted in the construction of a large levee on the basin floor to the east of Polarstern Bank.

The seismic data show that there is overlap between the distal toes of the CTMF strata (Unit 4) and the mini-basin fill (Unit 1) on the basin floor, but the lack of interfingering between basin-floor and TMF strata shows that major mass wasting was out of phase with TMF outbuilding. Correlation to ODP Site 693 suggests that the CTMF strata above unconformity 5 truncate lower Pliocene strata whereas TMF strata above unconformity 5 are upper Pliocene and Pleistocene in age. From the approximate volumes of Units 1, 2, and 3, we estimate that the volume of sediment that was remobilized to scour and source the down-dip mini-basin infill could have

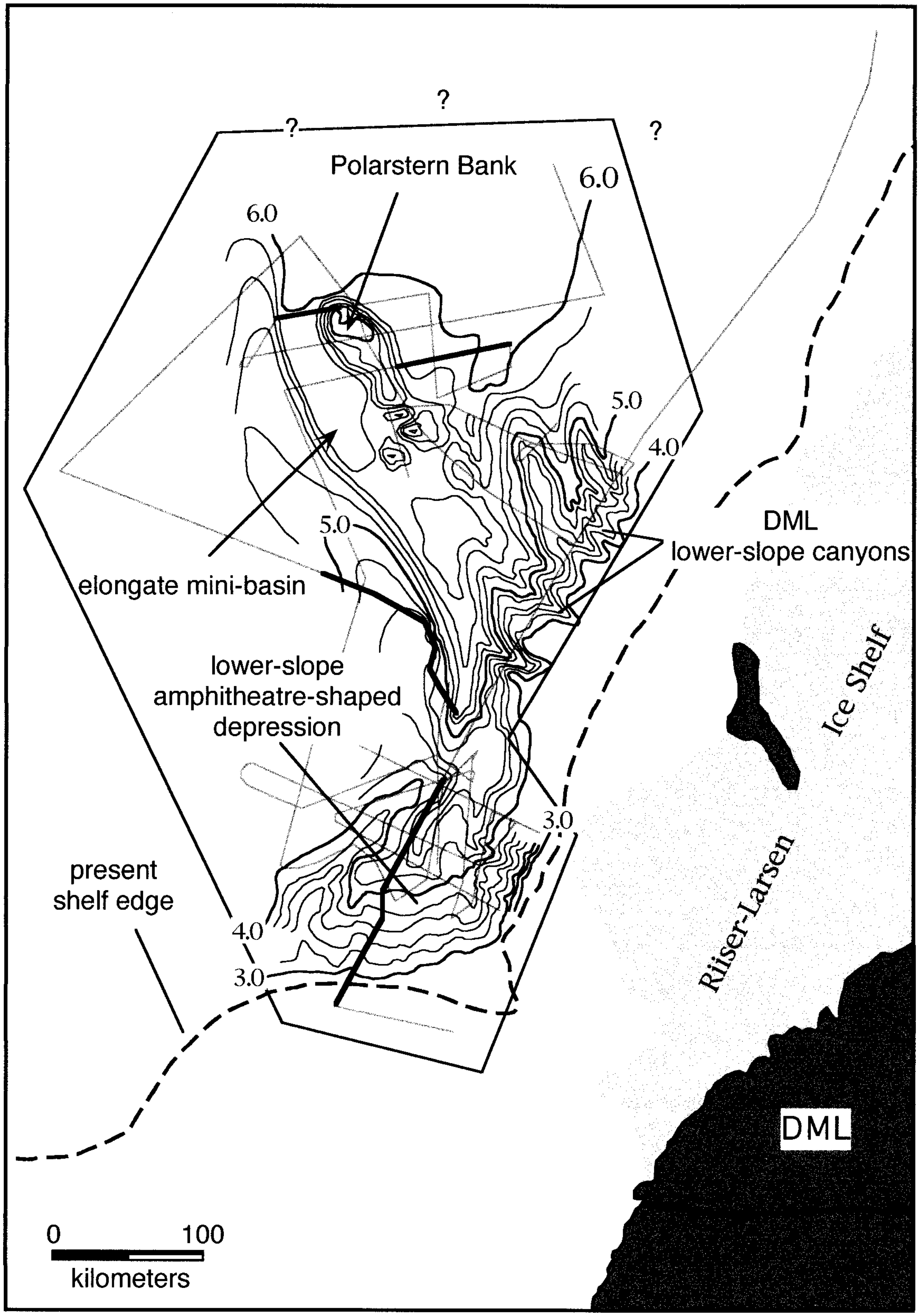
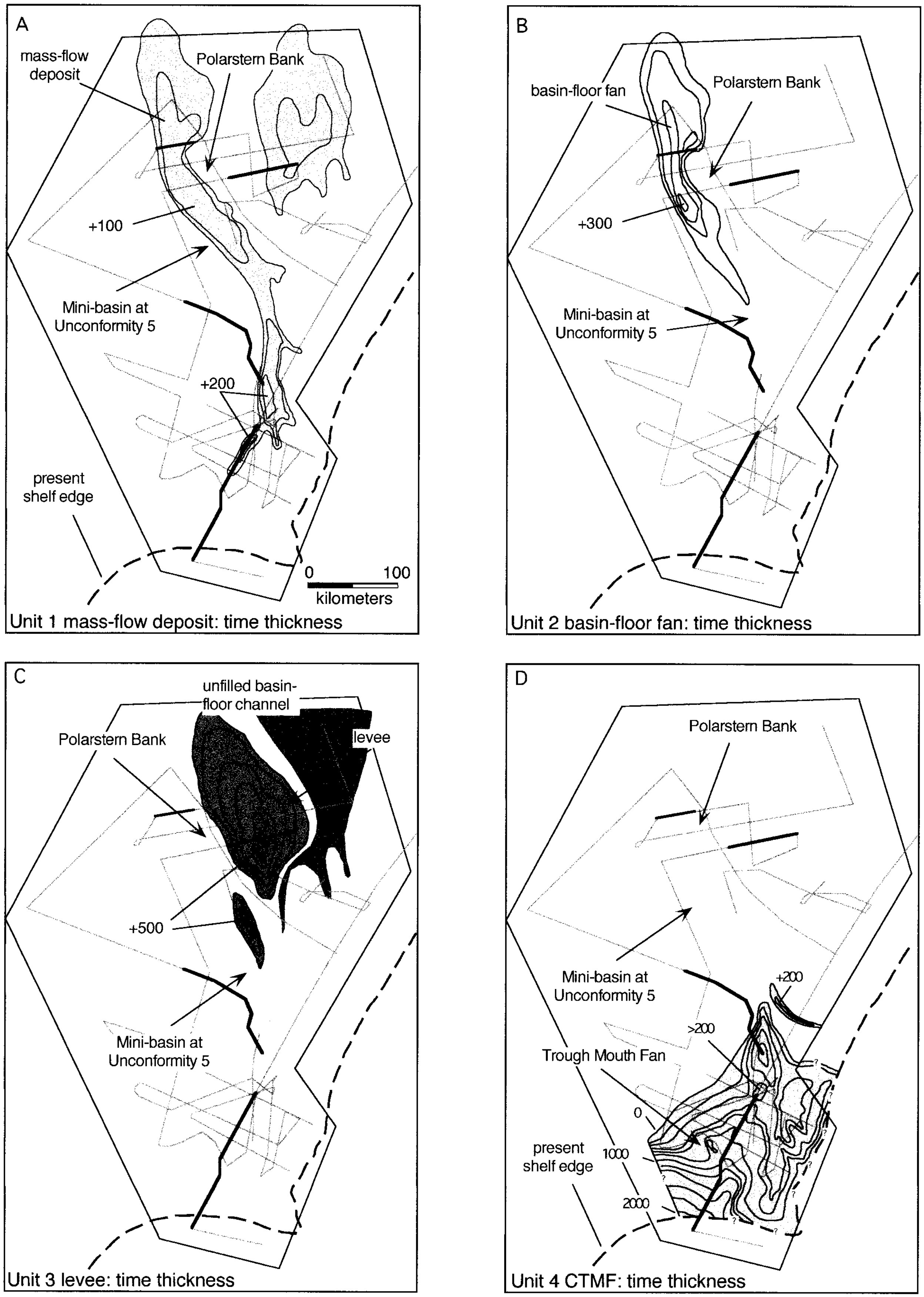


FIG. 7.—Contour map of Weddell Sea Unconformity 5 with extent of mini-basin topography. Contour values are in two-way travel time (seconds). The map was constructed from the seismic data. Contour interval = 200 milliseconds.


