First results from radar profiles collected along the US-ITASE traverse from Taylor Dome to South Pole (2006-2008)

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Abstract. The 2006-07 and 2007-2008 US-ITASE traverses from Taylor Dome to South Pole in East Antarctica provided opportunities to survey the subglacial and englacial environments using 3 MHz and 200 MHz radar. We present first results of these new ground-based radar data. A prominent basal deformation layer indicates different ice flow regimes for the northern and southern halves of the Byrd Glacier drainage. Buried dune stratigraphy that appear to be related to the Megadunes toward the west, occur at depths of up to 1,500 m. At least two new water-filled subglacial lakes were discovered, while two recently-drained lakes identified from repeat ICESat surface elevation surveys appear to be devoid of water.

Introduction

The International Trans-Antarctic Scientific Expedition (ITASE) is a multi-disciplinary research program whose goal is to reconstruct the recent climate history of Antarctica through ice coring and related geophysical, glaciological, and paleoclimate observations along traverses throughout the continent. The U.S. component of ITASE (US-ITASE) operates numerous scientific projects from a heavy traverse platform consisting of two tractor trains. The US-ITASE traverses provided an opportunity to collect ground-based radar data over long distances, covering a wide range of glaciological and geological environments (Figure 1). A third vehicle, a Pisten Bully used to scout for crevasses ahead of the heavy trains, was available for local radar profiles near the ice core sites. The size of the traverse trains makes it possible to collect shallow (200 MHz) and deep (3 MHz) radar simultaneously.

The first phase of US-ITASE collected over 3,000 km of deep-penetrating radar data along a series of traverses centered at Byrd Station (80S, 120W) and ending in January, 2003 at South Pole (references?). During the second traverse, vehicles drove from Taylor Dome to Byrd Glacier (2006-07 field season) in East Antarctica and then to South Pole via Titan Dome (2007-08 field season). Shallow (~100 m) 200 MHz profiles were recorded simultaneously with deep radar at 3 MHz and both were used in the field to determine the suitability of ice core sites.

The purpose of this paper is to show first results from both radar systems focusing on features of current glaciological interest: the Megadunes area, basal ice flow regimes, and subglacial lakes.

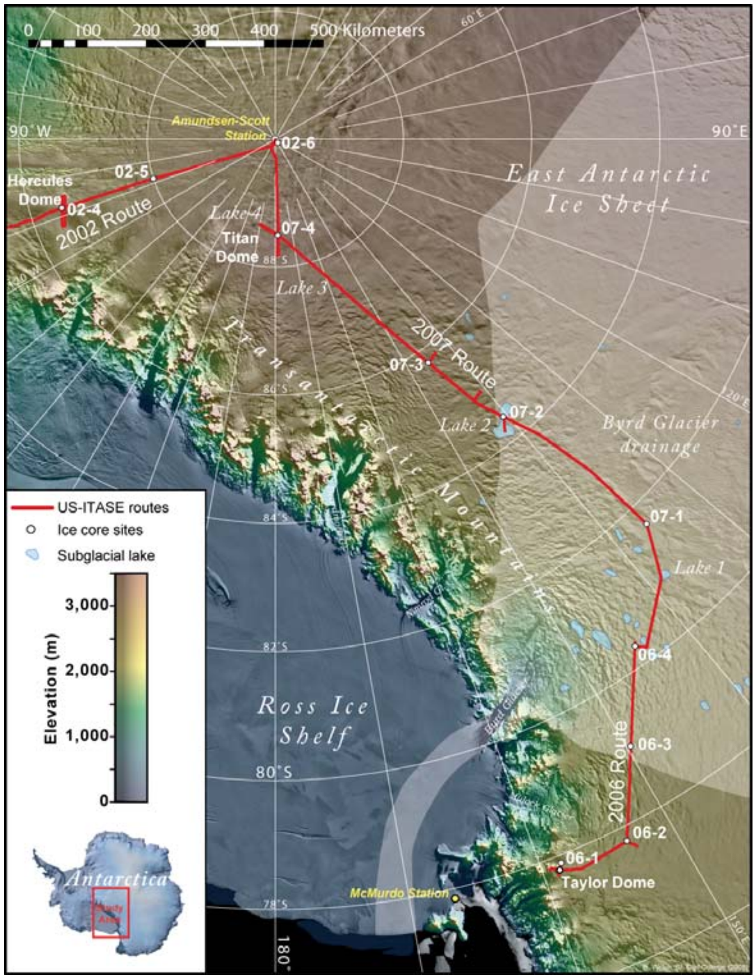

Figure 1. Shaded relief map showing the US-ITASE routes in East Antarctica (red lines), ice core sites (white dots), and subglacial lakes from satellite-derived surface elevation changes. Byrd Glacier drainage interpreted from ice surface elevation data. Elevation data from Liu and others [1999, http://www.nsidc.org/data/nsidc-0082.html], shading from MOA [Haran and others, 2005, http://www.nsidc.org/data/nsidc-0280.html].

