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New boundary conditions for the West Antarctic Ice Sheet: Subglacial topography of the Thwaites and Smith glacier catchments

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[1] Airborne radar sounding over the Thwaites Glacier (TG) catchment and its surroundings provides the first comprehensive view of subglacial topography in this dynamic part of the West Antarctic Ice Sheet (WAIS) and reveals that TG is underlain by a single, broad basin fed by a dendritic pattern of valleys, while Smith Glacier lies within an extremely deep, narrow trench. Subglacial topography in the TG catchment slopes inland from a broad, low-relief coastal sill to the thickest ice of the WAIS and makes deep connections to both Pine Island Glacier and the Ross Sea Embayment enabling dynamic interactions across the WAIS during deglaciation. Simple isostatic rebound modeling shows that most of this landscape would be submarine after deglaciation, aside from an island chain near the present-day Ross-Amundsen ice divide. The lack of topographic confinement along TG's eastern margin implies that it may continue to widen in response to grounding line retreat. **Citation:** Holt, J. W., D. D. Blankenship, D. L. Morse, D. A. Young, M. E. Peters, S. D. Kempf, T. G. Richter, D. G. Vaughan, and H. F. J. Corr (2006), New boundary conditions for the West Antarctic Ice Sheet: Subglacial topography of the Thwaites and Smith glacier catchments, *Geophys. Res. Lett.*, *33*, L09502, doi:10.1029/2005GL025561.

1. Introduction

[2] Modeling of WAIS deglaciation [*Stuiver et al.*, 1981] pinpointed Pine Island Glacier (PIG) and Thwaites Glacier (TG) as the most vulnerable features of the WAIS, leading *Hughes* [1981] to describe this sector as "the weak underbelly" of the WAIS. Satellite-based studies have since shown that the Amundsen Sea Embayment (ASE) of the WAIS, comprised almost entirely of the catchments for these two glaciers, stands out among the three major WAIS drainages as the only one exhibiting evidence consistent with ongoing deglaciation. Over the past decades, the grounding lines of both PIG [*Rignot*, 1998] and TG [*Rignot*, 2001] have retreated, ice in their catchments has thinned [*Wingham et al.*, 1998; *Shepherd et al.*, 2002], and PIG has accelerated [*Rignot et al.*, 2002] while TG may have widened [*Rignot et al.*, 2002]. Recent ice thickness profiles obtained over the ASE coastal zone [*Thomas et al.*, 2004] enabled new flux estimates confirming that ASE glaciers are significantly out of balance, with TG having the highest flux and contributing a mass imbalance of -36 ± 7 km^3/yr [*Rignot et al.*, 2004]. In a relative sense, Smith, Kohler, Pope, and Haynes Glaciers to the west are even more out of balance [*Rignot et al.*, 2004].

[3] These observations imply a recent dynamical change, possibly due to the warming of adjacent ocean water [*Payne et al.*, 2004; *Shepherd et al.*, 2004]. However, the suggestion of such a process and subsequent grounding line migration being responsible for the widespread decay of ASE glaciers can only be validated by ice sheet models constrained by accurate and well-sampled sub-ice topography [*Vieli and Payne*, 2005]. The data from early radar sounding studies [*Drewry*, 1983] were sparse (Figure 1d) and only sufficient to reveal the general morphology of the region (Figure 1a).

[4] In order to establish well-constrained boundary conditions for ice sheet modeling and to investigate subglacial and englacial processes, a collaborative US/UK aerogeophysical campaign surveyed the ASE during the austral summer of 2004/2005 using two Twin Otter aircraft operating from two bases. Measurements included surface elevations, ice thickness, subglacial bed elevations, gravity anomalies and magnetic anomalies. This paper focuses on ice thickness and subglacial bed elevation for the Thwaites, Smith, Kohler, Pope, and Haynes glacier catchments obtained primarily by an aircraft configured and operated by the University of Texas Institute for Geophysics (UTIG). A companion paper [*Vaughan et al.*, 2006] focuses on results from the British Antarctic Survey (BAS) for PIG.

2. Methods

[5] Our instrument suite consisted of a radar sounder, fixed laser altimeter, gravimeter and towed magnetometer. The methods detailed here pertain to the radar sounder.