A
mass-flow deposit
Polarstern Bank
+100
Mini-basin at Unconformity 5
+200
present shelf edge
0
100
kilometers
Unit 1 mass-flow deposit: time thickness
B
basin-floor fan
Polarstern Bank
+300
Mini-basin at Unconformity 5
Unit 2 basin-floor fan: time thickness
C
unfilled basin-floor channel
levee
Polarstern Bank
+500
Mini-basin at Unconformity 5
Unit 3 levee: time thickness
D
Polarstern Bank
Mini-basin at Unconformity 5
+200
>200
Trough Mouth Fan
0
1000
2000
present shelf edge
Unit 4 CTMF: time thickness

been similar to the volume that is presently contained in the CTMF strata above Unconformity 5.

Trigger to Early Pliocene Upper-Slope Collapse

Lack of interfingering between the basin-floor stratigraphy and TMF strata suggests that collapse was either after or before a period of TMF outbuilding, thus after or before a glacial period. This leaves the questions: To which mechanism might upper-slope collapse be attributable, and when during an interglacial is it most likely that upper-slope collapse occurred?

Several trigger mechanisms can be invoked to explain the large-volume collapse of the lower Pliocene CTMF strata: seismicity, methane-gas generation or gas-hydrate destabilization, sediment oversupply and slope oversteepening, isostatic rebound and extension and/or fault displacement, etc.

The Weddell Sea area has been an aseismic passive margin since the Jurassic breakup of Gondwana and emplacement of oceanic seamounts of the Polarstern Bank (Jokat et al. 1996). The nearest regions experiencing tectonic activity in the Cenozoic are the South Scotia Ridge (an active transform fault) and the northwestern margin of the Antarctic Peninsula (a convergent margin until the Pliocene). These regions are more than 1000 km from the study area. Because of the absence of seismicity near the study area, it is discounted as a triggering mechanism.

There is no evidence for abnormally high production of methane gas in antarctic sediments, and hence it appears unlikely that significant increases in pore pressure would result from this mechanism in the Weddell Sea region. Also, there are no indications of the presence of gas hydrates in the Weddell Sea. The nearest occurrences of gas hydrates were reported from the Pacific margin of the northwestern Antarctic Peninsula (Lodolo et al. 1993).

Instability associated with glacial-period oversupply of sediment and oversteepening is a possibility. However, numerous studies have shown that glacial margins are capable of maintaining high-angle slopes due to the poorly sorted nature of the material and armoring as fines are winnowed from surface sediments by contour currents (e.g., Larter and Barker 1989; Cooper et al. 1991; Bart and Anderson 1996). Moreover, since the Unconformity 5 collapse, glacial deposition at Crary Trough Mouth Fan has caused major outbuilding (Kuvaas and Kristoffersen 1991; Moons et al. 1992) during several glacial cycles without evidence of collapse or significant remobilization. For this reason, we discount oversupply and oversteepening by itself as a possible trigger mechanism for collapse, although it probably contributes to inherent instability.

During interglacials, isostatic rebound tends to induce extension on the shelf and upper slope. Rebound rates are high immediately following ice-sheet retreat and diminish thereafter (Walcott 1970; Boulton 1990). Because rebound diminishes late in an interglacial, slope instability is most likely to occur early during interglacial periods. However, upper-slope collapse was not associated with every interglacial, and it appears that in the antarctic, TMF strata generally remain intact through the glacial and interglacial. We propose that additional mechanisms are required to trigger large-volume mass wasting of the upper slopes.

