A time marker at 17.5 kyr BP detected throughout West Antarctica

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ABSTRACT. Deep radar soundings as part of the International Trans-Antarctic Scientific Expedition (US-ITASE) traverses in West Antarctica have revealed a bright internal reflector that we have imaged throughout widespread locations across the ice sheet. The layer is seen in traverses emanating from Byrd Station in four directions and has been traced continuously for distances of 535 km toward the Weddell Sea drainage, 500 km toward South Pole, 150 km toward the Executive Committee Range and 160 km toward Kamb Ice Stream (former Ice Stream C). The approximate area encompassed by the layer identified in these studies is 250 000 km^2. If the layer identification can also be extended to Siple Dome where we have additional radar soundings (Jacobel and others, 2000), the approximate area covered would increase by 50%. In many locations echo strength from the layer rivals the bed echo in amplitude even though it generally lies at a depth greater than half the ice thickness. At Byrd Station, where the layer depth is 1260 m, an age of ~17.5 kyr BP has been assigned based on the Blunier and Brook (2001) chronology. Hammer and others (1997) note that the acidity at this depth is >20 times the amplitude of any other part of the core. The depiction of this strong and widespread dated isochrone provides a unique time marker for much of the ice in West Antarctica. We apply a layer-tracing technique to infer the depth–time scale at the inland West Antarctic ice sheet divide and use this in a simple model to estimate the average accumulation rate.

RADAR INTERNAL LAYERS IN ICE SHEETS

Echoes from internal layers detected in radar soundings of polar ice provide a 'window into the past' that can be used to image changes in atmospheric deposition across broad spatial areas. Acting as isochrones, these signals can reveal important information about snow accumulation history and ice-flow deformation (e.g. Hodgkins and others, 2000; Nereson and others, 2000; Fahnestock, and others, 2001). When combined with results from ice-core chemistry, the radar internal layers can be used to extend the age–depth relationship from core locations to other parts of the ice sheet (e.g. Dahl-Jensen, and others, 1997; Siegert and Hodgkins, 2000) and to trace the spatial extent of particular chemical signatures, such as volcanic eruptions (e.g. Millar, 1981; Siegert and others, 1998).

Airborne radar surveys are an obvious way to obtain wide spatial coverage, but internal echoes from these surveys can be intermittent, and fading can limit the ability to trace layers for larger distances. Conversely, ground-based surveys that have good success imaging internal layers are typically limited spatially (e.g. Jacobel and others, 2000). The scientific platform provided by the United States portion of the International Trans-Antarctic Scientific Expedition (US-ITASE) (Mayewski, 1996) offered an opportunity to obtain ground-based radar observations across many hundreds of kilometers in West Antarctica (and extending to South Pole). The traverses took place over 4 years, each one departing from Byrd Station (80° S, 120° W) and traveling in a different direction (Fig. 1). A total of 2800 km of radar data have been acquired from these four traverses, sounding ice at distances of 835 km toward the Weddell Sea, 200 km toward the Executive Committee Range, 160 km toward Kamb Ice Stream (former Ice Stream C) and 1180 km to South Pole. The impulse radar system, which operates at a center frequency of 3 MHz, is described in more detail in Welch and Jacobel (2003).

A STRONG INTERNAL REFLECTOR

In each of these profiles we found a strong internal layer reflector that in many places rivaled or exceeded the bedrock reflection strength, even though it was often the deepest layer detected. Figure 2 shows a portion of the radar data from the 2002 traverse starting near Byrd Station and running 65 km toward South Pole. The bright layer is seen near 1260 m depth below the surface and is easily traced throughout the profile. Surface elevations are derived from global positioning system (GPS) measurements acquired on