2.1. Instrumentation

[6] UTIG maintains and operates the High-Capability Radar Sounder (HICARS) system [*Peters et al.*, 2005]. For this survey, the HICARS system was configured for a chirped 1 μs pulse (52.5–67.5 MHz, peak power 8000 watts) with repetition frequency 6408 Hz. Coherent integrations of 32 signals were recorded every ~35 cm along track. The antennas were cross-track-polarized flat-plate dipoles mounted beneath each wing. Positioning was accomplished with differential carrier-phase GPS. Post-

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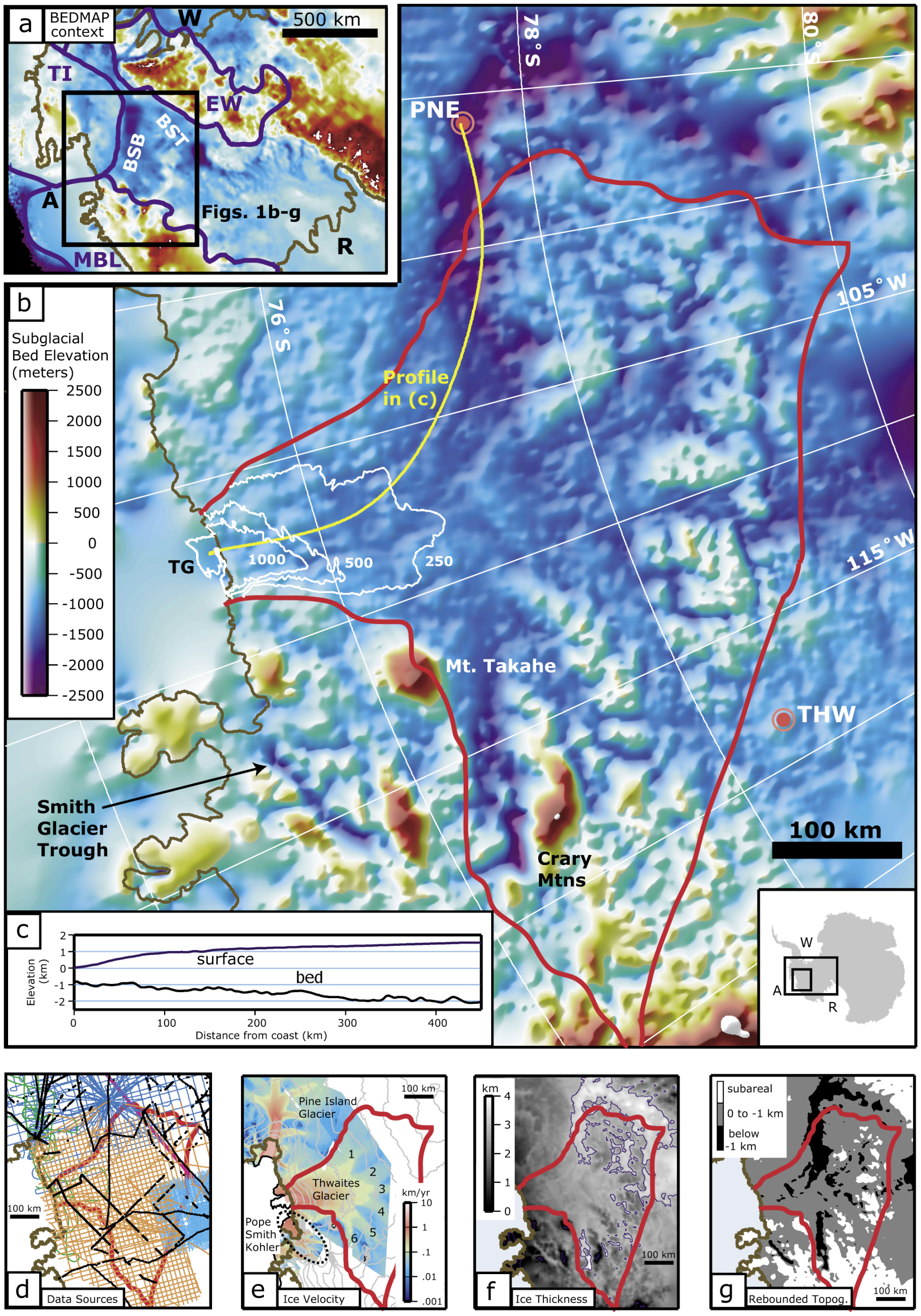

