Analysis of deep-penetrating radar surveys of West Antarctica, US-ITASE 2001

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[1] We collected 1850 km of ground-based radio echo-sounding (RES) data in West Antarctica along the 2001 US leg of the International Trans-Antarctic Scientific Expedition traverse (US-ITASE). These data represent the first high-resolution measurements of ice thickness and internal stratigraphy for portions of this area that bear on questions about the stability of the West Antarctic Ice Sheet (WAIS). Internal layers depicting isochrones have been traced continuously for much of the profile length and a date from the Byrd Deep Core is ascribed to one of these isochrones from which we estimate vertical velocities across the traverse route. Comparison of our ice thickness measurements with BEDMAP show good agreement in regions where the database is well constrained by data coverage. Where the BEDMAP dataset was forced to interpolate, differences are as high as 45% of the ice thickness. *INDEX TERMS:* 1827 Hydrology: Glaciology (1863); 1863 Hydrology: Snow and ice (1827); 9310 Information Related to Geographic Region: Antarctica. **Citation:** Welch, B. C., and R. W. Jacobel, Analysis of deep-penetrating radar surveys of West Antarctica, US-ITASE 2001, *Geophys. Res. Lett.*, *30*(8), 1444, doi:10.1029/2003GL017210, 2003.

1. Introduction

[2] The International Trans-Antarctic Scientific Expedition is a multi-national effort to characterize the last 200–2000 years of climate throughout Antarctica. The US portion of the program (US-ITASE) is a multi-disciplinary collaboration of more than a dozen academic and government institutions focused on the West Antarctic Ice Sheet (WAIS) [*Mayewski*, 1996]. During the austral summer field seasons of 1999, 2000, 2001 and 2002, US-ITASE conducted a series of overland traverses throughout West Antarctica and extending to the South Pole, each starting at Byrd Surface Camp (80°S, 120°W). A website describing major US-ITASE activities may be found in at http://ume.maine.edu/USITASE/.

[3] US-ITASE provides an opportunity to record high-resolution ground-based RES data at a scale similar to airborne RES in little-explored regions of the WAIS that have few, if any, ice thickness measurements. Information about bedrock topography and ice flow history from deep RES records is relevant to questions about ice divide stability in West Antarctica and is also important to assist in the interpretation of several of the US-ITASE experiments such as ice velocity measurements and the near-surface radar.

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[4] During the 2001 US-ITASE season we collected 3 MHz RES data along the entire traverse route and several local profiles near the 6 ice core drilling sites (Figure 1). This paper presents our interpretation of the two longest segments of the 2001 traverse: a 735 km profile from the upper reaches of the Rutford Ice Stream drainage basin to Byrd Surface Camp (B-D), and a 145 km profile from upper Pine Island Glacier to the upper Rutford Ice Stream basin near the Ellsworth Mts. (A-B-C). Each profile crosses a significant ice divide. Profile A-B-C crosses the Pine Island Glacier/Rutford Ice Stream divide, while Profile B-D crosses the Amundsen Sea/Ross Sea divide near the proposed site of the Inland WAIS Deep Ice Core.

[5] Previous ice thickness data in this region consist of a high-resolution airborne survey near Byrd Surface Camp to characterize the Inland WAIS Deep Core site [*Morse et al.*, 2003], several combined British and U.S. airborne flights from the 1970s, and numerous airborne RES flights by the British Antarctic Survey (BAS) in the Rutford Ice Stream/Pine Island Glacier region. There are also isolated seismic measurements in the region, most dating from IGY and post-IGY traverses. Some of these traverses linked the seismic ice thickness measurements with gravity data. Figure 2 is a map of data tracks and types of measurements included in the BEDMAP ice thickness database [*Lythe et al.*, 2001].

2. Instrumentation, Data Collection, and Processing

[6] We use an impulse radar similar in concept to other ground-based pulse systems deployed today but with a number of specialized adaptations because of the high traverse speeds, heavy vehicles and deep ice. The transmitter-antenna combination operates at a center frequency of 3 MHz (λ_{ice} = 56 m) and has a bandwidth of approximately 1 MHz. There are two competing requirements for a high-resolution mobile RES receiver: stacking more traces per recording interval to maximize signal to noise (S/N), versus increasing the spatial density of recorded waves to avoid aliasing. The US-ITASE traverse train travels up to 12 km/hr, leaving approximately 5 seconds to stack pulses to improve the signal to noise ratio within a quarter wavelength of travel. The impulse transmitter has a pulse repetition rate of approximately 300 Hz, thus limiting the number of stacks to about 1500 per recorded trace with the above criteria. The radar receiver is based on a 100 MHz digitizer board with 14-bit resolution, giving the system 84db of dynamic range. The long traverse distances, relatively high speeds, and heavy tractors of the traverse required protecting the four long (20 m) dipole antennas

