THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

CITATION

Bart, P.J., and L. De Santis. 2012. Glacial intensification during the Neogene: A review of seismic stratigraphic evidence from the Ross Sea, Antarctica, continental shelf. *Oceanography* 25(3):166–183, http://dx.doi.org/10.5670/oceanog.2012.92.

DOI

http://dx.doi.org/10.5670/oceanog.2012.92

Glacial Intensification During the Neogene

A Review of Seismic Stratigraphic Evidence from the Ross Sea, Antarctica, Continental Shelf

BY PHILIP J. BART AND LAURA DE SANTIS

(a) RVIB *Nathaniel B. Palmer* awaiting crew arriving from McMurdo Station in 2003. (b) Underway seismic data acquisition through sea ice patches with seismic source and stream being towed in the ship's wake to prevent damage to equipment. (c) Air guns being attached to orange floats on the *Palmer's* afterdeck. (d) OGS *Explora* awaiting crew. (e) Louisiana State University students Vince Adams and Katy Huber on the *Palmer* during a research cruise to the Ross Sea in February 2008.

ABSTRACT. Seismic stratigraphic and drill data from Antarctic continental margins have provided much direct evidence concerning ice sheet evolution as Earth's climate cooled from the warmth of the Eocene. Seismic facies analyses and correlations to sediment cores from Deep Sea Drilling Project Leg 28 drill sites show that the Ross Sea, the southwestern Pacific gateway of West Antarctica, was still mostly free of grounded ice for ~ 6 million years after Oi-1, the large-amplitude oxygen-isotope shift that signaled the abrupt onset of the current Antarctic glaciation. In the Ross Sea, our analysis shows that West Antarctic glaciation had begun by the late Oligocene, much earlier than usually interpreted from the paleoceanographic proxy data. Continental ice probably existed on Marie Bird Land and other highland areas of the West Antarctica. In the central Ross Sea, ice caps nucleated on the subaerially elevated basement horst blocks of the Central and Coulman Highs. Ice caps waxed and waned across the shallow-marine platforms rimming these broad basement uplifts. These temperate glacial systems delivered much sediment to the surrounding deepwater shelf basins. Ice cap oscillations during the early and middle Miocene also included significant intervals of grounded ice retreat and resumption of widespread marine sedimentation. By the end of the middle Miocene, glaciation intensified, local ice caps coalesced, and grounded ice with cross-shelf ice streams eventually extended across the entire Ross Sea continental shelf. Antarctic climate shifted from polar to temperate conditions during this time and ice streams advanced to the shelf edge. Full-bodied West Antarctic Ice Sheet advances continued and even occurred during the warmer-than-present early Pliocene. As a consequence of widespread and progressive glacial erosion, the shelf overdeepened in the latest Miocene. The surprisingly few advances of grounded ice preserved in Plio-Pleistocene strata suggest that the record is amalgamated and/or otherwise below the resolution of seismic data.

INTRODUCTION

Marine and land-based seismic reflection surveys provide a powerful, quick, and relatively inexpensive means of mapping subsurface geologic structures and stratigraphy over large areas. In the Antarctic, a key goal of many marine seismic investigations is to understand the long- and short-term evolution of the cryosphere from the perspective of the continental margin stratigraphy. For example, marine surveys of Antarctic shelf seismic stratigraphy can provide direct evidence of ice sheet advance and retreat during the last glacial cycle in the form of glaciogenic units and erosion surfaces. A regional seismic stratigraphic framework is important because the scale of grounding-line translation is so large—several hundred kilometers (the grounding line is the boundary between a floating ice shelf and the ice resting on bedrock). Seismic correlations are also important because they provide a framework in which scientific drill sites can be selected. The seismic framework constitutes a regional stratigraphic context in which drill-site data can be interpreted. This latter issue is extremely important because drill-site data in isolation could not be used to distinguish whether a glacial erosion surface interpreted from sedimentologic evidence corresponded to a major versus a minor advance of grounded ice in the absence of a detailed regional seismic correlation of the erosional surface in question. Age and lithologic control from drill-site data can be integrated with seismic data to interpret the timing, frequency, and rate of ice sheet advance and retreat. Documenting the long- and short-term past dynamics of the Antarctic cryosphere is fundamental to establishing which factors cause the Antarctic ice sheets to advance and retreat. This level of understanding of past dynamics provides insight that can be used to predict how the Antarctic ice sheets might respond to or cause global climate and/or eustatic (global sea level) change.

Despite these positive aspects of seismic investigations, reconstructing Antarctic glacial history from direct evidence is extremely difficult because the ice-covered continent is rimmed by a wide but seasonally variable band of sea

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ice. Moreover, the Antarctic cryosphere consists of three elements (Figure 1): (1) the East Antarctic Ice Sheet (EAIS), (2) the West Antarctic Ice Sheet (WAIS), and (3) the Antarctic Peninsula Ice Sheet (APIS), and it is unlikely that the ice sheets oscillated in lockstep. The primary distinguishing characteristics of these glacial systems include significant 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 glacial cycles. Because of these differences, the ice masses probably evolved and responded to forcing mechanisms independently.

The conventional view concerning the evolution of Antarctic ice sheets is that: (1) the EAIS, a large, mainly land-based ice sheet, began nucleating on the interior highlands prior to the Oligocene (Barron et al., 1989), attained continental-scale proportions in the middle Miocene (Shackleton and Kennett, 1975; Kennett, 1977; Clapperton and Sugden, 1990), and has since been a stable part of the Antarctic cryosphere, experiencing only small ice-volume fluctuations (Kennett and Hodell, 1993). (2) WAIS, an intermediate-sized, marine-based ice sheet, evolved in the late Miocene (Hughes, 1975; Mercer, 1978) and has since been inherently unstable due its capacity to respond to changes in sea level and climate (Mercer, 1978). (3) APIS is usually considered a part of the marine-based WAIS, but the peninsula is a narrow highland volcanic arc that constitutes the northernmost extension of Antarctica; thus, the land-based APIS may have been particularly sensitive to climatic changes, and its oscillations during the late Neogene may have had no relationship to that of the WAIS.

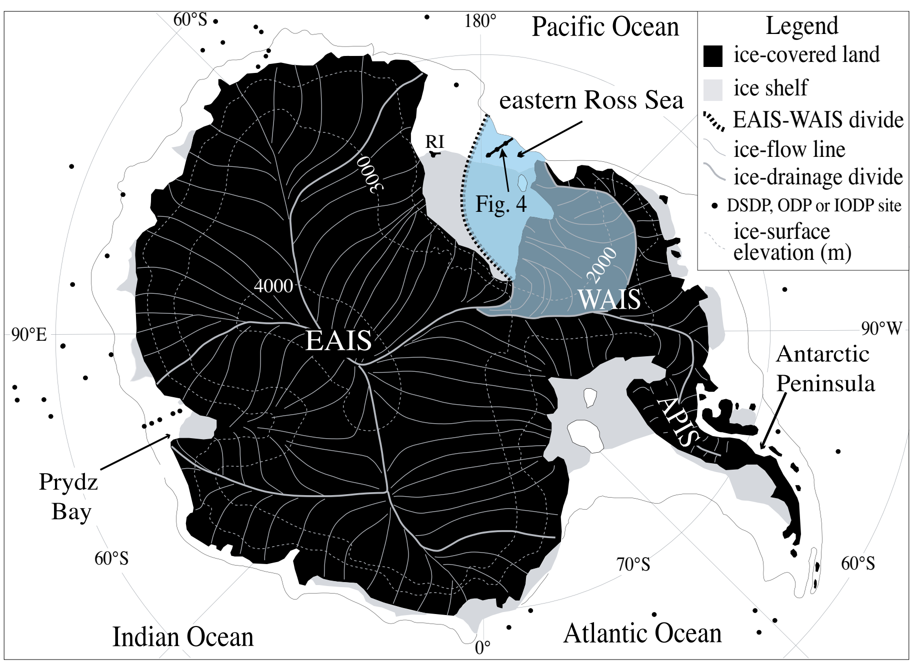

Figure 1. Map of Antarctica. The blue shaded areas represent that sector of the West Antarctic Ice Sheet that flow into the eastern Ross Sea. The solid black line of the outer shelf shows the location of a seismic line that crosses Deep Sea Drilling Project (DSDP) Leg 28 drill sites. McMurdo Sound is to the west of Ross Island. EAIS = East Antarctic Ice Sheet. WAIS = West Antarctic Ice Sheet. APIS = Antarctic Peninsula Ice Sheet. RI = Ross Island.

