West Antarctic paleotopography estimated at the Eocene-Oligocene climate transition

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[1] One generally recognized limitation of models for rapid growth of Antarctic ice near the Eocene-Oligocene transition is that they are based on present topography, corrected only for removal of modern ice. For West Antarctica, this results in large areas below sea level that would not readily host ice. In the recently active West Antarctic rift system, other factors may have contributed to significant vertical motions since the Eocene: Additional corrections for thermal contraction resulting from tectonic extension and for erosion and sedimentation since 34 Ma restore most of West Antarctica to above sea level, increasing total Antarctic land area by 10–20%. Because ice sheets have convex slopes, the potential increase in ice volume is larger than the increase in land area. Accounting for large changes in West Antarctic topography may resolve conflicts between ice models and data by demonstrating the possibility of an early, large West Antarctic Ice Sheet. **Citation:** Wilson, D. S., and B. P. Luyendyk (2009), West Antarctic paleotopography estimated at the Eocene-Oligocene climate transition, *Geophys. Res. Lett.*, *36*, L16302, doi:10.1029/2009GL039297.

1. Introduction

[2] Coupled ice sheet-general circulation climate models depict growth of a large ice sheet on East Antarctica (EAnt) at the Eocene-Oligocene boundary (E/O) at ~34 Ma in response to decreasing CO_2, with very limited ice on West Antarctica (WAnt) [*DeConto and Pollard*, 2003a, 2003b]. However, sea-level and oxygen-isotope data imply that more ice existed than is predicted by the models [*Miller et al.*, 2008a, 2008b; *Pekar and Christie-Blick*, 2008; *Pekar et al.*, 2002]. Possible locations for additional ice include the northern hemisphere, considered unlikely [*DeConto et al.*, 2008; *Miller et al.*, 2008b], and WAnt. To date, climate modeling has assumed that the only factor that has changed Antarctic topography is the load of the modern ice sheets. This assumption yields WAnt as an archipelago of large islands surrounded by moderately deep water (~500 m; Figure 1). Several lines of evidence suggest that subsidence in the West Antarctic Rift System (WARS [*Behrendt et al.*, 1991]) has been rapid enough to substantially affect topography over the Cenozoic [*Decesari et al.*, 2007; *DeSantis et al.*, 1999; *Wilson and Luyendyk*, 2006]. Particularly important is Deep Sea Drilling Project (DSDP) Site 270 in the Ross Sea, where basement passed below sea level during the Oligocene and is now more than 1000 m deep [*Hayes et al.*, 1975].

[3] We present a model for 34 Ma paleotopography based on the interpretation that WAnt was an orogenic highland in the Early Cretaceous that subsided over Late Cretaceous and Cenozoic time to current levels. Key to this interpretation are new concepts on the origin of the Transantarctic Mountains (TAM), which define the boundary between EAnt and WAnt. Once thought to be the result of Cenozoic uplift, new evidence suggests that the TAM are the remnant edge of a subsided highland that once included the WARS [*Bialas et al.*, 2007; *Studinger et al.*, 2004].

2. Reconstruction Elements

[4] Our topographic reconstruction starts with the Antarctic BEDMAP compilation [*Lythe et al.*, 2001] of sub-ice bed topography and bathymetry (Figure 1). As described below, we treat four separate factors that have affected topography since 34 Ma: loading from growth of ice sheets; subsidence from thermal contraction as a result of prior tectonic extension; erosion and sediment deposition; and horizontal tectonic motion since 34 Ma.

[5] We calculate the restoration for ice load using a standard thin-plate over inviscid asthenosphere flexural isostasy model. Current load removed is the ice thickness from BEDMAP. The load of the water that replaces the ice is iteratively adjusted to account for rebound. Effective elastic thickness is poorly known and probably varies from the stable EAnt craton to the WARS. For simplicity, we use a uniform thickness of 35 km, which probably does not grossly overestimate the value for WAnt. Our resulting topographic model is shown in Figure 1, with only minor differences from the previous restoration of *Bamber and Bindschadler* [1997].

