Radar Investigations of Ice Stream Margins: Data Report

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Geophysical measurements of Siple Dome (SDM), the largest inter-ice stream ridge in West Antarctica, were initiated in 1994 to (1) characterize the site for an ice core drilling program and (2) assess the stability of the ridge relevant to the history and evolution of the West Antarctic Ice Sheet (Raymond et al., 1995; Nereson and Raymond, 1995; Nereson et al., 1997, 1998; Fisher et al., 1995; Scambos and Nereson, 1995). Those studies revealed that SDM has been a relative stable divide for the past several thousand years and is presently near steady-state (Nereson et al., 1998). The boundaries of SDM are defined by relict ice stream margins which flowed a few hundred years ago (Gades et al., 2000; Nereson, 2000, B. Smith, pers comm.,). At these margins, the otherwise continuous internal layer structure of the ice is truncated (Jacobel et al., 1996, 2000). Analysis of the bed reflectivity suggested that these relict margins mark a transition from frozen to thawed conditions (Gades et al., 2000). Thermo-mechanical models of ice stream margins predict localized melting at the bed beneath active shear margins (Jacobson and Raymond, 1998). These predictions for potential of localized basal melting could possibly be the cause of local down-warping of the internal layer pattern near the relict margins of Siple Dome.

These studies of SDM motivated interest in the characteristics of other ice stream margins and inter-ice-stream ridges in West Antarctica. To date, images of West Antarctic ice from airborne radar measurements do not reveal details of the internal layer structure beneath other inter-ice-stream ridges and do not give information about the stratigraphy or bed properties at the ice-ridge/shear-margin interface.

In 1998, we used a surface-based radar system to make measurements of the geometry of the bed, surface, and internal layers as well as bed reflectivity across two other ice stream margins and across two other inter-ice-stream ridges. Our first site was near the margin of Ice Stream E on Ridge DE, the second site was near the margin of Ice Stream B on Ridge BC. At each site, we made a profile of densely spaced radar measurements across the shear margin in several places. In addition, we made measurements across the divide of Ridge DE and Ridge BC to examine their history over the last few thousand years. Survey poles were also placed in the ice along the cross-ridge profiles and measured with GPS survey techniques.

Our measurements were carried out in collaboration with colleagues at The Ohio State University (OSU). Our radar profiles across the shear margins coincide with lines of survey poles the OSU group placed in the ice and measured with GPS survey techniques.

In this report, we present our radar data from each site and highlight some immediate scientific implications of these data and areas we are pursuing further analysis.

## 2 Data Collection and Analysis

All radar data presented here were collected using 2 MHz antennae (wavelength = 80 m in ice). Records were collected every 5 meters for profiles across the ice stream shear margins and about every 20 meters for profiles on the inter-ice-stream ridges. Because the airwave signal swamps the first $1\mu$s of the record, the first step in data processing is to remove the mean waveform from the profile in an effort to remove the airwave effect and reveal shallow layer information in the first micro-second. The data are then run through a 4th-order Butterworth bandpass filter at 2 to 10
MHz. The amplitude of each sample is mapped to a color for display. Travel time is converted to depth accounting for antennae geometry and using $170 \text{m/s}^{-1}$ as the velocity of electro-magnetic waves in ice. The relative surface elevation is interpolated between GPS measurements using barometric altimetry from a pressure transducer record. Since the GPS data have not yet been fully processed, absolute error in vertical elevation could be as large as 50 meters, and the displayed elevation scales for the radar profiles should be considered approximate.

3 Site 1: Ridge DE

3.1 Ice Stream E Margin Profiles

Figure 1 shows a LANDSAT satellite image of Ridge DE and Ice Streams D and E. Radar profiles measured in this area are denoted by the white lines, and endpoint coordinates are given in Table 1. Three profiles were made perpendicular to the Ice Stream E margin, each about 6 km long and separated by 8 km. Two of the profiles, EMAR-C (Fig. 3) and EMAR-W (Fig. 4), originate on Ridge DE, cross the shear margin, and continue for about one kilometer onto Ice Stream E. These profiles show that the ice thickness is about 800 meters on the ridge and increases to about 1200 meters in the ice stream. The onset of surface crevasses in the shear margin is associated with the edge of a bedrock trough. The internal layers are continuous on the ridge-side of the profile and visible to the bedrock. These layers penetrate about 1 km into the shear margin before becoming substantially disturbed. Since the layers generally conform to the bed topography and do not intersect the bed, there is no obvious evidence for concentrated melting at the bed beneath the shear margin at these locations. The complicated nature of layer deformation as the layers become sheared is an area for further study.