Radar systems

Altogether we acquired more than 2100 km of deep radar profiles using an impulse system with a center frequency of 3 MHz [Welch and Jacobel, 2003]. Recent improvements to the system for this project included: a dual-channel digitizing board to record low-gain and high-gain signals simultaneously, increase in sampling frequency to 200 MHz, and a faster trigger acquisition speed (up to 1.5 kHz). The transmitter was upgraded to a Kentech pulser with higher amplitude (4kV) and a pulse frequency of 1 kHz. Individual stacked traces (1000 triggers/stacked trace) were recorded at an average spacing of 3.5 m with trace locations and surface elevations determined by continuously recorded high-precision GPS measurements. Profiling speeds were as high as 14 km/hr during the traverse.

While stacking traces in the field eliminates much of the environmental noise, some is inevitably present. The impact on data quality is noticeable only in regions of high signal attenuation and ice thickness greater than 3 km (e.g. deepest segments of Byrd Glacier); however, internal stratigraphy was detected to depths of over 2.7 km.

All 3 MHz data were recorded with the same dual-channel radar system configuration, except that the transmitter-receiver offset in 2006-07 was 207 m while it was shortened to 125 m in 2007-08. The shorter offset causes the direct wave to saturate the receiver to nearly 500 m in the high-gain channel of the 2007-08 data; however, the near-surface horizons are still recoverable in the low-gain channel.

The shallow radar data were collected with a GSSI SIR6 system with a 200 MHz dipole antenna towed in a plastic sled behind one of the traverse trains. Both radars were run on the same sledge train for most of the traverse. Simultaneous GPS observations collected with each radar system allow the data sets to be correlated with accuracy better than 20 m after consideration of slight differences in travel path due to the long tow ropes of the 3 MHz system.

Findings

Thick basal ice in upper Byrd Glacier

Byrd Glacier is one of the major outlets of ice from East Antarctica, and the largest contributor of East Antarctic ice to the Ross Ice Shelf. The deep radar profiles show that the basal ice in the northern half of the Byrd Glacier drainage differs from that found in the southern half. Representative profile sections from these two regimes that we observerd continuously for xx hundreds of kilometers are shown in Figure 2 and are located on the map, Figure 3. In particular, there is a thick (500+ m) region of basal ice where there are no internal horizons recovered by the 3 MHz radar (Figure 2b). The upper ice contains laterally continuous layers. The transition between the upper stratigraphy and the basal ice is marked by what appear to be small fragments of horizons in a 100-200 m thick band. In contrast, the northern half of the Byrd Glacier drainage exhibits internal horizons that are continuous nearly to the bed (Figure 2a).

The thick basal ice lacking coherent reflectors is found between 81S and 83.75S, as shown by the blue line in Figure 3. This zone ends about 80 km north of ice core site 07-2, within 100 km of the southern margin of the Byrd Glacier drainage basin where deep stratigraphy becomes restored (or something?).