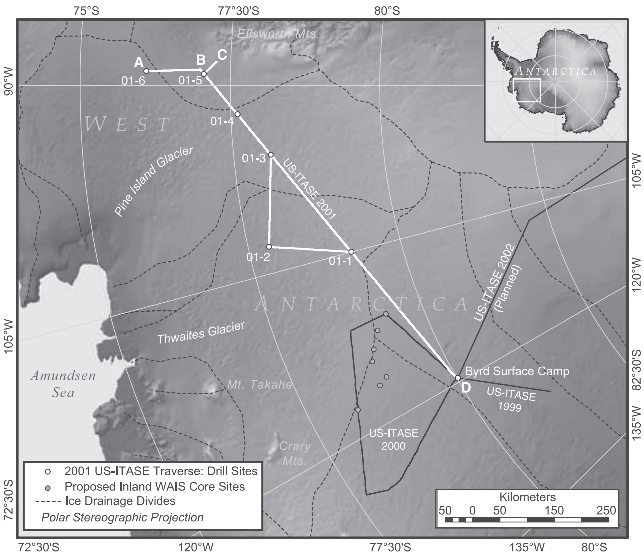

Figure 1. Map of the 2001 US-ITASE traverse overlying the RAMP DEM [*Liu et al.*, 2001] showing ice core locations and major drainage divides. Deep-penetrating radio echo sounding data were collected over the entire length of the traverse. Profiles ABC (142 km) and BD (735 km) are described in the text.

in heavy-duty hydraulic hose. The resulting system has collected bedrock reflections from ice over 3.5 km in thickness and internal ice reflections from depths up to 2.5 km.

[7] Profile ABC (Figure 1) starts at US-ITASE ice core site 01-6 and extends for 142 km toward the Ellsworth Mountins with a short 10 Km 'kink' where it intersects the other profile. This profile crosses the ice divide between Pine Island Glacier and Rutford Ice Stream near km 25. Profile BD overlaps profile ABC for its first 10 km then continues to Byrd Surface Camp for a total distance of 735 km. It crosses the Amundsen Sea/Ross Sea ice divide at km 430 near the proposed Inland WAIS Deep Core site [*Morse et al.*, 2003], as well as the basin flow divides separating Pine Island Glacier, Thwaites Glacier, and Rutford Ice Stream.

[8] Distances and coordinates, as well as surface elevations along the traverse were determined every 30 seconds by precision GPS receivers operated by US-ITASE colleagues from the University of Maine [*Hamilton and Spikes*, 2003. Differential GPS coordinates were recorded with a base station at Byrd Surface Camp and a receiver in one of the traverse sleds. RES recorded waveforms were tagged with a time stamp synchronized to the GPS clock for later processing as described in the interpretation section.

[9] Post-field processing included a simple bandpass filter to improve signal to noise and to remove low-frequency responses due to the direct coupling between the transmitter and receiver from the transmitted pulse. A normal move-out (NMO) correction was used to remove the 135 m offset between the transmitter and receiver antennas. We investigated the effect of migrating the data to correct for the finite beamwidth of the antennas. Only in cases of the very steepest slopes or severe sideswipe did migration produce a discernable change in reflector locations and so the data presented in plots here have not been migrated.

3. Data Interpretation

[10] Interpretation of the RES data consists of two steps: (1) digitizing echoes from the bedrock and internal ice reflectors and (2) replotting them as depth beneath the GPS-determined ice surface at the actual data locations along the traverse. In determining precise bed and internal echo depths, we use a computer-assisted digitizing routine to pick the maximum amplitude of the earliest portion of the reflector wavelet. We pick the location of the specific reflector and the routine finds the precise depth of the arrival wavelet. Figure 3a shows surface, bed and internal stratigraphy for the two long profiles indicated in Figure 1. Approximately 80% of the bed echoes are unambiguous, the remaining portions dashed) were picked with the aid of adjacent topography and internal stratigraphy.

[11] The bed interpretation in Figure 3 shows that the subglacial bedrock surface is below sea level throughout the traverse route except for one significant mountain peak in profile ABC near km 135 (Figure 3a, left panel). With the exception of this rise, the subglacial topography in profile ABC is generally smooth. In contrast, the bed relief throughout most of the profile BD is rough with local relief over 1500 m (Figure 3a, right panel).