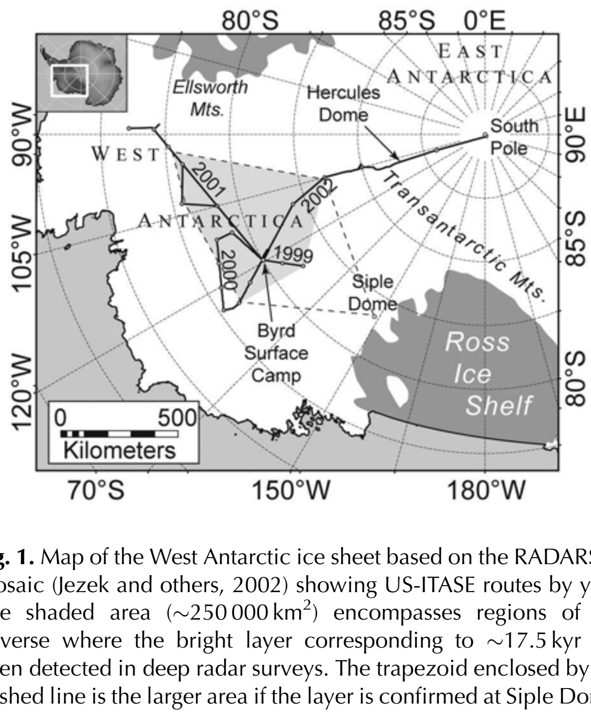

Fig. 1. Map of the West Antarctic ice sheet based on the RADARSAT mosaic (Jezek and others, 2002) showing US-ITASE routes by year. The shaded area (~250 000 km^2) encompasses regions of the traverse where the bright layer corresponding to ~17.5 kyr has been detected in deep radar surveys. The trapezoid enclosed by the dashed line is the larger area if the layer is confirmed at Siple Dome.

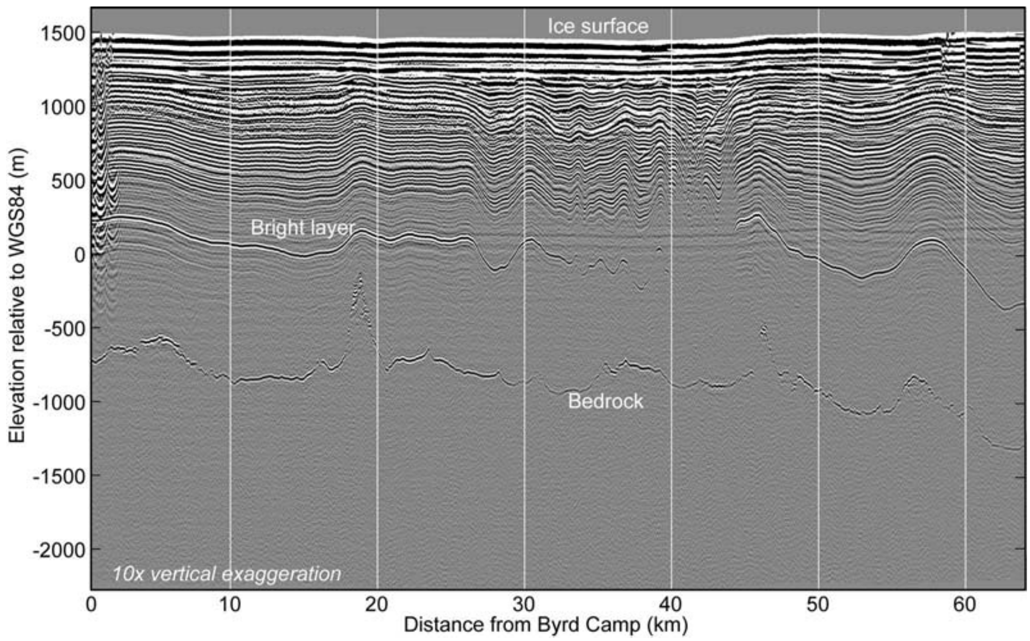

Fig. 2. Radar data processed and migrated as an elevation section from the 2002 US-ITASE traverse. Byrd Station is at the left and the traverse extends in the general direction of South Pole to the right. The bright layer is seen at approximately 1260 m depth near the station. Hyperbolic echoes near Byrd Station are from buried debris associated with relict camp structures. Note the rough bed topography in the vicinity of the camp, and the brightness of the layer which rivals bed echo amplitudes.

the radar sled during the traverse and processed by ITASE colleagues at the University of Maine, Orono, ME, USA. The radar data have an average horizontal sampling density of 12 m per recorded trace, with a few thousand waveforms 'stacked' to produce each trace. The data have been corrected for the offset separation between transmitter and receiver and migrated to account for the finite antenna beamwidth. Diffractors near the start of the profile (Fig. 2, left) arise from buried debris around Byrd Camp, the site of ice-core drilling in 1968. The core location is approximately 1.5 km abeam of this profile, about 2 km from the start.