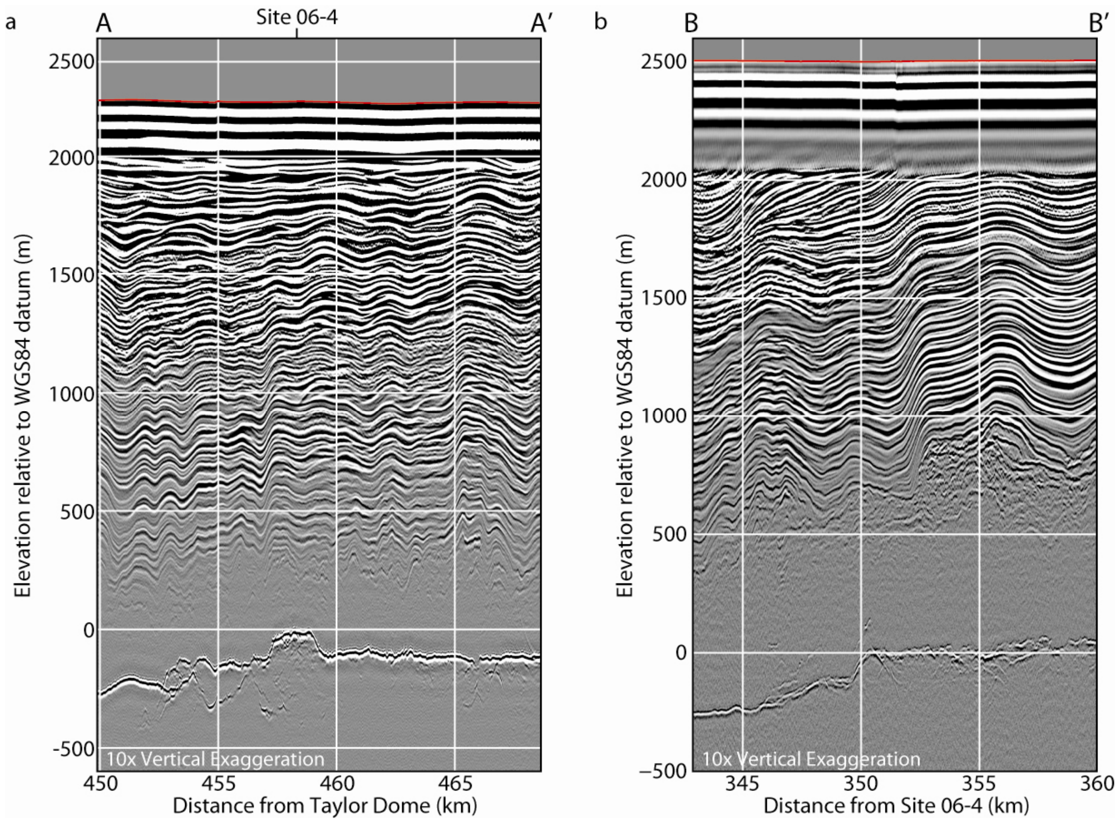

Figure 2. a) Elevation-corrected 3 MHz profile (A-A') from northern half of the Byrd Glacier drainage. Note that the near-bed reflectors are conformable to one another and similar in shape to the bed topography. b) Depth-section profile (B-B') from the 2007 traverse shows that the southern half of the Byrd Glacier drainage is marked by a much thicker basal layer with no stratigraphy and is separated from the upper coherent stratigraphy by a zone of highly disrupted reflectors. The near-surface ringing is greater in B-B' due to the shorter transmitter-receiver offset.

The traverse crosses the drainage nearly perpendicular to flow, so the change in basal stratigraphy is not likely be a result of profile orientation relative to ice flow. Possible causes of the lack of horizons in the near-bed radar data include: 1) increased attenuation, perhaps due to warmer basal ice, 2) disruption of the layers due to upstream basal topography, or 3) higher rates of ice flow in the southern half of the drainage basin. We cannot determine the specific cause of the thicker basal ice without further along-flow radar profiles that would provide constraints on ice flow models. However, the difference between the northern and southern halves of the Byrd Glacier drainage could have implications for historical or modern ice flow. Case 1 might indicate regional differences in basal geothermal flux. In case 2, the difference might reflect substantial differences in bed roughness in the upper Byrd Glacier drainage that would deform and warm the ice as it flows over the basal topography. For case 3, it might imply differing responses to changes in the flow of ice into the Ross Ice Shelf. Were that to be the case, the stratigraphy could be showing a past change in ice flow in response to an abrupt change in conditions within the basin; perhaps draw-down of the ice surface after the Ross Ice Shelf grounding line retreated past the Byrd Glacier Outlet [Conway and others, 1999].