[12] The Amundsen Sea/Ross Sea ice divide is located near a significant subglacial mountain range near km 460. According to the RAMP DEM [*Liu et al.*, 1999], the actual divide location is some 50 km toward Byrd Station. Depiction of the bed topography and internal layers in the vicinity of the Amundsen Sea/Ross Sea divide and the fact that it exists in proximity to a large change in bed elevation is an important result of this traverse, extending the coverage of

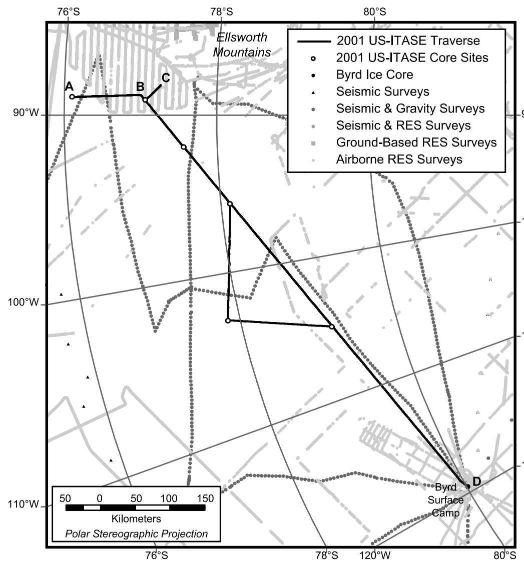

Figure 2. Map of ice thickness measurements contributing to the gridded BEDMAP database overlain by the route of the 2001 US-ITASE traverse. The large data gaps represent regions of poorly constrained ice thickness derived by interpolation in the BEDMAP grid.