[6] Our restoration of thermal contraction following extension uses the simple, 1-D model of *McKenzie* [1978], which assumes instantaneous, pure-shear extension and subsequent gradual cooling by conduction. Post-extension subsidence over a given time interval depends only on the stretching factor, β, and the time of extension. We derive extension history for the WARS from plate-circuit data, extended from *Sutherland* [2008] as detailed in the auxiliary material.[4] We interpret three primary phases of extension in WARS: the first, affecting western Marie Byrd Land (wMBL) and eastern Ross Sea, predates sea floor spreading

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[4]Auxiliary materials are available in the HTML. doi:10.1029/2009GL039297.

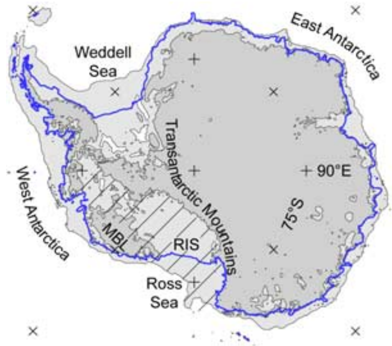

Figure 1. Location map. Bold line shows Antarctic coastline, including ice shelves. Darker gray shading shows bed elevation above modern sea level, after applying a rebound correction for ice load (see text); lighter shading shows bed shallower than −1000 m. Hachures show West Antarctic Rift System, active in Late Cretaceous and Cenozoic [*Behrendt et al.*, 1991]. Abbreviations: MBL, Marie Byrd Land; RIS, Ross Ice Shelf.

between Campbell Plateau and WAnt (>∼80 Ma [*Stock and Cande*, 2002]; the second, inferred from spreading history and plate circuits [*Cande and Stock*, 2004] affects the central Ross Sea at ∼60 Ma; and the third, synchronous with Adare Trough spreading [*Cande et al.*, 2000] affects the western Ross Sea, ∼46–28 Ma. The oldest phase of extension is well studied [*Behrendt et al.*, 1991; *Luyendyk et al.*, 2001, 2003]. Age constraints include cooling ages of basement rocks in wMBL [*Richard et al.*, 1994], and of dredged mylonite from the easternmost Ross Sea [*Siddoway et al.*, 2004], and the constraint that the rifted continental margin is undeformed, judged from the shape match to the Campbell Plateau margin [*Lawver and Gahagan*, 1994]. The amount of extension is only approximately constrained. The timing and amount of extension for the youngest phase are well constrained by mapping of magnetic anomalies C12–C21 (30–46 Ma) flanking Adare trough over a width of 170 km (Figure 2a) [*Cande et al.*, 2000]. Evidence for the ∼60 Ma phase of extension is primarily from the sea floor spreading record [*Cande and Stock*, 2004]. For anomalies C27–C21, the spreading rate on the Scott Rift (Figure 2a), between West Antarctica and the southeast corner of the Australian plate is about 12 mm/yr [*Cande et al.*, 2000], much faster than the 3 mm/yr observed between central Australia and the Wilkes Land area of EAnt [*Tikku and Cande*, 1999]. Plate circuit calculations (EAnt-Australia-New Zealand-WAnt) indicate at least 100 km and probably 150–200 km of EAnt-WAnt extension between chrons C30 and C21 (68-46 Ma, see auxiliary material). Water depths greater than 2000 m, suggestive of oceanic crust, extend ∼130 km west of Iselin Bank to Hallett Ridge (Figure 2a). Though this sea floor does not have identified magnetic anomalies, its position suggests a similar age to the adjacent ∼60 Ma sea floor at Scott Rift. The 130-km width of this ocean crust provides a lower bound for the ∼60-Ma extension between EAnt-WAnt, plus any extension distributed across Iselin Bank.

[7] Our model of the stretching history for the WARS (Figure 2b) is idealized by assuming stretching factor β is uniform for each phase of extension, probably not a realistic description of continental extension but convenient for applying *McKenzie*'s [1978] simple thermal subsidence model. Applying this model predicts about 200 m subsidence since 34 Ma for wMBL and about 500 m subsidence in the central WARS.