Figure 3 shows an interpretation of the bedrock topography and several of the internal layers based on picks of the radargrams from the traverses done in 2001 and 2002 (Fig. 1). US-ITASE core locations and significant bedrock and surface features are also shown in the figure. The bright layer at 1260 m depth at Byrd Station (near sea level in elevation) can be traced continuously for 535 km toward the Weddell Sea (2001 route, left portion of Fig. 3) where it becomes too weak to detect (Welch and Jacobel, 2003). Likewise, it is traceable continuously for 503 km toward South Pole (2002 route, right portion of Fig. 3).

A 116 km gap in the data between core sites 02-2 and 02-3 interrupts continuous observations of the layer. This is also the section where the traverse passes through the 'Bottleneck' where ice is funneled through a gap in the Transantarctic Mountains from the East Antarctic ice sheet into West Antarctica. Strain rates increase in this region and it is difficult to trace individual layers for any distance because of fading. However, we are able to identify the original layer in traverse sections beyond the Bottleneck based on comparing the radar stratigraphy on either side of the gap. Thus, beginning again at km 725, we trace the layer another 455 km to South Pole. We have also identified the same bright layer based on radar stratigraphy in sections of data acquired on the 2000 route toward the Executive Committee Range and in data acquired near the Swithinbank automatic weather station site in 1999. Based on these four end-points (excluding the segment from the Bottleneck to South Pole), the estimated area over which this layer has been identified is 250 000 km^2 (shaded area in Fig. 1).

INTERNAL REFLECTOR PHASE AND LAYER CHARACTERISTICS

In the areas where the bright layer is readily identified (i.e. within the shaded area of Fig. 1) the wavelet phase is 'white–dark–white', the same as the bedrock echo (Fig. 2). The observed phase and wavelet characteristics for energy returned from a layer with a thickness less than the radar wavelength in ice (about 56 m for our system) depend on the dielectric properties of that layer, its thickness and possible interference from energy returned due to any other adjacent layers. The separation of internal layers in an ice sheet varies with the accumulation pattern and vertical strain; thus layers most commonly pinch together where ice flows over bedrock obstacles and are further apart when the bed is deep. Consequently, layers depicted in radar data often become too close to be resolved where the ice becomes thinner; they appear to merge together and then reappear where the ice is thicker.

The bright layer we have traced across the Bottleneck initially shows the same phase observed at Byrd Station (Fig. 2), but south of Hercules Dome near km 825 the phase reverses, indicating a change in the layer properties or in its vertical relationship to layers nearby. By km 900 the depth to this layer is only about 40% of the ice thickness, whereas near Byrd Station it is 60% of the ice thickness. This difference is due primarily to the lower accumulation rate on the polar plateau. In the final 300 km of data from the colder

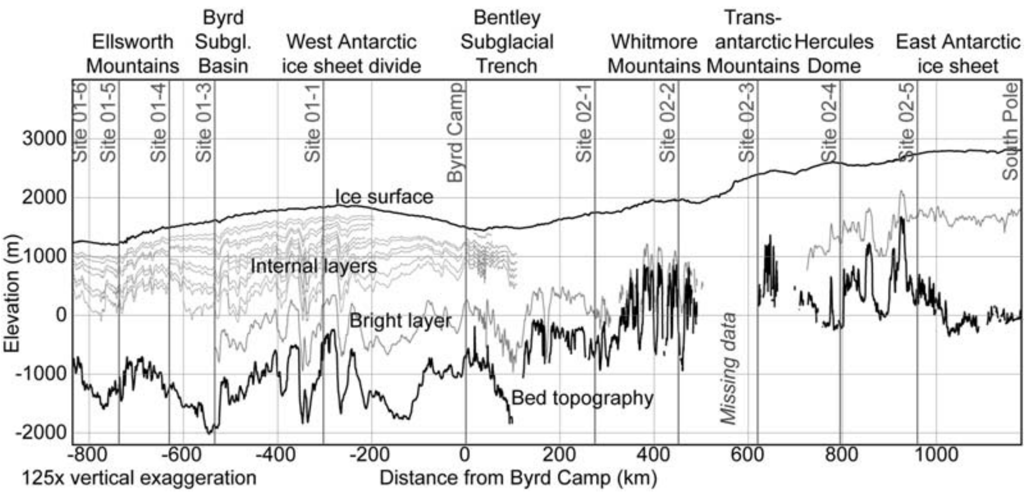

Fig. 3. Interpretation of US-ITASE radar profiles from 2001 and 2002 showing surface and bed topography, ice-core locations and internal stratigraphy. The bright layer discussed in this paper is the deepest layer depicted. Other internal layers between Byrd Station and South Pole are visible in the data but not yet processed. Significant geographic features are labeled.