Because of the extensive ice cover on land, and the difficulty of accessing ice covered marine areas, much of this perspective on Antarctic glacial history is inferred from deep-sea proxy evidence. Barrett (2008) is consistent with some, but not all, aspects of the direct Antarctic evidence from onshore and offshore areas. In this article, we first review the conceptual models of erosion and deposition on the Antarctic shelf, and then follow up with a general review of glaciogenic features used to interpret Antarctic ice sheet evolution from the perspective of continental shelf seismic stratigraphy. We then provide a brief review of previous seismic-based results from the Ross Sea, which show that ice caps initially advanced to sea level in the late Oligocene, followed by glacial intensification resulting in shelf-wide advances of the WAIS by the end of the middle Miocene.

SEISMIC DATA ACQUISITION IN ANTARCTICA

Much seismic data has been acquired since the first surveys in the 1970s. Seismic data acquisition on the Antarctic continental shelf is limited to the short two- to three-month austral summer season when sea ice extent greatly contracts southward toward the continent. Research vessels operating in the Antarctic and used for geophysical surveys include the *Nathaniel B. Palmer* (see photo a on p. 166), *Polarstern*, *James Clark Ross*, *Hespirides*, *OGS Explora* (see photo d on page 166), *Oden*, *Polar Duke*, *Aurora Australis*, *Tangaroa*, *Hakurei-Maru*, *Akademik Alexander Karpinsky, Araon*, and others. Obtaining good-quality seismic data on the Antarctic shelves is difficult because of the extreme cold climate and frequent severe wind/wave conditions. Harsh weather can approach quickly and create problems for deploying and retrieving seismic acquisition equipment. Seismic data are often acquired as the ship maneuvers through sea ice with gear towed in the ship's wake with large amounts of engine noise and turbulence, resulting in water-column noise or data gaps for some records. Despite the challenges, when seismic data are obtained, the data quality generally is good (e.g., Larter and Barker, 1989; Alonso et al., 1992; Brancolini et al., 1995a; Bart et al., 1999).

To interpret crosscutting strata relationships and relatively thin units associated with individual glacial cycles, seismic data must be of sufficiently high resolution. Single-channel seismic surveys usually use a high-resolution seismic source (see photos on p. 166). The reflection data are recorded using a single-channel streamer. Digital filter cutoffs are typically set at 30 and 800 Hz. The dominant frequency of seismic data ranges between 130 and 200 Hz, providing a theoretical stratigraphic resolution of 2.5 to 4 m, based on the Rayleigh resolution limit criteria and an average sediment velocity equal to 2 km s^{-1}. Multichannel surveys use larger-volume sources and longer recording streamers, which produce slightly lower-resolution seismic data, but permit deeper penetration of acoustic signal below the seafloor, cancellation of the effects of false echoes, and indirect estimation of rock and sediment density from the acoustic wave propagation velocity below the seafloor (Brancolini et al., 1995a).

The stratal complexity of glaciated margins is such that seismic data grids must be dense enough to map individual units (Figure 2). Transects should be of sufficient regional extent to discern the large scale of glacial troughs. To visualize the large scale and low relief of erosional and depositional features, seismic profiles are typically displayed at a high vertical exaggeration (i.e., the horizontal scale is compressed and the vertical scale is expanded). The seismic profiles shown in this article are displayed at a vertical exaggeration of 25:1. The horizontal axis on the seismic sections is distance at the surface, whereas the vertical axis is in two-way travel time, corresponding to the time it takes for seismic energy to travel from the seismic source downward to a reflecting horizon and back to the surface where the arrival time of the reflected seismic energy is recorded. The velocity of sound in water is 1,500 m s^{-1}, so water depth can be directly calculated from two-way travel time. Converting travel time to subsurface depth requires knowledge of seismic energy velocity in the subsurface. Seismic interpretations are confirmed by correlation to lithologic and chronologic control at drill sites (Figure 3). There have been several successful drilling campaigns on Antarctic margins (e.g., Deep Sea Drilling Project [DSDP] Legs 28 and 35, Ocean Drilling

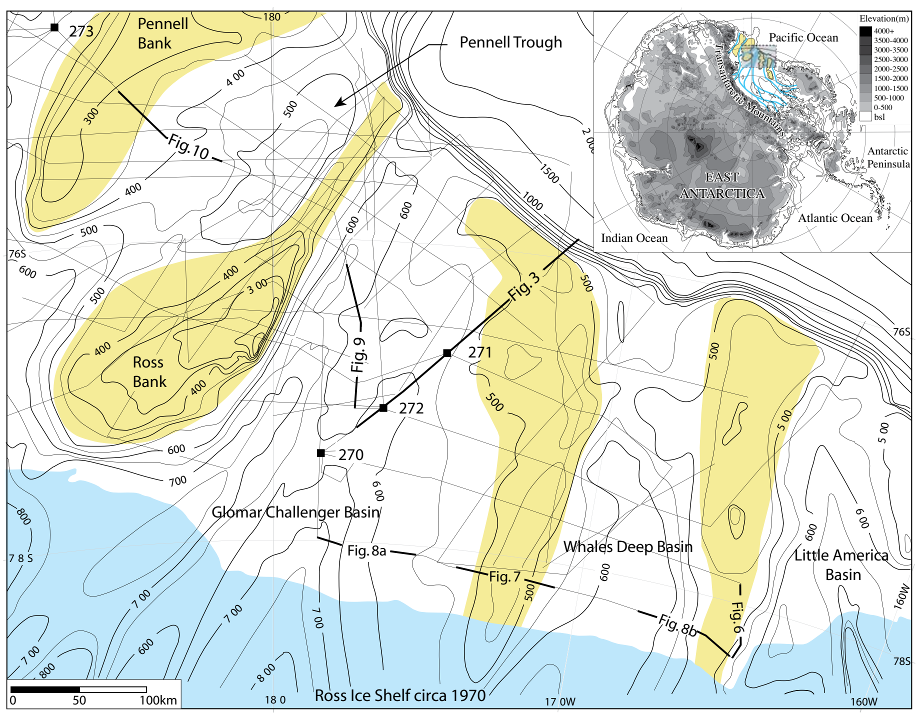

Figure 2. Base map for the central and eastern Ross Sea outer shelf. The inset shows Antarctica's land elevation with blue lines on West Antarctica corresponding to the projections of ice streams as they existed at the Last Glacial Maximum. The location of the large map is shown by the dashed shaded box on the Pacific Ocean margin of the Ross Sea. The Ross Sea base map shows bathymetric contours in meters. The yellow shaded areas are large-scale banks that exist between basins. These bathymetric basins correspond to former locations of ice streams. The rectangular grid corresponds to seismic data available to author Bart acquired during several cruises by international institutions. The blue shaded area shows the Ross Ice Shelf at its calving front.

Program [ODP] Legs 113 and 119, and Integrated Ocean Drilling Program [IODP] Legs 178, 188, and 318). In the Ross Sea, four shelf sites were drilled during DSDP Leg 28 (Figures 1 and 2). Several sites were also drilled in McMurdo Sound (e.g., Cenozoic Investigations of the Ross Sea [CIROS], McMurdo Sound Sediment and Tectonic Study [MSSTS], Cape Roberts Project [CRP], Dry Valley Drilling Project [DVDP], and ANtarctic geological DRILLing [ANDRILL]), which is in the southwestern Ross Sea between the Transantarctic Mountains and Ross Island (see Figure 1).

CONCEPTUAL MODEL OF ICE SHEET EROSION/DEPOSITION ON THE ANTARCTIC SHELF

At present, six large zones of convergent ice flow (i.e., ice streams) drain the WAIS toward the Ross Sea (Figure 1). These long and wide streams flow at rates of 500 m yr^{-1} (Whillans and van der Veen, 1993). Radar data demonstrate that grounding zone wedges (i.e., till deltas) are actively constructing at the mouths of ice streams (Anandrakrishnan et al., 2007). This view of the modern system provides the basis of a general conceptual model of ice sheet erosion and deposition on the continental shelf (Bart, 2003, 2004). During major glacial periods, the extent of grounded ice expands toward the outer shelf (Figure 4a). The ice-covered inner continental shelf becomes a zone of net erosion (ten Brink et al., 1995; Anderson, 1999). Ice streams erode and transport sediment basinward. At the terminus of grounded ice, subglacial debris is released subaqueously as gravity-driven sediment flows construct chaotic mass flows as low-angle prograding foresets (Alley et al., 1989). As grounded ice expands basinward, the till deltas deposited early during the ice sheet advance are overrun and are at least partly eroded by grounded ice (Bart and Anderson, 1996; Figure 4b). When ice sheet retreat from the outer shelf is relatively rapid, the subglacially eroded unconformity is draped by open-marine sediment (Figure 4c). The grounding event (an advance and retreat of grounded ice into the marine realm) is seismically manifest as a regional unconformity that truncates the underlying strata (Figure 3).