In addition to isostatic rebound, a rapid and anomalously large-volume ice-sheet retreat would cause appreciable geoidal effects at the high-latitude margins. Indeed, relative to the late Miocene, the early Pliocene is generally regarded as a time of reduced antarctic ice volumes and slightly warmer than present temperatures (Shackleton et al. 1995). Despite the reduced ice volumes in the early Pliocene, high-resolution δ^{18}O records indicate several significant ice-volume reductions, with the largest of these believed to correspond to relative sea level rise of 35 m (Kennett and Hodell 1993).

In the early Pliocene (i.e., before the development of Northern Hemisphere ice sheets), a large-volume antarctic ice-sheet retreat would initiate rebound and thus relative sea-level fall at the antarctic margin. On the basis of numerical modeling, Clark and Lingle (1977) predicted the global variation of rebound and relative sea-level change following a uniform thinning of the antarctic ice sheet. At the Weddell margin (a near-field location), a temporary (approximately 1000 years) relative sea-level fall occurs during the reestablishment of gravitational stability associated with the new configurations of ice and water volume on the Earth's surface. Isostatic rebound and geoidal affects associated with major antarctic ice-volume reduction could theoretically combine to produce relative sea-level falls of 50 to 500% of the average global sea-level rise (Clark and Lingle 1977), depending upon location on the antarctic margin. At locales distant from Antarctica (far-field locations), relative sea level would have risen to higher than the average global sea-level rise. With time, the near-field and far-field water-level elevations are predicted to converge toward the global average.

Regional sea-level fall at the Weddell margin probably caused a significant decrease in overburden pressure on the shelf and upper-slope strata previously at equilibrium under higher overburden pressures produced by the expanded ice sheet. Glacially overcompacted muds at the sea floor and high mud content of glacial sediments (Anderson et al. 1983) may have limited significant leakage of high pore pressures. Therefore, we propose that it is most likely that CTMF and DML upper-slope collapse began in an interglacial shortly after major ice-sheet drawdown.

Implications for Antarctic Glacial History

With regard to reconstruction of antarctic glacial history from TMF stratigraphy, an immediate implication of upper-slope collapse is that all stratigraphic manifestation of the major ice-volume drawdown (including possible melt-water features) and/or of preceding glacials would be removed from the outer-shelf and upper-slope settings. Warming and ice-volume drawdowns are suggested for the antarctic during the Miocene and Pliocene, but the magnitudes of the temperature variations and ice-volume drawdowns are being debated. Oxygen-isotope stratigraphy suggests that the middle Miocene was a time of rapid ice-volume buildup in Antarctica (Miller et al. 1987; Prentice and Matthews 1988; Abreu and Anderson 1998). The eustatic curve indicates fairly low-frequency, large-amplitude (approximately 60 m) sea-level variations during the middle Miocene to early Pliocene (Haq et al. 1987), which presumably were controlled by antarctic ice-sheet fluctuations. Dramatic reduction of antarctic ice volume to the extent proposed by several authors (Webb et al. 1984; Webb and Harwood 1991; McCartney and Wise 1990) would be equivalent to approximately 50 m of sea-level rise. However, there is strong evidence from the Dry Valley region denying the possibility of such an extreme deglaciation (e.g., Denton et al. 1993; Hall et al. 1993; Marchant et al. 1993). The estimates of early Pliocene extreme deglaciation exceed the 25 to 35 m magnitude of sea-level rise that is predicted from studies of Enewetak Atoll (Wardlaw and Quinn 1991) and from the U.S. Middle Atlantic coastal plain (Krantz 1991). Nonetheless, these more conservative estimates of early Pliocene sea-level rise (25 to 35 m) reflect major antarctic ice-sheet drawdowns, the largest of which may have been sufficient to trigger upper-slope mass wasting.

Unfortunately, the chronostratigraphic constraints available for our study are not adequate to confidently correlate with the high-resolution results from the δ^{18}O curves or other proxy records. Available age constraints from Site 693 indicate that Unconformity 5 formed sometime in the early

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FIG. 8.—Time–thickness contour maps of strata infilling unconformity 5 mini-basin: **A)** Unit 1 mass-flow deposit; **B)** Unit 2 basin-floor fan; **C)** Unit 3 channel-levee; and **D)** Unit 4 trough-mouth fan strata. Contour interval = 100 milliseconds.