The eastern profile, EMAR-E (Fig. 2), originates on Ridge DE and ends just prior to the shear margin of Ice Stream E. Here, the bedrock trough is outside the shear margin. This trough corresponds to a surface expression that is evident on satellite images of the area (Fig. 1). The internal layers are continuous throughout the profile and appear to follow the contour of the bedrock trough. Because the layers are continuous into the trough, the shear margin has not coincided with the bedrock trough at this upstream location for at least several hundred years.

In all profiles, the character of the bed is dominated by the presence of the bedrock trough. Although the reflectivity of the bed appears higher over the dome-ward side of the profile, this may be solely due to reduced geometric spreading of the signal in thinner ice.

3.2 Margin-Parallel Profiles

We collected two profiles parallel to the Ice Stream E margin. The southern profile (EPARA-S, Fig. 5) is about 2 km from the Ice Stream E margin, while the northern profile (EPARA-N, Fig. 6) is about 1 km from the Ice Stream E margin. Both profiles originate down stream and terminate upstream. These profiles intersect the cross-margin profiles and show that the character of the ice and bed is relatively homogeneous along the length of the 18-km study area. The two profiles lie on either side of the linear surface feature that is associated with the bedrock trough in EMAR-Eprofile. The EPARA-N profile (Fig. 6) shows a bedrock drop-off as the profile approaches this
surface feature. We interpret this drop-off as evidence that the trough-edge in all the cross-margin profiles is the same geologic feature. The ice stream appears to follow this trough-edge in some places, but not others. Why this is so is a question for further study.

3.3 Ridge DE Profiles

We measured two cross-dome profiles, spaced about 8 km apart. Both profiles (RDE-E, Fig. 7 and RDE-W, Fig. 8) show continuous internal layers to bedrock. Ice thickness at the divide is $1042 \pm 5$ m at the RDE-E site and $1021 \pm 5$ m at the RDE-W site. The internal layers are slightly warped upward beneath the present divide at both sites. This feature suggests general stability of Ridge DE divide position. We are in the process of quantifying this stability. The internal layers are also asymmetric about the divide, with layers appearing shallower on the southern side of the ridge. A similar asymmetry that is present in the internal layer pattern at Siple Dome has been interpreted as a signal of non-uniform accumulation distribution. We expect the asymmetry on Ridge DE to be of the same origin and work is in progress to quantify the accumulation pattern from these layer shapes.

4 Site 2: Ridge BC

4.1 Ice Stream B Profiles

Figure 9 is an AVHRR image of Ridge BC showing locations of radar measurements. Endpoint coordinates are given in Table 1. The three profiles perpendicular to the Ice Stream B margin, BMAR-E, BMAR-C and BMAR-W (Figs. 10, 11, and 12), are spaced about 8 km apart. Each profile begins in the chaotic zone of the ice stream margin and extends a few kilometers onto Ridge BC. These profiles show that the Ice Stream B margin at this location is not associated with significant bed topography or significant changes in bed reflectivity.

In all cases, the internal layers are continuous several kilometers into the shear margin and the pattern of deformation of the internal layers is generally different at each site with strong synclines present in some profiles and strong anticlines in others. One common feature is a slight broad dip in the internal layers near the onset of the crevasse zone. This dip may indicate local basal melting at the ice stream margin, but since the layers do not clearly intersect the bed, this conclusion is not obvious and requires further study.

4.2 Margin-Parallel Profiles

The profiles named BPARA-N and BPARA-S shown in Figures 13 and 14 originate upstream and run 18 km downstream parallel to the Ice Stream B margin. These profiles show that the bedrock along this length is flat and homogeneous. The internal layers are deformed in a way not obviously associated with the bed topography. Possibly, the undulations in the layer pattern are caused by flow over bed topography in the along-flow direction as the ice flows from Ridge BC to the ice stream (approximately perpendicular to these profiles).
4.3 Ridge BC Profiles

The profiles that cross the Ridge BC divide (Figs. 15 and 16) show that Ridge BC is about 1000 meters thick with internal layers that are continuous over the entire profile and visible to the bedrock. Ice thickness at the divide is $979 \pm 5$ m and $941 \pm 5$ m for the RBC-E and RBC-W profiles, respectively. Unlike Siple Dome and Ridge DE, there does not appear to be an up-warping in the internal layer pattern beneath the divide in either profile. This suggests that the Ridge BC divide position is unstable at both locations. The internal layer pattern across the divide is only slightly asymmetric, suggesting a more uniform accumulation distribution across the divide than at Siple Dome or Ridge DE.

