Oligocene development of the West Antarctic Ice Sheet recorded in eastern Ross Sea strata

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ABSTRACT

Seismic-reflection data from the easternmost Ross Sea image buried scour-and-fill troughs and flat-topped ridges interpreted as having formed by glacial erosion and deposition during the Oligocene. The NNW-SSE orientation of the troughs and lack of similar Oligocene glacial features within the central Ross Sea suggests that the ice issued from the highlands of Marie Byrd Land located 100 km away and that portions of the West Antarctic Ice Sheet formed earlier than previously accepted. Existing global climate models (GCMs) do not produce West Antarctic ice caps for the Oligocene, in part due to low elevations modeled for that time. Evidence for Oligocene ice beyond the paleocoast suggests a higher elevation for the early Cenozoic Marie Byrd Land and Ross Embayment than at present.

Keywords: Antarctic Ice Sheet, Marie Byrd Land, West Antarctica, seismic stratigraphy, Ross Sea, Oligocene, basins.

INTRODUCTION

Oxygen isotopes have been interpreted to indicate the growth of continental-sized Antarctic ice sheets at the Eocene-Oligocene boundary (Zachos et al., 2001). Ice is modeled to have first accumulated on the high-elevation plateau of East Antarctica (DeConto and Pollard, 2003), but the extent to which West Antarctica participated in Oligocene glaciation is not known. Indeed, the oldest seismic stratigraphic evidence for regional grounded ice in the eastern Ross Sea is variously interpreted as late Oligocene (Bartek et al., 1992), middle Miocene (Bart, 2003), and late Miocene (De Santis et al. 1999). Glacial erosion between ca. 28 Ma and 15 Ma of dated volcanoes in the interior of northern Marie Byrd Land as well as hydrovolcanic rocks suggest a small Oligocene ice cap there (Rocchi et al., 2006). More data are required to determine how important West Antarctica was to the major early Oligocene expansion of the Antarctic cryosphere.

Global climate models (GCMs) are used to understand mid-Cenozoic ice-sheet development. GCMs incorporate atmospheric composition, paleo-elevation, heat transport by ocean currents and atmosphere, and orbital parameters (DeConto and Pollard, 2003). Late Oligocene to present uplift of a dome in northern Marie Byrd Land has been proposed to explain the current elevation of a Cretaceous erosion surface there (LeMasurier and Landis, 1996). Regional subsidence due to crustal cooling is thought to have occurred after the end of Late Cretaceous extension for much of Marie Byrd Land and the Ross Sea (Decesari, 2006; Luyendyk et al., 2001). Subsidence means that, at least for areas outside the dome, Marie Byrd Land was much higher-standing during Oligocene time than the mid-Cenozoic West Antarctic archipelago calculated by DeConto and Pollard (2003). Their GCM was able to grow a mid-Cenozoic ice sheet only on an elevated East Antarctica, with no regional ice cap on West Antarctica. If data show that Oligocene strata, now far below sea level, preserve evidence of West Antarctic ice, then the regional subsidence model is supported.

SETTING AND RESULTS

The West Antarctic rift system includes the Ross Embayment, the region now covered by the Ross Sea, and the Ross Ice Shelf (Fig. 1A). Cretaceous and early to middle Cenozoic lithospheric extension between East and West Antarctica has produced several topographic highs and adjacent major basins (Fig. 1A; Cooper et al., 1995). We have recently acquired seismic-reflection and multibeam bathymetry data in areas that were covered by Ross Ice Shelf until 2000, when giant icebergs calved (Fig. 1B). Details of the acquisition and processing of the reflection data are available elsewhere (Decesari, 2006). Higher-resolution single-fold reflection data were recorded using a single air gun (Fig. 2) coincident with deep-imaging multichannel data. Both reflection and bathymetry data image basement exposed at or near the seafloor on a ridge extending north from the Roosevelt Island ice dome (Figs. 1B and 3A). An ~3-km-deep sedimentary basin, here named the Roosevelt subbasin, is present between this ridge, named Roosevelt Ridge, and Marie Byrd Land (Fig. 3).