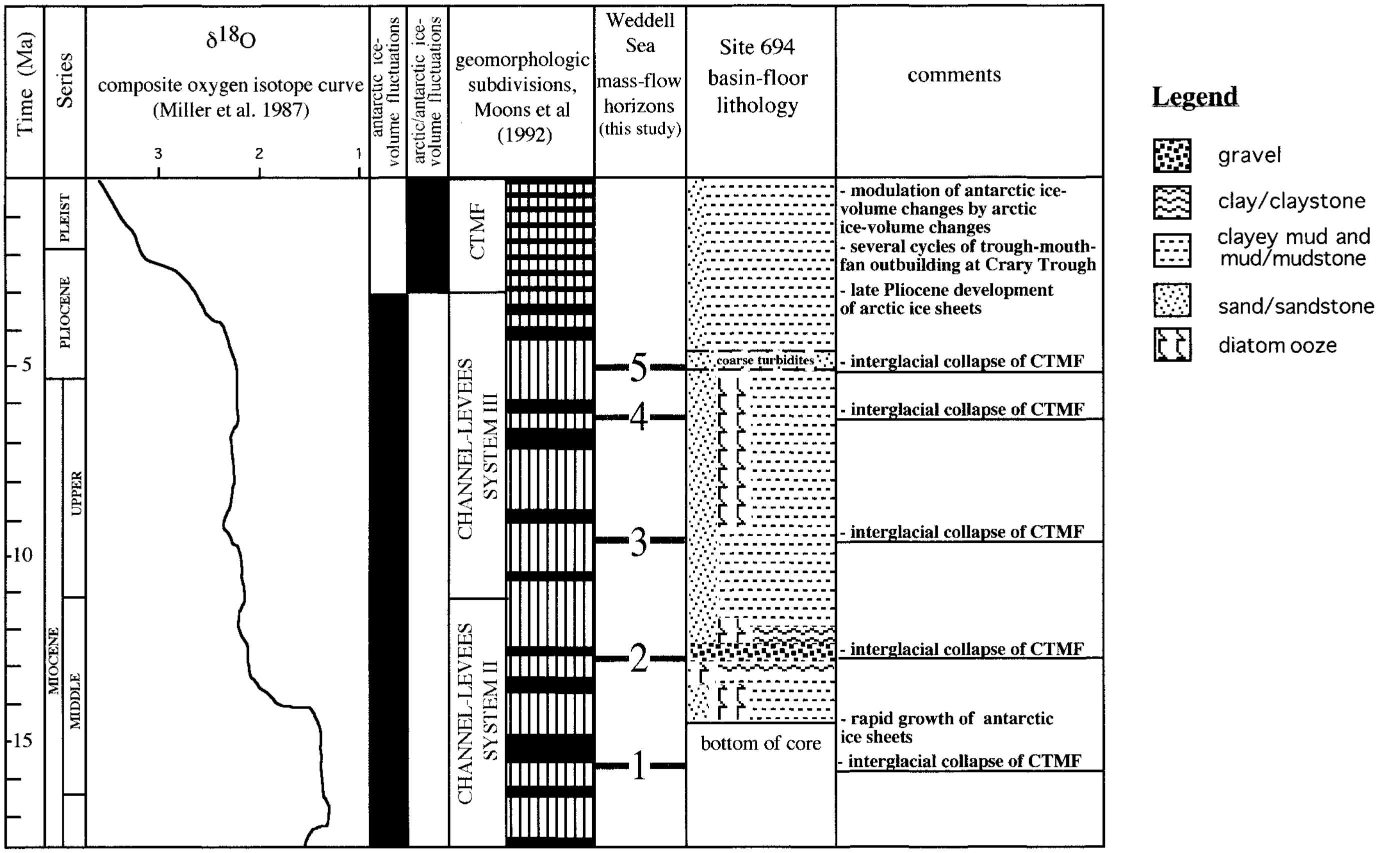

FIG. 9.—Chronostratigraphic summary of southeastern Weddell Sea seismic stratigraphy with ODP stratigraphy. On the column indicating geomorphologic subdivisions, the vertical-line pattern corresponds to periods of nondeposition, whereas the black horizontal lines correspond to periods of deposition as inferred by Moons et al. (1992).

