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Ice Elevation Near the West Antarctic Ice Sheet Divide During the Last Glaciation

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[1] Interior ice elevations of the West Antarctic Ice Sheet (WAIS) during the last glaciation, which can serve as benchmarks for ice-sheet models, are largely unconstrained. Here we report past ice elevation data from the Ohio Range, located near the WAIS divide and the onset region of the Mercer Ice Stream. Cosmogenic exposure ages of glacial erratics that record a WAIS highstand ~125 m above the present surface date to ~11.5 ka. The deglacial chronology prohibits an interior WAIS contribution to meltwater pulse 1A. Our observational data of ice elevation changes compare well with predictions of a thermomechanical ice-sheet model that incorporates very low basal shear stress downstream of the present day grounding line. We conclude that ice streams in the Ross Sea Embayment had thin, low-slope profiles during the last glaciation and interior WAIS ice elevations during this period were several hundred meters lower than previous reconstructions. **Citation:** Ackert, R. P., Jr., S. Mukhopadhyay, B. R. Parizek, and H. W. Borns (2007), Ice elevation near the West Antarctic Ice Sheet divide during the Last Glaciation, *Geophys. Res. Lett.*, *34*, L21506, doi:10.1029/2007GL031412.

1. Introduction

[2] Recent observations of thinning and acceleration of outlet glaciers and ice streams following loss of buttressing ice shelves on the Antarctic Peninsula [*Rignot et al.*, 2005], supports the hypothesis that the West Antarctic Ice Sheet (WAIS) is susceptible to rapid collapse in response to warmer air and sea temperatures [*Mercer*, 1978]. Moreover, recent field results indicate that much of the WAIS recession occurred during the middle to late Holocene without substantial sea level or climate forcing [*Hall and Denton*, 2000], indicating that the present grounding line could continue to retreat even in the absence of further external forcing [*Conway et al.*, 1999]. As a result, estimates of future sea-level rise based only on temperature-induced changes in ice-sheet mass balance may significantly underestimate the potential contribution of the WAIS [*Alley et al.*, 2005]. Dynamic ice-sheet models are necessary to predict the response of the WAIS to future climate and our confidence in the predictive capabilities of these models increases when they successfully simulate the past history of the WAIS. However, observational data that can serve as benchmarks for ice-sheet models, such as past ice elevations, are still quite poorly constrained in key sectors of the WAIS.

[3] The footprint of the WAIS during the past 20 kyr of its history, referred to here as the last glaciation, has largely been determined from the distribution of glacial deposits and erosion features on the continental shelves, and to a lesser extent on ice-free land [e.g., *Anderson et al.*, 2001; *Hall and Denton*, 2000]. In the western Ross Sea, the grounding line of the WAIS advanced to the vicinity of Coulman Island during the Last Glacial Maximum (LGM, ~20 ka) with retreat underway by 14.5 ka (Figure 1, top) [*Licht et al.*, 1996; *Conway et al.*, 1999]. In the Ford Ranges, which project through the WAIS near the Marie Byrd Land (MBL) coast (Figure 1, top), the occurrence of erratics on mountain peaks indicates that the WAIS overtopped the range during the last glaciation. Cosmogenic dating of erratics indicates that ice elevations were at least 700 m higher than present near the periphery of the ice sheet, ~13,000 years ago [*Stone et al.*, 2003]. In contrast to the position of the ice sheet margins during the LGM, variations of ice elevation in interior WAIS are poorly constrained and largely restricted to MBL. Past ice elevations, modeled using analyses of gas contents and stable isotope data of the Byrd ice core (Figure 1, top), are ~300 meters higher between 8 to 10 ka, and somewhat lower at LGM [*Raynaud and Whillans*, 1982; *Steig et al.*, 2001]. At Mt. Waesche, a volcano near the dome of the WAIS in MBL, exposure ages of boulders in moraine bands indicate that maximum ice elevations were only 45 m higher than the present ice surface and that thinning began ~10 ka, 3000 years later than in the coastal Ford Ranges [*Ackert et al.*, 1999] (Figure 1, top).