ice near South Pole there are also more layers of comparable brightness at almost every depth. Because of the combination of these changes, the 'bright layer' is no longer the brightest layer but simply one of a number of layers observed at this depth. While the echo almost certainly results from the same depositional event observed at Byrd Station, the distinctive amplitude characteristic has changed and therefore it is not as useful as an indicator. Thus we have been conservative in estimating the area over which it may be readily identified as a unique marker and do not include the segment from km 503 to South Pole.

CORRELATION WITH BYRD CORE STRATIGRAPHY

Figure 4 (right panel) shows a portion of the radar record near the Byrd core location, with the age–depth scale derived from Hammer and others (1994) (above 1100 m) and from the gas age chronology of Blunier and Brook (2001) at the lower depths. At 1260 m depth, the bright layer corresponds to a gas age of ~17.4 kyr at the Greenland Ice Sheet Project (GISP2) site or 16.8 kyr at the Greenland Icecore Project (GRIP) site. According to Hammer and others (1997) who measured electrical conductivity and acid content in the 1968 Byrd core, 'the most spectacular volcanic activity recorded . . . occurred over a 4 m long increment between 1279.5 m to 1283.5 m. The total acid deposit is more than 20 times higher than for any other event [in the core]. A remarkable peculiarity of this event is its multiple pulsed continuity sustained for nearly 170 years.'

The difference of approximately 20 m between the Hammer and others (1997) depth and our radar depth is likely attributable to a combination of two factors. First, we have assumed a constant velocity of 169 m μs^{-1} in converting travel time to depth. A correction for the radar wave velocity in the firn would increase our reported depths an additional 7–10 m depending on the precise depth–density relationship. Second, the distance between the radar profile and the 1968 core location is approximately 1.5 km in an area where the bed and internal layer elevations vary considerably. Consequently, small distance offsets could cause layer depths to vary by several meters.

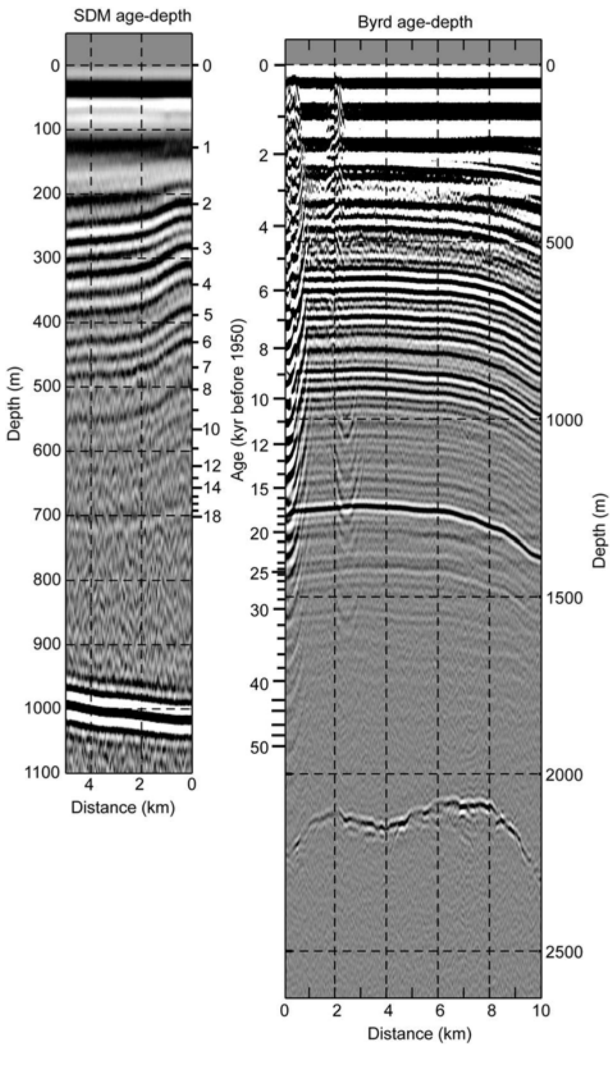

Fig. 4. Detail of radar profiles near the Byrd Station and Siple Dome core sites with superposed age–depth scales nearest the core locations (see text for references). The profiles are scaled vertically to match at 0 and 18 kyr. The deepest observed layer at Siple Dome is very close in age to the bright layer at Byrd Station near 17.5 kyr.