4.4 The Eye Profiles

A prominent feature on the satellite image of Ridge BC is a “dimple” or “eye-shaped” feature just south of the summit. The radar profile over this feature (Fig. 17) shows that it is associated with a steep, rough, bedrock pinnacle that is 400 meters high and 3 km wide. The internal layers are deformed as the ice flows over and around this pinnacle to form a train of 2 “waves” downstream of the feature. A profile crossing on the flank of the pinnacle, about 1 km to the east of the main EYE profile (Fig. 18), shows a reduced pinnacle height and a down stream wave pattern that is much more subdued. Research is in progress to determine whether the localized “wave” layer pattern associated with this pinnacle would be expected under steady flow conditions. The smooth character of the bedrock on either side of the rough pinnacle suggests that the pinnacle is geologically different (perhaps crystalline) from the surrounding rock which is likely marine sedimentary in origin.

5 Discussion

5.1 Ice Stream Margins

Ice Stream E appears to follow the sharp edge of a bedrock trough in its down-stream reaches. Upstream, the ice stream diverges from this bedrock feature. The internal layers across the Ice Stream E penetrate 1 km into the shear margin before becoming discontinuous. There is no obvious evidence for major changes in bed reflectivity or transition from frozen to thawed conditions across the shear margin. Interpretation of bed characteristics is complicated by the presence of the bedrock trough.

The Ice Stream B margin is not associated with any obvious change in bed topography or characteristics. In this location, the transition from frozen to thawed bed conditions is not obvious, although the broad trough in the internal layer pattern at the shear margin edge may be indicative of some local melting at the bed. The internal layers penetrate beneath the surfaces crevasses a few km into the Ice Stream B shear margin. It is not clear whether these layers are continuous across the entire shear margin, since our measurements did not cross the full width of the shear margin. However, we believe that we crossed the location of maximum shear-strain rate. Thus, the layers are not easily disrupted by the shear.
5.2 Inter-Ice-Stream Ridges

The shape of internal layers beneath the Ridge DE divide indicate that the divide has been within a few ice thicknesses of its present position for the past several thousand years. This stability suggests limited changes in the configurations of the ice streams which bound Ridge DE in that time. Quantification of the duration of the divide position stability will provide firmer limits on the past activity of Ice Stream D and E.

The internal layer pattern beneath the Ridge BC divide shows no evidence for long-term stability of the divide position. This suggests that changes occurring at the boundaries of Ridge BC may be causing the divide position to fluctuate more than a few ice thicknesses from its present position.

5.3 Ice Flow Around Obstacles

The “eye” feature south of the Ridge BC summit is associated with a bedrock hill 400-meters high and 3 km wide. The internal layers down stream of this feature form “waves”, presumably associated with flow over and around this hill. To date, little research has been done to determine what internal layers should look like after flowing over an obstacle. Therefore, it is unclear whether internal layer pattern is expected under steady flow conditions. This new data set will help guide ice flow modeling of flow over obstructions.

5.4 Regional Characteristics from Internal Layers

These data, together with surface-based radar data from Siple Dome, provide information about internal layer shapes over a large portion of the Siple Coast inter-ice-stream ridges. It may now be possible to trace individual internal layers or packets of layers across the region to estimate regional accumulation rate pattern and/or mark the depth transition to major climate events.

6 Acknowledgements

We thank Maurice Conway for his assistance and company in the field. We are also indebted to John Chin and Anthony Gades for their diligent help and expertise in maintaining and upgrading the radar equipment. This work was funded by NSF grant OPP-9725882. Our radar profiling in the ice stream margins was aided by our collaboration with Ian Whillans and colleagues from OSU.

References


Table 1. End-point coordinates, labels, and length of all radar profiles.

Figure 1. Landsat image of Ridge DE and Ice Streams D and E. Radar profiles are shown by white lines. Inset panel shows close-up view of the main study area near the Ice Stream E margin with each radar profile labeled. Image courtesy P. Vornberger and R. Bindschadler, NASA.

Figure 2. EMAR-E: Eastern profile perpendicular to Ice Stream E margin. Bedrock step corresponds to surface feature apparent in satellite imagery. The profile starts on Ridge DE and terminates just prior to the Ice Stream E shear margin.

Figure 3. EMAR-C: Camp profile perpendicular to Ice Stream E margin. Profile starts on Ridge DE and ends on Ice Stream E. A bedrock step is associated with the beginning of surface crevasses on the ridge-ward side of the shear margin.