Observations

A succession of broad (10–20 km) and narrow (2–5 km) buried U-shaped troughs are present in Roosevelt subbasin (Figs. 2 and 4). A succession of flat-topped ridges separates the narrow troughs. All of the troughs and flat-topped ridges have similar amplitudes, ~150 m, and are between 700 and 900 m depth, with the top of the succession of troughs between 0 and 150 m below seafloor (Fig. 2). Below the interval of the troughs is a 200-m-thick succession of offlapping sequences that have an apparent (two-dimensional) progradation toward the southwest (between cyan and violet reflections on Fig. 4B). These sequences are associated with a flat-topped ridge at their distal (southwest) end, at 1200–1400 m depth (Fig. 4C). The broad troughs can be individually correlated between four parallel profiles and are aligned NNW-SSE, and our tentative correlations between profiles indicate that the narrow troughs and flat-topped ridges may be aligned NW-SE to W-E (Fig. 1B).

Correlation of Chronostratigraphic Control

We use the Antarctic Offshore Acoustic Stratigraphy (ANTOSTRAT; Cooper et al., 1995) stratigraphic nomenclature for sediments filling the Eastern Basin, as modified by Luyendyk et al. (2001) (Fig. 3). In the Eastern Basin, the units are named "RSS-" sequences (RSS-1 = oldest) separated by regional unconformities "RSU-" (RSU1 = youngest). These units and unconformities were dated by Deep Sea Drilling Project (DSDP) Leg 28, which sampled the west flank of the Eastern Basin (Fig. 1A; Hayes and Frakes, 1975). The oldest marine sedimentary rocks DSDP recovered are dated as late Oligocene (RSS2-upper; ca. 25 Ma), based on foraminifera from Site 270 (Leckie and Webb, 1986). Although the correlation path from DSDP Site 270 to the northeast Roosevelt subbasin is 450 km long, the correlation is straightforward because of uniform marine deposition and near total lack of deformation. The underlying RSS2-lower strata, including the offlapping sequences, have not been sampled, but they are also presumed to be Oligocene because they overlie the putative Oligocene RSU-6 unconformity (Fig. 4B; Cooper et al., 1995; Luyendyk et al., 2001). The RSS2-upper reflections seen in the northern part of the survey (Fig. 4D) are from