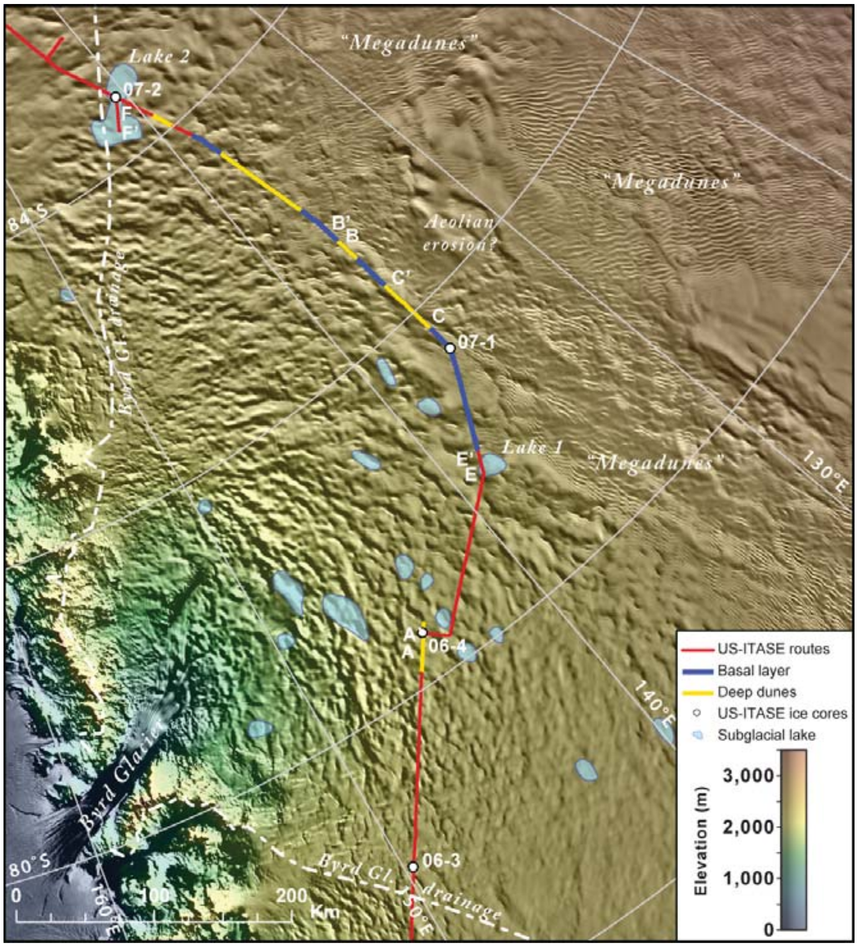

Figure 3. Locations of thick basal ice zone (blue line) in the southern half of Byrd Glacier. The locations of buried dunes (yellow lines) are superimposed over the thick basal ice and red line of the traverse route.

Near-surface features

The addition of a low-gain channel to the radar system allowed the recovery of shallow reflectors that previously had been masked by the power of the air wave arrival. We have correlated the shallow reflectors in our data with data recorded by the 200 MHz radar system to examine several interesting near-surface features found along the traverse route. We find evidence of buried dunes (yellow lines in Figure 1), aeolian erosion at the surface, and layer deformation due to subglacial topography.

Profile C-C' (Figure 4) shows deep and shallow radar data in a region near the margin of the Megadunes (Figure 3). The 200 MHz radar data show clear evidence of buried dunes in the upper 80 m of firn. We infer the white bands in the shallow radar profile (e.g. Km 250, 50 m depth to Km 270, 5 m depth) as zones of intense thermal metamorphism, which occur throughout 5-15 km^2 regions of stratified and buried dunal structures (how do we know this? Fig 3?). We interpret the foreset beds in the deep radar profiles directly below these zones to be large-scale anti-dunal structures buried up to 1.5 km within the ice (Albert and others, 2004). This particular location exhibits the greatest stratigraphic disruption due to deep buried dunes seen on the traverse. The magnitude of

