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December 2021

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Final report

Approved for public release; distribution is unlimited.

Prepared for National Science Foundation
Alexandria, VA 22314

Under NSF Grants 1246400 and 1245915; NSF Grant T-940

Preface

This work was supported by the National Science Foundation (NSF) under science grants 1246400 and 1245915 to the University of Maine and Dartmouth College, respectively, through the Division of Polar Programs. J. Palais was Program Manager. Also, NSF grant T-940 was provided to the USACE Engineering Research and Development Center-Cold Regions Research and Engineering Laboratory (ERDC-CRREL).

The work was performed by the Engineer Research and Development Center, Cold Regions Research Engineering Laboratory, the University of Maine, and Dartmouth College. At the time of publication of this paper, the Deputy Director for ERDC-CRREL was Mr. David Ringelberg and the Director was Dr. Joseph Corriveau.

This paper was originally published online in *Geophysics* on 23 September 2015.

The Commander of ERDC was COL Teresa A. Schlosser and the Director was Dr. David W. Pittman.

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Ground-penetrating radar profiles of the McMurdo Shear Zone, Antarctica, acquired with an unmanned rover: Interpretation of crevasses, fractures, and folds within firn and marine ice

ABSTRACT

The crevassed firn of the McMurdo shear zone (SZ) within the Ross Ice Shelf may also contain crevasses deep within its meteoric and marine ice, but the surface crevassing prevents ordinary vehicle access to investigate its structure geophysically. We used a lightweight robotic vehicle to tow 200- and 400-MHz ground-penetrating radar antennas simultaneously along 100 parallel transects over a 28 km² grid spanning the SZ width. Transects were generally orthogonal to the ice flow. Total firn and meteoric ice thickness was approximately 160 m. Firn crevasses profiled at 400 MHz were up to 16 m wide, under snow bridges up to 10 m thick, and with strikes near 35°–40° to the transect direction. From the top down, 200-MHz profiles revealed firn diffractions originating to a depth of approximately 40 m, no discernible structure within the meteoric ice, a discontinuous transitional horizon, and at least

20 m of stratified marine ice; 28–31 m of freeboard found more marine ice exists. Based on 10 consecutive transects covering approximately 2.5 km², we preliminarily interpreted the transitional horizon to be a thin saline layer, and marine ice hyperbolic diffractions and reflections to be responses to localized fractures, and crevasses filled with unstratified marine ice, all at strikes from 27° to 50°. We preliminarily interpreted off-nadir, marine ice horizons to be responses to linear and folded faults, similar to some in firn. The coinciding and synchronously folded areas of fractured firn and marine ice suggested that the visibly unstructured meteoric ice beneath our grid was also fractured, but either never crevassed, crevassed and sutured without marine ice inclusions, or that any ice containing crevasses might have eroded before marine ice accretion. We will test these interpretations with analysis of all transects and by extending our grid and increasing our depth ranges.

INTRODUCTION

Shear zones (SZs) in glaciers and ice sheets have velocity gradients that cause tensile stresses, which lead to fractures and crevasses. SZs can be tens of kilometers long and several kilometers wide. They generally occur near margins at which the ice flow is slowed by land (Thomas and Macayeal, 1982; Scambos et al., 2004; Vieli et al., 2007), or by the confluence with, or flow against another ice body. Crevasses are best known in firn (snow more than one year

old) and usually start to close by approximately 30 m depth within the plastic, stronger, and more solid firn (at 820 kg m⁻³; ice is at 917 kg m⁻³), which marks the beginning of the meteoric ice regime. Bottom crevasses and sutured rifts that extend upward into the meteoric ice of an ice shelf may contain weaker marine ice (Rignot and MacAyeal, 1998; Khazendar et al., 2009) leading to shelf disintegration and a progressing inability to slow the flow of grounded ice to the shelf (Rignot et al., 2004; Scambos et al., 2004; Nowbahar et al., 2011; McGrath et al., 2012). Here, we interpret the presence

and some structure of the crevassing, fracturing, and folding within the McMurdo SZ of the Ross Ice Shelf (RIS; Figure 1), Antarctica, from images we obtained with robotically towed ground-penetrating radar (GPR) during the first year of a three-year project. Consequently, some interpretations are preliminary and await more analysis and extension of our data set.

The SZ is a 5–6-km-wide strip of crevassed firm riding on ice that originated from Mulock and Skelton Glaciers and now flows south to north. Figure 1 suggests that visible surface crevassing begins south and east of the volcanic ridge Minna Bluff, possibly over a submerged extension. Further north, these rifts suture and rotate as they flow into McMurdo Sound (Figure 2). The SZ extends to the northern end of Ross Island. Accreted marine ice at the meteoric base was first detected in 60-MHz airborne radio-echo soundings (Neal, 1979), but the thickness could not be interpreted. Moholdt et al. (2014) report weak melting and refreezing patterns near the noise level of NASA's Ice, Cloud, and land Elevation Satellite (ICESat) observations throughout RIS. No cores have been obtained by anyone in this area. Only 6 m of marine ice have been found 800 km to the southeast (Zotikov et al., 1980; Zotikov and Jacobs, 1985), with a platelet structure similar to sea ice and to marine ice cored beneath the Amery Ice Shelf (Craven et al., 2009), but different (without platelets; Oerter et al., 1992) than beneath the Filchner-Ronne Ice Shelf (FRIS).