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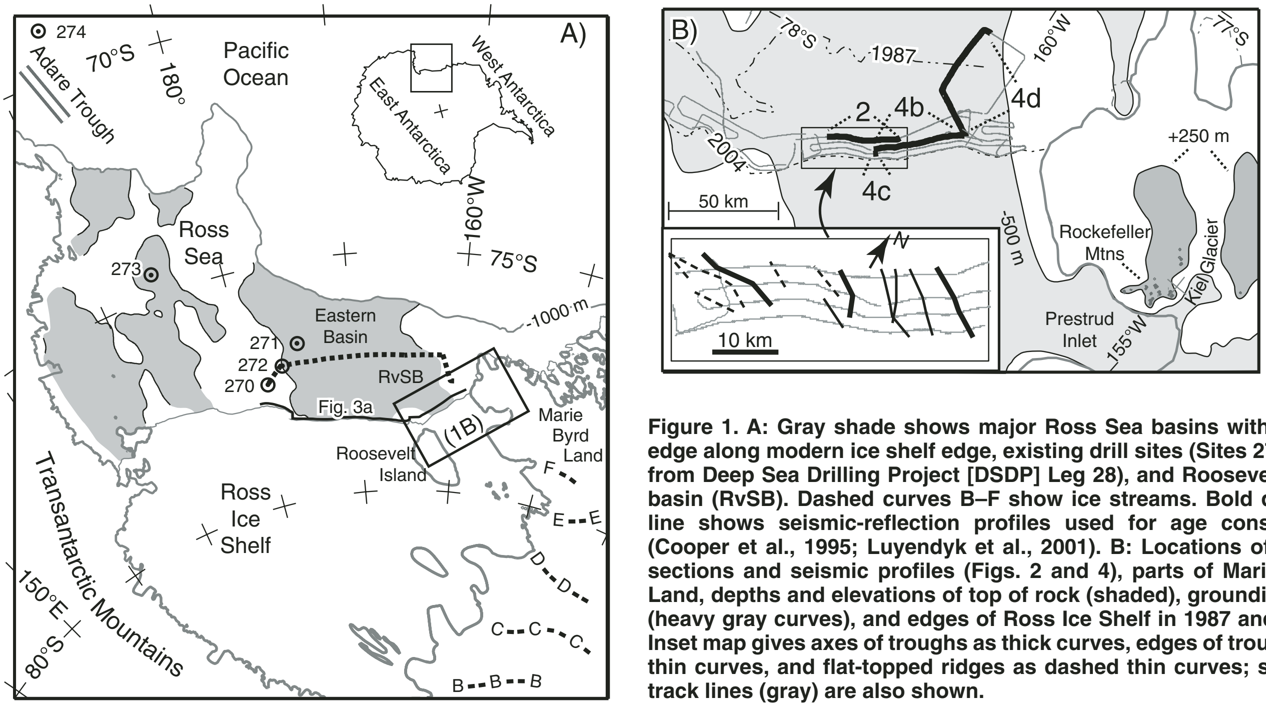
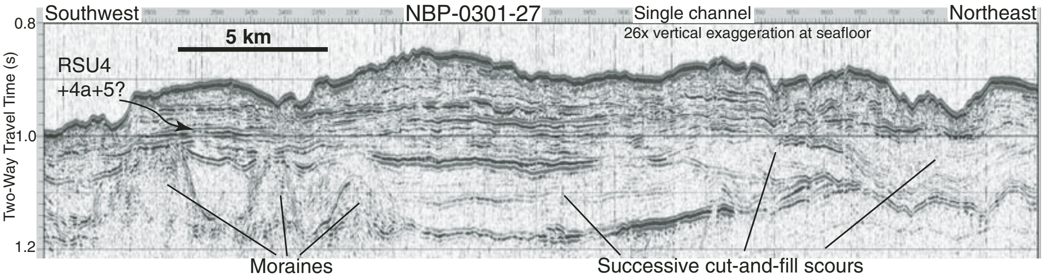


Figure 1. A: Gray shade shows major Ross Sea basins with south edge along modern ice shelf edge, existing drill sites (Sites 270–274 from Deep Sea Drilling Project [DSDP] Leg 28), and Roosevelt subbasin (RvSB). Dashed curves B–F show ice streams. Bold dashed line shows seismic-reflection profiles used for age constraints (Cooper et al., 1995; Luyendyk et al., 2001). B: Locations of cross sections and seismic profiles (Figs. 2 and 4), parts of Marie Byrd Land, depths and elevations of top of rock (shaded), grounding line (heavy gray curves), and edges of Ross Ice Shelf in 1987 and 2004. Inset map gives axes of troughs as thick curves, edges of troughs as thin curves, and flat-topped ridges as dashed thin curves; seismic track lines (gray) are also shown.

Figure 2. Nonmigrated single-channel seismic profile NBP 0301-27 (Fig. 1B). We interpret broad U-shaped troughs to have been successively cut and filled by ice. Flat-topped ridges are interpreted as moraines deposited in successive stages. This profile coincides with upper part of depth section in Figure 3B. Separate sequence boundaries within middle of Eastern Basin (Fig. 3A) merge eastward and are labeled RSU4+4a+5.



the base of that interval and underlie the ca. 25 Ma strata cored at DSDP Site 270. Basal RSS2-upper along with RSS2-lower thus predate 25 Ma.