The trough and bank topography on the Ross Sea outer shelf provides strong evidence that six paleo-ice streams occupied these basins during the last glacial maximum (Hughes et al., 1981). Within the framework of north-directed drainage via multiple ice streams, seafloor banks may have evolved in at least three basic ways: (1) as erosional ridges formed between distinct ice streams (zones of fast-flowing ice) that deeply eroded into underlying strata (Figure 5a), (2) as constructional 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; Figure 5b), or (3) as lateral moraines where a tongue of grounded ice lifts off the seafloor (Figure 5c).

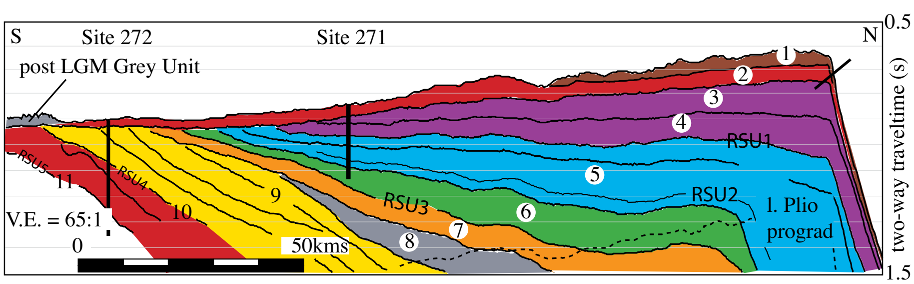

Figure 3. Interpretive line drawing of seismic line PD90-30 acquired by John Anderson. The transect shows stratal interpretations and correlations to lithologic and age control at DSDP Sites 272 and 271 in Glomar Challenger Basin. The numbers 1 through 11 correspond to seismic units defined in Anderson and Bartek (1992). The surfaces labeled RSU1 through RSU5 correspond to regional unconformity surfaces defined by De Santis et al. (1995). LGM = Last Glacial Maximum. V.E. = vertical exaggeration

OVERVIEW OF GLACIAL FEATURES ON THE SHELF

There is abundant seismic evidence of glaciogenic sedimentation on the Antarctic shelves. Seismic correlations to lithologic control at drill sites confirm the glaciogenic interpretation. Glaciogenic features have been described in different polar settings (e.g., Powell and Domack, 1995; Shipp et al., 1999; Powell and Cooper, 2002; Nielsen et al., 2005). On the basis of seismic characteristics, glaciogenic features can be grouped into seven general categories (Table 1): (1) foredeepened subglacial erosion surfaces, (2) glacial trough/bank topography, (3) isolated and irregular glacial moraine mounds, (4) prograding grounding zone wedges (GZWs; i.e., till deltas), (5) tabular till sheets, (6) outwash bottom-flow channels, and (7) trough mouth fans.

Glacial Unconformities

Major advances of grounded ice usually are manifest as regional erosional surfaces that generally correspond to the topset portion of shelf clinoforms (e.g., Larter and Barker, 1989; Bartek et al., 1991; Cooper et al., 1991; Anderson and Bartek, 1992; Figure 3). Landward-dipping (i.e., foredeepened) surfaces of erosion are formed when grounded ice advances into the marine realm. The most striking examples of glacial unconformities occur in areas where the underlying strata dip at a relatively high angle to the erosional unconformity (Figure 6). This pattern of truncation shows that many hundreds of meters of strata were removed from the shelf. Pronounced angular unconformities probably represent an amalgamation of erosion from multiple advances of grounded ice. Depending on the orientation of the seismic profile, glacial unconformity surfaces can also appear in two-dimensional sections as parallel to the strata in which they are contained. The seafloor essentially represents a surface of subglacial erosion associated with advance of grounded ice during the Last Glacial Maximum (LGM).

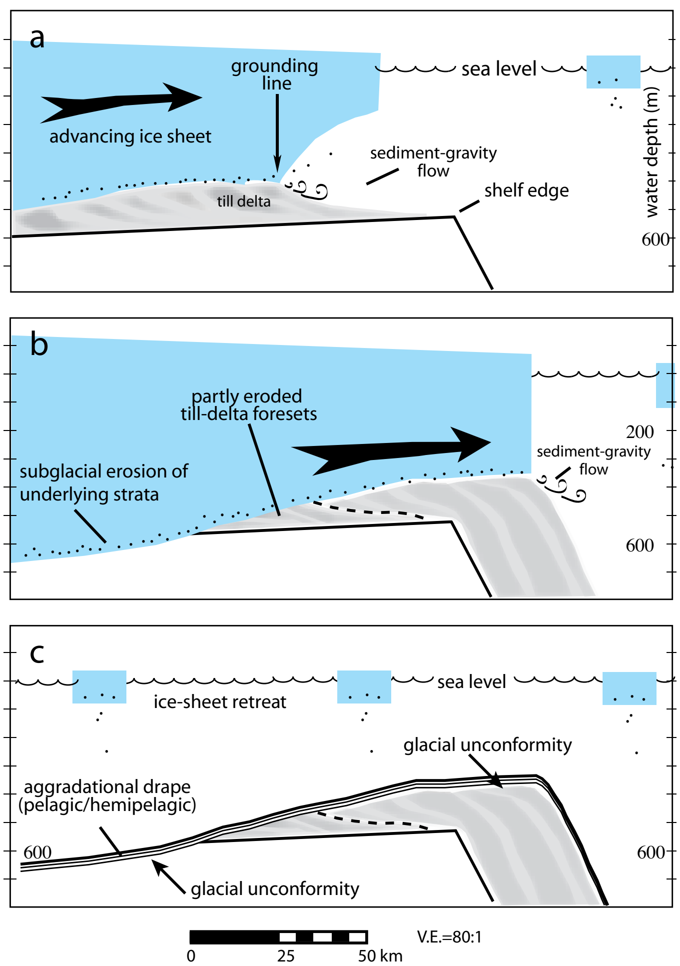

Figure 4. Conceptual model of erosion and deposition in dip-oriented view at the mouth of an ice stream. (a) A till delta is deposited at the mouth of the ice stream. Sedimentation occurs basinward of the grounding line as sediment gravity flow. (b) The advance of grounded ice during glacials partly erodes the till-delta deposited during the earlier phase of ice sheet advance. The inner shelf becomes a zone of net erosion into the underlying strata. (c) Abrupt retreat of grounded ice from the outer shelf is followed by deposition of a condensed layer of pelagic and hemipelagic sediment that drapes the seafloor.