[4] Past variations in ice-elevation data from near the WAIS divide (Figure 1, top), between the Ronne and the Ross drainage areas, can provide important constraints on fluctuations in WAIS thickness and volume. However, past elevation data along the ice divide are completely lacking. Because even small elevation changes in interior ice elevations can cause large ice volume changes, WAIS volume changes since LGM remain uncertain with estimates ranging from 9.4 m to 15 m sea-level equivalent [*Denton and Hughes*, 2002; *Huybrechts*, 2002]. In the absence of deep ice cores, the mapping of glacial geologic features, such as erratics and trimlines on nunataks, offers an alternative way to constrain past ice elevations in interior parts of the WAIS. Here we report on ice elevation and retreat history of the WAIS during the last glaciation from the Ohio Range, at the southern end of the Transantarctic Mountains (85°S,

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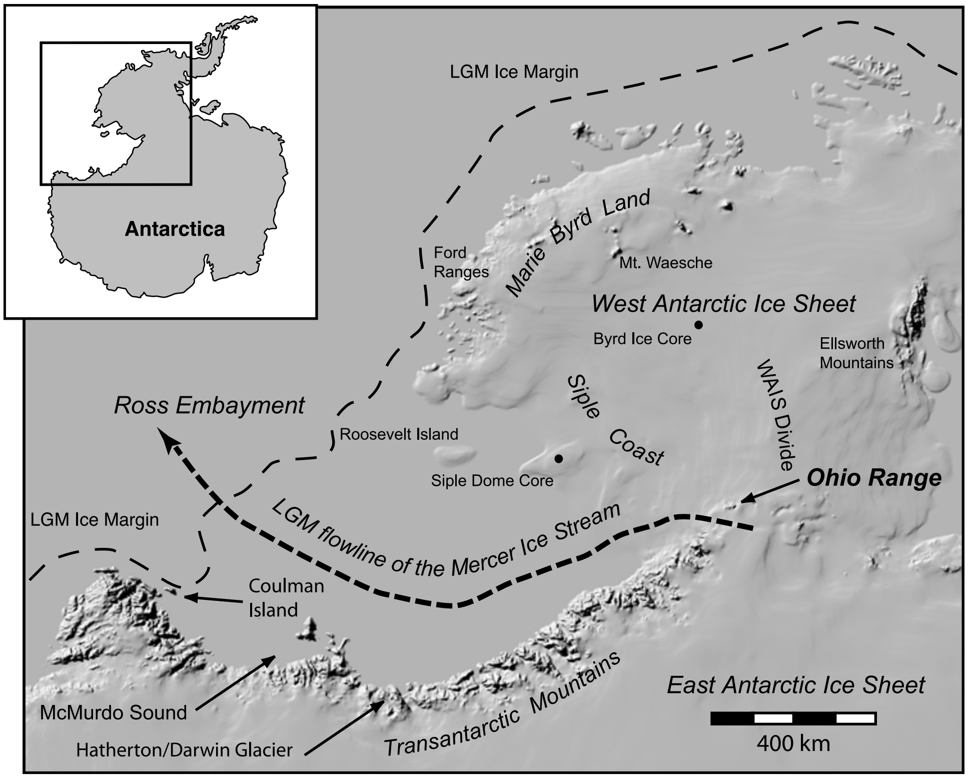

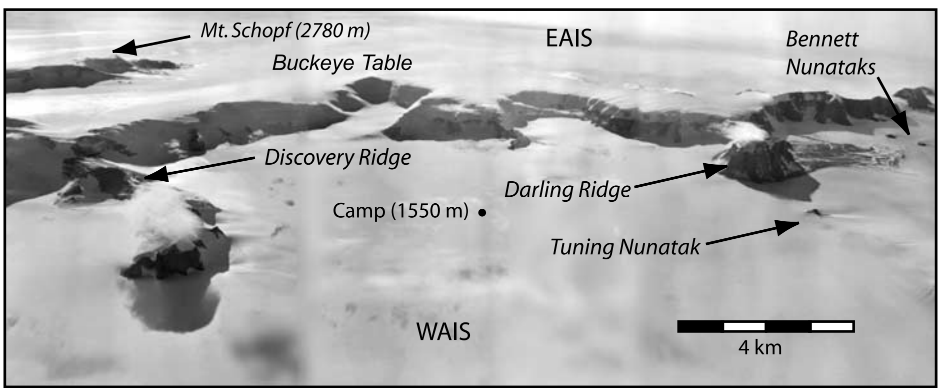

Figure 1. (top) Location Map of the Ohio Range. (bottom) Oblique panorama of Ohio Range Escarpment looking southward showing locations of field areas that are described in the text. The scale bar applies to areas between Discovery and Darling Ridge.