Unlike along the correlation path shown on Figure 1A, the troughs and flat-topped ridges cannot be dated by direct correlation from northeast to the central Roosevelt subbasin because the sedimentary sequences containing them pinch out along the southern part of the profile shown in Figure 4D. However, based on their seismic character and similarity between their occurrence southwest of point T1 and the occurrence of RSS-2-upper north of point T2 (Fig. 4), a correlation spanning ~30 km, we interpret these units to be similar in age to the late Oligocene basal part of RSS-2-upper. Additionally, along the eastern margin of the Eastern Basin, the early Miocene part of RSS-2 and younger sequences pinch out and do not occur south of ~77°S (Luyendyk et al., 2001). Unconformities above RSS-2 dip northward throughout the Eastern Basin (De Santis et al., 1999; Luyendyk et al., 2001), so post-Oligocene units are unlikely to be present at 800 m depth in Roosevelt subbasin.

DISCUSSION AND CONCLUSIONS

We interpret offlapping sequences (Fig. 4B) to be deltas formed adjacent to the grounding line of a glacier (see Bart, 2003) and the synchronous flat-topped ridge (Fig. 4C) to be a moraine. Above these deltas, we interpret the flat-topped ridges to be buried moraines and the broad troughs to have been carved by glaciers. If the flat-topped ridges were instead erosional remnants, their internal reflections would be horizontal. The internal reflections are instead subparallel to the edges of the troughs, as would be expected for a moraine (Fig. 2). Diapirism is not a likely explanation for the ridges because trough fill onlaps them without upwarping on Figure 2 and nearby. Continuous reflections cross beneath the ridges in Figure 2 and at deeper levels on both the coincident multichannel stack and a nearby stack, with slight pull-up beneath each ridge interpreted as a velocity effect. The sizes of the features are not unexpected for a moraine: a series of moraines is imaged on seismic-reflection data in Glacier Bay, Alaska, that has up to 200 m amplitude and a spatial pattern that is similar to that in Figure 2 (Gulick et al., 2004). We do not expect that a series of 10–20-km-wide troughs, with consistent ~150 m relief, could be carved by nonglacial processes on the shelf of a passive margin.

A fluvial explanation for the troughs and ridges is precluded if they formed below sea level, and the expected late Oligocene water depth gives a minimum thickness for grounded ice. The depositional load of RSS-2 may be a factor in tilting and subsidence, but younger units of sufficient thickness to cause post-RSU5 subsidence are not present in close proximity to Roosevelt subbasin (Fig. 3A; Luyendyk et al., 2001). Thermal subsidence (e.g., McKenzie, 1978) resulting from earlier extension is a viable mechanism for moderate subsidence, but reasonable stretching factors and extension ages from Late Cretaceous to early Tertiary limit post–25 Ma thermal subsidence to at most ~400 m (Decesari, 2006). The current 700–900 m depth of the trough and fill sequences indicates that they were deposited in marine conditions at depths of several hundred meters.

The troughs were filled with sediment as ice retreated; then, as ice advanced, a new trough was cut into the fill (Fig. 2). These successive