Pliocene (Moons et al. 1992). We infer that the final stage of an early Pliocene major antarctic glacial expansion to the shelf edge was preceded by slight warming which may have caused snow precipitation on the antarctic ice sheet to increase (Huybrechts 1994). The ice sheet may have responded to higher precipitation with higher discharge (streaming) and, hence, greater erosion of the continental shelf (ten Brink et al. 1995). Thus, increased early Pliocene precipitation probably initiated little additional isostatic depression but probably caused severe erosional overdeepening and foredeepening of the land/sea floor of the Weddell margin. This is also a time of widespread glacial erosion on the Ross Sea (Anderson and Bartek 1992; DeSantis et al. 1995) and Antarctic Peninsula shelves (Bart and Anderson 1995). We infer that large volumes of detritus were deposited within the early Pliocene TMF during this time. The major ice-sheet drawdown that we believe was responsible for the collapse of these early Pliocene TMF strata may have been partially caused by the severe erosional overdeepening of the continental shelf.

The thick lower Pliocene terrigenous deposits from ODP Site 694 in the center of Weddell Sea (Kennett and Barker 1990) may be reflective of the same major ice-sheet drawdown. The type of stratigraphy at Site 694 is perhaps the distal facies equivalent of the Unit 1 chaotic seismic facies described in this study. However, the northeast-directed orientation of the Unconformity 5 erosional channel shows that these units could not be directly contiguous. More data would be necessary to confirm this, but we hypothesize that a major early Pliocene antarctic ice-sheet drawdown caused regional collapse of the TMFs and other upper-slope deposits around the Weddell Sea margins.

Large-scale collapse has evidently not occurred with great frequency. Nevertheless, our seismic data show at least four other erosional unconformities with basal infill by chaotic seismic facies to be present stratigraphically below Unconformity 5: Unconformities 1 to 4. Correlation to ODP Site 693 suggests that these unconformities are all of middle to late Miocene age (Fig. 9). We tentatively propose that they may have been caused by a process similar to the one described for Unconformity 5.

The TMF strata above Unconformity 5 were formed during consecutive late Pliocene to Pleistocene glacial periods (Moons et al. 1992), a time during which antarctic ice-volume fluctuations were presumably modulated by Northern Hemisphere ice-sheet fluctuations (Alonso et al. 1992; Anderson and Bartek 1992). After the buildup of Northern Hemisphere ice in the late Pliocene, arctic and antarctic ice-volume fluctuations were more or less in phase (Fig. 9). In such a scenario, numerical models predict that the near-field and far-field geoidal effects associated with a major drawdown of the antarctic ice volume would be balanced by a like but opposite-directed near-field and far-field geoidal effect associated with a Northern Hemisphere ice-volume drawdown (Clark and Lingle 1977; Tushingham and Peltier 1991). Therefore, neither polar region would have experienced geoidally induced interglacial relative sea-level fall during the late Pliocene and Pleistocene, which would—in our scenario—have reduced the potential for upper-slope collapse in the antarctic. This may explain why the post-Unconformity-5 CTMF is still intact today.

Weddell Sea Depositional Model

On the basis of the seismic stratigraphic analysis, interpretation of contour maps, and on the above-stated inferences, we propose a simplified conceptual model to illustrate the development of Weddell Sea basin-floor stratigraphy, its stratigraphic relationship to the CTMF and DML upper