114°W), ~180 km from the ice divide of the WAIS, and near the onset area of the Mercer Ice Stream (Figure 1, top).

2. Methods

[5] The Ohio Range forms an east–west trending escarpment rising 500 m above the adjacent surface (~1550 m) of the WAIS. We conducted transects from the lateral ice margin of the WAIS to the peaks of Tuning and Bennett Nunataks and at Discovery and Darling Ridge on the escarpment (Figure 1, bottom). The distribution of glacial deposits (erratics) and erosional features were mapped in order to determine the past vertical extent of the WAIS. The granite bedrock exposed on the escarpment, and the nunataks exhibits cavernous weathering pits, with areas between pits reduced to delicate centimeters thick structures (tafoni). Along the escarpment face, up to 150 meters above the present day elevation of WAIS, the delicate tafoni have often been broken off, leaving sharp edges. We interpret a transition from surfaces that preserve the delicate tafoni, to those lacking it as a trimline that records the maximum highstand of the WAIS. The minimum elevation change is constrained from the elevation of the highest erratics.

[6] To constrain the age of past WAIS elevation changes, glacial erratics were sampled for surface exposure dating at four locations along the Ohio Range Escarpment; Discovery

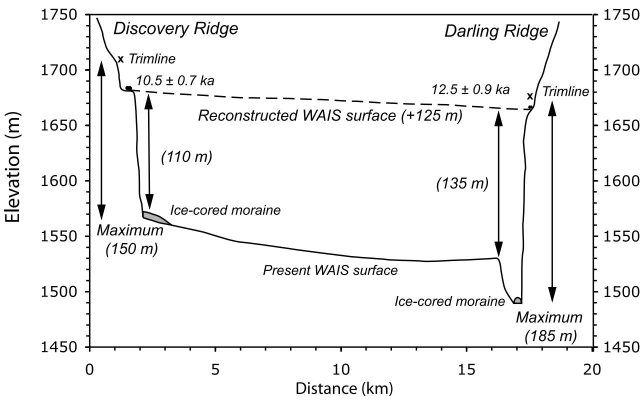

Figure 2. Schematic representation of WAIS elevation changes at the Ohio Range. Vertical exaggeration is 40x. Crosses represent the trimline and filled circles represent glacial erratics. The reconstructed WAIS surface is ∼125 m above the present day ice surface.

Ridge, Darling Ridge, Tuning Nunatak and Bennett Nunataks (Figure 1, bottom). In interior Antarctica, extremely low subaerial erosion rates and non-erosive cold-based ice suggests that prior exposure of erratics and bedrock is common [e.g., *Brook et al.*, 1993]. On the other hand, low erosion rates mean that for LGM and younger samples, exposure ages are not affected by erosion of the erratics. Presently, accumulation of snow or ice is inhibited due to high winds in locations where erratics are currently exposed. The presence of erratics shows that these locations were also ablation areas when the ice was thicker, so shielding of erratics by snow cover, which could result in lower apparent exposure ages, is very unlikely. There is also no evidence that the erratics have been covered by till deposits in the past. In summary, while older apparent exposure ages from prior exposure are expected in the Ohio Range, anomalously young exposure ages are highly unlikely. Thus, the samples with the lowest apparent exposure ages provide the best estimate of the most recent retreat of the WAIS.

3. Results

3.1. Glacial Geology

[7] Presently, little ice spills over the escarpment from the Buckeye Table; ice elevations along the escarpment are determined by the adjacent WAIS. While dolerite boulders are abundant in moraines on the flanks of Mt. Schopf on the Buckeye Table, they were not observed in the glacial deposits below the escarpment. We infer from the lack of dolerite erratics that neither ice from the Buckeye table nor from a thicker EAIS has flowed over the escarpment in the past. Thus, we interpret evidence for higher ice elevation, as recorded by erratics and trimlines along the escarpment, to reflect regional changes in WAIS.

[8] At Tuning and Bennett Nunataks (Figure 1, bottom) granite erratics occur on the weathered surface of the peaks (up to 1600 m) and delicate tafoni have been broken off. These observations clearly indicate that the WAIS overtopped the nunataks, suggesting a minimum change in ice elevation of 85 m, with respect to adjacent blue-ice areas. At Discovery Ridge, erratics occur on a granite bench at 1680 m, 120 m above the adjacent blue-ice areas and 110 m above ice-cored moraines (Figure 2). The granite erratics on the bench are concentrated in an arcuate band that we interpret as an ice marginal moraine (see auxiliary material).[1] As erratics do not occur beyond the moraine on the proximal part of the bench, we conclude that the ice margin barely overtopped the bench. In any case, maximum ice elevations at Discovery Ridge are limited to 1710 m as indicated by preserved tafoni on a sandstone outcrop, 30 m above the granite bench.

