Subglacial roughness of the West Antarctic Ice Sheet

D. A. Young, D. D. Blankenship, and J. W. Holt

Jackson School of Geosciences, University of Texas Institute for Geophysics, Austin TX 78758, USA (duncan@ig.utexas.edu, blank@ig.utexas.edu, jack@ig.utexas.edu)

Summary We use basal roughness, a property accessible to airborne ice penetrating radar, to examine the dynamics of the West Antarctic Ice Sheet. We examine roughness through analysis of the along track variability of basal elevation profiles collected over the Siple Coast and the Thwaites Glacier catchment, at length scales between 400 meters and 4 kilometers. There are significant differences in the patterns of roughness between catchments. A one-to-one correlation between roughness and proposed sedimentary basins identified in potential fields data in the Siple Coast is not apparent. However, roughness does systematically decrease downstream, likely reflecting the effect of mobile tills. Under Thwaites Glacier, smooth areas are more localized, and restricted to the interior. In addition, we find that in the Siple Coast region, the plateaus underlying the major interstream ice ridges are remarkably smooth at all length scales, while flat bedrock platforms do not exist near Thwaites Glacier.

Citation: Young, D. A., D. D. Blankenship, and J. W. Holt (2007) Subglacial Roughness of the West Antarctic Ice Sheet, in Antarctica: A Keystone in a Changing World – Online Proceedings of the 10th ISAES X, edited by A. K. Cooper and C. R. Raymond et al., USGS Open-File Report 2007-1047, Extended Abstract 056, 5 p.

Introduction

The West Antarctic Ice Sheet (WAIS) is the last major marine ice sheet on Earth. The stability of this ice sheet is a major unknown in predictions of future sea level change. In part this due to uncertainties in the nature of the coupling of the ice sheet to its bed; in part it is due to the fact that the Neogene history of the WAIS remains controversial. One observable property of the ice sheet, accessible using ice penetrating radar, which may inform both issues is basal roughness. Here we examine basal roughness of the Thwaites Glacier Catchment and the Siple Coast Ice Streams using two approaches: direct analysis of basal topographic profiles, and examination the nature of the recorded basal echo.

One aspect of the base of the ice that may be elucidated by measurements of basal roughness is the rheology of the substrate. A smooth surface may indicate water-saturated sediments soft enough to be readily mobilized by over-riding ice (e.g. Rippin et al., 2006) or an ice-water interface controlled by basal melting (e.g. Carter et al., 2007). Alternatively, a rougher interface may result from incision by subglacial floods (e.g Lowe and Anderson, 2003), basal cracking or drumlin formation under fast flow conditions (e.g. Smith et al., 2007). An additional possibility is that the morphology was inherited from before the formation of the ice sheet (for example, wave cut platforms).

Previous work

Drewry (1975) did early work using profile-derived subglacial roughness in East Antarctica. The first attempt to quantify the basal roughness of the West Antarctic Ice Sheet at regional scales was carried out by Siegert et al. (2004), who used 1970's NSF/SPRI/TUD airborne survey data over the Siple Coast ice streams. The ice penetrating radar data was sampled at 2.2 kilometers along track. They used a spectral approach (Talyor et al., 2004) to integrate the power spectra of 70-kilometer windows along the bed elevation profiles. Siegert et al. (2004a) found that basal roughness increased toward the interior of the ice sheet, and suggested that marine sedimentary drapes suggested in potential fields data (Studinger et al., 2001; Blankenship et al., 2001) are restricted to areas currently showing ice streaming.

Rippin et al. conducted similar work (2006), studying East Antarctica's Slessor Glacier system using airborne ice penetrating radar collected by the British Antarctic Survey in 2001/2002. They used the standard deviation of both the bed elevation and the basal reflected power, measured over 5x5 kilometer bins, to evaluate roughness. They found considerable variation between the three active tributaries of the Slessor Glacier, with a tributary modeled as requiring basal sliding (Rippin et al., 2003) showing the least roughness. Rippin et al. (2006) also used the duration of the basal echo to characterize the bed, as suggested by Oswald (1972) and Robin et al. (1969).