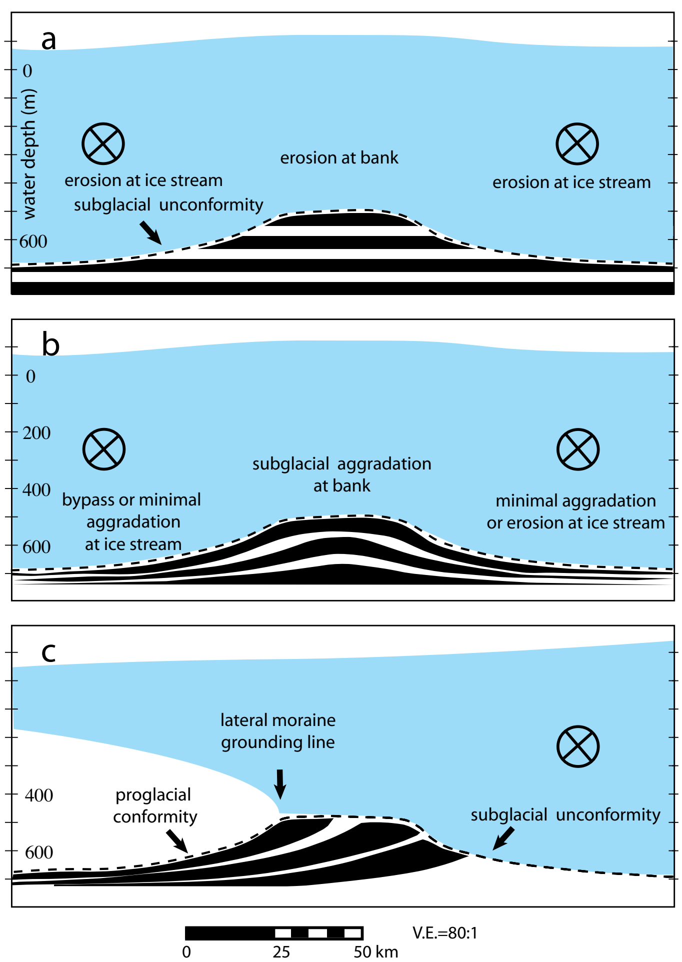

Figure 5. Conceptual models of erosion/deposition in strike-oriented view below grounded ice sheet on the outer shelf. (a) Ice streams erode deep basins into the underlying strata whereas erosion between ice streams is minimal. (b) Subglacial aggradation of sediment where ice flow is slowest between ice streams constructs a bank. (c) Lateral accretion of till delta foresets into open water from a tongue of grounded ice.

Table 1. Summary of the seven glaciogenic features observed in seismic data from the Ross Sea, the seismic characteristics of the features, and the glacial interpretation.

SEISMIC FEATURE	SEISMIC CHARACTERISTIC	GLACIAL INTERPRETATION
1. Foredeepened surfaces	Low-angle landward dipping erosional surfaces	Surface formed by isostatic depression and/or subglacial erosion
2. Trough/bank topography	Dip-aligned U-shaped troughs exhibiting 200–400 m relief, hundreds of kilometers width	Erosional surface associated with ice-stream erosion during glacial advance
3. Isolated or irregular mounds	Units exhibiting an irregular undulating upper surface and lacking internal reflections	Tongue of subglacial till often associated with laminated proglacial sediment from a temperate ice sheet
4. Grounding zone wedges	Dip-aligned units that exhibit topset truncation of basinward prograding foresets	Till deltas composed primarily of proglacially deposited diamict
5. Tabular till sheets	Broad units lacking internal reflections and bound by subhorizontal surfaces	Subglacially deposited till from streaming or nonstreaming ice
6. Outwash channels	Dip-aligned shallow channels several tens of meters thick occurring in clusters spaced tens of kilometers apart	Sand-filled channels formed by sediment-charged meltwater released at the grounding line
7. Trough mouth fans	Prograding wedges of upper-slope sediment at the mouths of glacial troughs	Mass flow deposition from streaming ice when grounded ice is at the shelf edge

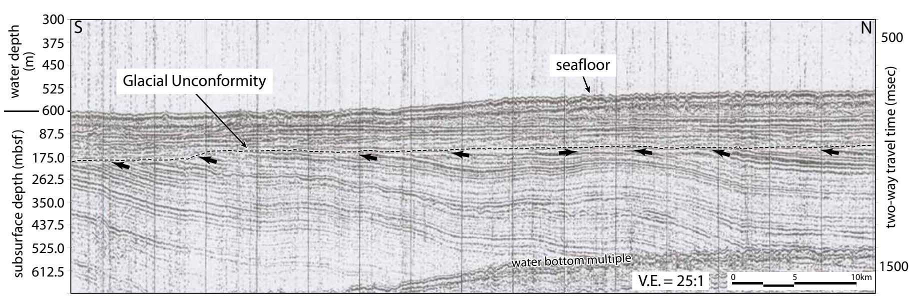

Figure 6. Dip-oriented seismic line showing an example of regional truncation associated with advance of grounded ice. The location of the profile is shown in Figure 2. Unconformities of this type are seen in strata of various ages. The unconformity shown is inferred to be of late Miocene age because it is above the youngest middle Miocene sampled at DSDP Site 272 but older than the oldest Pliocene sampled at Site 271. The unconformity represents an important transition from ice caps on subaerial highlands to a fully marine-based West Antarctic Ice Sheet that coalesced across the deeper parts of the shelf (De Santis et al., 1995). The glacial unconformity is the dashed line. At the left-hand side of this line, the glacial unconformity is at a subseafloor depth of approximately 175 m. The reflector labeled "water-bottom multiple" is the seismic energy from the seafloor surface that traveled through the water column twice.

Paleotrough/Bank Topography

Most glacial erosion probably is associated with ice streams. Judging from the dimensions of troughs on the outer shelf (Figure 2), ice streams existing during the LGM had dimensions as large as 100 km in strike view. Ice flow was considerably slower between ice streams, and these zones coincided with intra-ice stream banks. If there was sufficient accommodation (space available for sediment to accumulate), in some instances, trough and bank topography was preserved in the subsurface after subsequent advances of grounded ice (Figures 5a and 7). In most instances, successive intervals of ice sheet advance produced widespread crosscutting stratal relationships so that a single horizon preserves the full trough-bank relief observed at the seafloor (Bart and Anderson, 1995; Bart et al., 2005). Crosscutting stratal patterns thus indicate that ice stream locations can shift during successive advances of grounded ice. In other instances, lateral accretion suggests that some strata flanking banks were deposited as lateral moraines (Figures 5c and 7). Individual glacial unconformities and the units they separate on the shelf and slope can be correlated to create contour maps of subsurface horizons. Subsurface glacial unconformities sometimes show relief similar to the large-scale trough and bank topography of the modern seafloor that itself is a consequence of erosion and deposition by grounded ice during past glacial maxima (Figure 2).

Isolated Moraines/Till Tongues Within Glacial Marine Strata

Isolated irregular mounds encapsulated in acoustically laminated units (closely spaced parallel reflections) are interpreted to be till tongues and irregular moraines (Anderson and Bartek, 1992; Sorlien et al., 2007), based on similarity with features known to be associated with temperate glaciation on Arctic margins (Figure 8). Till tongues represent deposition below grounded ice juxtaposed to a lateral facies equivalent of glacial marine sediment deposited in the proglacial setting. The tongue of till is formed in association with aggradation of sediment during a gradual advance and retreat of grounded ice. The occurrence of these features in Antarctic shelf successions demonstrates an interval of temperate climatic conditions (prior to the current polar climatic conditions).

Grounding Zone Wedges

The isolated and relatively thin till tongues and similar moraine features (Figure 8 a,b) are distinct from till deltas (Figure 9). In contrast to till tongues,

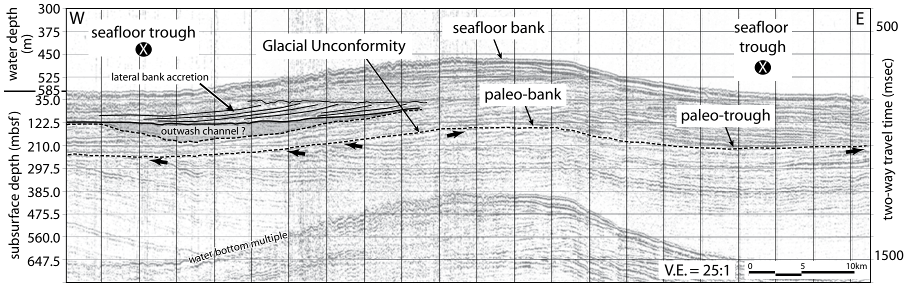

Figure 7. Strike-oriented seismic line crossing a paleobank. Figure 2 shows the location of the profile. The orientation of paleo-ice stream flow is into the page (i.e., to the north as confirmed by megascale lineations observed on multibeam data in the trough axes). Similar trough-bank topography is seen at the glacial unconformity shown by the dashed line in the subsurface. This pattern matches the genetic relationships shown in Figure 5a. The unconformity is of the same age as inferred for the glacial unconformity shown in Figure 6. Above this stratigraphic level, stratal surfaces dipping to the west are consistent with the view of lateral accretion into open water as shown in Figure 5b. A possible outwash channel underlies the lateral accretion foresets.