[9] At Darling Ridge, granite erratics occur up to 1665 m, 10 m below bedrock with preserved tafoni. Thus, the reconstructed ice elevation is quite consistent for over 15 km along the escarpment. The highest erratics at Darling Ridge are 135 m above the blue ice areas but 175 m above nearby ice-cored moraines. However, the ice-cored moraines lie in a wind scoop that is 40 m below the adjacent WAIS surface. We attribute the wind scoop to locally enhanced ice ablation (Figure 2). The upper limit on ice elevation change is determined from the difference in elevation between the trimline and ice-cored moraines, and is 185 m. Hence, our reconstructed ice elevations changes for Discovery and Darling Ridge are 120^{+30}_{-10} and 135^{+50}_{-10} m, respectively, suggesting that on average, ice elevations changed at the Ohio Range by ∼125 m since the last glaciation.

3.2. Surface Exposure Ages

[10] Cosmogenic ^{3}He provides minimum exposure ages for the erratics. Due to the expectation of prior exposure, and the time and expense associated with ^{10}Be measurements, 45 erratics from various elevations were screened for prior exposure by measuring the ^{3}He concentrations in quartz separates. In line with expectations of pervasive prior exposure, 40 out of the 45 erratics have ^{3}He exposure ages older than the LGM. The five samples with LGM or younger ^{3}He exposure ages, along with 10 additional samples, were selected for ^{10}Be measurements (see auxiliary material). Of these, only two had ^{10}Be exposure ages younger than the LGM, consistent with diffusive loss of ^{3}He. The remaining samples all show evidence of prior exposure. Here we will focus on the two that constrain the age of the most recent highstand (Figure S1, Data Set S1). Although the number of samples is low, as discussed before, it is extremely difficult to produce spuriously low exposure ages in this environment. Hence, we attribute meaningful chronological information to the youngest exposure ages.

[11] The ^{10}Be exposure age of 12.5 ± 0.9 ka is from the highest erratic sampled on Darling Ridge (1665 m), within 10 m of the trimline and ∼135 m above the adjacent blue ice areas of the WAIS. The youngest exposure age on Discovery Ridge (10.5 ± 0.7 ka) occurs at 1680 m, 120 m above the adjacent blue ice areas and within 30 m of the highest possible ice elevation at this location (Figure 2). We infer that the WAIS surface near the onset region of the Mercer ice stream stood at ∼1680 m, ∼125 m above the

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2007gl031412. Other auxiliary material files are in the HTML.