The AGASEA and CASERTZ data sets

The Corridor Aerogeophysics of the Eastern Ross Transect Zone (CASERTZ) airborne survey was conducted between 1991 and 1996 as a collaboration between the University of Texas Institute for Geophysics, Lamont-Doherty Earth Observatory, and the U. S. Geological Survey. A twin engine aircraft conducted an integrated geophysical survey involving altimetry, gravimetry, magnetics and ice penetrating radar was flown in a five-kilometer spaced grid between the Amundsen Sea/Ross Sea Divide to the onset regions of Kamb and Willians Ice Stream, and along the length of Bindshadler Ice Stream to Siple Dome (Blankenship et al., 2001). The radar transmitter operated at 60 MHz with a 250 nsec pulse and a pulse repetition rate of 12.5 kHz, resulting in a system bandwidth of 4 MHz. The incoherent receiver varied between the seasons; early seasons used 20,/40 nsec sampling (~ 1.7/3.4 meters in ice), while later work used 16 nanoseconds. The radar traces were log detected and staked to an output rate of 4 Hz (~ 10-20 meters along track, depending of aircraft velocity). A semiautomatic picker was used to find the onset of the basal echo, which was used here to find the ice thickness. Laser altimetry was used to find the surface and thus the bed elevation.

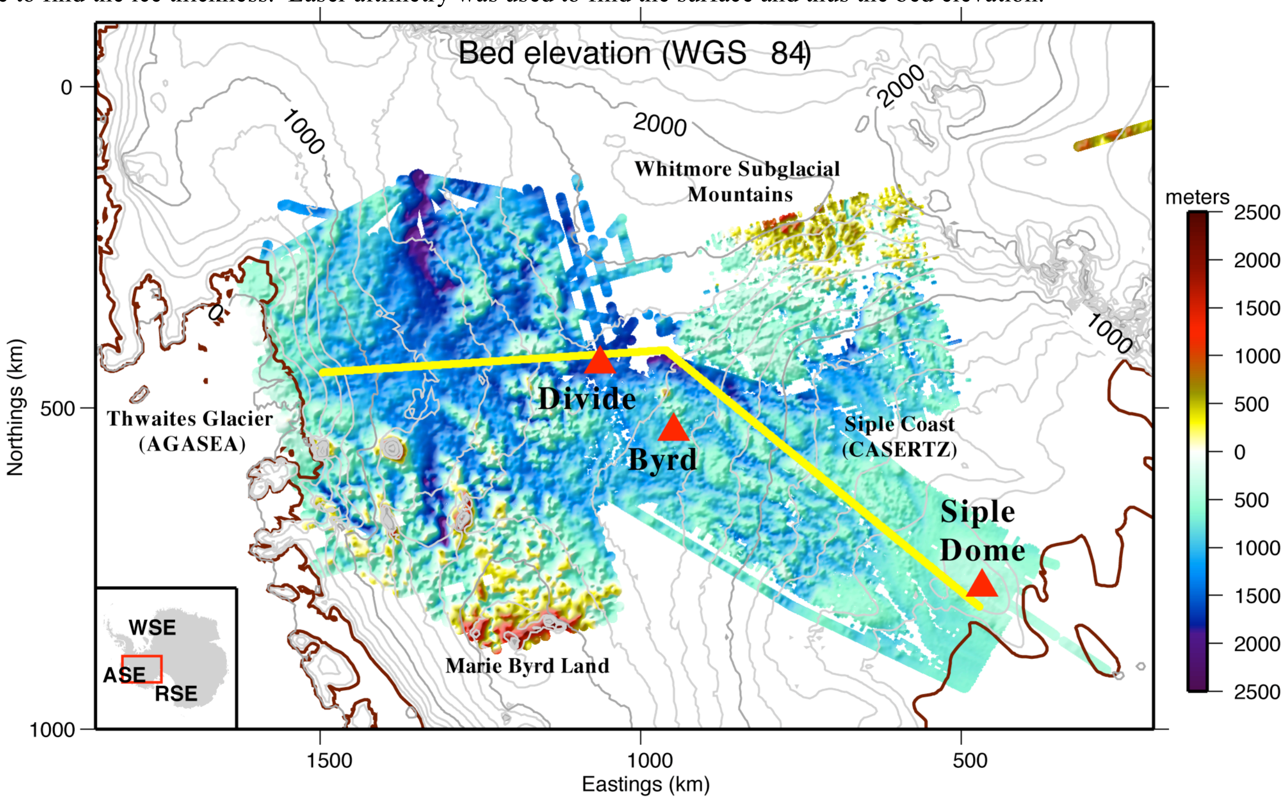

Figure 1. Map of bed elevations derived from the AGASEA/BBAS survey **(left)** and the CASERTZ survey **(right).** Yellow line shows location of Figure 2. Ice coreing sites are also shown, in addition to surface elevation contours from (Liu et al., 2001). The grounding line is in red.

The 2004/2005 Airborne Geophysical Survey of the Amundsen Embayment was a collaboration between UTIG and BAS, using two similarly equipped, although upgraded, aircraft to map Thwaites and Pine Island Glaciers (Holt et al., 2006, Vaughan et al., 2006). The catchment of Thwaites Glacier was surveyed with 15 km line spacing. The radar used by UTIG at Thwaites Glacier was greatly improved, allowing coherent acquisition and the use of a "chirp' rather than a pulse, increasing the sensitivity, recorded sample rate and the bandwidth (15 MHz), and hence the fidelity of the basal echoes. The initial data was processed in a manner similar to that of the CASERTZ data, to speed the release of ice thicknesses to the community; however, once fully processed the data will allow analysis on length scales of meters (Peters et al., 2005; in press). As pulse compression produces a non-casual echo shape, the interpolated peak power was picked as the basal interface.