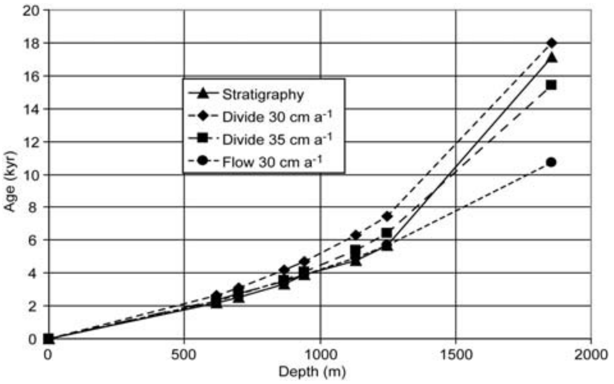

Fig. 5. Age–depth relationship at the inland WAIS divide location (solid line) inferred from layer tracing and the age–depth scale at Byrd Station. Also shown are three model calculations (dashed lines) of the age–depth curve based on assumed average accumulation rates of 30–35 cm a^{-1} (ice equivalent) and either a constant divide location or steady-state flow on a divide flank.

Hammer and others (1997) point out that the extremely high acid values described above appear in HF and HCl with no apparent rise in H_2SO_4. Also the acid spike does not coincide with any excess dust or particulate deposition, leaving a puzzle as to the location of the 'massive eruptive event'. One hypothesis is that the source was distant from Antarctica, allowing particulates to fall out of the ash cloud, but that leaves unexplained the extremely high concentrations of hydrophilic acids which should also be depleted by precipitation scavenging (Hammer and others, 1997). Another possibility discussed by these authors is a subglacial eruption closer to Byrd Station where a substantial fraction of the sulfur remained with the magma, preferentially releasing HF and HCl.

Based on a qualitative assessment of our echo amplitudes, the brightness of the layer seems more consistent with the local source hypothesis. The layer brightness (relative to bed echo amplitude) is highest close to Byrd Station and decreases inland away from the station both in the direction toward South Pole and toward the Weddell Sea sector. In the traverse segment toward the Executive Committee Range, our data are not as clean, but it does appear that the layer brightness is substantially stronger than the bed here, supporting the idea that the source location is in this direction.

EXTENSION TO SIPLE DOME?

A series of depth measurements of a dated internal ice horizon across several hundred thousand km^2 of West Antarctica should be ideal for scientists seeking to model ice flow. In addition to the data presented here, the layer can presumably be detected in future surveys within the bounds of the area shown in Figure 1, and perhaps beyond. Toward that end, we have compared US-ITASE radar data with an earlier ground-based radar survey operating at 3 MHz conducted at Siple Dome (SDM; Jacobel and others, 1996, 2000). The SDM survey depicts a number of internal layers down to approximately 70% of the ice thickness. These layers can be matched to the SDM age–depth relationship derived from a combination of annual-layer counting (Taylor and others, 2004) and gas age matches to the GISP2 core (Brook and others, 2005). Our hope in this effort is that we can find evidence at SDM for the same bright layer that we have imaged on the US-ITASE routes.

Figure 4 (left panel) shows a portion of the SDM radar record near the core location 500 m south of the summit. The age–depth scale from Taylor and others (2004) and Brook and others (2005) is superposed at the left. Although it is marginally visible, the brightest deep internal layer in the radar record at SDM comes at approximately 695 m and corresponds to an age just over 17 kyr.

It is tempting to conclude that the layer at 690 m at SDM is the same bright layer seen at Byrd Station and elsewhere throughout West Antarctica; however, several caveats should be noted. The pattern of radar internal stratigraphy, including spacing and relative brightness, is clearly not the same near both cores, precluding a 'fingerprint' match of the deep layer from one site to the other. However, given the different characteristics of the two radar systems and a separation of >530 km between these two sites, it would be surprising if the patterns were similar. Therefore, an extension of the bright layer to SDM, if it is possible, will need to await an analysis of the chemistry from the two ice cores. In principle, forward modeling of the radar pulse (e.g. Eisen and others, 2003) may be used together with a knowledge of ice chemistry to verify the reflector origin.