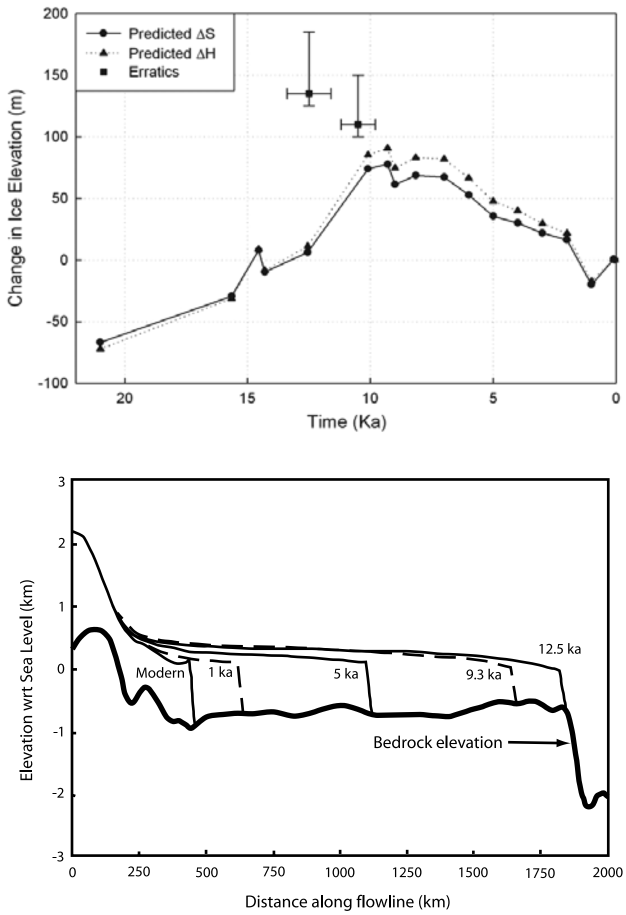

Figure 3. (top) Variations in ice thickness (Δh) and change in ice-surface elevation (Δs) near the Ohio Range with respect to present WAIS elevation as predicted by *Parizek and Alley*'s [2004a] 2-D thermomechanical flowline model of the Mercer Ice Stream. The flowline is shown in Figure 1. Model details along with the numerical values for the parameters used to generate the predicted changes are the same as those given by *Parizek and Alley* [2004a]. The predicted (Δs) is in reasonable agreement with our observations. (bottom) Simulated flowline profiles along Mercer Ice Stream from 12.6 ka to present highlighting the low surface slope of the ice surface in the Ross Embayment and the small changes in surface elevation behind the modern grounding line.

present ice surface at ~11.5 ka and drawdown of the WAIS surface began thereafter. These are the first constraints on past ice elevation changes from near the WAIS divide.

4. Discussion

[12] The erratic exposure ages of ~11.5 ka from close to the Ohio Range trim line are similar to the ~10 ka ages obtained from boulders 45 m above the present ice surface at Mt. Waesche near the WAIS dome in MBL. These geologic constraints from opposite ends of the WAIS divide, along with stable isotope and gas content data from the Byrd Ice Core, suggest that ice elevation changes during the last glaciation in interior WAIS were typically quite modest and limited to at most a couple hundred meters. Further, the results indicate that the deglaciation history in interior WAIS, on either side of the Ross Embayment was similar. Specifically, maximum ice elevations occurred or persisted until 10 to 11.5 ka, ~3000 years after the periphery of the ice sheet in the Ross Sea had begun to retreat [*Licht et al.*, 1996; *Stone et al.*, 2003]. Hence, our observational data from the Ohio Range strongly support inferences drawn from ice-sheet models that maximum interior ice elevations occurred in the early Holocene in response to increasing accumulation rates and that during deglaciation a wave of thinning propagated upstream from the coast reaching the head of the ice streams in ~3000 years [*Ackert et al.*, 1999; *Steig et al.*, 2001].

[13] Meltwater pulse 1A, a rapid rise of ~20 m in sea level, occurred ~14.5 ka [*Fairbanks*, 1989]. The WAIS has been suggested as a source of this meltwater due to a lack of evidence for a Northern Hemisphere source [*Clark et al.*, 1996]. We note that because thinning near the ice divides and domes of the WAIS did not occur until the early Holocene, and that overall thinning was modest, deglaciation of interior WAIS cannot be a source of meltwater pulse 1A.

[14] A recent challenge in reconstructing the past history of the WAIS has been reconciling the ice-elevation history inferred from the Siple Dome Ice core (615 m), near the Siple Coast grounding line, with the WAIS reconstructions based on glacial geologic data in the TAM and Ross Sea [e.g., *Denton and Hughes*, 2002] (Figure 1, top). The latter reconstruction, incorporating the elevations of lateral moraines in the TAM [*Denton and Hughes*, 2002] indicates ice elevations of ~1400 m at Siple Dome. In contrast, models of accumulation and thinning at Siple Dome constrained by measured layer thickness in the ice core [*Waddington et al.*, 2005], and isotopic and temperature data [*Price et al.*, 2007], indicate that elevations at Siple Dome were only 800–1000 m during the last glaciation.

[15] The discrepancy (400–600 m) in modeled ice elevation in the Central Ross Embayment is substantial, and results from a fundamental difference in modeling ice-stream dynamics. For example, *Denton and Hughes* [2002] suggest that ice streams are floored by bedrock in the onset regions of the ice streams but become increasingly decoupled towards the ice margins as a result of increasing basal water and deformable sediments. An alternative viewpoint, inspired by the surprisingly low Siple Dome elevations during the last glaciation implied by the ice core data, is that the Siple Coast ice streams were largely decoupled from the bed along the entire length downstream of the present-day grounding line [e.g., *Parizek and Alley*, 2004a]. *Parizek and Alley* [2004a] employ a 2-D thermomechanical flowline model that incorporates isostatic compensation and a weak, linear-viscous basal rheology beneath extensive ice streams that promotes the reconstruction of thin, low-slope ice-stream profiles extending across the Ross Embayment. The model simulations show ice elevation changes in the region of Siple Coast to be ~200 m for the Kamb and Whillans Ice Streams, and ~300 m for the Mercer Ice stream.