Neither dataset was migrated; as such, higher basal slopes will be underestimated, and there should be a slight bias toward smoother slopes with depth.

Evaluating roughness along profiles

As we intend to examine the scale dependence of roughness underlying the WAIS, we need to go beyond the binning approach of Rippin et al. (2006); following the recommendations of Shepard et al. (2001), we evaluate the RMS slope of the bed elevations profiles at a range of baselines, from 200 meters to 40 kilometers. For the CASERTZ survey, the bed was not reliably picked when the echo signal strength dropped below –107 dBm, Bed picks with signal strengths of less than this value were filtered out. We then regularize the picked bed locations to a 20 meters point spacing using an Akima spline. Then for every point, we obtain the absolute different between the point's elevation and that of those points at exactly 'lag' meters ahead and behind it, and find the RMS slope of those two differences. The along profile slope data are then processed using a 3 km median filter, and interpolated to a grid using a tension spline. No detrending is performed, in order to sample all length scales for this initial analysis.

Results

Figure 2 shows a profile (yellow line in Figure 1; also see Diehl et al., 2007) demonstrating the results of this method. The red line corresponds to roughness with lags of 4 km; green has a lag of 2000 meters, and blue reflect roughness at the 400 meter length scale.

Systematic issues

The CASERTZ survey area is generally is biased toward small-scale roughness ('bluer') than the AGASEA area. While would appear likely to be due to the lesser bandwidth and sensitivity of the older radar, comparison of the median filtered RMS slope obtained by a HiCARS flights across the CASERTZ survey area to that extracted from the grid at the same locations indicate similar roughness at similar length scales, demonstrating the effectiveness of the prefiltering.