Any bottom crevassing at the Mulock-Skelton grounding lines and rifts from passage by Minna Bluff are likely to have filled completely or partially with marine ice (as in the FRIS; Rignot and MacAyeal, 1998). In the former case, bottom erosion (Depoorter et al., 2013) may have occurred before the ice was thin enough to allow basal accretion of marine ice. Given that the ability of GPR to image upward-penetrating bottom crevasses (Jezek et al., 1979; Jezek and Bentley, 1983; MacGregor et al., 2012; McGrath et al., 2012; Vaughan et al., 2012; Jacobel et al., 2014) is mainly possible because of the presence of marine ice we hypothesized that evidence of deep crevassing and any associated real or apparent folding beneath our study area (Figure 2) will be detectable with GPR. Our

Figure 1. A 1997 RADARSAT1 image of the SZ and its context. The SZ is the bright vertical strip, west of which is the McMIS. The SZ defines a local western boundary of the RIS and is fed by extensions of Mulock and Skelton Glaciers (inset). The bright returns indicate near-surface roughness. The dashed line approximately separates the merged Mulock-Skelton flow from the Byrd flow.

objective then, was to image the firm, meteoric, and marine regimes over a region of the SZ to gather spatial dimensions of any features. However, we needed to deal with hidden crevasses; aircraft (Delaney and Arcone, 1995; Kanagaratnam et al., 2004) were not an option because of poor grid control and compromised resolution caused by speed and altitude.

Although open crevasses have never been observed within our study area during flights across the SZ, snow bridges can be as thin as 0.3 m (Delaney et al., 1995; Arcone et al., 1996). Based on our polar experience with robotics (Ray et al., 2004, 2005, 2007; Lever et al., 2006a, 2006b, 2013; Lever and Ray, 2008), success with robot-towed GPR (Koh et al., 2010) just off the SZ safe-crossing road, and in imaging the firm and meteoric ice shelf thickness where the SZ transitions to the McMurdo Ice Shelf (McMIS; Arcone and Laatsch, 2004), we used low-ground-pressure, robotically towed GPR to survey a gridded, 28 km² area. We guided our battery-powered robot (named *Yeti*; Lever et al., 2013) by programmed global positioning system (GPS) coordinates along 100 evenly spaced transects; here, we present results taken from 10 consecutive ones over 2.5 km², and from five spaced south to north over most of the grid. We operated two GPR antenna units simultaneously, with one at 200-MHz pulse-bandwidth center frequency to profile deeper than the SZ firm and meteoric ice thickness, and the other at 400-MHz to provide higher resolution of the firm to approximately

Figure 2. A 1994 SPOT satellite image of the SZ environment with superimposed velocity contours (in m a⁻¹) and arrows indicating flow direction (after Whillans and Merry, 2001). The box approximately locates our survey area, which lies on the SZ. The sutured rifts from Minna Bluff have been rotated and pushed into McMurdo Sound, where they indicate gentle buckling, not crevasses. These rifts may extend within our survey. “Linda” approximately locates a tractor lost in 1991 and moved 10–12 km × 2015.

19 m depth. GPS data were automatically recorded along each profile.

Crevasse in the firm has long been imaged with 400-MHz GPR (Delaney and Arcone, 1995; Arcone et al., 1996; Arcone and Delaney, 2000) to approximately 20 m in depth. In meteoric ice near grounding lines, Jezek et al. (1979) and Jezek and Bentley (1983) used 100 MHz GPR to image 100 m of vertical penetration by bottom crevasses, Vaughan et al. (2012) and McGrath et al. (2012) used less than 10 MHz to image 300 m penetration, and MacGregor et al. (2012) and Jacobel et al. (2014) imaged basal crevasses at 3 MHz. Beneath the FRIS, Blindow (1994) used 40 MHz to penetrate 85 m of stratified marine ice below 150 m of meteoric firm and ice. A borehole (Oerter et al., 1992) revealed a transitional saline layer approximately 1 m thick, and 400 m of stratified marine ice. The layer was far less saline than fresh sea ice, lacked its characteristic brine pocket structure, and, along with the marine ice, was interpreted to have the same relative dielectric permittivity ϵ_r as meteoric ice. Those profiles, others obtained with airborne 35–60 MHz radar (Lambrecht et al., 2007), and 50-MHz profiles beneath the Larsen Ice Shelf (Luckman et al., 2012; Jansen et al., 2013) failed to find the marine ice bottom. The cause was surmised to be a slushy, undefined interface. Here, at 200 MHz, we also found no evidence of the bottom, but we did obtain much greater detail, which allows some structural interpretation of the meteoric-marine interface.

STUDY SITE

The SZ within our study area is approximately 5.7 km wide. Ice flow is almost due north (Figure 2). Meteoric firm and ice thickness is approximately 145 m on the west side (Arcone and Laatsch, 2004). Absolute velocities estimated from satellite imagery (Figure 2) and precisely measured along the safe-crossing road (J. Scanniello, personal communication, 2012) found up to a 300 m a^{-1} speed differential across the SZ. We have determined that stations grid area west (GAW) and home free south (HF-S) (Figure 3) have

moved at average speeds of 256 and 406 m a^{-1} , respectively, since 2002; the contours in Figure 2 suggest approximately 300 and 500 m a^{-1} .

Crevasse strikes in the SZ firm should be linear at 45° to the flow direction across local linear velocity gradients, but they can be warped because of variable gradients, likely caused by added compression against Minna Bluff, White Island, and the McMIS (Figures 2 and 3). The airborne radar images in Figure 3 suggest strikes range from approximately 20° to 50° relative to the direction orthogonal to flow, which appears to be directly east–west. Maximum lengths within the more chaotic area appear to be less than 500 m. Some areas have a wider range of strikes; some are curvilinear. Consistently, opened crevasses (by dynamite; Figure 4) revealed vertical, sheared, curvilinear layers; steeply dipping strata; sagging; and broken snow bridges. We have also seen tunnels within crevasse walls. These features show that as the ice moves northward crevasses open, close, warp, and rotate.