Figure 1. Gridded results. All elevations are relative to WGS-84 sea level. (a.) BEDMAP topography [*Lythe et al.*, 2000] with ice sheet grounding line (brown), hypothesized crustal boundaries (blue) [*Dalziel and Lawver*, 2000] (TI = Thurston Island; EW = Ellsworth Whitmore; MBL = Marie Byrd Land), and the three major West Antarctic embayments (W: Weddell; A: Amundsen; R: Ross). (b) New subglacial topography resulting from all available data, as shown in Figure 1d, with select ice surface velocity contours from 1996 (m/yr) [*Rignot et al.*, 2004], Thwaites Glacier catchment (red) [*Vaughan et al.*, 2001], and location of profile of Figure 1c indicated by yellow path. Inset map shows Antarctic context. (c) Surface and bed elevation along profile indicated in Figure 1b. (d) Location of onshore data used in Figures 1b and 1f. UTIG flights (orange: 2004–05; lt. blue: previous years), BAS flights (dk. blue), NASA-CECS flights (green), ITASE traverse (violet), BEDMAP (black). See text for references. (e) 1996 ice surface velocities [*Rignot et al.*, 2004] and surface elevation (200 m contour intervals) with Thwaites tributaries numbered as by *Lang et al.* [2004]. (f) Ice thickness data; 3 km contour shown. (g) Deglaciated topography with Airy isostatic compensation.

processed vertical crossover discrepancies were 25 cm RMS; horizontal errors are smaller.

2.2. Survey

[7] Data were acquired on a 15 × 15 km grid over most of the area, augmented by seven along-flow profiles of the major trunks and tributaries. Over 43,500 line-km of geophysical data were collected by UTIG in 77 survey flights over 7 weeks, using Thwaites Camp (78.5°S, 118°W) as the primary base and Pine Island Camp (77.57°S, 95.93°W) as a secondary base (Figure 1b). Data were also acquired on five flights by BAS over the TG catchment.

2.3. Data Reduction

[8] The radar data were processed for interpretation of the ice surface and bed interface echoes necessary for obtaining ice thickness. Coherent integration of 10 records (~350 cm along track) preserved bed slopes up to 6 degrees without significant phase interference. Pulse compression was performed to improve range resolution. Additional incoherent integration resulted in final observations every ~ 17.5 m along track.

[9] Radar data were interpreted following the methods of *Blankenship et al.* [2001], modified to identify the peak signal amplitude. A low-gain channel was used for surface echoes while a high-gain channel was used for bed echoes. Ice thicknesses were obtained from the time difference between bed and surface echoes. The velocity within the ice was taken to be 168.374 m/μs, with no firn correction.

3. Subglacial Topography

[10] The thickest observed ice in our new data is 4,024 m (bed −2,443 m at 76.43°S, 118.27°W), just north of the Crary Mountains. Crossover discrepancies in ice thickness (mean 8 m, RMS 47 m) are primarily due to off-nadir echoes in steep subsurface topography. To generate a complete new data set, our ice thickness data were augmented by results from BAS flights [*Vaughan et al.*, 2006], ITASE traverses [*Welch and Jacobel*, 2003], CECS-NASA overflights [*Thomas et al.*, 2004], earlier sources compiled for BEDMAP [*Lythe et al.*, 2000], and offshore bathymetry (www.ngdc.noaa.gov). Our bed elevation model was constructed after *Lythe et al.* [2000], with 3 km binning of the ice thickness data followed by interpolation using a continuous curvature spline with a tension factor of 0.35. A 9-km Gaussian filter as implemented in GMT [*Wessel and Smith*, 1998] was followed by registration to a recently developed surface topography (J. L. Bamber, personal communication, 2005).

[11] This compilation is a major increase in data density relative to the BEDMAP compilation [*Lythe et al.*, 2000]. For the TG catchment, 64.5% of all points in a 1-km grid now have observations lying within 2.5 km versus 6.6% in BEDMAP (51% vs. 8.8% for PIG). A digital version of this grid suitable for ice sheet modeling is available at the U.S. National Snow and Ice Data Center (www.nsidc.org).

4. Discussion

[12] Our new data reveal that the TG catchment is underlain by a single, large deep basin bounded by a broad coastal sill of low topographic relief and fed by a dendritic pattern of deeply incised valleys (Figures 1b and 1f). All six of the TG tributaries identified by *Lang et al.* [2004] from ice surface velocities (Figure 1e) correspond to deep subglacial troughs, yet the TG trunk lies in a very broad trough that may allow for rapid changes in flow geometry akin to ice stream reorganizations on the Siple Coast [*Alley and Bindschadler*, 2001] of the Ross Embayment (Figure 1a). More specifically, the zone of fastest TG flow is confined by subglacial topography on its western margin (Figure 1b); however, topography beneath its eastern margin, while clearly influencing ice flow to some degree (e.g., 250 m/yr contour; Figure 1b), lacks such a gradient. This could be a factor in the apparent widening of fast flow near the TG grounding line [*Rignot et al.*, 2002], and indicates that the fast flow zone could widen further.