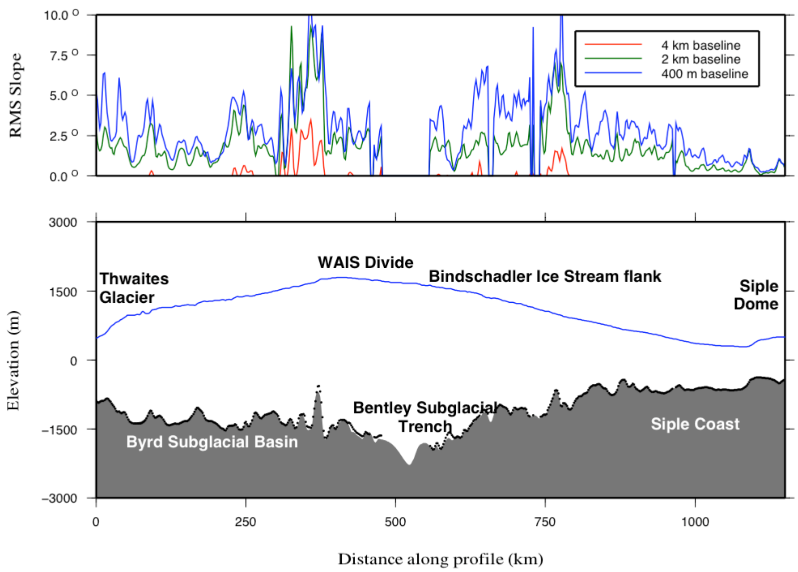

Figure 2. Profile across the WAIS. **(Bottom)** Cross-section of the WAIS - bedrock is grey, bed reflectors used for this analysis are in black, and the ice surface is in blue; **(Top)** RMS slopes at 400 , 2 km and 4 km baselines; the gap at 500 km due to missing data

Comparison with gravity data

When compared to the gravity derived profiles in Diehl et al. (2007), it is apparent that there is not a simple relationship between roughness and major sedimentary basins. While there is a slight anticorrelation between RMS slope and low density in the Byrd Subglacial Basin and Bentley Subglacial Trench regions, basins 'd ' and 'e' of Diehl et al. (2007) in the Siple Coast region correlate with enhanced roughness. It is evident that roughness must be interpreted in the context of regionally distributed processes.

Transition from interior to streaming to ice shelf

Within 200 km of the grounding line the bed of the Siple Coast are smooth (Figure 2, 3); however, a gradient in roughness is seen upstream, as noted in Siegert et al. (2004a). This roughness gradient may represent progressive infilling of topography by mobilized tills. However, the onset region of Kamb Ice Stream is smooth, especially when compared to the onset zone of Bindschadler Ice Stream. Further upstream, the region between the Byrd Station 1968 ice core site and the ASE/RSE ice divide is also smooth – this area corresponds to a ice driving stress low, and internal layers indicate both basal melting and large changes flow direction in the past (Siegert et al., 2004b). A subglacial water system directly was also identified at Byrd during coring. Discrete portions of the interior of the Thwaites Glacier catchment are also very smooth at all length scales. In general, the Byrd Subglacial Basin and Bentley Trench regions are smooth, contrasting with rougher (especially at smaller length scales) regions in the tributary region of Bindschadler Ice Stream, implying that in this deep ice regime, a different process likely responsible for smoothing topography.

Highlands

Eastern Marie Byrd Land and the Ellsworth-Witmore Subglacial Mountains, two discrete crustal blocks underlying the WAIS (Dalziel and Lavwer, 2001), are notably rough at all scales. An area fringing the Ellsworth-Witmore Subglacial Mountains, identified as the Witmore Mountains-Ross Embayment transitional crust in Blankenship et al., (2001) largely on the basis of potential fields data, is modernly smooth by comparison. Most reconstructions of a deglaciated West Antarctica put the transitional crust at or above sea level; this work suggests that is crust was shaped in a fundamentally different geomorphic regime to the higher crustal blocks.