[8] Perhaps the most obvious component of a paleotopographic restoration is correcting for the effects of erosion and sedimentation. In the Antarctic, limitations on seismic data and especially core samples mean that only the Ross Sea is well enough mapped to regionally estimate the stratigraphic position of the E/O boundary with reasonable confidence. Figure 3 shows the thickness of sediment above the Oligocene or older RSU6 unconformity [*ANTOSTRAT*, 1995] in the Ross Sea. Where well mapped, the mean thickness is 2.5 km, reflecting the very large flux associated with glacial sediment transport. Sediment thickness under the Ross Ice Shelf was estimated by extrapolating trends observed in the Ross Sea guided by gravity anomalies [*Decesari et al.*, 2007]. Total sediment volume including extrapolation under the Ross Ice Shelf appears to be at least 2×10^6 km^3. We quantify the erosion restoration for WAnt by estimating a smooth Eocene topographic surface above topography adjusted for ice rebound and thermal subsidence, and checking that the eroded volume defined by the difference between that surface and the topography is an adequate fraction of the sediment volume downstream following current drainages. In this preliminary study, we

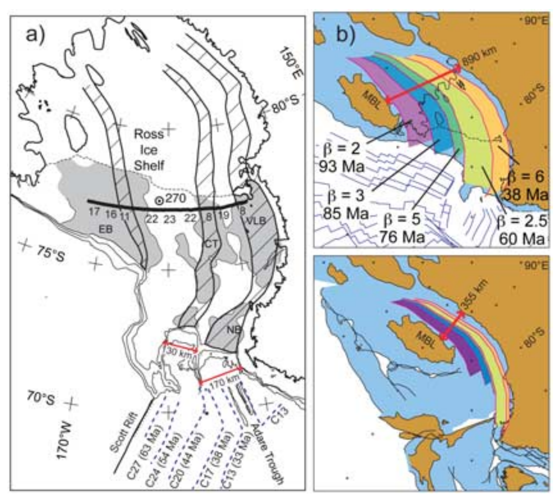

Figure 2. (a) Tectonic features of the Ross Sea area. Isobaths at 1000, 1500, and 2000 m are from Davey and Nitsche (ftp://ftp.ldeo.columbia.edu/pub/fnitsche/RossSeaBathymetry/). Dashed lines show magnetic-anomaly isochrons from *Cande et al.* [2000]. Grey shading shows sedimentary basins, defined by basement deeper than 2500 m [*ANTOSTRAT*, 1995; *Decesari et al.*, 2007]. Bold line is refraction profile of *Trey et al.* [1999] with thickness of crust in km. Hachured bands are gravity highs associated with deepest regions of sedimentary basins [*Decesari et al.*, 2007]. (b) West Antarctic Rift System shown (bottom) before extension and (top) after extension. Pastel colors highlight modeled areas of uniform stretching factor β, with mean ages of extension labeled. Cumulative extension is over 500 km, and most extension predates 34 Ma. Magnetic isochrons are shown in blue.

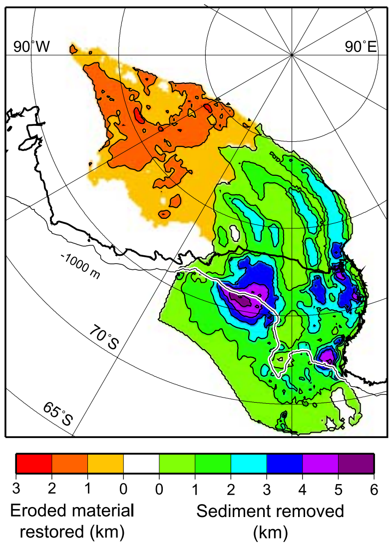

Figure 3. Thickness corrections for erosion and sedimentation in Ross Sea drainage. Thickness of Oligocene RSS-2 and younger sediments is well mapped in Ross Sea, with a mean thickness of ~2.5 km [*ANTOSTRAT*, 1995]. Extrapolated sediment thickness under Ross Ice shelf was guided by gravity anomalies and bathymetry [*Decesari et al.*, 2007]. Erosion restoration is estimated as a moderate fraction of sediment thickness.

do not estimate erosion on the EAnt craton. Factors including biogenic material in sediment (up to 30% at DSDP Site 270 [*Hayes et al.*, 1975]), greater density of the eroded source vs. the deposited sediment (2.5 vs. 2.3 gm/cc assumed here), and unknown fraction of WAnt sediment coming from EAnt can lead to the WAnt volume eroded being about half or less of the volume of sediment deposited downstream. For the WAnt Ross Sea drainage, our erosion restoration of 13% of the sediment volume is a conservative minimum.