ACCUMULATION RATE ESTIMATES

While its volcanic origins may still be uncertain and its full extent is not yet defined, it is clear that a prominent ice internal layer corresponding to an age of 17.5 kyr can be traced throughout a large fraction of West Antarctica. As noted, this isochrone is potentially useful in providing an approximate age–depth relationship and thus a measure of average accumulation wherever it has been measured. It can also be used, in principle, to explicitly link ice-core chronologies at distant sites. For example, Hercules Dome (86.3° S, 107° W), long viewed as a possible deep core site (Ice Core Working Group, 1988), was explored by the US-ITASE traverse en route to South Pole (Jacobel and others, 2005), and the bright layer is clearly imaged there at 1350 m depth (Fig. 3). This layer provides a link from Hercules Dome to Byrd Station and possibly to the SDM core.

Likewise, the inland West Antarctic ice sheet (WAIS) core will likely be located near the Ross Sea–Amundsen Sea divide, close to the 2001 US-ITASE traverse route. The bright layer is well depicted over this divide at 1850 m depth (Fig. 3) and, together with several other layers, can be traced continuously for nearly 200 km to Byrd Station, providing a direct way to correlate the stratigraphy between these two cores. We have used the Byrd age–depth relationships (Hammer and others, 1994; Blunier and Brook, 2001) to create an age–depth scale at the Ross Sea–Amundsen Sea divide location by tracing seven of the internal layers spanning from the near surface to the bright layer at approximately 17.5 kyr. One of the questions from the ice-core community considering sites for an inland WAIS core is about accumulation rates at the divide. A simple estimate of the average accumulation rate can be made from these data based on the model of Dansgaard and Johnsen (1969). The model assumes steady-state accumulation and a constant vertical strain rate down to some level a few hundred meters above the bed where the strain rate then decreases linearly to zero (Equation (1)). For a location directly over an ice divide, the model is altered slightly so that vertical strain rate decreases linearly from the surface (Equation (2)) (Paterson, 1994, p. 278).

$$t = \frac{2h-h'}{2c} \ln\left(\frac{2h-h'}{2z-h'}\right), \quad z > h' \tag{1}$$

$$t = \frac{h}{c}\left(\frac{h}{z} - 1\right), \qquad h > z > 0 \tag{2}$$

In these equations, t is the layer age, c is the accumulation rate (assumed here for several scenarios), h is the total ice thickness, z the layer height above the bed and h' is a constant (the height above the bed at which vertical strain rate begins decreasing linearly toward zero), taken here to be 400 m.

Figure 5 shows the inferred age–depth relationship for the Ross Sea–Amundsen Sea divide location down to about the Last Glacial Maximum (LGM) based on layer tracing, along with several model calculations derived from different accumulation rates and divide scenarios. The data for mid-level layers below about 600–700 m are matched best by the model assuming divide conditions (linearly decreasing strain rate) and an average accumulation rate on the order of 30–35 cm a^{-1} (ice equivalent). The more recent layers require unreasonably high accumulation rates under all divide scenarios, or the assumption of a constant vertical strain rate (non-divide physics) and an accumulation rate of about 30 cm a^{-1}.

This exercise includes several caveats. The model assumes constant accumulation, a flat bed (layer thickness not varying spatially) and, for the divide scenarios, a symmetric isothermal ice divide. The bed beneath the divide location is certainly not flat (Fig. 3) and the accumulation rate has clearly not been constant, although that in itself is an important result. Also, we have not attempted to fit deeper portions of the thickness section below the LGM, when conditions are likely to have been different.

CONCLUSIONS

Measurements of the depth of the bright layer, together with bed topography, may likewise be used to constrain more sophisticated ice-flow models of the WAIS in other locations, providing a surface in time–depth that must be matched by accumulation and strain history. Other layers from the dataset, as they are analyzed, will provide additional model constraints. Clearly these extended ground-based radar traverses, while not giving the same kind of broad spatial coverage as aerial surveys, have a value in providing high-resolution, detailed measurements of both bedrock and internal stratigraphy that can be used to address a number of problems in glaciology.

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