The most intensive firm crevasse (Delaney and Arcone, 1995; Arcone and Delaney, 2000; Koh et al., 2010) is along an east–west stretch of approximately 3 km. Construction of the safe-crossing road in 2002–2003 remediated 26 crevasses, detected with a 400-MHz GPR antenna unit mounted on a boom in front of a tracked vehicle (Figure 5; Delaney et al., 2004; Wright, 2006). Remediation included imploding sections of snow bridges and filling the voids; the largest is in Figure 4a. The road has been annually surveyed and maintained (Lever and Thur, 2014) and provided our access.

Figure 6 shows our grid and the position of the safe-crossing road by November 2014. Prior to the main survey, we conducted several Yeti GPR surveys along the western boundary, which ensured that it was crevasse free. The grid is $5.7 \times 5.0 \text{ km}$ comprising 100 east–west transects spaced 50 m apart and numbered 130–176. Transect 177 runs south–north along the west border. Each pair of 200- and 400-MHz profiles included a west–east segment (e.g., transect 160A) followed by an east–west segment 50 m farther south (e.g., transect 160B). We display all grid profiles from east to west,

Figure 3. Detail of a 2011 10-GHz airborne synthetic aperture radar survey at 0.3-m pixel resolution (updated; after Bickel and Sander, 2010). The system is known as the New York Air National Guard/Sandia National Laboratories crevasse detection radar. GAW and HF-S are the 2002 positions of the monumented end points of the safe-crossing road. The ice flow is almost due north. The image shows lineation from crevasses, the strikes of which range from approximately 20° to 50° with a likely mean near 45° ; a few are labeled. The arrows in the inset enlargement of the area within the dashed box point at curved (or warped) lineations, which also occur at the lower left. The north–south dark streaks are large-scale folds caused by the push of the RIS toward McMurdo Sound. The diagonal texture is artificial.

and we discuss only a sample in detail. We installed a strain network of 29 stations covering a 10×10 km region to measure surface elevation, velocity, and strain rate. Seven are within our grid, which we accessed by helicopter. We repeated the survey during a 14-day period in October and November 2014. Future surveys will provide smaller uncertainties.

METHODS

Robotics

We deployed the four-wheel-drive, battery-powered rover Yeti (Figure 5; Lever et al., 2013) from October to November 2014. Yeti weighed 77 kg, and the GPR sled weighed 68 kg. We surveyed the main grid in seven days of continuous 24-h operation. We changed batteries and saved files after each out-and-back run (two transects within 2.2 h). Battery capacity was approximately 1200 W-h for six batteries, which provided ample reserve beyond the 740 W-h average consumed for each run. We changed radar control unit batteries every 12 h, or after 5–6 runs. We operated a PistenBully (Figure 5) tracked vehicle along the western boundary of the grid to service the rover and GPR.

Yeti reliably followed GPS waypoints. Typically 18–22 satellites were in view, and the position accuracy (horizontal dilution of precision) was 0.6–0.7 m. Yeti normally deviated only 1–2 m from a straight line between transect end waypoints, with infrequent excursions of 3–5 m from undetermined causes. Although GPS coordinates were constantly recorded, the constant speed (average 1.52 ms^{-1}) and precise GPS measurement of transect lengths al-

lowed simple correlation between the profile trace number and distance. The GPS data showed surface undulations of 2–3 m at approximately 1 km wavelengths. The nearly flat surface (Figure 5) precluded profile elevation corrections.

We used a directional Yagi antenna on a mast approximately 7 m high and maintained communication to the eastern boundary of the grid during each run. Yeti experienced several minute-long radio drop-outs during each run, also of undetermined cause. These drop-outs also occurred after mounting the antenna 2 m higher on the PistenBully. Except for two operator-induced interruptions, Yeti always returned to the western boundary on schedule.

Ground-penetrating radar

We used a Geophysical Survey Systems SIR30 32-bit two-channel control unit and model 5103 400-MHz and model 5106A 200-MHz antenna units. Antenna impedance loading by the snow was minimal, and so the dominant frequencies within the radiated pulse spectra were close to 200 and 400 MHz. Transmitted pulse waveforms for both units are mainly 1.5 cycles with a $- + -$ polarity sequence for the sequential half-cycles (Figure 5). This sequence also occurs for a reflection from an interface between a relatively higher ϵ_r medium (e.g., water) above a relatively lower ϵ_r one (e.g., ice), and from an isolated, electrically thin (less than 0.3 wavelengths) layer with ϵ_r lower than that of the surrounding material. The opposite cases reverse the sequence. Pulse lengths in firm at approximately a 40-m depth ($\epsilon_r = 2.4$) at 400 MHz and in ice ($\epsilon_r = 3.2$) at 200 MHz are approximately 0.72 and 1.26 m, respectively, which translate to interface resolutions of 0.36 and 0.63 m, respectively.

Figure 4. Photographs we have taken within crevasses along the safety road. (a) Largest crevasse remediated during the 2002–2003 safety road construction. The person is 2 m tall. The crevasse and snow bridge were at least 12 m wide and 8 m thick, respectively. (b) Crevasse wall containing steeply dipping strata, likely from a previous snow bridge within a crevasse that has rotated nearly 90° . The vertical termination is labeled “Bow.” (c) Snow bridge sagging between irregular crevasse walls. (d) Sheared and warped firm layers. (e) Arched walls resulting from the weight of the sagging snow bridge, which has lost a lower layer. The inset shows a simple slot crevasse with snow bridge that is partially caved and broken.

Antenna polarization was perpendicular to transect directions. The $\epsilon_r = 1.8$ for near-surface firm provides a wide, two-way 3-dB beamwidth that narrows to 45° in the electric field plane (parallel to the antennas) and to 92° in the magnetic field plane (along transect and perpendicular to the antennas) in ice ($\epsilon_r = 3.18$) for surface antennas. These wide widths give only approximately 10 dB of round-trip gain in the normal direction (Arcone, 1995) and provided strong sensitivity to out-of-plane reflections and diffractions, which allowed us to interpret crevasse orientations.