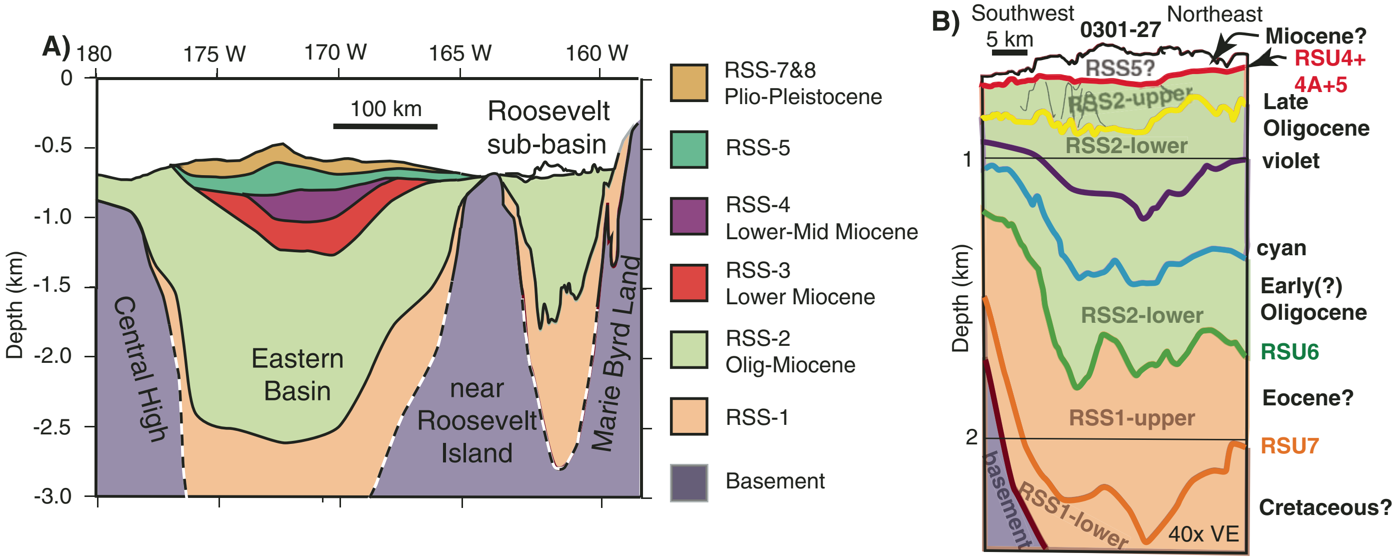


Figure 3. Both cross sections are drawn from interpreted depth-migrated seismic-reflection profiles. A: Cross section across eastern Ross Sea at ice-shelf edge (Fig. 1A) showing that strata in Eastern Basin and Roosevelt subbasin are separated by a basement high. B: Detail of cross section across western Roosevelt subbasin. Colors of horizons are same as in Figure 4. Thin black lines within RSS2-upper outline flat-topped ridges seen in Figure 2. VE—vertical exaggeration.