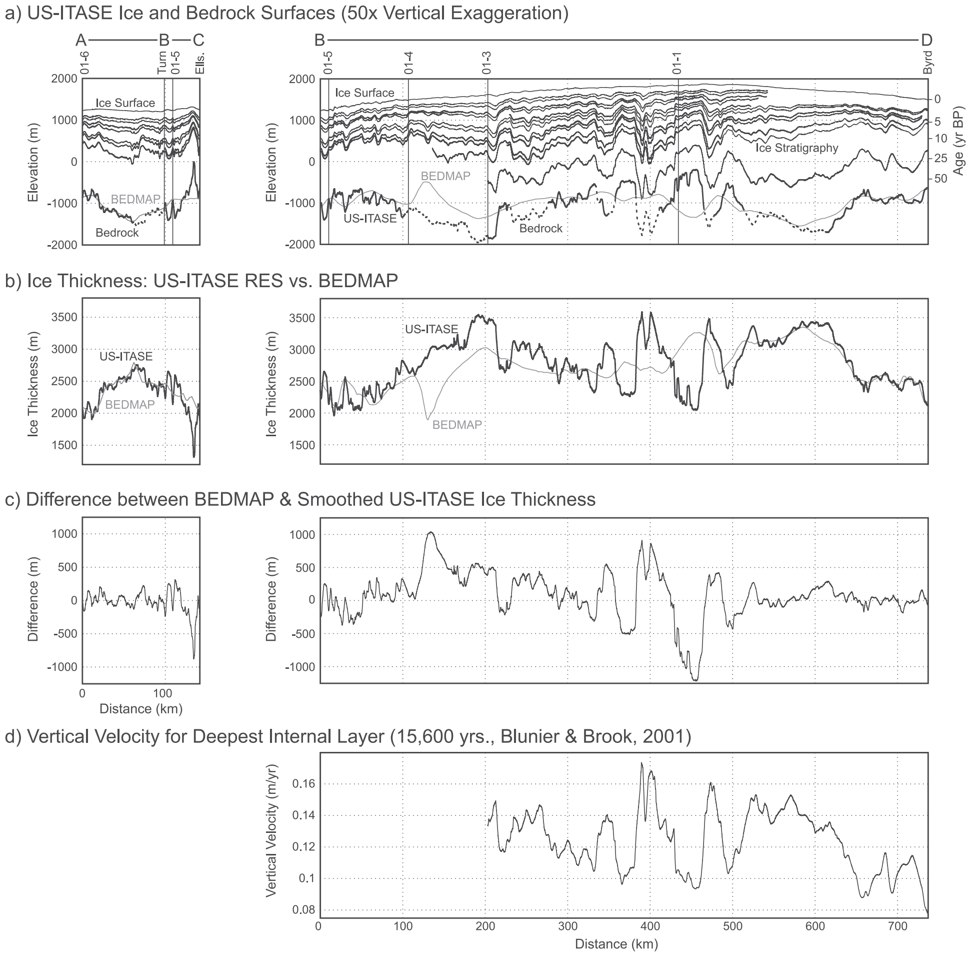

Figure 3. Interpretation of deep-penetrating RES data from profiles ABC and BD. a) Interpreted RES bedrock and internal reflections. The ice surface is derived from simultaneous GPS measurements. A bedrock surface interpolated from the BEDMAP database is shown in gray [*Lythe et al.*, 2001]. The timescale at the right is from *Hammer et al.* [1994]. b) The US-ITASE (black) and BEDMAP (gray) ice thickness measurements. c) The difference between the US-ITASE ice thickness and BEDMAP ice thickness exceeds 1200 m, as much as 45% of the ice thickness as measured by US-ITASE. d) Calculated balance velocity for the deepest internal ice layer in Profile BD shows that the ice dynamics alters the depositional record in deep ice.

the *Morse et al.* [2001] airborne survey. We shall return to questions about this divide below. In some cases, flow divides correspond to bedrock highs - as with the one just described; in others they do not. The Pine Island Glacier/Rutford Ice Stream divide, crossed at two different points in these profiles (Figure 3a, right panel, km 90; Figure 3a, left panel, km 25), in both cases is located on the flanks of small bed rises.

[13] Twelve internal ice layers were also digitized to produce representative internal stratigraphy extending throughout most of the two profiles. Many other internal reflectors are discernable locally, but may not extend through the entire profile length due to spatial variations in ice chemistry or due to vertical resolution limitations of the RES system where two adjacent layers are too close together to be uniquely identified. These layers are assumed to be isochrones representing the spatial extent of relatively short-lived events such as changes in conductivity due to acid deposition. Some of them may be identified from the Byrd core as described next.

[14] We have used the recently computed age-depth scale from the deeper portion of the 1968 Byrd core [*Blunier and Brook*, 2001] to associate an age with the deepest layer we are able to resolve. This layer can be located near the right margin of Figure 3a (Byrd Station) at a depth just a few meters above sea level and according to the Blunier and Brook chronology corresponds to an age of 15.0 to 15.5 KYBP - coincident with the transition from the last glacial to the Holocene. Layers shallower than 1000 m may be related to a date derived from the original *Hammer et al.* [1994] time scale indicated at the right of Figure 3a.

[15] In principal, the depth to an isochronal surface is a combination of integrated accumulation at the surface, melting at the bed (if it occurs) and the vertical strain history due to ice flow. To fully understand the topography of isochrones seen in RES data in general requires an ice flow model to extract the components due to ice flow, basal melt and surface accumulation. In Figure 3d the topography of the deepest interpreted internal reflector more resembles the bedrock topography than the ice surface. This indicates

that vertical strain or possibly basal melt are more important than the spatial variation in accumulation along this profile. We expect that vertical strain would vary significantly across this profile as it crosses several ice drainage divides and we are hopeful that ongoing modeling efforts may be able to extract this information as well as conclusions about possible basal melting.

[16] Current interest in the stability of the Ross Sea Amundsen Sea divide region exists because of a proposed deep climate core in this area (Figure 3a, Km 510). Changes in ice flow dynamics and/or accumulation over time can result in migration of an ice divide [*Nereson et al.*, 1998; *Conway et al.*, 1999]. These effects generally produce irregularities in the pattern of internal layers, and ice flow models may be used to infer the nature of some of these changes. While it is tempting to try to draw conclusions about divide stability from the internal layer pattern we see, the high-relief and complex bed topography near the divide in this study precludes a simple interpretation without a more rigorous modeling effort.

4. Comparison to BEDMAP

[17] The BEDMAP ice thickness database compiled by *Lythe et al.* [2001] represents the most comprehensive collection of Antarctic ice thickness measurements to date. This data set is an important tool for ice sheet modeling, especially at large spatial scales. Subsequent RES surveys such as this one provide not only opportunities to add to the database but also to check the quality of the interpolated ice thickness grid in regions of Antarctica that were poorly constrained in the original data.