We recorded 20 traces s^{-1} at time ranges of 200 ns at 400 MHz and 2200 ns at 200 MHz. We recorded 4096 32-bit samples/trace with time-variable gain that approximately compensated spherical beam spreading loss; interfacial refraction and transmission losses made exact compensation impossible. We determined the time zero by accounting for antenna separation (0.16 m for the 400-MHz unit and 0.33 m for the 200 MHz unit). We used the echo transit time formula $d = ct/2n$, where $n = \epsilon_r$ is the real part of the refractive index, and $c = 0.3 \text{ m ns}^{-1}$ to transform round-trip transit time t (ns) into thickness (m). We used $\epsilon_r = 2.17$ for an average, single-layer equivalent firm depth calibration over the top 19 m. This value is predicted by an effective density of 0.56 kg m^{-3} , consistent with density profiles obtained on the nearby McMIS (Kovacs et al., 1982).

We estimate the near-surface error in our depth profiles to be no worse than 9% because $\epsilon_r = 1.8$ in the top meter (density = 0.4 kg m^{-3}). We used $\epsilon_r = 3.0$ for the full thickness calibration at 200 MHz, considering an average of 2.5 for the top 40 m and 3.18 for the lower 120–136 m. This value gives the depths to the base of the meteoric ice and an error of only 3% in measuring the thickness of any bottom layer or horizon separation. Robot positional accuracy was generally consistent with diffraction hyperbolas that originated at or near the bottom of most of our firm crevasse profiles because by modeling, they mostly provided $\epsilon_r = 2.17$. These are the narrowest of the major diffractions; wider ones are hyperbolic reflections from features oblique to the transects. The matching error in the velocity that produces ϵ_r is 4% (e.g., hyperbolas generated by $\epsilon_r = 2.17$ and 2.34 can be distinguished). We estimate an error of ± 5 ns in picking any 200 MHz event and ± 1 ns for any 400 MHz event. Timing errors of 2 and 5 ns in determining the total depth of firm and ice, respectively, translate to depth errors of approximately 0.2 m in firm 19 m thick (a 187 ns delay) and 0.4 m in ice 160 m thick (an 1848 ns round-trip delay).

We display profiles in either a grayscale format with an exponential proportion between

intensity and signal strength to give weaker signals greater amplification and to discern signal phase, or in a linear color or grayscale format to emphasize stronger signals, and so represent the crevasses

Figure 5. (a) Yeti robot towing 400- and 200-MHz antenna control units. Inset, transmitted pulse waveform for either antenna unit, with its phase polarity sequence $(- + -)$ and corresponding band colors within a grayscale format. The large vehicle is a Pisten-Bully with a boom used to hold the 400-MHz antenna unit for operational advance crevasse detection. Mt. Erebus is in the background. (b) Yeti during profiling showing tracks after a transect. Note the lack of sastrugi.

Figure 6. (a) Survey grid superimposed on the 2011 synthetic aperture radar image of the SZ. (b) Our grid with crossing roads and definition of the crevasse strike angle θ . Grid spacing is 50 m. The angle θ defines crevasse strike relative to our east–west transect direction. Numbers 130–170 and 177 (right side of the grid) refer to transects.

as true voids and not unstratified ice. In the exponential format, black bands represent negative-amplitude half-cycles and white bands represent positive. We discern the phase polarity sequence from traces, rather than profiles because the profile gain often saturates strengths of minor half-cycles. The linear format shows only signal strength. We used a broadband finite-impulse response filter to alleviate high-frequency noise and low-frequency modulation,

Figure 7. Plan view diagram of the antenna unit on the SZ, with coordinates and strike angle θ , of crevasses or fractures used to compute model hyperbolic diffractions ($\theta = 90^\circ$) and reflections ($\theta < 90^\circ$) originating at depth z_0 . A point inhomogeneity at any direction produces the same response as for 90° for a given R .

and stacked deeper profiles threefold or more to improve imaging and to include context with important features.

We used single-layer Kirchhoff migration to collapse and find the origin of diffractions, to image crevasse voids, and to resolve crevasse orientation. Figure 7 shows our coordinates for modeling crevasse reflections and diffractions, and the simple formula for the range R , between a feature strike at depth (e.g., the bottom of snow bridge) and an antenna moving along the east–west axis. The time delay is $t = 2Rn/c$. We measured the crevasse strike angle θ , from the east–west direction of transects. If $\theta = 90^\circ$, then the hyperbolic response is the same as that from a point scatterer. If $\theta < 90^\circ$, then reflections from the normal direction to the fracture produce a hyperbolic reflection horizon. Hyperbolas widen as θ approaches 0° .

RESULTS AND INTERPRETATIONS

Overview

Figure 8 gives a 200-MHz profile general representation of the SZ beneath our grid. The upper 20–30 m contains bright diffractions from crevasses and fractures. Their apexes generally occur to approximately 40 m depth, below which their asymptotes are predicted by a reasonable value of $\epsilon_r = 2.5$ for the overlying firm, and so they originated beneath the antennas. Rare apexes appear at 63 m range, but these may be off-nadir returns. We interpret the bright horizons to be responses from a saline layer frozen to the base of

Figure 8. A 33-fold stacked profile of transect 170A showing the general location of crevassing and of bottom profiles of following transects spaced at 1 km increments. The firm and bottom disturbances occur along the same sections of all profiles. The insets at the left show a section of the saline layer horizons along transect 140A and the reflected pulse waveforms at 0.70 km. The saline-layer thickness is approximately 70 cm and both of its waveforms have the + – + polarity sequence characteristic of a higher permittivity or conductivity medium beneath one of lower values. The high signal-to-noise ratio of the waveforms was enhanced by the stacking.

the meteoric ice, as seen beneath the FRIS (Oerter et al., 1992), and up to 70 cm thick (Figure 8, inset). The meteoric firm and ice thickness throughout the grid varies from 155 to 168 m; it is 157–162 m from 2.5–2.7 km across the monocline in transect 170A. Stratified marine ice appears below the saline layer. As discussed earlier, this ice may or may not be structurally similar to sea ice, but likely has $\epsilon_r = 3.2$. Freeboard at seven GPS grid stations ranged from 28.4 to 31.2 m. Given this range, 40 m of firm at an average density of 0.700 kg m^{-3} , marine and meteoric ice at 917 kg m^{-3} , 157 m of meteoric firm and ice, and seawater density of 1027 kg m^{-3} , we estimate the minimum shelf thickness at 186.2 m, and marine ice thicknesses of 29.2–55.4 m.