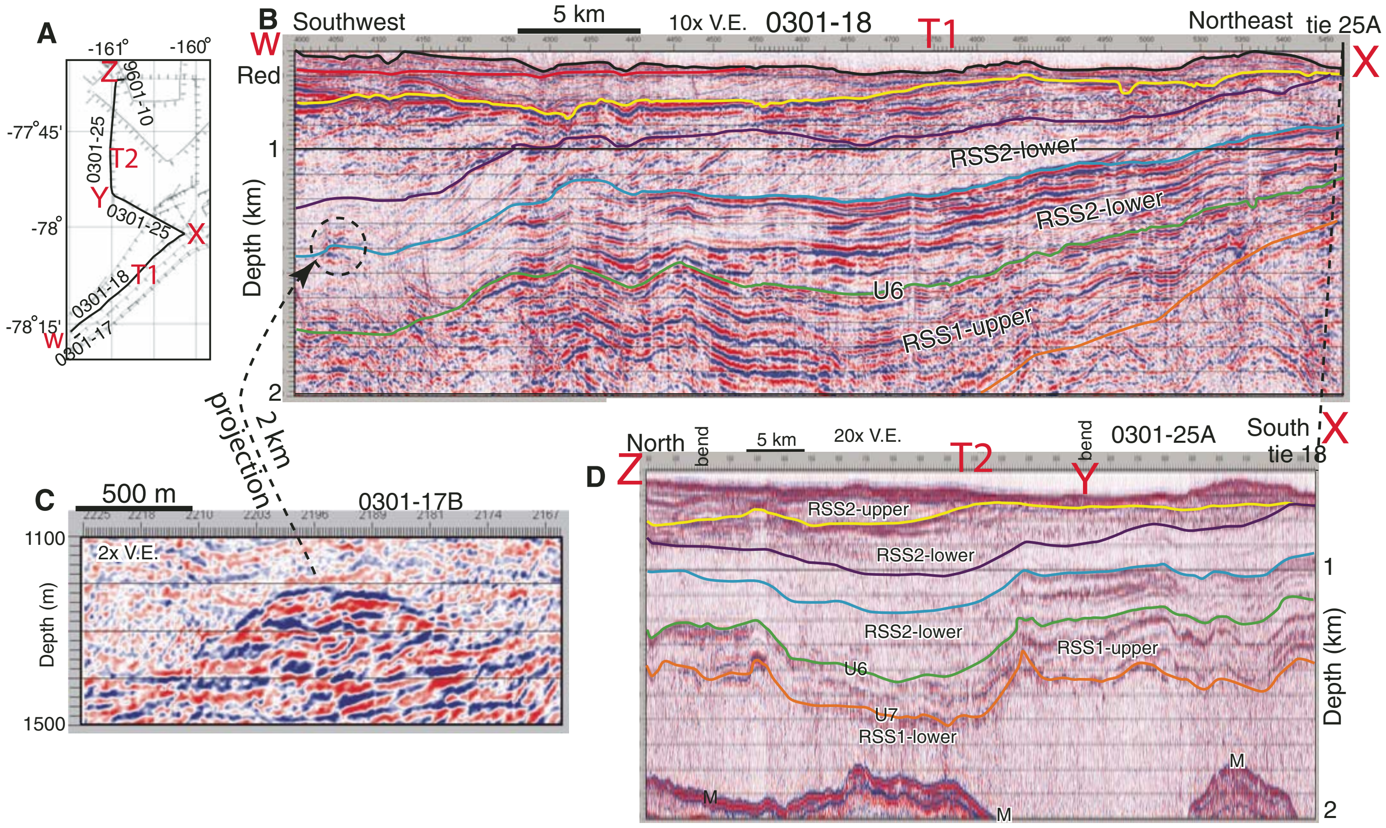


Figure 4. A: Location map for profiles and reference points. B: Migrated multichannel seismic-reflection depth section across eastern half of Roosevelt subbasin to its intersection with profile in D at (X) (Figs. 1B and 4A). Offlapping sequences (between cyan and violet) are interpreted as deltas deposited near grounding line of a glacier. These features are within lower part of RSS-2-lower (pre-25 Ma), beneath a 20-km-wide U-shaped trough. C: Migrated depth profile of flat-topped ridge interpreted as moraine and as synchronous with distal part of offlapping sequences. Profile is located in A, and its projected location is indicated by dashed arrow and circle in B. D: Nonmigrated single-channel seismic-reflection profile displayed in depth, shown between its intersections with profile in B (X) and NBP 9601 Line 10 (Z) from Luyendyk et al. (2001) (also http://projects.crustal.ucsb.edu/colbeck/Colbeck5a.html). Line 10 is directly correlated to Deep Sea Drilling Project (DSDP) Site 270 along dashed path in Figure 1A. Trough at T2 is overlain by basal RSS2-upper, so it predates 25 Ma. We interpret that troughs seen on Figure 4B are the same age. V.E.—vertical exaggeration.

advances and retreats are consistent with the dynamic Antarctic ice caps interpreted by Pekar et al. (2006) for the late Oligocene. The lower offlapping sequences are restricted to the eastern half of Roosevelt subbasin, adjacent to Marie Byrd Land, and may represent the first appearance of glaciers in the present area of the eastern Ross Sea. Ice may have been more extensive in paleohighlands located to the southeast (Fig. 1B).