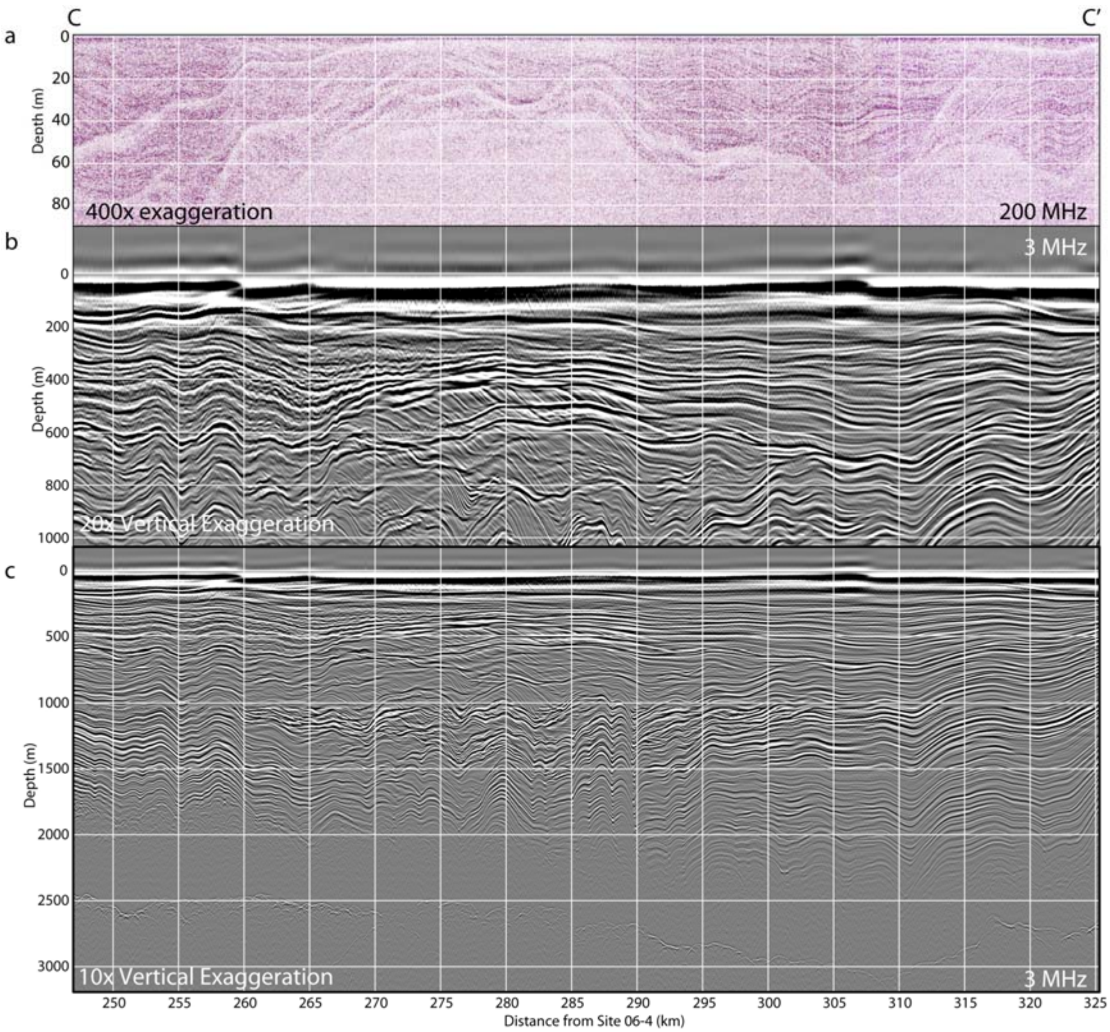

Figure 4. Profile C-C' shows evidence of buried dune structures. a) 200 MHz data show near-surface dunes. The hazy white bands are interpreted as zones of intense metamorphism. b) 3 MHz intermediate-depth data from the low-gain channel showing a complex depositional history. c) Full 3 MHz profile showing relatively simple bed topography.

the disturbed stratigraphy found in this location may result from highly variable accumulation due to changes in air flow around the topographic rise seen upstream in the MOA mosaic (Figure 3).

In other areas, the low and even negative accumulation rates in East Antarctica are apparent where the radar stratigraphy intersects the ice surface, usually due to the flow of ice over bedrock topography. These are regions where aeolian transport and erosion exceed local accumulation rates, usually due to surface relief that exposes the surface to higher wind speeds [Welch and Jacobel, 2004]. An example is shown in profile D-D' (Figure 5) between ice core sites 07-3 and 07-4 where the ice flow is within 30° of the profile direction. Here the ice flows over a subglacial mountain, causing a bulge in the surface. Wind acting on that topographic high increases the aeolian erosion rate to the point where the net mass balance is negative. The intersection of the ice stratigraphy