The monocline in the meteoric ice horizons precedes the onset of firm crevassing and most disturbances within the saline layer, including discontinuities, diffractions, and dipping reflection horizons. There is insignificant evidence of any disturbance immediately above the saline horizons or throughout the meteoric ice, even when examined in more detail.

Firm: 400-MHz

Figure 9 shows profiles in two display formats of two slot-type crevasses along transect 160A. The grayscale format reveals numerous relatively weaker diffractions that originate at discontinuities beneath the snow bridge and then at deepening density discontinuities that intersect the crevasse walls. Relatively weaker diffraction asymptotes overlap the void, which interrupts the re-

flection horizons. The color-scale versions simplify the crevasse image because they do not show the overlapping diffractions. The deeper diffractions correspond with $\epsilon_r = 2.17$, which strongly indicates that they originated from point scatterers beneath the transect.

Figure 10a and 10b shows profiles from transect 130A containing a wide hyperbolic reflection from which secondary diffractions originate. The migration in Figure 10c used $\epsilon_r = 2.34$ and $\theta = 90^\circ$ to reveal a crevasse with a maximum width of approximately 16 m and a snow bridge approximately 10 m thick. The 200 MHz version (Figure 10b) better reveals the stratigraphy, on which the crevasse signature is superimposed, and diffraction apexes to approximately 35 m depth, which may originate near the bottom of the crevasse. Figure 10d shows an outline of this horizon and two theoretical horizons for crevasse strikes of 35° and 40° , between which the strike must lie. Consequently, the diffractions in Figure 10a originate along the strike of the snow bridge.

Figure 10e shows a 22-fold stack of a 1400 m section from transect 157A, also processed with automatic gain to approximately equalize maximum amplitudes. The dark areas are where stacking obliterated voids and associated steeply dipping strata. The internal layering is gently folded with wavelengths varying from approximately 300–700 m. Crevasses or associated steeply dipping horizons appear at anticlines centered near 2300, 2700, and possibly 3150 and 3350 m. Apparent crevasses at 2300 m appear unrealistically 40 m wide; hence, the width is partly caused by the suppression of steep horizons.

Figure 9. 400-MHz profiles of simple crevasses centered at (a and b) 4.117 and (c and d) 2.777 km along transect 160A, in exponential, gray line-intensity and linear, color line-intensity formats, the latter of which does not show the weaker hyperbolic asymptotes, and so reveals a better picture of the crevasse. The crevasse in panels (a) and (b) has a maximum width of approximately 2 m, and a snow bridge 2 m thick. The one in panels (c) and (d) is approximately 1 m wide, and has a 1-m-thick snow bridge. If these were crossed at 45° to their strike, then the widths are approximately 1.4 and 0.7 m.

Figure 10. (a) A 400-MHz profile of a deep crevasse along transect 130A, (b) 200-MHz profile of the same crevasse, (c) migration of panel (a) for $\epsilon_r = 2.34$ and $\theta = 90^\circ$ (best collapses diffractions along the wide hyperbola), (d) same as panel (c) but with a hand-drawn outline of the hyperbolic reflection (dashed blue line) and theoretical matching curves (pink lines) for two crevasse strikes at the labeled angles, and (e) 22-stack version showing the context of folded strata and crevasses from 2000 to 3400 m. In panels (a) and (b), strata are visible beneath the wide hyperbolic reflection horizon. Close examination of panel (b) shows the diffractions along this horizon and deep diffractions (arrow). The arrow in panel (e) indicates the crevasse in the other panels.

Figure 11. Marine ice sections from transects (a) 160B and (b) 160A 50 m north. Labeled events are: the saline layer ("sl"); visibly closed or nearly closed crevasse or fracture ("cc"); open crevasses ("oc"); and stratified marine ice ("sm"). Angles less than 90° next to the modeled hyperbolic asymptotes refer to the strike that produced these matching hyperbolic reflections. Numbers on the diagonal dashed lines refer to the calculated crevasse strike angle considering the 50 m offset between profiles. The 90° diffractions indicate point diffractors because the crevasse strikes were not orthogonal to the transect. The arrows indicate diffraction asymptotes steeper than predicted for $\epsilon_r = 3.2$. The series of cc events in panel (b) appear to progressively close from west to east.

Marine ice: 200-MHz

Figures 11–13 show disturbed sections of the marine ice. The time range allowed 28 m of its thickness to be recorded. The main features are the reflection horizons from the saline layer and the stratification below, discontinuities in the saline horizon, hyperbolic reflections and diffractions, and linear to curvilinear reflection horizons that falsely appear embedded within the marine ice. Strata deeper than approximately 11 m (west end, Figure 13b) are not visible in these sections.