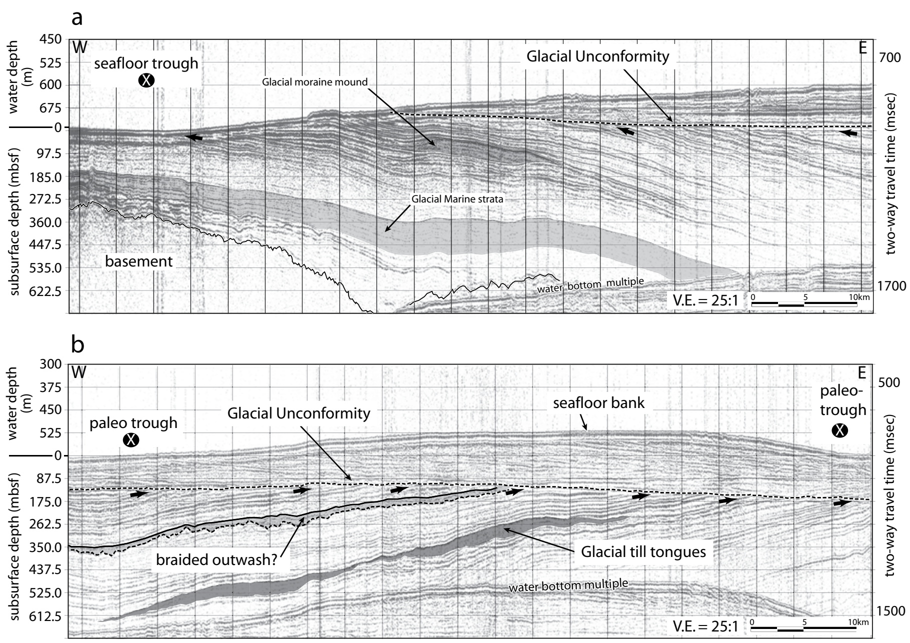

Figure 8. (a) Strike-oriented seismic line showing an isolated glacial moraine mound of the type that occurs in section of late Oligocene age. Figure 2 shows he location of the profile. The underlying section labeled "glacial marine" consists of subhorizontal stratification of closely spaced seismic reflections. The acoustically laminated zones are devoid of glacial erosion surfaces and other glaciogenic features and typify the seismic stratigraphy of sections older than late Oligocene. The obliquity of the angular unconformity demonstrates that a thick section of strata was removed from the outer shelf. The reflection-free zone underlying the stratified section represents crystalline basement. Broad areas of basement horst were emergent in the central Ross Sea during the Eocene through the middle Miocene. (b) Irregular mounds shaded gray are typically free of internal reflections. Figure 2 shows the location of the profile. The overlying shaded section is an example of a feature interpreted as an outwash plain because of its irregular erosional base and conformable top.

till deltas exhibit internal foreset surfaces indicating that till deposition occurred by progradation (Anderson and Bartek, 1992; De Santis et al., 1995). Foreset reflections are coarsely spaced within massive till delta successions. The preserved foreset truncation (i.e., the absence of backstepping stratal patterns) suggests that liftoff retreat of grounded ice was abrupt. Till delta foresets exhibit maximum heights of 250 m in lower Miocene units from the Ross Sea, which indicates the minimum water depth below the grounding line into which the deltas were constructed. The till delta foresets can be traced downdip to aggrading, horizontally stratified, bottomset strata, which suggests that in the ice-distal areas a significant fraction of suspension mode sedimentation occurred. The major thicknesses and large volumes of these deltas and ice distal marine sediments suggest that temperate climate systems with abundant meltwater and suspended sediment probably persisted during the deposition of these features into relatively deep water. GZWs associated with the last glacial cycle are significantly thinner (average 35 m thickness), perhaps reflecting the generally lower flux of the current dry polar climate.

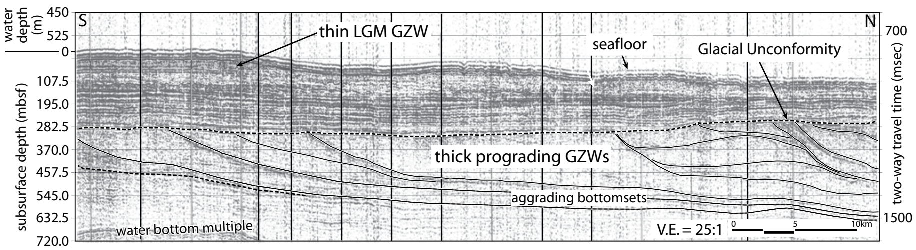

Figure 9. Thick progading grounding zone wedges (GZWs) are common in early and middle Miocene strata. Figure 2 shows the location of the profile. The foresets are more than 250 m high and can be traced laterally to finely laminated aggrading bottomsets. This observation suggests that a significant suspension-mode component existed at the grounding zone. It is in contrast to the modern setting in which proximal suspension-mode sedimentation is negligible due to the dry polar setting.

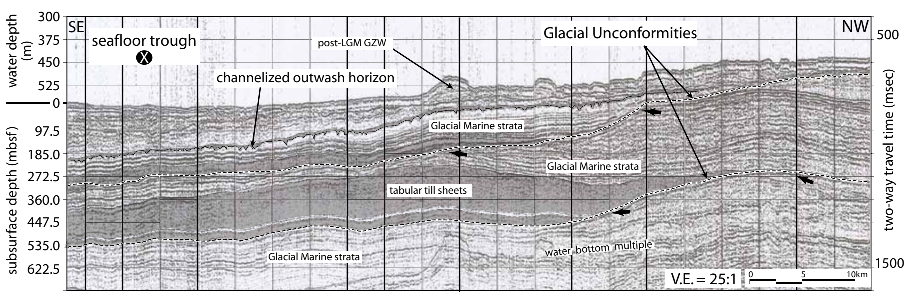

Figure 10. Massive till sheets occupy the bases of paleotroughs. The image shows the lateral pinchout of stacked till sheets. Figure 2 shows the location of the profile. In contrast to the prograding GZWs (Figure 9), till sheets are free of internal reflections. The channelized outwash horizon is found within strata provisionally interpreted to be glacial marine based on the fine acoustic laminations. Alternately, the features might represent seafloor flutes. The up section stratigraphic association from a basal till sheet to laminated glacial marine strata suggests the channel horizon was formed during an overall retreat. Based on correlations to DSDP Site 272, the outwash and channel features are not found in strata younger than middle Miocene.

Tabular Till Sheets

Reflection-free tabular units (i.e., with sheetlike dimensions) are usually bound by topset unconformities that exhibit low-angle crosscutting. The tabular units have variable thicknesses ranging from +100 to 20 m (Alonso et al., 1992; Shipp et al., 1999; Bart, 2004; Figures 3 and 10). The absence of reflections within these units might be due to the monotonous lithology and/or disturbed bedding due to subglacial shearing. The lateral dimensions of these till sheets are large (many tens of kilometers) in strike and dip views. In many instances, these till sheets appear to occupy the axes of previously eroded paleotroughs (Figure 10).

Outwash and Sediment-Laden Charged Channels

Outwash channels are found within some acoustically laminated sections (interpreted to represent fine-grained sediment from meltwater plumes; Figures 6 and 10). The isolated occurrence of channelization as single horizons suggests aperiodic massive release of sediment-laden melt that moved as an erosive bottom flow (Anderson and Bartek, 1992; Chow and Bart, 2003).

Trough Mouth Fans

Large upper-slope depocenters at the mouths of paleo-ice streams are referred to as trough mouth fans (TMFs; Figure 11). These upper-slope fans represent proglacial sedimentation by ice grounded at the shelf edge. TMF progradation extended the shelf beyond the paleo-shelf edge (Bart et al., 1999, 2001). The TMF is a composite of multiple episodes of ice sheet advance and retreat (Bart, 2001). During successive advances, the ice stream reoccupied the same general paleotrough location on the outer shelf. The deposits probably consist of remobilized and remolded sediment gravity flow deposits similar in composition to proximal till sediment found on the shelf. TMFs have been described in both Arctic and Antarctic margins (Vorren et al., 1989; Kuvaas and Kristoffersen, 1991; Ó Cofaigh et al., 2003). Nielsen et al. (2005) presented a comparison of glaciogenic features from the north and south polar regions.

LATE NEOGENE INTENSIFICATION OF THE ANTARCTIC GLACIATIONS

This overview concerns the Ross Sea sector and, hence, primarily pertains to the geologic record of West Antarctica ice volume changes inferred from seismic stratigraphy. It is important to note that the western Ross Sea received ice flow from East Antarctica after the EAIS attained continental scale. It is also important to note that the WAIS Ross Sea glacial history should not necessarily be expected to represent a lockstep version of glacial changes occurring elsewhere in Antarctica, given the different characteristics of Antarctic glacial systems.