[13] Smith, Pope and Kohler Glaciers (Figure 1e) converge just west of TG to flow through an extremely deep, narrow trench that is more than 2 km below sea level, 20 km wide, and at least 100 km long (Figure 1b). This isolated trench cuts linearly through the Marie Byrd Land volcanic province, suggesting strong geologic control. The deep ice draft of these glaciers near the grounding line likely increases their sensitivity to deep, warm circumpolar water [*Jacobs et al.*, 1996; *Rignot and Jacobs*, 2002] and may be a factor in their highly negative mass balance [*Rignot et al.*, 2004].

[14] Topographic control on ice flow in the TG catchment contrasts sharply with that of the Siple Coast where small-scale (<50 km across) rift structures draped by marine sediments play an important role in the onset and flow of ice streams [*Blankenship et al.*, 2001]. Based on ice surface velocities (Figure 1c), U-shaped tributary valley morphology (Figure 1b), dendritic drainage patterns (Figures 1b and 1f), and the rebounded coastline (Figure 1g), the topographic features controlling ice flow in the TG catchment appear to be the result of maritime glaciation predating the existence of the current WAIS. This dominance of erosion over rifting/sedimentation as the major influence on fast glacier flow in the ASE may also indicate significant differences between the Ross and Amundsen Sea Embayments in other, less obvious ways including crustal characteristics (e.g., geothermal flux) that are critical for modeling ice sheet dynamics.

[15] These new data provide improved estimates of potential sea-level contributions and new insights into deglaciation scenarios through the definition of relevant topographic features. The TG catchment contains sufficient ice to raise global sea level by ~59 cm while Smith-Kohler-Pope Glaciers could contribute an additional ~3 cm. While PIG has a highly confined main trough and northern basin which would probably limit the extent of rapid deglaciation [*Vaughan et al.*, 2006], the situation is very different for TG. Inland of the coastal sill, the bed in the TG catchment slopes consistently toward the deepest parts (and thickest ice) of West Antarctica (Figures 1b, 1c, and 1f). Although this geometry alone has not been proven to promote grounding line retreat, there is no topographic obstruction that would halt such a retreat if it were to begin. In such a scenario, TG retreat could eventually capture the southern basin of PIG with its ~28 cm of sea level rise [*Vaughan et al.*, 2006].

[16] Our results over the Ross-Amundsen ice divide extend those of more focused studies [e.g., *Morse et al.*,

2001] and show that the "sinuous ridge" described by *Jankowski and Drewry* [1981] is, in fact, discontinuous and heavily dissected. Numerous deep connections between the Ross and Amundsen Sea Embayments provide the means to dynamically link the ice in these two major drainages. Substantial ASE ice retreat could therefore result in the drawdown and/or migration of the ice divide and reduce the Ross ice stream catchments, as postulated by *Stuiver et al.* [1981]. The (Airy) isostatically rebounded topography expected with complete deglaciation (Figure 1g) shows that these dissected highlands may have previously formed a substantial island chain. During WAIS growth, an ice cap nucleating along this island chain could have helped to bridge the ~500 km gap between ice caps that presumably formed first in the highlands of Marie Byrd Land and the Ellsworth Whitmore Mountains.

5. Conclusions

[17] Our new subglacial topography represents a substantial improvement in boundary conditions available for modeling past and future WAIS changes and reveals important details that were not apparent with previously available data. Topography within the TG catchment is very different from that of PIG [*Vaughan et al.*, 2006], exhibiting a less pronounced bedrock sill near the grounding line and a much larger subglacial basin with steadily inland-sloping topography and a radiating pattern of incised tributary valleys. This erosion-dominated landscape exerts strong control on ice flow, yet the lack of a well-defined channel beneath the trunk of TG could enable future widening and increased ice flux. It is also clear that large-scale retreat of TG could result in the removal of ice from most of the ASE and possibly impact the Ross Sea Embayment. The deglaciated and rebounded topography indicates the presence of an island chain near the present-day Ross-Amundsen ice divide that may have played an important role in the nucleation and growth of the WAIS.

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