Figures 11 and 12 show side-by-side sections from transects 160A and 160B. For several reasons, our preliminary interpretation is that the hyperbolic signatures are diffractions and reflections from fractures or local crevasses (i.e., locally opened fractures) within the marine ice. First, their apexes coincide with the saline layer; disturbances rarely extend a few meters up into the meteoric ice. Some apexes are associated with steep diffraction asymptotes (e.g., indicated by arrows) that can be modeled only by assuming a false ϵ_r much greater than for ice. These asymptotes are parts of multiple diffractions originating in the saline layer; multiples always dip more steeply than the primary event. Second, this region of disturbance coincides with that of firm crevassing. Third, those we label as open crevasses, “oc,” show two progressions of diffractions with

depth, which we interpret to have originated from discontinuities along the opposing walls, as seen in Figure 9 for the firm crevasses. The clearest examples are at 2.85 km in Figure 11b, at 3.23 km in Figure 12a, and at 3.27 km in Figure 12b. Their generation required crevasses filled with unstratified marine ice to create the discontinuities and which appear as voids. We interpret hyperbolic events labeled as closed (labeled “cc”) or nearly closed crevasses (labeled “oc”), to be fractures or terminations of crevasses; it is unlikely that they ever sutured after being filled with water that later froze. In these cases, the wall diffractions merge to form broad apexes (e.g., 2.92 km in Figure 11a, 2.94 km in Figure 11b, 3.15 km in Figure 12a, and 3.26 km in Figure 12b); those closer than 14 m in the 90° case would not clearly separate. Those in Figure 11b appear to progressively narrow eastward.

A fourth reason is based on the broader hyperbolic reflections, which also occur in firm (Figure 10). In Figures 11–13, we matched five with model full or half-hyperbolas to find the strike angles θ , assumed to be along crevasse edges. Those for $\theta = 90^\circ$ are from point sources. For the three cases in Figure 11, the formula in Figure 7 gives $\theta = 35.0^\circ$, and 45.6° and 45° for cases in Figures 12b and 13a, respectively, all of which are reasonable given alignments in the firm.

A fifth reason is based on the apparently deepening reflection horizons in Figures 12 and 13b (events “oi”), which we interpret

Figure 12. Marine ice sections from transects (a) 160B and (b) 160A farther west than those in Figure 11. Labeled events along the saline layer are the same as in Figure 11. Horizons “oi” are from vertically offset, off-nadir interfaces, with visible and apparently conformable layering below them; horizons “oif” are faulted sections. Numbers next to the modeled hyperbolic asymptotes refer to the strike angle that produced these matching hyperbolic diffractions (at 90°) or reflections (less than 90°). Numbers on the diagonal dashed lines refer to the crevasse strike angle interpreted from the offset between profiles. Beneath label “oc” in panel (b) are diffractions whose deepening apexes originate from sidewall interface terminations and faint diffractions that originate at the surface (at 3.27 km), but whose asymptotes steepen inward. The left inset shows interpreted offset interface strike within the profile in panel (a), which correlates only qualitatively with any interpretation based on the profile in panel (b). The center inset shows that the waveform polarity of horizon “oi” is the inverse of that of the marine layer. The right inset gives an interpretation of how apparent strata generate below interface “oi.”

to be further evidence for complex fracturing. These horizons also appear faulted (events “oif”) into piecewise linear sections, and folded, as also seen in the firn image in Figure 3. Their opposing directions of apparent deepening in Figure 12 show that they originated from vertically offset, off-nadir interfaces along sides of faulted sections, so that the apparent deepening resulted from increasing off-nadir distance. Consequently, the off-nadir view allowed imaging of the faulting and its curvature. The right inset interprets the horizons in Figure 12a to have been caused by an interface with an east–northeast strike of only 14° from the east–west direction, similar to those in firn in the inset and at the lower left in Figure 3. The polarity of their reflected waveforms (center inset) is inverted from that of the saline layer, which means the returning pulses reflected twice from a corner (Jacobel et al., 2014), consistent with our geometric interpretation. The right inset ray diagram shows how this also caused apparent strata beneath the horizons. Two other similar horizons occur along transect 158B (Figure 13b), one of which is folded. A faint horizon may connect these sections. Neighboring profiles also show curved, off-nadir horizons between transects, but we have yet to find evidence of their continuation across transects.

Figure 14 shows our north–south profile of transect 177, along which there is minimal interference from crevasses. The bottom

strata conform with the saline layer, folds are insignificant, and the stacking reveals faint strata to 20 m depth. The strata are likely caused by variations in ion content (Oerter et al., 1992) and marine inclusions (Zotikov and Jacobs, 1985). The limited penetration is caused by conductive attenuation; loss from Maxwell-Wagner relaxation is unlikely because Blindow (1994) reached 85 m depth in the FRIS marine ice at 40 MHz, which is within the high attenuation bandwidth of this effect (Arcone and Boitnott, 2012).

Firn and marine ice

Figures 15 and 16 show stacked profiles that reveal large-scale firn and marine ice folds along transect 157A (for example). Both regimes are referenced to a horizontal plane, have the same depth scales and show amplitudes of only a few meters in the folds, as does the surface elevation. The firn and marine ice folds do not appear synchronous within the first 2.6 km (Figure 15), where there are few crevasses, first-order fold wavelength is on the order of 1 km, and the large meteoric-marine interfacial syncline is displaced 400 m from a similar firn syncline. However, from 2.6 to 3.8 km (Figure 16), within which stratigraphy is least obliterated by hyperbolic reflections and steep horizons, fold wavelengths are on the order of 0.5 km, and folding in both regimes appears synchronous.

Figure 13. (a) Marine ice sections from farther east along transect 160A, and (b) from the west side of 158B. Events labeled are the same as in Figures 11 and 12. Numbers in panel (a) refer to the strike angle that produced the matching model diffraction (at 90°) and reflection horizon (40°). We interpret the hyperbolic events that originate along the 40° asymptotes to be responses to fractures and discontinuities along strike. The arrow indicates deviation caused by strike curvature. In panel (b), the displaced interface has been folded; the two sections may be part of the same feature.