Paleocene to Early/Middle Eocene

To our knowledge, no stratigraphic sections of Paleocene age are known from the Ross Sea, but fossil wood from the larger McMurdo region indicates that forests existed during the Eocene (Francis, 2000, 2008). Sections of early to middle Eocene age have not been drilled in the Ross Sea, but McMurdo glacial erratics at Mount Discovery and Minna Bluff provide information about conditions during this time. Paleontological and lithological evidence from the McMurdo erratics demonstrate that warm "greenhouse world" conditions existed in western Ross Sea coastal regions (Levy and Harwood, 2000a,b). Unlike today, much of the West Antarctic interior may have been subaerial during the Eocene (Wilson and Luyendyk, 2009). Likewise, broad areas of the central Ross Sea probably were subaerial (ANTOSTRAT, 1995). The oldest section overlying basement rock from the outer shelf basins in the Ross Sea does not exhibit seismic stratigraphic evidence suggestive of significant glacial erosion and ice-proximal or subglacial sedimentation (Figure 8a).

Late Eocene to Early Oligocene

The abrupt shift to larger oxygen isotope values at the Eocene-Oligocene boundary (Oi-1) is associated with a shift from "greenhouse" to "icehouse" climatic conditions (Zachos et al., 2001, 2008). This climate shift has traditionally been attributed to the opening of oceanic gateways (Kennett, 1977), but recent modeling suggests that declining CO_2 levels in the atmosphere must have played the critical role (DeConto and Pollard, 2003). Sections that may predate the shift (e.g., latest Eocene) and the earliest Oligocene section have only been drilled in the western Ross Sea at CIROS-1 (Barrett, 1989; Wilson, 1989; Barrett et al., 1991) and CRP-3 (Sagnotti et al., 1998). At these sites, the evidence suggests sedimentation associated with the advance/retreat of tidewater glaciers with ice-rafted debris accumulating in nearshore settings throughout the late Eocene/early Oligocene. Given the existence of ice-contact deposits in coastal zones, subaerial highland parts of the West Antarctic interior would have also hosted land-based ice at this time.

Recent results suggest that significantly larger portions of West Antarctica were above sea level. If so, West Antarctica would have supported a large volume of land-based ice (DeConto and Pollard, 2003; Wilson and Luyendyk, 2009; Wilson et al., 2011).

It is not possible to make a direct correlation from the inner shelf at CIROS-1 and CRP-3 to the outer shelf sectors

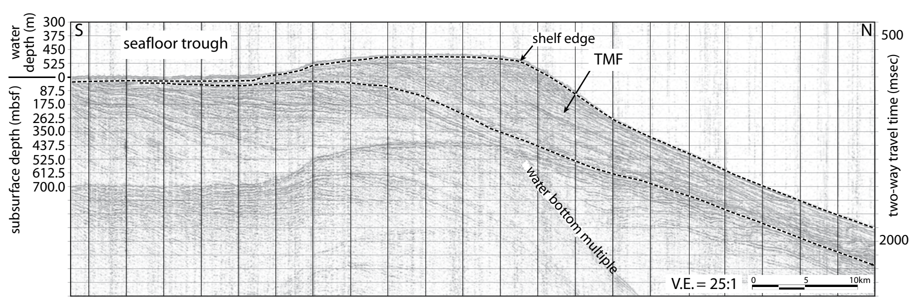

Figure 11. Trough mouth fan (TMF) depocenter at the outer shelf and upper slope. A ramp exists at the basinward end of the seafloor trough. The location of the profile is at the mouth of Joides Basin to the north and west of Pennell Bank shown in Figure 2. The grounding line was at the shelf edge. The TMF depocenter is bound by the dashed lines, but regional correlations show that many of the slope reflections are correlative conformities of surfaces that represent glacial unconformities on the outer shelf. The TMF thins and pinches out on the lower slope beyond the limit of the seismic section shown and is inferred to be of Pliocene-Pleistocene age based on correlation to DSDP Site 273.

of the Ross Sea because of crosscutting at younger stratigraphic levels and because of the Victoria Land Basin volcanic intrusion and fault displacement. However, late Oligocene strata drilled on the eastern Ross Sea continental shelf is known from DSDP Site 270. At this site, nonglacial shallow-marine late Oligocene sandstone dated to 26.7 million years ago (McDougall, 1977; D'Agostino and Webb, 1980) overlies Proterozoic basement gneiss (Ford and Barrett, 1975). Isolated moraines in the southeastern Ross Sea were deposited on land by grounded ice advancing from Marie Byrd Land (Sorlien et al., 2007). In the adjacent offshore areas, the absence of glacial features in the pre-26.7 million years ago seismic sequences is consistent with the view of an ice-free marine setting during the early Oliogocene. Paleoseabed restoration demonstrates that the subaerial Central High was flanked by a deepwater ramp that dipped basinward (De Santis et al., 1999). Apparently, the Antarctic climate had not yet cooled sufficiently for marine-based ice to exist on the Ross Sea outer shelf. This detailed view of West Antarctic ice restricted to the TAM coastal fringes of the Ross Sea in the late Eocene/earliest Oligocene cannot be unambiguously inferred from interpretation of proxy evidence (i.e., Mg/Ca data or composite δ^{18}O records).

Late Oligocene

By the late Oligocene, a well-developed glacial drainage system existed on broad basement uplifts of the Central High and Coulman High (De Santis et al., 1995; Brancolini et al., 1995b). At this time, deepwater areas flanked these elevated basement blocks, and a shelf-slope configuration of the margin had not yet developed. From these basement highs, ice caps advanced and retreated into the surrounding shallow-water areas. Thus, West Antarctic glaciation, at least in the Ross Sea, began by the late Oligocene when ice caps nucleating from subaerially elevated basement horst blocks in the central Ross Sea advanced across shallow and narrow marine platforms rimming the broad basement uplifts. The adjacent deepwater basins remained free of grounded ice in the late Oligocene. The oldest glaciogenic features include small till tongues and erosion surfaces encapsulated within dominantly finely laminated glacial marine strata. These temperate glacial systems delivered voluminous sediment to the intervening deepwater shelf basins. The sedimentation caused the deep shelf basins to progressively shoal as accommodation was filled. Seismic correlations to DSDP Leg 28 Sites 270 and 273 show that the thick successions of acoustically laminated strata of these types are composed of silty claystones. The presence of scattered ice-rafted granules and pebbles within the claystones indicates that sedimentation was influenced by nearby glaciers from at least the late Oligocene. Foram data indicate that the environment was still temperate and that the shelf abruptly deepened from a shallow-water environment (Leckie and Webb, 1983, 1996). The deepening may have been a consequence of the Oligocene glacial erosion and isostatic depression and also of tectonic subsidence (De Santis et al., 1999). Cenozoic tectonic activity widely affected the Ross Sea sequences in the western and central Ross Sea (Cooper and Davey, 1987; Salvini et al., 1997; Busetti et al., 1999; Rossetti et al., 2006; Davey and De Santis, 2006), but extensional faults are also observed in the central and eastern Ross Sea in the Oligocene and Miocene sequence (Busetti et al., 1999; De Santis et al., 1999; Rossetti et al., 2006). The general absence of glacial erosion surfaces within late Oligocene and older strata in the basins flanking the basement highs suggests that ice was not extensively grounded on the Ross Sea outer shelf. The initial advance of grounded ice caps on shallow-water areas of the Ross Sea outer shelf probably was coeval with valley and piedmont glaciers advancing from the coastal peripheries at the Transantarctic Mountain front to the west, in Marie Byrd Land to the east, and in the West Antarctic interior highlands to the south.