[18] We used a two-dimensional linear interpolation to obtain ice thickness values from BEDMAP that correspond to US-ITASE RES trace locations (gray lines in Figure 3a). The BEDMAP database utilized linear distance weighting to give values on a 5 km grid [*Lythe et al.*, 2001] that is oriented at approximately 45 degrees to the US-ITASE traverse route. Therefore, we have smoothed the US-ITASE ice thickness interpretation in Figures 3b and 3c with a 7.5 km running average to obtain approximately the same spatial difference between points as BEDMAP data. Ice thickness measurements by US-ITASE have errors that depend only on the RES system (roughly $\lambda/4$ = 14 m), whereas bedrock elevation data also require ice surface elevations from GPS and therefore have slightly larger errors. Potential errors in BEDMAP data are similarly less for ice thickness so we make comparisons in terms of ice thickness rather than bed elevation data.

[19] Figures 3b and 3c show comparisons between BEDMAP and US-ITASE ice thickness for both profiles. There is reasonably good agreement between BEDMAP and US-ITASE RES ice thickness measurements in profile ABC (Figure 3b). The agreement is also good in profile BD near Byrd Surface Camp (Figure 3b, right side). For much of profile BD, however, the agreement is poor and the differences can exceed 1200 m, in some places as much as 45% of the ice thickness as measured by this study (Figure 3c). On average the difference between the datasets is on the order of ±15%. The reason for the poor agreement is readily apparent from the BEDMAP data coverage map shown in Figure 2. There is little previous ice thickness data for much of the 2001 US-ITASE traverse route except near Byrd Surface Camp and Rutford Ice Stream. The previous seismic/gravity measurements that nearly parallel the traverse route near Byrd Surface Camp consist of seismic measurements made approximately every 50 km with gravity measurements between [*Lythe et al.*, 2001]. Given the rough bedrock terrain in this region, it is not surprising that gravity measurements do not correspond well with the RES measurements.

[20] The large discrepancies between the poorly-constrained interpolated regions of BEDMAP and the RES data of this study provide a caution to those interested in using BEDMAP as input for ice flow models. These models are highly sensitive to ice thickness because it is a nonlinear term in ice flow equations. Similarly, ice flow models that "grow" ice sheets from the BEDMAP bedrock surface are not immune to these errors as the BEDMAP bedrock surface is derived from the interpolated grid of ice thickness data [*Lythe et al.*, 2001].

[21] It is difficult to assess the accuracy of BEDMAP beyond the extent of the profiles shown in this study. The data from this study would improve this portion of BEDMAP to a degree, but single profiles will still result in the necessity of interpolations between existing data sets. Coarse grids of data would be a better method to produce ice thickness maps of the accuracy required for continent-scale ice flow models. Focused ice flow models of specific regions will require higher-resolution data from more closely spaced ice thickness surveys.

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References

Blunier, T., and E. Brook, Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period, *Science*, *291*, 109–112, 2001.

Conway, H., B. L. Hall, G. H. Denton, A. M. Gades, and E. D. Waddington, Past and future grounding-line retreat of the West Antarctic Ice Sheet, *Science*, *286*, 280–283, 1999.

Hamilton, G. S., and V. B. Spikes, Kinematic GPS tests of a satellite altimeter derived digital elevation model of Antarctica and glaciological implications, *Global and Planetary Change*, submitted, 2003.

Hammer, C. U., H. B. Clausen, and C. C. Langway Jr., Electrical conductivity method (ECM) stratigraphic dating of the Byrd Station ice core, Antarctica, *Ann. Glaciol.*, *20*, 115–120, 1994.

Liu, H., K. C. Jezek, and B. Li, Development of an Antarctic digital elevation model by integrating cartographic and remotely sensed data: A geographic information system based approach, *J. Geophys. Res.*, *104*(B10), 23,199–23,213, 1999.

Lythe, M. B., D. G. Vaughan, and BEDMAP Consortium, BEDMAP: A new ice thickness and subglacial topographic model of Antarctica, *J. Geophys. Res.*, *106*(B6), 11,335–11,352, 2001.

Mayewski, P. A., *US ITASE: Science and Implementation Plan*, 52 pp., Univ. of N. H., Press, Durham, 1996.

Morse, D. L., D. D. Blankenship, E. D. Waddington, and T. A. Neumann, A site for deep ice coring in West Antarctica: Results from aerogeophysical surveys and thermo-kinematic modeling, *Ann. Glaciol.*, in press, 2003.

Nereson, N. A., C. F. Raymond, E. D. Waddington, and R. W. Jacobel, Migration of the Siple Dome ice divide, West Antarctica, *J. Glaciol.*, *44*(148), 632–652, 1998.

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