Figure 4. EMAR-W: Western profile perpendicular to Ice Stream E margin. Profile starts on Ridge DE and ends on Ice Stream E. A bedrock step is associated with the onset of surface crevasses in the ice stream shear margin. The apparent bright layer at about -450 meters is an instrumentation artifact.

Figure 5. EPARA-S: Northern profile running parallel to Ice Stream E margin, about 2 km ridge-ward of the shear margin. The margin-perpendicular profiles cross this profile at about 0 km 8 km and 15.5 km.

Figure 6. EPARA-N: Northern profile running parallel to Ice Stream E margin, about 1 km ridge-ward of the shear margin. The margin-perpendicular profiles cross this profile at about 0 km, 8 km and 15.5 km. The bedrock step at about 9 km is evidence that the bedrock step, or trough edge, in each of the perpendicular profiles is the same geologic feature.

Figure 7. RDE-E: Profile across Ridge DE, starting near Ice Stream D and ending near Ice Stream E. Apparent bright layer at about -250 meters at the beginning of the profile is an instrumentation artifact.

Figure 8. RDE-W: Profile across Ridge DE divide, 8 km downstream (west) of Figure rdee. Apparent bright layer at -200m is an instrumentation artifact.

Figure 9. AVHRR image of Ridge BC and Ice Streams B and C. Radar profiles are shown by white lines. Inset panel shows close-up view of the main study area near the Ice Stream B margin with each radar profile labeled. Image courtesy T. Scambos, NSIDC.

Figure 10. BMAR-E: Eastern profile perpendicular to Ice Stream B margin. The profile starts in the Ice Stream B shear margin and terminates on Ridge BC. Solid vertical bands are regions where data are missing.

Figure 11. BMAR-C: Camp profile perpendicular to Ice Stream B margin. Profile starts in Ice
Stream B shear margin and ends on Ridge BC. Solid vertical bands are regions where data are missing. Vertical column at 2.5 km is signal from antennas and metal poles near camp.

Figure 12. BMAR-W: Western profile perpendicular to Ice Stream B margin. Profile starts in Ice Stream B shear margin and ends on Ridge BC. The apparent bright layer at about -450 meters is an instrumentation artifact.

Figure 13. BPARA-N: Northern profile running parallel to Ice Stream E margin, about 1.5 km ridge-ward of the shear margin. The margin-perpendicular profiles B-MARC and BMAR-W (Figs. 11 and 12) cross this profile at about 0 km 8 km.

Figure 14. BPARA-S: Southern profile running parallel to Ice Stream E margin, about 0.5 km ridge-ward of the shear margin. The margin-perpendicular profiles B-MARC and BMAR-W (Figs. 11 and 12) cross this profile at about 0 km and 8 km.

Figure 15. RBC-E: Profile across Ridge BC, starting near Ice Stream B (continuation of Fig. 11) and ending over the divide near Ice Stream C (see Fig. 9).

Figure 16. RBC-W: Profile across Ridge BC divide, about 15 km west of the summit (see Fig. 9).

Figure 17. EYE: Profile across “dimple” or “eye” feature south of the summit. Profile begins near Ice Stream B (continuation of BMAR-W, Fig. 12), crosses several surface terraces and the eye feature, and ends about 15 km from the summit. Apparent bright layer at -350m is an instrumentation artifact.

Figure 18. EYE-E: Profile across the eastern side of the “eye” feature south of the summit, 1 km from Fig 17 (see Fig. 9).
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<th>Profile Name</th>
<th>Start Coords</th>
<th>End Coords</th>
<th>Length</th>
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<td>32 km</td>
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<td>Ice Stream B</td>
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<td></td>
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<td>BMAR-E</td>
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<td>83.2667 138.4764</td>
<td>4.5 km</td>
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<td>B7(long) 138.4764</td>
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<tr>
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Table 1: Radar profile labels, endpoint locations, and total length.
Ridge DE Profile Key

EMAR-E = East Margin Profile (5.5km)
EMAR-C = Camp Margin Profile (6.0km)
EMAR-W = West Margin Profile (5.5km)
EPARA-S = South Parallel Profile (18km)
EPARA-N = North Parallel Profile (16km)
RDE-E = East Ridge DE Profile (60km)
RDE-W = West Ridge DE Profile (30km)

Figure 1: Landsat image of Ridge DE and Ice Streams D and E. Radar profiles are shown by white lines. Inset panel shows close-up view of the main study area near the Ice Stream E margin with each radar profile labeled. Image courtesy P. Vornberger and R. Bindschadler, NASA.
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Figure 18: EYE-E: Radar profile over topographic “eye” feature, one kilometer to the east of EYE profile.