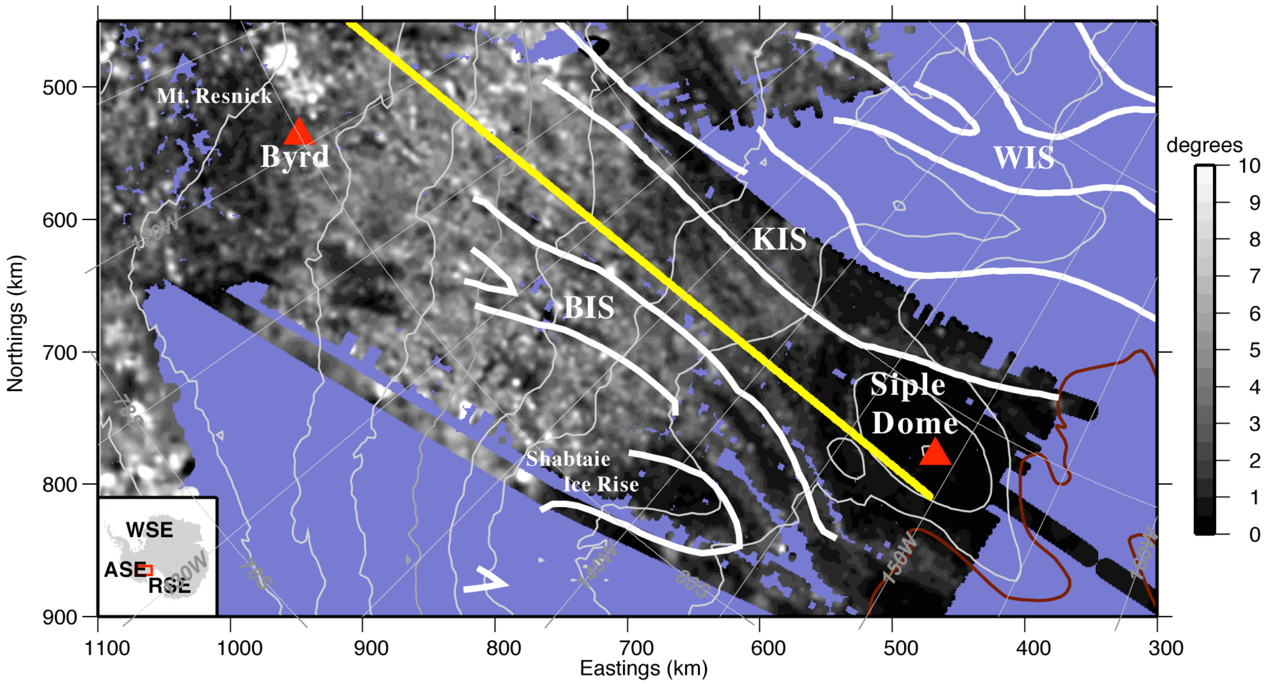

Figure 3. Map of 400-meter RMS slope over the Siple Coast (BIS=Bindschadler Ice Stream; KIS=Kamb Ice Stream; and WIS is Willans Ice Stream). Yellow is part of the profile in Figure 2; red is the grounding line. The Byrd and Siple Dome ice core sites are also shown, the bright spot near Byrd is subglacial Mt. Resnick.

Bedrock platforms

The plateaus underlying Siple Dome and Shabtaie Ice Ridge are second only to the Ross Ice Shelf in terms of smoothness. The trough holding the formerly active Siple Ice Stream is as smooth as the bed of Siple Dome, demonstrating that km scale roughness alone does not control ice streaming.

Acknowledgments. This work was supported by the National Science Foundation (OPP-0230197, OPP-9120464, and 9319369), the Jackson School of Geosciences, and the G. Unger Vetlesen Foundation. We thank Matt Peters, Sasha Carter, Becky Ghent and Scott Kempf for useful discussions on this topic, and co-editor Michael Studinger.

References

Blankenship, D. D., D. Morse, C. A. Finn, R. E. Bell, M. E. Peters, S. D. Kempf, S. M. Hodge, M. Studinger, J. C. Behrendt, and J. M. Brozena (2001), Geological controls on the initiation of rapid basal motion for West Antarctic Ice Streams: A geophysical perspective including new airborne radar sounding and laser altimetry results, in The West Antarctic Ice Sheet: Behavior and Environment, Antarctic Research Series, vol. 77, edited by R. B. Alley and R. A. Bindschadler, pp. 105–121, American Geophysical Union.

Dalziel, I. W. D., and L. A. Lawver (2001), The Lithospheric Setting of the West Antarctic Ice Sheet, in The West Antarctic Ice Sheet: Behavior and Environment, Antarctic Research Series, vol. 77, edited by R. B. Alley and R. A. Bindschadler, pp. 13–44, American Geophysical Union.

de Q. Robin, G., S. Evans, and J. T. Bailey (1969), Interpretation of radio echo sounding in polar ice sheets, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 265, 437–505.

Diehl, T., D. Blankenship, J. Holt, D. Young, T. Jordan, and F. Ferraccioli (2007), Exposing subglacial sediments across West Antarctica with isostatic gravity anomalies, in Antarctica: A Keystone in a Changing World – Online Proceedings of the 10th ISAES X, edited by A. K. Cooper and C. R. Raymond, USGS Open-File Report.

Drewry, D. J. (1975), Terrain units in eastern Antarctica, Nature, 256, 194–195.