DISCUSSION

Firn

The crevasse strike orientations determined from hyperbola matching are similar to those in Figure 3. Although we give only one example, many exist. Crevasse positions within transects 158–162 reveal a few isolated linear alignments between 40° and 60° relative to transect direction, and a maximum length of at least 450 m.

In the east–west direction, Figures 10e, 15a, and 16a show large-scale, first-order folding likely caused by east–west compression against the McMIS. This is also evidenced by the vertical, dark streaks in Figure 3, which indicate elevation changes. In the crevassed sections, steeper, second-order folding caused by ongoing sagging of snow bridges above opening crevasses, and by compression in the along-strike direction (a principal stress axis) between adjacent crevasses, is superimposed. The sagging of snow bridges steepens synclines with depth, which makes them appear like anharmonic compressional folding.

Marine ice

Our preliminary interpretation of the hyperbolic signatures is that they are from crevasses, or more generally, fractures of likely limited extent and which locally widen. They are not likely caused by debris entrained along the bottom of the meteoric ice because melting occurs near the grounding line followed by freeze-on of supercooled water at a distant location, where thinner ice elevates the

freezing temperature (Oerter et al., 1992). Additionally, their hyperbolic reflections from along-strike discontinuities also occur from the firn crevasses. Our preliminary interpretation of displaced sections provides further evidence of complex marine ice fracture.

We used two methods to test the strike angles θ , derived from hyperbola matching. Both assume that crevasses and fractures are aligned southeast to northwest, as shown by the dashed lines in Figures 11 and 12, which connect similar features. First, in Figure 11b, the half-hyperbola labeled at 35° for the crevasse centered at 2840 m predicts that the connected crevasse along transect 160B was detected along transect 160A at a range of $R = 170$ m (Figure 7). At an ice thickness of 157 m, the projected distance of R to the crevasse along the marine ice surface is 65 m. This is the same distance along transect 160A between where the hyperbola intersects 170 m depth (2730 m), and where transect 160A is directly across from the crevasse along transect 160B (2772 m) because the two sides of 42 and 50 m also give 65 m distance.

Second, we measured the angle of the dashed lines given the 50-m transect separation. For the open crevasses, these connections give 27.8° and 32.4° in Figure 11 and 45.6° in Figure 12. The accuracy of these values is approximately $\pm 3^\circ$, given a possible error of 5 m in the distance determinations. Our speculative alignments for the visibly closed (or narrower) numbered crevasses in Figure 12 give 49.3°, 48.7°, and 39.8°. However, these alignments appear limited because they do not extend to diffractions along the neighboring transects (159B and 161A), either because they have terminated or because their strikes may be folded or offset by faulting. For example, the west-side asymptote in Figure 13a deviates from the linear model, which implies strike nonlinearity. Deviations from hyperbolic form also occur near 2.6 and 2.7 km in Figure 11a. Consequently, we use the term *preliminary* to describe these features as crevasse responses because they may not have the linear extent seen in the firn, and therefore, these may represent a complex network of fractures that are locally open.

In the profile direction of Figure 14, the meteoric ice is in extension, as evidenced by its thinning. In contrast, the marine strata appear uniform, which suggests simultaneous, widespread freeze-on. Although episodic and prolonged discharges of supercooled water have been measured elsewhere (Bombosch and Jenkins, 1995; Lefanue and Craven, 2004), as here, the source and causes are unknown. A series of lakes beneath Byrd Glacier are known to discharge (Stearns et al., 2008; van der Veen et al., 2014), but the volume would provide insignificant thickness over such a large area.

Meteoric ice

Although significant basal melting may have eroded and removed any evidence of fracture after the ice left the grounding line and before marine ice accreted (Rignot and Jacobs, 2002; Depoorter et al., 2013), clearly, the Minna Bluff area generated crevassing. Consequently, the absence of visible diffractions within the meteoric ice beneath our grid could be because intruded marine ice or any other means of generating a dielectric contrast within sutured crevasses does not exist, or this meteoric ice never fractured. Reflection horizons below approximately 40 m are also not present; they are absent in the nearby alpine glaciers of the Dry Valleys, possibly caused by uneven ionic deposition (Arcone and Kreutz, 2009). Complex fracturing, rotation from compression, and suturing might also have obliterated ionic stratification inherited from Byrd catchment, which is easily detected at 150 MHz (Gogineni et al., 2014). Although pos-

Figure 14. The 203-fold stacked (a) firn and (b) marine profiles along transect 177. The only crevassing occurs in firn near 1 km and just above the small marine anticline. The arrow indicates the deepest indication of marine ice strata, best viewed edgewise.

sibly stratified, legacy ice from Byrd catchment may be long extended and buried by accumulation during the 150-km flow from the estimated grounding line positions of Mulock and Skelton Glaciers. At an estimated average speed of 650 m a^{-1} (Clausen et al., 1979) approximately 230 years of, at most, 16 cm water equivalent per year, would provide only approximately 40 m of ice equivalent at our site. This would leave approximately 120 m of legacy ice from the catchment, yet within which we find no stratification.

CONCLUSIONS

The wide hyperbolic reflections, deepening wall diffractions, and off-nadir horizons in the marine ice reveal that these features are responses to linear, piecewise linear, and warped crevasses and fractures, similar to those within firn (Figure 3). The marine ice crevassing may be local and strike linearity may last less than 100 m without significant distortion by faulting and folding. The coincidence of this region with that of crevassed firn, and the synchronous folding suggest coeval fracturing of these regions and persistence of the SZ surface velocity profile at depth. Consequently, we temporarily conclude that the meteoric ice must also have coevally frac-

tured, but any evidence beneath our relatively small grid may be too subtle to detect. This absence of visible evidence also suggests that the deep meteoric ice presently beneath our grid was never subject to any significant grounding line crevassing, the features we imaged formed downflow from any glacial grounding line and sufficiently east of Minna Bluff to avoid ground contact, and that the Minna Bluff suture contours in Figure 2 may not extend beneath our grid.