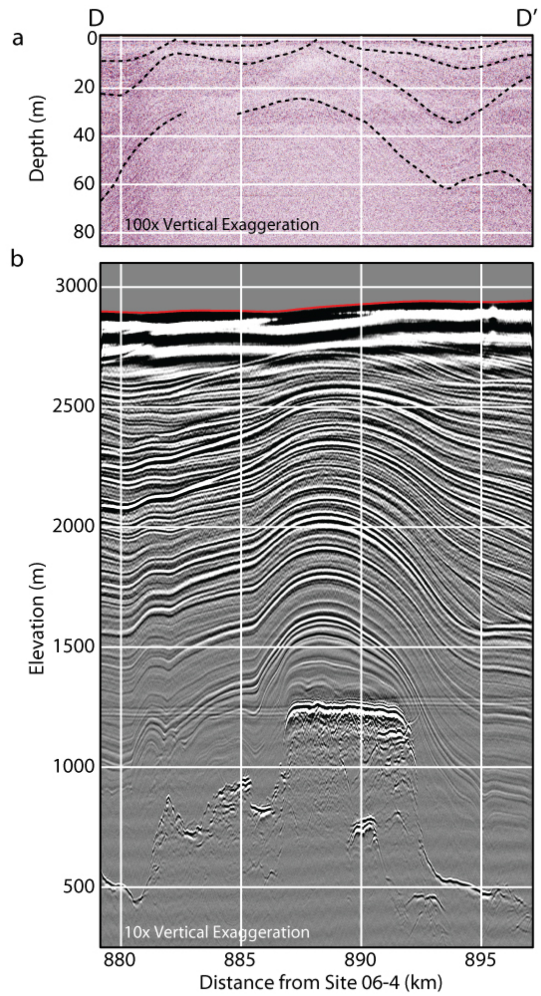

Figure 5. Profile D-D' is an example of layers intersecting the ice surface. a) 200 MHz data show the intersection of near-surface layers with the surface. Some prominent reflectors are highlighted. b) Migrated and elevation-corrected 3 MHz data show that a subglacial mountain has created a vertical strain in the ice and a topographic high where aeolian erosion rates are higher. The horizontal stripes at 1200 m are an artifact of the horizontal filter.

with the surface is seen in both the 3 MHz and 200 MHz radar data. Once dating of the two adjacent ice cores is complete we may be able to determine the age of the exposed ice at the surface if we can trace stratigraphy back to the erosion site.

These areas where the layers intersect the surface are regions of long-standing and ongoing erosion, generally on the leeward sides of topographic bumps [Arcone and others, 2005, Fig. 5]. Such sites were found in many locations between Taylor Dome and Titan Dome and are of great importance for the interpretation of ice core records as the aeolian erosion eliminates significant periods of accumulation history and brings older layers near the surface.

Subglacial Lakes

The identification of subglacial lake drainage through time-series measurements of satellite-derived ice surface topography has emphasized the likely importance of water drainage in controlling local and regional ice flow [Fricker and others, 2007, Anandakrishnan and Winberry, 2004]. We utilized maps of subglacial lakes provided by B. Smith (pers. comm.) to ensure that the traverse route crossed a number of these recently drained lakes. In addition, we found at least two other water-filled subglacial lakes that do not appear in the existing lake catalogues.

We crossed the edge of Lake 1 (Figure 3) between ice core site 06-4 and site 07-1 (81°S, 139°E). The bed is quite rough in the area identified as a subglacial lake (Km 140-151), but is a distinct and abrupt depression in the bed surface (Figure 6a). There is no indication of higher reflectivity generally associated with subglacial water. Lake 2 is located in the deepest basin crossed during the traverse with ice up to 3.3 km thick. It is

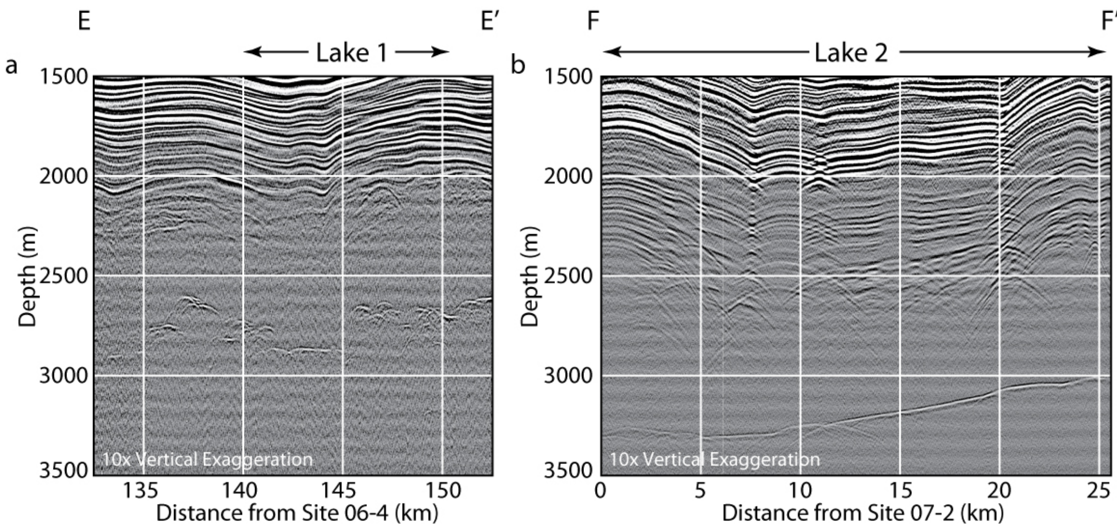

Figure 6. a) Profile E-E' showing the bed reflector and deep stratigraphy at Lake 1 (defined by satellite from Km 140-151). A deep cleft in the bedrock is visible in the rough bed surface. b) Profile F-F' showing the bed reflector and deep stratigraphy at Lake 2, location of the thickest ice seen in the 2007 traverse. The bed rises about 300 m along the center axis of the proposed lake bed. Reflectivity is relatively constant in