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. Corr (2006), New boundary conditions for the West Antarctic ice sheet: Subglacial topography of the Thwaites and Smith Glacier catchments, Geophysical Research Letters, 33(L09502), 10.1029/2005GL025561.

Liu, H., K. C. Jezek, and B. Li (1999), Development of an Antarctic digital elevation model by integrating cartographic and remotely sensed data: A geographic information system based approach, Journal of Geophysical Research, 104(B10), 23,199–23,214, 10.1029/1999JB900224.

Lowe, A. L., and J. B. Anderson (2003), Evidence for abundant subglacial meltwater beneath the paleo-ice sheet in Pine Island Bay, Antarctica, Journal of Glaciology, 49(164), 125–138.

Oswald, G. K. A. (1975), Investigation of sub-ice bedrock characteristics by radio-echo sounding, Journal of Glaciology, 15(73), 75–87.

Peters, M. E., D. D. Blankenship, and D. L. Morse (2005), Analysis techniques for coherent airborne radar sounding: Application to West Antarctic ice streams, Journal of Geophysical Research, 110(B06303), 10.1029/2004JB003222.

Peters, M. E., D. D. Blankenship, S. P. Carter, D. A. Young, S. D. Kempf, and J. W. Holt (in press), Along-track focusing of airborne radar sounding data from West Antarctica for improving basal reflection analysis and layer detection, IEEE Transactions on Geoscience and Remote Sensing,

Rippin, D., J. Bamber, M. Siegert, D. Vaughan, and H. Corr (2006), Basal conditions beneath enhanced-flow tributaries of Slessor Glacier, East Antarctica , Journal of Glaciology, 52(179), 481–490.

Rippin, D. M., J. L. Bamber, M. J. Siegert, D. G. Vaughan, and H. F. J. Corr (2003), Basal topography and ice flow in the Bailey/Slessor region of East Antarctica, Journal of Geophysical Research, 108(F1), 6008, 10.1029/2003JF000039.

Shepard, M. K., B. A. Campbell, M. H. Bulmer, T. G. Farr, L. R. Gaddis, and J. J. Plaut (2001), The roughness of natural terrain: A planetary and remote sensing perspective, Journal of Geophysical Research, 106(E12), 32,777–32,795, 1029/2001JE001429.

Siegert, M. J., J. Taylor, A. J. Payne, and B. Hubbard (2004a), Macro-scale bed roughness of the Siple Coast ices streams in West Antarctica, Earth Surface Processes and Landforms, 29, 1591–1596, 10.1002/esp.1100.

Siegert, M. J., B. Welch, D. Morse, A. Vieli, D. D. Blankenship, I. Joughin, E. C. King, G. J.-M. C. L. Vieli, A. J. Payne, and R. Jacobel (2004b), Ice Flow Direction Change in Interior West Antarctica, Science, 305(5692), 1948–1951, 10.1126/science.1101072.

Smith, A. M., T. Murray, K. W. Nicholls, K. Makinson, G. Aoalgeirsdóttir, A. E. Behar, and D. G. Vaughan (2007), Rapid erosion, drumlin formation, and changing hydrology beneath an antarctic ice stream, Geology, 35(2), 127–130, 10.1130/G23036A.1.

Studinger, M., R. E. Bell, D. D. Blankenship, C. A. Finn, R. A. Arko, D. L. Morse, and I. Joughin (2001), Subglacial sediments: A regional geological template for ice flow in West Antarctica, Geophysical Research Letters, 28(18), 3493–3496, 10.1029/2000GL011788.

Taylor, J., M. J. Siegert, A. J. Payne, and B. Hubbard (2004), Regional -scale bed roughness beneath ice masses: measurement and analysis, Computers & Geosciences, 30, 899–908, 10.1016/j.cageo.2004.06.007.

Vaughan, D. G., H. F. J. Corr, F. Ferraccioli, N. Frearson, A. O'Hare, D. Mach, J. Holt, D. Blankenship, D. Morse, and D. Young. (2006), New boundary conditions for the West Antarctic Ice Sheet: Subglacial Topography beneath Pine Island Glacier, Geophysical Research Letters, 33(L09501), 10.1029/2005GL025588.