We will test these preliminary interpretations by extending our grid 5 km south to provide greater coverage of firn and marine ice features and possibly better evidence for any consistency in fracture strike in the marine ice. We will continue to seek evidence of fractures in the meteoric ice by increasing the time range for the 400-MHz survey to 1000 ns, and use our 200-MHz antennas to look for evidence of marine ice within the sutures in McMurdo Sound. We will use 40–100 MHz to increase penetration along an extended south–north transect to test for thicker marine ice and continued uniform horizon spacing in the north–south direction.

We found at least 20 m of marine ice along transect 177; the nearest freeboard (29.8 m), measured 500 m north of this transect, predicts approximately 42 m. It therefore may be possible to reach the bottom of the marine ice with a lower frequency and more powerful

Figure 15. (a) Stacked and migrated firn section along the first 2.8 km of transect 157A, (b) the stacked marine ice section below it, and (c) the surface elevation. The display format in panel (a) only shows the signal intensity to better reveal the stratification. The migration helped to reduce diffractions. The profiles reveal first-order, compressional folding; the synclinal and anticlinal stratigraphy associated with the crevasses (amorphous vertical streaks in panel [a]) are obliterated by the stacking. The surface elevation shows some correlation with the topography of the meteoric-marine ice interface.

Figure 16. (a) Stacked and migrated firn section from 2.6 to 3.8 km along transect 157A, (b) stacked marine section below it, and (c) surface elevation. The amorphous areas and vertical white streaks, including the thin line at 3.54 km, in panel (a) are either crevasses or steeply dipping strata. This is the only section between 2.6 and 5.7 km within which folds in the firn are not completely obliterated by the steep dips. Arrows locate where strata folds or dips in panels (a) and (b) appear similar.

antenna system. ICESat surveys found that signals here are difficult to interpret for marine ice thickness. Consequently, robotic multi-frequency GPR and GPS surveys could supplement such surveys and identify marine-meteorite ice interfacial structures.

ACKNOWLEDGMENTS

Support for this work was provided by National Science Foundation science grant nos. 1246400 and 1245915 to the University of Maine and Dartmouth College, respectively, through the Division of Polar Programs, J. Palais program manager, and NSF grant T-940 to U.S. Army Engineering Research and Development Center-Cold Regions Research and Engineering Laboratory (ERDC-CRREL). All GPR and GPS equipment was supplied by the U.S. Army ERDC-CRREL; permission to publish was granted by the director. We thank CRREL's D. Punt for developing the SIR-30 power supply, summer interns M. Preston and H. Sellmer of Worcester Polytechnic Institute, and B. Winn, formerly of ERDC-CRREL, for their support in testing and improving software. We also thank M. Armstrong and the 109th New York Air National Guard for supporting the Sandia Corporation's development and testing of the 10-GHz imaging radar.

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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE December 2021		2. REPORT TYPE Final		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Ground-Penetrating Radar Profiles of the McMurdo Shear Zone, Antarctica, Acquired with an Unmanned Rover: Interpretation of Crevasses, Fractures, and Folds within Firn and Marine Ice				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER NSF T-940, 1246400 and 1245915	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Steven A. Arcone, James H. Lever, Laura E. Ray, Benjamin S. Walker, Gordon Hamilton, and Lynn Kaluzienski				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) See next page.				8. PERFORMING ORGANIZATION REPORT NUMBER ERDC/CRREL MP-21-29	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Science Foundation Alexandria, VA 22314				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES This article was originally published online in <i>Geophysics</i> on 23 September 2015. Support provided by National Science Foundation science grants 1246400 and 1245915 to the University of Maine and Dartmouth College, respectively, (Division of Polar Programs), and NSF grant T-940 to ERDC-CRREL.					
14. ABSTRACT The crevassed firn of the McMurdo shear zone (SZ) within the Ross Ice Shelf may also contain crevasses deep within its meteoric and marine ice, but the surface crevassing prevents ordinary vehicle access to investigate its structure geophysically. We used a lightweight robotic vehicle to tow 200- and 40 MHz ground-penetrating radar antennas simultaneously along 10 parallel transects over a 28 km ² grid spanning the SZ width. Transects were generally orthogonal to the ice flow. Total firn and meteoric ice thickness was approximately 160 m. Firn crevasses profiled at 400 MHz were up to 16 m wide, under snow bridges up to 10 m thick, and with strikes near 35°–40° to the transect direction. From the top down, 200- MHz profiles revealed firn diffractions originating to a depth of approximately 40 m, no discernible structure within the meteoric ice, a discontinuous transitional horizon, and at least 20 m of stratified marine ice; 28–31 m of freeboard found more marine ice exists. Based on 10 consecutive transects covering approximately 2.5 km ² , we preliminarily interpreted the transitional horizon to be a thin saline layer, and marine ice hyperbolic diffractions and reflections to be responses to localized fractures, and crevasses filled with unstratified marine ice, all at strikes from 27° to 50°. We preliminarily interpreted off nadir, marine ice horizons to be responses to linear and folded faults, similar to some in firn. The coinciding and synchronously folded areas of fractured firn and marine ice suggested that the visibly unstructured meteoric ice beneath our grid was also fractured, but either never crevassed, crevassed and sutured without marine ice inclusions, or that any ice containing crevasses might have eroded before marine ice accretion. We will test these interpretations with analysis of all transects and by extending our grid and increasing our depth ranges.					
15. SUBJECT TERMS Ground penetrating radar; Autonomous robots; Glacial crevasses; Ice; McMurdo Ice Shelf (Antarctica); Ross Ice Shelf (Antarctica)					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 20	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code)

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