Early Miocene

The isolated and relatively thin till tongues and other late Oligocene moraine features were replaced by massive and thick till deltas that are common in lower Miocene strata (Anderson and Bartek, 1992; De Santis et al., 1995). The interpretation of sedimentation in a grounding-zone proximal shelf setting is confirmed by correlation of the seismic facies to drill data at DSDP Sites 272 and 270 (De Santis et al., 1995). In the Ross Sea, till deltas have foreset heights of 250 m, indicating that grounded ice caps advanced into progressively deeper accommodation (De Santis et al., 1995). The major thicknesses and large volumes of these strata and the assemblage of foraminifera observed in DSDP Site 270 cores (Leckie and Webb, 1983; Steinhauff and Webb, 1987) suggest that temperate climate systems with abundant meltwater probably persisted at this time. These till deltas and their topset truncations indicate more widespread grounded ice existed by virtue of offshore progradation, but the extent of grounded ice still rimmed relatively shallow-water platforms surrounding basement highs. The glaciogenic features are interbedded with thick successions of strata that are devoid of glacial erosion surfaces and moraine units. Seismic correlation to lithologic control at DSDP Leg 28 drill sites shows that these finely laminated seismic facies are composed of claystones containing ice-rafted debris (De Santis et al., 1995). The presence of ice-rafted debris demonstrates that grounded ice capable of producing icebergs existed at sea level. These stratigraphic associations indicate that ice cap advances were periodically interrupted by significant retreat of grounded ice and glacial marine sedimentation on the outer shelf during the early Miocene.

Middle Miocene

Advances of the West Antarctic ice caps during the middle Miocene were also interrupted by deglacial retreats (De Santis et al., 1995; Chow and Bart, 2003). One such ice retreat led to the Mid-Miocene Climatic Optimum (MMCO), the warmest interval since the initial transition to ice house conditions at Oi-1 in the early Oligocene. Meltwater channels exist in sections estimated to be of MMCO age. Palynological evidence from ANDRILL-2A sites in South McMurdo Sound also indicates that freshwater discharge occurred in the MMCO (Warny et al., 2009). Subsequent to the MMCO, grounded ice re-advanced in a major intensification of the late Neogene glaciation during the Middle Miocene Shift (MMS; Bart, 2003; Chow and Bart, 2003). Major expansions of grounded ice from isolated subaerial basement highs such as the Central High on the West Antarctic outer shelf was probably coincident with advance of grounded ice from the periphery of Ross Sea from Victoria Land and possibly from the Marie Bird Land coast (De Santis et al., 1995). Grounded ice may have advanced into the deep basins and scoured these zones when full-bodied East and West Antarctic Ice Sheets occupied the Ross Sea outer shelf in the latter part of the middle Miocene (Chow and Bart, 2003). By the end of the middle Miocene, accommodation on the shelf was filled, basement highs had subsided, and a classic shelf-slope type margin had developed (De Santis et al., 1995, 1999). At the top of a section assigned to the middle Miocene, the first unequivocal seismic evidence of a major cross-shelf paleotrough shows that extensive grounded ice with ice streams extended over the central area of the Ross Sea (De Santis et al., 1995). The southwest-northeast orientation of the paleotrough across the Central High and Central Trough suggests that grounded ice drained from East Antarctica, possibly through an ancestral Byrd outlet glacier. Further studies on the mineral composition of the sediment filling such troughs will be needed to verify the location of the source area. Subglacial delta features are preserved in the paleotrough axis and extend to the paleo-shelf edge. A TMF formed at the shelf edge of the Eastern Basin in association with shelf wide advance of grounded ice. On the continental slope and rise, the large volume of early to middle Miocene strata eroded from the continental shelf suggests erosion by ice streams and possibly the last occurrence of high volume meltwater discharge to the deep sea in association with channel-levee depositional systems. This stratigraphic pattern is commonly observed around the Antarctic margin in Miocene sections (Escutia et al., 2000; De Santis et al., 2003).

The middle Miocene intensification of glaciation probably was associated with a reduction in the volume of meltwater. In the outer Ross Sea, definitive meltwater and outwash features are absent from strata younger than the middle Miocene. In addition, laminated glacial marine sections become progressively thinner and less common by the end of the middle Miocene.

The seismic data interpretation is consistent with onshore data from the Dry Valleys region of the Transantarctic Mountains, which indicates that the warmer and wetter glacial conditions of the early Miocene were replaced by colder and drier conditions in the middle Miocene (Marchant et al., 1996a,b; Lewis et al., 2006, 2007). These stratigraphic observations are generally consistent with the global view of progressive ice volume increase, climate cooling, and sea level fall via a series of steps in the middle Miocene shift.

Late Miocene and Early Pliocene

An upper Miocene section has not been recovered by drilling but it is assumed to exist between the youngest middle Miocene drilled at DSDP Site 272 and the oldest Pliocene drilled at DSDP Site 271 (Anderson and Bartek, 1992). Shelfwide WAIS advances occurred in the late Miocene and even during glacials of the warmer-than-present early Pliocene (Bartek et al., 1991; Bart et al., 2000; Bart, 2001). As a consequence of widespread and progressive glacial erosion, the shelf overdeepened in the latest Miocene/earliest Pliocene (De Santis et al., 1995, 1999). Meltwater channels are largely absent in sections of late Miocene and younger age. Small-scale incisions at the top of aggrading till sheets were initially interpreted to be meltwater channels at a paleo-shelf edge (Alonso et al., 1992); however, subsequent studies showed that similar scale features are found capping deposits of the LGM (Shipp et al., 1999). Hence, these incisions can be re-interpreted as upper-slope gullies unrelated to temperate climate conditions (Anderson, 1999; Shipp et al., 1999; Dowdeswell et al., 2004). Topset surfaces correspond to glacial unconformities that bound internally massive till sheets. Backstripping results suggest that stratal surfaces within this section formed during a time of progressive change from seaward- to landward-dipping geometry in the eastern Ross Sea and reached a generally overdeepened configuration similar to the present-day profile of the shelf (De Santis et al., 1999). In the Ross Sea, a stratal change from aggradation to progradation occurred in the late Miocene to early Pliocene, and the shelf locally prograded > 30 km beyond the paleo-shelf edge in parts of the eastern Ross Sea (Bartek et al., 1991; Anderson and Bartek, 1992). A sea level rise of +22 m higher than present and +2°C higher deep-sea temperatures are inferred for the warm Pliocene interval (e.g., Miller et al., 2012). At least one shelfwide advance of the WAIS occurred in the Ross Sea during the early Pliocene (Bart, 2001). Thus, early Pliocene dynamics included shelfwide grounding events in the early Pliocene alternating with times of significant ice sheet retreat (Bart, 2001). TMF development may have occurred in association with higher precipitation during the warmer-than-present early Pliocene. Early Pliocene TMF development is also known from the Crary TMF (Bart et al., 1999), Prydz Bay (Cooper and O'Brien, 2004), and Antarctic Peninsula Pacific margins (Bart and Iwai, 2012), suggesting that TMF development was continent-wide (Rebesco et al., 2006).

Late Pliocene and Pleistocene

The Pleistocene section contains till sheets and erosional unconformities indicative of shelfwide advances of grounded ice (Alonso et al., 1992). Much sediment delivered from land was sequestered on the outer shelf and the upper slope, whereas sediment bypass to the adjacent slope and rise was reduced in the late Pliocene and Pleistocene. A similar stratal pattern is noted from the Antarctic Peninsula Pacific margin (Bart and Anderson, 1995; Bart and Iwai, 2012), Prydz Bay margin (Cooper and O'Brien, 2004; O'Brien et al., 2007), and Wilkes Land (De Santis et al., 2003; Donda et al., 2007). The overall reduction in sediment production and delivery to the margin is taken by some to represent a shift to significantly drier climatic conditions (De Santis et al., 2003), coincident with the onset of Northern Hemisphere glaciation (Rebesco et al., 2006). A section assigned to the late Pliocene and Pleistocene thickens toward the outer shelf with minimal (< 1 km) upper slope progradation on a per glacial unit basis (Bart and Anderson, 1995, 1996). Mapping indicates that slightly foredeepened subglacial erosion surfaces bound till sheets. Thus, these glacial units have an overall aggradational form, and sediments below the glacial unconformities are overcompacted (Bohm et al., 2009). Seismic data for the late Pliocene and Pleistocene on the outer shelf contain relatively few glacial unconformities (Alonso et al., 1992) relative to the high frequency of glacial cycles inferred from oxygen isotope data (Lisiecki and Raymo, 2005). The record of higher-frequency advances for the late Pliocene and Pleistocene is either amalgamated or below the resolution of seismic data. Alternately, perhaps there simply were few major WAIS expansions to the outer shelf (Bart et al., 2011). The low sedimentation rates on the Antarctic Peninsula continental rise during the Pliocene and Pleistocene (Barker and Camerlenghi, 2002) suggest that the outer shelf did not experience significant erosion and bypass to the deep sea. The "Overdeepening Hypothesis" provides one possible explanation for the few unconformities on the outer shelf and the low sedimentation rates on the continental rise (Bart and Iwai, 2012). The hypothesis, developed based on seismic stratigraphic and drill data from the Antarctic Peninsula Pacific margin, predicts that overdeepening of the shelf may be linked to reduced frequency of outer-shelf grounding events. This hypothesis suggests that warm water intrusion accelerated melting at the marine terminus of the ice sheet, which in turn limited the number of major glacial advances during the late Pliocene and Pleistocene.