[16] Both the *Denton and Hughes* [2002] and *Parizek and Alley* [2004a] WAIS simulations incorporate a 2-D

model with the Mercer Ice Stream flowline passing near the Ohio Range. Hence, our new glacial geologic constraints on ice elevation can be used as an independent test of the different reconstructions and the nature of coupling between the ice streams and their bed. The *Denton and Hughes* [2002] reconstruction indicates that the WAIS highstand in the Ohio Range is ~1950 m, indicating that ice elevation was ~400 m thicker during the last glaciation. Thus, the *Denton and Hughes* [2002] reconstruction overestimates interior ice elevations near the Ohio Range by over 250 m. Because *Denton and Hughes* [2002] do not use a time-dependent model, the relative timing of the highstand is not constrained.

[17] The predicted increase in WAIS elevation near the Ohio Range using the *Parizek and Alley* [2004a] model is ~75 m, 50 m lower than our observations, while maximum ice elevations occur at ~10 ka (Figure 3). We note the *Parizek and Alley* [2004a] model underestimates ice surface elevations, which is an artifact of 2-D flowline simulations that omit a parameterization of convergent flow within the catchment [*Parizek and Alley*, 2004b; *Parizek et al.*, 2005]. Incorporating convergence within the model, while maintaining an accurate reconstruction of the ice divide, would likely lead to a thicker inland profile, increased driving stresses, enhanced ice flow, and the potential for somewhat larger relative changes in ice thickness, in closer agreement with both the Ohio-Range and Siple-Dome data. Nevertheless, the predicted changes in ice elevation at the Ohio Range obtained by differencing the modeled highstand and present profiles should not be largely affected by these considerations.

[18] Figure 3 (bottom) shows the ice elevation profiles for Mercer Ice Stream (Figure 1, top) as simulated by the *Parizek and Alley* [2004a] model during deglaciation of the Ross Embayment that are consistent with the geologic constraints in the Ohio Range and the modeling results from Siple Dome. Significant features are the low surface slope of the Mercer Ice Stream in the Ross Embayment and the small changes in elevation behind the modern grounding line. While the modern elevation at the reconstructed and observed ice divide is within ~8 m, the inland thickness downstream of the divide is significantly underestimated due to the omission of flow convergence as noted above. Overall, the model predictions (Figure 3) are in reasonable agreement with our observations at the Ohio Range and provide a significantly better match to the ice elevation changes than the *Denton and Hughes* [2002] model. Hence, we believe that this strongly strengthens the case for decoupling of ice streams from their beds in the Ross Sea Embayment during the LGM and provides independent validation of low ice elevation in the central Ross Embayment [*Waddington et al.*, 2005; *Price et al.*, 2007].

[19] Recent modeling of the interaction between the WAIS and the Hatherton and Darwin outlet glaciers [*Anderson et al.*, 2004], suggests that the projected WAIS elevation of 1100 m [*Denton and Hughes*, 2002] along the TAM is high by several hundred meters. Both our data from the Ohio Range and the *Waddington et al.* [2005] and *Price et al.* [2007] ice thinning estimates from Siple Dome indicate limited thickening of the ice upstream of the present-day grounding line. Thus, ice elevations in the entire Ross Sea drainage area are likely to have been two- to several-hundred meters lower than the *Denton and Hughes* [2002] reconstruction.

5. Conclusions

[20] We report the first ice-elevation history from near the WAIS divide and the onset region of the Mercer ice stream. Our data indicates maximum ice elevations of ~125 m above the modern ice-sheet surface occurred ~11.5 ka. A 2-D thermomechanical ice-sheet model that simulates thin, low-slope ice streams over a widespread, soft, deformable bed, predicts changes in ice elevations near the Ohio Range that closely mimic the observational data. The WAIS elevation constraints and chronology, combined with the model results, support the concept of a slippery, deformable bed that resulted in low surface slopes and ice thickness in the Ross Embayment during the LGM. This conclusion implies that the WAIS ice volume was smaller than has been proposed, which has important implications for interpretation of bedrock uplift rates in the Ross Embayment that typically assume thicker ice loads during the LGM, and for the contribution of the WAIS to post LGM sea-level rise.

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