just outside the southern Byrd Glacier zone of thick basal ice, located at or very near the drainage divide between Byrd and Nimrod Glaciers (Figure 6b).

Lakes 1 and 2 were identified by Smith (pers. comm..) based on rapid deflation of the ice surface elevation, as seen in ICESat altimetry measurements. The cause of the deflation is interpreted to be the drainage of water from subglacial cavities [Fricker and others, 2007]. It is important to note that while the basal reflectors are not rough, there are occasional scattering reflectors indicative of bumps or cracks in the ice. These may indicate that the ice lies directly on the bed which is not as smooth as one might expect for a water-filled lake. The bed at Lake 1 is quite rough for a subglacial lake, although there is a deep notch at Km 142-145. While the basal reflector at Lake 2 is relatively smooth, the low basal reflectivity seen in the 3 MHz radar data leads us to believe that there is currently little or no water present at these sites. This supports the observation of recent drainage and that there has been virtually no subsequent refilling of the basins [Smith and others, 2007]. Future work, including modeling of attenuation, is required to develop the quantitative reflectivity of the basal reflectors. However, the apparently low basal reflectivity compared to adjacent regions of rough bedrock at similar depths, leads us to conclude that there is no significant basal water present at these sites at this time. Lake 3 is located 40 km north of Titan Dome (Figure 1). It is a bright, relatively flat reflector between km 1034-1041 (Figure 7). The geometry of the local topography would indicate a possible water depth of 10 m or more. In general the basal reflectivity in this region is much higher than for Lakes 1 & 2, both of which are within the Byrd Glacier

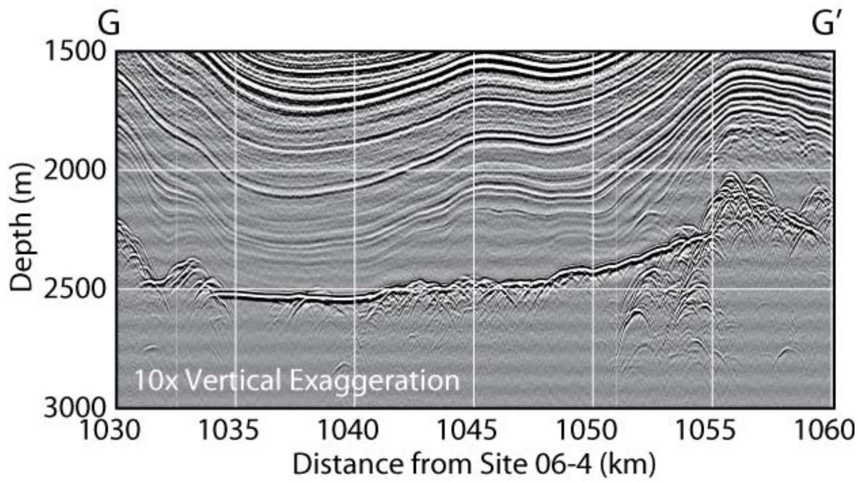

Figure 7. Profile G-G' (high-gain channel) showing a subglacial lake (km 1034-1041) and submerged terrain where water may be flowing down a slope (km 1046-1055).

drainage. Englacial stratigraphy is concave upward in this area and visible to within 100 m of the bed and there is little evidence of a basal ice layer with high attenuation, as was seen in Lakes 1 & 2 in the Byrd Glacier drainage.

The relatively high reflectivity and smooth reflector indicates the probable presence of ponded water at km 1034-1041. At km 1046-1055 there is a bright, relatively smooth reflector, at the bed, but it is not horizontal. The diffraction hyperbolas within the basal reflector indicate some basal roughness, but they are mostly masked by the strong smooth reflector. We hypothesize that water in this area is flooding much of the basal roughness, and is perhaps flowing into Lake 3.