We are confident that the troughs and flat-topped ridges are of glacial origin, but because the interval that contains them pinches out along Figure 4D, the interpretation that they predate 25 Ma is based on a comparison of seismic stratigraphy (Figs. 4B and 4D). The older offlapping sequences can be continuously correlated to beneath pre–25 Ma basal RSS2-upper strata (Figs. 4B and 4D). It is, however, less certain that these offlapping sequences were deposited proximal to a glacier. Our preferred interpretation is that all of the troughs, ridges, mounds, and offlapping sequences predate 25 Ma and postdate RSU6. We infer RSU6 to have formed during sea-level falls of ~50 m between 33.7 and 33.5 Ma and/or between 28.3 and 28.1 Ma (Miller et al., 2005).

Narrow erosional troughs and reflective mounds or ridges are imaged within pre–25 Ma strata on the west flank of Roosevelt Ridge, but such features are not present in the deep part of the Eastern Basin near the ice-shelf edge, even though Oligocene sedimentary rocks are preserved there. If the ice that scoured the troughs in Roosevelt subbasin came from East Antarctica, then similar features related to glacial erosion and deposition might be preserved in the Eastern Basin near the ice-shelf edge, and they are not seen. These observations suggest that the ice within Roosevelt subbasin originated from West Antarctica and that these sedimentary sequences may contain a direct record of the history of the West Antarctic Ice Sheet.

Incision of troughs hundreds of meters below sea level by a grounded ice sheet requires substantial ice on a nearby landmass. Presently, the nearest high-elevation rock surface is in the Rockefeller Mountains; these highlands of Marie Byrd Land are located over 100 km to the southeast (Fig. 1B). The modern Prestrud Inlet (Fig. 1B) is a flow path for ice sourced from highlands even farther southeast. Evidence for a late Oligocene ice cap in northern Marie Byrd Land (Rocchi et al., 2006) suggests the possibility of a regional, late Oligocene West Antarctic Ice Sheet.

If the seismic stratigraphic correlation (Fig. 4) presented here is correct, then this paper documents the first evidence for marine Oligocene grounded ice located far from an elevated source in Marie Byrd Land. This places the initiation of the West Antarctic Ice Sheet during the late Oligocene and helps explain global ice volumes calculated for that time as high as 125% of the modern East Antarctic Ice Sheet (Pekar et al., 2006). Input of a high-standing Oligocene Marie Byrd Land, rather than an archipelago, into a GCM, favors growth of the West Antarctic Ice Sheet for expected Oligocene atmospheric composition and heat transport. Even if northern Marie Byrd Land dome experienced Oligocene and Neogene rock uplift and surface uplift (Rocchi et al., 2006), this does not preclude regional subsidence of the Roosevelt subbasin and adjoining western Marie Byrd Land, because the two regions are spatially distinct. If the deeper offlapping sequences and associated flat-topped ridge are indeed glacial proximal deltas and moraines, then an episode of Oligocene grounded ice that predates formation of the troughs imaged in Figure 2 occurred near or beyond the paleocoast of Marie Byrd Land. It is possible that Oligocene grounded ice only affected the SE corner of the Ross Sea, adjacent to Marie Byrd Land, which is not inconsistent with Miocene initiation of grounded ice in the area of the Eastern Basin some hundreds of kilometers to the northwest (Bart, 2003; De Santis et al., 1999), or with late Oligocene grounded ice there sourced from East Antarctica or the Central High (Bartek et al., 1992).

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REFERENCES CITED

Bart, P.J., 2003, Were West Antarctic Ice Sheet grounding events in Ross Sea a consequence of East Antarctic Ice Sheet expansion during the middle Miocene?: Earth and Planetary Science Letters, v. 216, p. 93–107, doi: 10.1016/S0012–821X(03)00509–0.

Bartek, L.R., Sloan, L.C., Anderson, J.B., and Ross, M.I., 1992, Evidence from the Antarctic continental margin of late Paleogene ice sheets: A manifestation of plate reorganization and synchronous changes in atmospheric circulation over the emerging Southern Ocean?, *in* Prothero, D.R., and Berggren, W.A., eds., Eocene-Oligocene Climatic and Biotic Evolution: Princeton, New Jersey, Princeton University Press, p. 131–159.