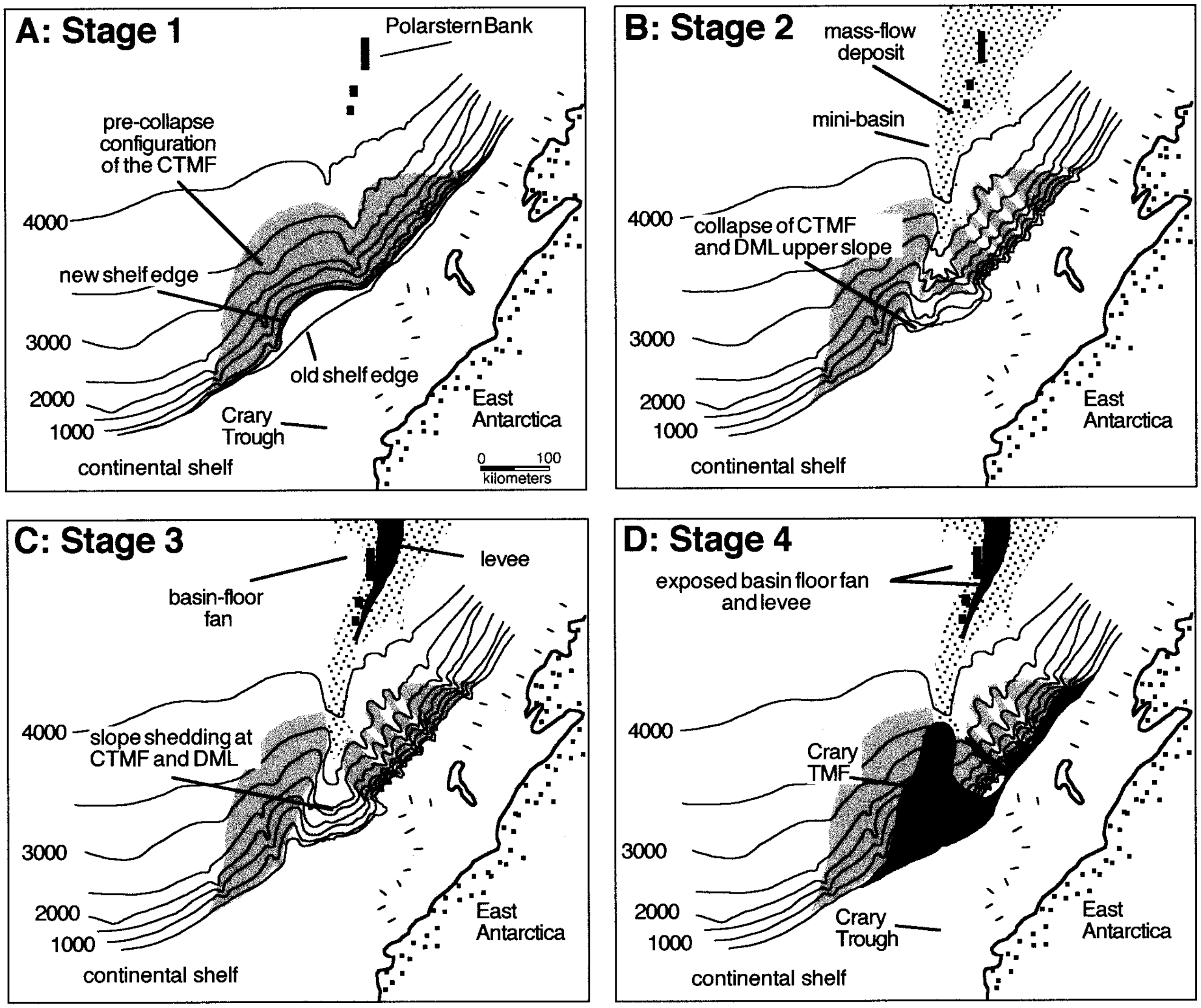

FIG. 10.—Conceptual model of southeastern Weddell Sea TMF and basin fan development. **A)** Deposition of large TMF; **B)** interglacial mass wasting of TMF strata producing erosive sediment gravity flows, formation of mini-basin on basin floor, and partial infill by mass-flow deposits; **C)** continued interglacial shedding and infilling of distal part of mini-basin; **D)** infilling of proximal mini-basin by TMF strata during subsequent glacial periods. The bathymetric contour interval is 500 m, and contours range from 500 m (approximate shelf-edge location) to 4000 m.

slope, and the implications of the stratal relationships to antarctic glacial history (Fig. 10A–D). The model shows a map-view perspective of physiography and sediment distribution at four stages.