Lake 4 is a small feature roughly 19 km southeast of ice core site 07-4 (Figure 1). The basal reflector is smooth and very intense (Figure 8). A neighboring reflector (Km 12-15) in an elevated basin is also a very strong reflector, but the roughness implies that the bed topography influences the ice contact.

The presence or absence of subglacial water is an important factor in ice flow dynamics and the use of ICESat data to identify the movement of water is a key step in characterizing the extent and activity of subglacial hydrology. Ice-penetrating radar provides critical information about the extent of water drainage and the morphology of the glacier subsurface that will be needed in order to calculate water flux if any lake empties or starts to refill.

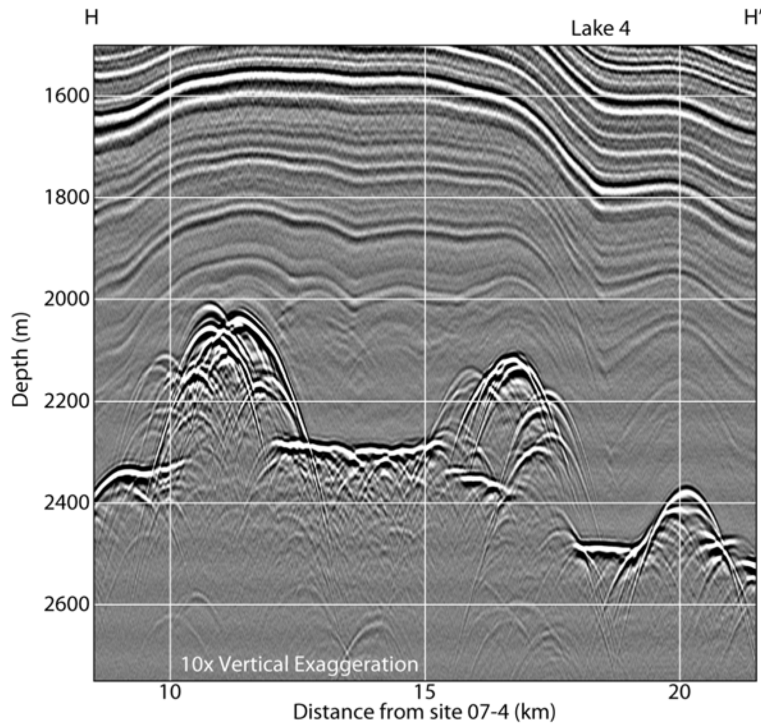

Figure 8. Profile H-H’ showing subglacial Lake 4, a small pond roughly 1 km across. The adjacent basin at km 12-15 has a strong reflector, but a rough surface, implying that the bed surface influences the ice-bed contact.

Future Work

We are completing the processing of the entire radar data set, including migration to recover a more accurate geometry of the reflector surfaces, and digitizing reflector horizons for quantitative measurements of total ice thickness and changes within englacial stratigraphy. The digitized layers provide a more quantitative comparison of the density-related reflections of the 200 MHz radar with the conductivity-dominated reflections of the 3 MHz radar system. The basal reflections at the subglacial lakes will provide a calibrated reference for the reflectivity analyses.

Mapping the spatial and vertical extent of the dune structures will lead to a better understanding of the temporal longevity of dune-forming conditions. As work continues to understand the wind and accumulation rate processes that govern dune formation, we may be able to recover past climatic conditions in these areas that will enhance our ability to tie together the ice core glaciochemical and climate results.

The basal layer seen in Byrd Glacier and the differences between the northern and southern halves indicate the presence of two distinct regions feeding the main outlet glacier into the Ross Ice Shelf. Constant-midpoint profiles recorded along the traverse should provide details about the dielectric attenuation within the drainage basin and allow comparisons with attenuation measured in West Antarctica [see Jacobel and others, this issue; MacGregor and others, 2007]. Ongoing work to determine the formation history of the prominent basal deformation in the southern half of the drainage will lead to a better understanding of the contribution of ice from Byrd Glacier into the Ross Ice Shelf.

Determination of conditions within recently-drained subglacial lakes is significant for understanding the impact of such lakes on ice flow. We have found that at least two lakes identified by satellite-derived surface topography have little or no water today. Subsequent altimeter evidence of ice surface inflation, indicative of water refilling the subglacial basin, would provide incentive for repeat radar surveys to determine the presence and volume of water. We will attempt to identify other likely sites of subglacial lakes utilizing more quantitative methods (e.g. Oswald and Gogineni, 2008).

Acknowledgments

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