FUTURE OUTLOOK AND CHALLENGES

Regional seismic-based investigations of Antarctic continental shelves remain the most efficient way to evaluate the large-scale dimensions of erosional surfaces and depositional features associated with the small- and large-scale advance and retreat of grounded ice. Correctly characterizing the timing, frequency, and rate of past dynamics requires detailed correlations to well-dated drill site data. A critical challenge will be to find high-resolution records of past change that can be dated. A detailed understanding of past dynamics is a fundamental aspect of assessing what spectrum of factors might trigger a dynamic shift from the current Antarctic ice sheet stability. For example, in terms of the potential that global warming might cause the cryosphere to contract, three basic questions that cannot yet be adequately answered from the perspective of direct data are: (1) When and under what circumstances might the current grounding event end with ice sheet retreat? (2) What would be the magnitude and rate of sea level rise? (3) How would the pattern of global climate change if the extent and elevation of Antarctic ice sheets were reduced? How scientists answer these questions is of obvious importance to policymakers.

Put differently, whether policymakers take these questions seriously depends upon what the scientific data reveal. Providing scientific answers to these questions requires additional seismic and drill data from Antarctica because the continent is so large and so many regions remain unexplored. With respect to seismic data we reviewed, it is important to keep in mind that on the Ross Sea outer shelf, the glaciogenic features reveal the maximum extent of grounded ice. In other words, the evidence that we summarized pertains specifically to the seismic evidence for WAIS oscillations on the Ross Sea shelf sector. Additional data are needed to fully characterize the amplitude of interior ice sheet inflation/deflation. Moreover, data from inner-shelf sites are needed to determine the maximum retreat of grounded ice. Data from the Antarctic should also be considered within the context of global climate and eustatic change data (Figure 12). A detailed discussion of where the proxy and direct data agree/disagree is beyond

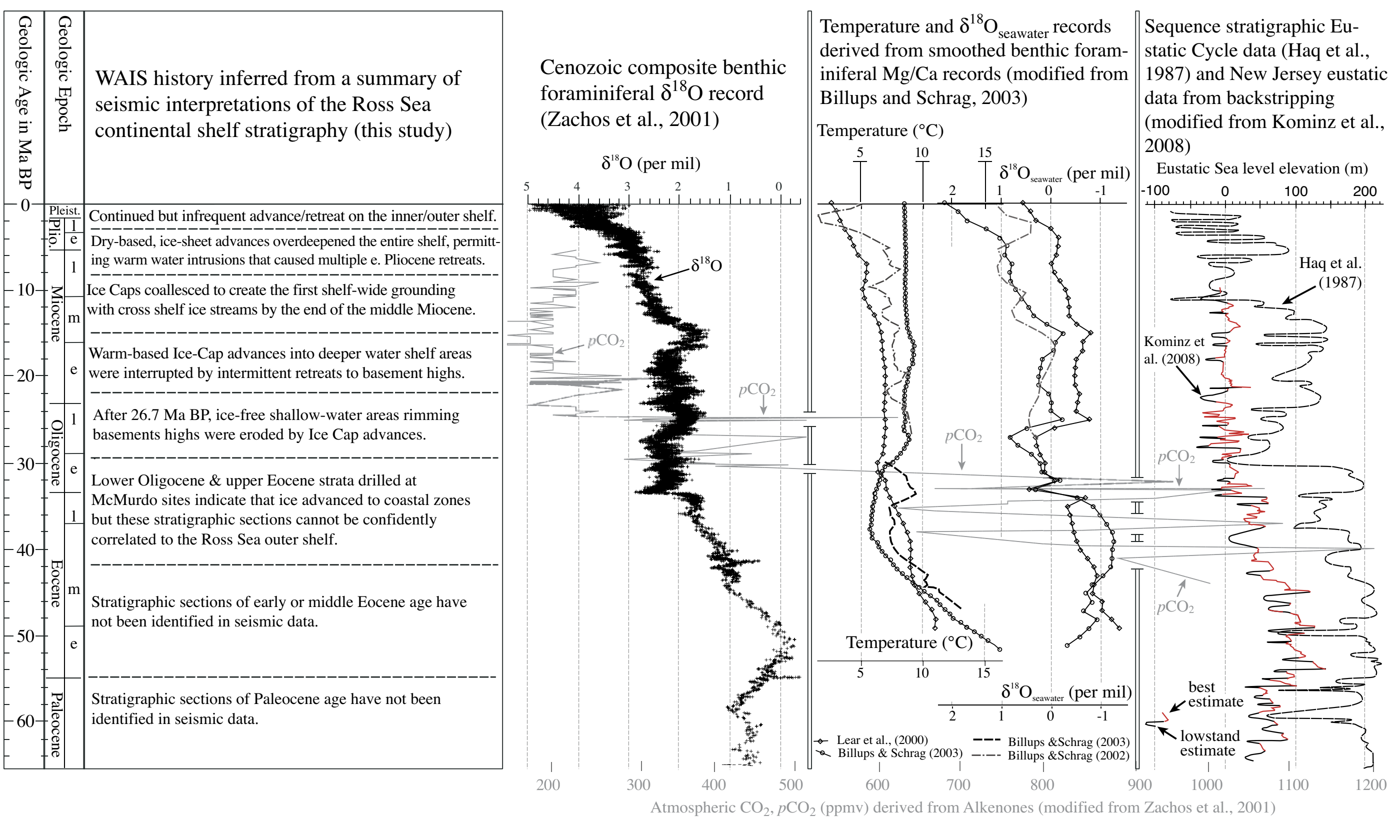

Figure 12. Summary of West Antarctic Ice Sheet (WAIS) history inferred from seismic interpretations of the Ross Sea outer shelf stratigraphy compared to the Cenozoic composite benthic foraminiferal $\delta^{18}O$ record, temperature and $\delta^{18}O_{sw}$ from Ca-Mg records, the Eustatic Cycle chart (Haq et al., 1987), and the New Jersey eustatic data (Kominz et al., 2008).

the scope of our review. Nonetheless, these considerations highlight the need for large-scale integration of well-dated direct data from the Antarctic continental interior and continental margins with eustatic and deep-sea proxy data.

CONCLUSIONS

Isolated moraines indicate that ice caps advanced and retreated on the shallow-marine platforms of the Coulman and Central Highs of West Antarctica after 26.7 million years before present, some 6 million years after the Oi-1 event, the major oxygen-isotope shift signalling the onset of early Oligocene glaciation. Ice caps on the Ross Sea outer shelf probably coalesced with grounded ice from the East and West Antarctic interior by the end of the middle Miocene. The shift from ice caps to shelfwide grounding events represents an intensification of Neogene glaciation. TMF development occurred in the latest Miocene/earliest Pliocene. Erosion during this time frame eventually overdeepened and foredeepened the outer shelf. The early Pliocene included multiple intervals of ice sheet retreat but the dynamics also included an interval of major advance to the outer shelf. The WAIS probably experienced few advances to the Ross Sea outer shelf during the latest Pliocene and Pleistocene.

ACKNOWLEDGMENTS

We thank K. Hinz and the Bundesanstalt für Geowissenschaften und Rohstoffe, Germany; A. Cooper and the United States Geological Survey; J. Wannesson and the Institute Française du Pétrole; S. Sato and the Japanese National Oil Company; Igor Zayatz and the Joint Stock Marine Arctic Geological Expedition, Russia; J.B. Anderson, Rice University, Houston, Texas; L. Bartek, University of Alabama, Tuscaloosa; the US National Science Foundation; the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Italy; and PNRA (Programma Nazionale delle Ricerche in Antartide) for kindly providing access to the seismic data used in this investigation through the Antarctic Seismic Data Library System. We thank Stuart Henrys and Chris Sorlien for suggestions and comments that greatly improved the paper.

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