Stage 1 (Fig. 10A) shows the culmination of a major early Pliocene (?) glacial period and TMF outbuilding. TMFs were morphologically expressed as large lobes on the upper slope, the largest of which was CTMF. During this stage, the continental rise and basin floor were relatively sediment-starved.

In stage 2 (Fig. 10B), decoupling, large-volume ice-sheet drawdown, and temporary relative sea-level fall triggered collapse of the early Pliocene TMFs. Initial mass wasting of poorly sorted glacial sediments from the upper slope probably produced sediment-gravity-flow transitions including large-volume mass flows and turbidity currents. On the slope and basin floor, the faster-flowing turbidity currents probably occupied and excavated the axis of the previously existing channel-levee system to create an elongate mini-basin around the flanks of Polarstern Bank. Slower-moving mass flows partially infilled the base of the mini-basin with poorly sorted deposits. In the more distal areas, the depth of the mini-basin decreased until it no longer acted to confine the turbidity currents. Beyond the limits of the study area, unconfined turbidity currents may have penecontemporaneously deposited thick and fining-upwards sandy turbidite sequences, like the amalgamation of turbidites sampled at ODP Site 694.

In stage 3 (Fig. 10C), rebound rates decreased and relative sea level began to rise to that of the global average. Late-phase shedding of sediment gravity flows from the upper slopes involved smaller volumes. Turbidity currents produced by this time-transgressive process of upper-slope shedding continued the erosion of Unconformity 5 on the upper slope and the progressive backfilling of the mini-basin on the basin floor. These relatively small-volume mass-wasting events formed basin-floor fan lobes and channel-levee deposits within the elongate mini-basin respectively to the west and east of Polarstern Bank. The abyssal plain was probably sediment starved, except for very dilute turbidity currents and hemipelagic and pelagic deposition.

Stage 4 (Fig. 10D) represents the culmination of the last glacial maximum and TMF outbuilding following a series of several high-frequency late Pliocene and Pleistocene (?) glacial cycles. Throughout this period, the TMF remained intact, and the continental rise and abyssal plain were essentially sediment starved.

CONCLUSIONS

The orientation, width, and depth of a major erosional channel and its chaotic infill on the Weddell Sea basin floor indicates that this feature was formed by strongly erosive mass wasting of glacial sediments from the CTMF and DML slopes. Stratal patterns and isopach maps indicate that the channel backfilled as sediment supply was gradually shut off. Seismic-facies analysis suggests that the base of the channel is filled with thick poorly sorted mass-flow deposits. We infer that the erosion of the mini-basin and deposition of its basal infill occurred during an early phase of upper-slope mass wasting. The distal ends of these deposits extend far into the basin and may have a well-sorted sandy turbidite equivalent beyond the study area. From the backfilling style of the channel, we infer that late-phase filling involved small-volume mass wasting from the adjacent slopes, and hence basin-floor fan and channel-levee strata overlie the mass-flow deposits within the axis of the basin-floor channel.

Seismic correlation and mapping shows that these units extend beyond the study area in a basinward direction but that they thin and pinch out at the base of slope in a landward direction. Correlation of the erosional unconformity landward shows that it can be traced to erosional topography at the lower slopes of the CTMF and DML. Stratigraphic relationships between the basin-floor deposits and TMF strata suggest that the basin-floor deposits are not formed coevally with TMF outbuilding. On the basis of available information, we conclude that these strata were sourced from the slopes during interglacial collapse of preexisting TMFs.

Correlation to ODP Site 693 suggests that Unconformity 5 is early Pliocene. We tentatively infer that mass wasting was triggered shortly after a large-volume ice-sheet retreat in the early Pliocene. Collapse may have been due to isostatic rebound and temporary relative sea-level fall, a geoidal effect unique to the Miocene and early Pliocene. Similar stratigraphy at Unconformities 1 to 4 suggests that large-volume ice-sheet drawdown may have occurred on four other occasions in the Miocene.

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