[9] In detail, the procedure for restoration of sedimentation and erosion consisted of the following steps: (1) subtract sediment thickness from bed topography already corrected for ice load and thermal contraction; (2) calculate isostatic rebound for removal of the sediment load; (3) restore WAnt-EAnt plate motion by rotating WAnt elevations on the Pacific side of the WARS about the rotation pole 71.5°S, 35.0°W, 1.14°, a rotation within the confidence interval of the C13 rotation pole of *Cande et al.* [2000]; (4) add elevations for the model of eroded thickness; and (5) calculate isostatic response of the load of eroded material. The plate motion restoration needs to be applied before the erosion restoration to avoid introducing distracting artifacts, and is applied after sediment removal for simplicity.

[10] In contrast to models only correcting for ice load, such as *Bamber and Bindschadler* [1997], which only have a small fraction of WAnt above sea level, our final topographic model (Figure 4) for the latest Eocene has a majority of WAnt above modern sea level. Details of the model are of course uncertain, but we estimate that the reasonable range for the increase in total Antarctic land area relative to previous models is about 10–20%. We speculate that extending the model to account for erosion and thermal subsidence along the EAnt passive margin could produce an increase in above-sea-level Antarctic land area as high as 25%.

3. Discussion

[11] We consider the increased land area above sea level for our latest Eocene WAnt model to be a robust result, as applying a restoration for either thermal contraction or erosion can produce it. For the modern extensive WAnt submerged areas to have already existed in the Eocene as employed in the models of *DeConto and Pollard* [2003a, 2003b] and apparently all other existing ice-sheet models relevant to the Paleogene [e.g., *Jamieson and Sugden*, 2008], both of the following must be true. First, that there are errors in identifying marine magnetic anomalies such that the ~60-Ma extension episode (Figure 2) did not affect a large area, and pre-Adare-trough extension is of smaller magnitude and older than we have interpreted. Second, that the source area for the very large volume of Oligocene and younger sediment deposited in the Ross Sea (Figure 3) must have been almost entirely from areas that remain above sea level at the present. On the first point, we consider the fact that our model restores DSDP Site 270 to slightly above sea level (Figure 4) to be strong evidence in favor of subsidence resulting from a major ~60-Ma extension episode. On the second point, the enormous volume of post-Eocene sediments in the Ross Sea requires glacial erosion as an agent as opposed to fluvial systems. If that volume was from the locations of the present highlands, requiring them to have been much higher, then remnants of this higher topography would be found today, as glacial erosion tends to make valleys deeper and to preserve peaks and highlands.

[12] The extension history of Figure 2b implies that the importance of topographic restoration for ice and climate modeling increases for times going back to the Cretaceous.

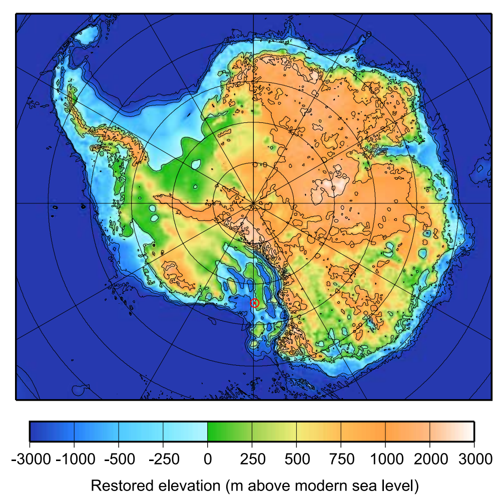

Figure 4. Model for latest Eocene Antarctic elevations. Restorations include ice-load removal for the entire continent, and the effects of thermal contraction, erosion, sedimentation, and horizontal plate motion for West Antarctica. Most of West Antarctica, including DSDP Site 270 (circle), restores above sea level. Total area above modern sea level is 12.1×10^6 km^2, vs. 10.6×10^6 km^2 for removing ice load alone.

Stretching factors and modern crustal thicknesses (Figure 2a) imply that the pre-extension crustal thickness of the WARS was about 50 km, supporting recent interpretations that the Transantarctic Mountains are a small remnant of a previous highland [e.g., *Huerta*, 2007; *Studinger et al.*, 2004]. Such a highland should be investigated for whether it could collect enough ice to be responsible for 20-m sea level drops inferred for the Late Cretaceous [*Miller et al.*, 2008b].

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