Cooper, A.K., Barker, P.F., and Brancolini, G., eds., 1995, Geology and seismic stratigraphy of the Antarctic margin: American Geophysical Union Antarctic Research Series, v. 68, 301 p., atlas, CD-ROM.

Decesari, R.C., 2006, The Mesozoic and Cenozoic depositional, structural, and tectonic evolution of the Ross Sea, Antarctica [Ph.D. thesis]: Santa Barbara, University of California, 232 p.

DeConto, R.M., and Pollard, D., 2003, A coupled climate-ice sheet modeling approach to the early Cenozoic history of the Antarctic ice sheet: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 198, p. 39–52, doi: 10.1016/S0031–0182(03)00393–6.

De Santis, L., Prato, S., Brancolini, G., Lovo, M., and Torelli, L., 1999, The Eastern Ross Sea continental shelf during the Cenozoic: Implications for the West Antarctic Ice Sheet development: Global and Planetary Change, v. 23, p. 173–196, doi: 10.1016/S0921–8181(99)00056–9.

Gulick, S.S., Powell, R.D., Jaeger, J.M., Cowan, E.A., Mayer, L.A., Mix, A.C., Finney, B.P., Pisias, N.G., Prahl, F., and Stoner, J.S., 2004, Glacial advances and retreats in tectonic southeast Alaska during the Little Ice Age and Last Glacial Maximum: Preliminary results from EW0408 [abs.]: Eos (Transactions, American Geophysical Union), v. 85, no. 47, Fall Meeting supplement, abstract H51A–1099.

Hayes, D.E., and Frakes, L.A., 1975, General synthesis, Deep Sea Drilling Project Leg 28, *in* Hayes, D.E., and Frakes, L.A., et al., Initial Reports of the Deep Sea Drilling Project, Leg 28: Washington, D.C., U.S. Government Printing Office, p. 919–942.

Leckie, R.M., and Webb, P.-N., 1986, Late Paleogene and early Neogene foraminifers of Deep Sea Drilling Project Site 270, Ross Sea, Antarctica, *in* Kennett, J.P., and von der Borch, C.C., et al., Initial Reports of the Deep Sea Drilling Project, Volume 90: Washington, D.C., U.S. Government Printing Office, p. 1093–1120.

LeMasurier, W.E., and Landis, C.A., 1996, Mantle-plume activity recorded by low-relief erosion surfaces in West Antarctica and New Zealand: Geological Society of America Bulletin, v. 108, p. 1450–1466.

Luyendyk, B.P., Sorlien, C.C., Wilson, D.S., Bartek, L.R., and Siddoway, C.H., 2001, Structural and tectonic evolution of the Ross Sea rift in the Cape Colbeck region, Eastern Ross Sea, Antarctica: Tectonics, v. 20, p. 933–958, doi: 10.1029/2000TC001260.

McKenzie, D., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25–32, doi: 10.1016/0012–821X(78)90071–7.

Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., and Pekar, S.F., 2005, The Phanerozoic record of global sea-level change: Science, v. 310, p. 1293–1298, doi: 10.1126/science.1116412.

Pekar, S.F., Harwood, D., and DeConto, R., 2006, Resolving a late Oligocene conundrum: Deep-sea warming versus Antarctic glaciation: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 231, p. 29–40, doi: 10.1016/j.palaeo.2005.07.024.

Rocchi, S., LeMasurier, W.E., and Di Vincenzo, G., 2006, Oligocene to Holocene erosion and glacial history in Marie Byrd Land, West Antarctica, inferred from exhumation of the Dorrel Rock intrusive complex and from volcano morphologies: Geological Society of America Bulletin, v. 118, p. 991–1005, doi: 10.1130/B25675.1.

Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K., 2001, Trends, rhythms, and aberrations in global climate 65 Ma to present: Science, v. 292, p. 686–693, doi: 10.1126/science.1059412.

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