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The Cryosphere Discussions

High resolution boundary conditions of an old ice target near Dome C, Antarctica

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Abstract. A high resolution (1 km line spacing) aerogeophysical survey was conducted over a region near the East Antarctic Ice Sheet's Dome C that may hold a 1.5 million year old climate record. New ice thickness data derived from an airborne coherent radar sounder was combined with unpublished data that was unavailable for earlier compilations. We find under the primary candidate region elevated rough topography, near a number of subglacial lakes, but also regions of smoother bed. The high resolution of this ice thickness dataset also allows us to explore the nature of ice thickness uncertainties in the context of radar geometry and processing.

1 Introduction

The oldest stratigraphically intact record of Antarctic ice is located in the EPICA Dome C ice core, collected near the joint Italian-French Concordia Station in Wilkes Land, Antarctica (EPICA Community Members, 2004). The interpreted section of this ice core, which extends back to 800 ka, records the isotopic and gas imprint of eight glacial cycles with a periodicity of ∼100 ka. Marine records of oxygen isotopes, however, reveal that prior to 800 ka ago, the global climate system was driven by shorter, lower amplitude obliquity-driven ∼40 ka cycles. A key goal of the international ice core community is to collect a deep ice core that samples both a local climate history of Antarctica and a global record of greenhouse gas concentration going back to 1.5 Ma (Fischer et al., 2013).

The requirements for a stratigraphically intact ice column of this age are: (1) low geothermal heat flux, to restrict basal melt rates; (2) low accumulation, to restrict vertical thinning rates and increase temporal resolution; (3) proximity to an ice divide, to limit vertical thinning rates and disturbance due to lateral flow, and simplify the altitude history of the surface; (4) limited basal roughness, in order to restrict disruption of basal ice; and (5) ice thicknesses of about 2500 m, in order to limit thermal

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insulation of the basal ice. Given the significant logistical requirements of ice core recovery, another important criteria for any old ice site is accessibility.

Based on ensemble ice sheet modeling, tuned by the then known distribution of subglacial lakes, Van Liefferinge and Pattyn (2013) identified a number of potential regions of frozen bed with old predicted basal ages (informally known as 'blobs'). A key constraint on this prediction was the use of the Bedmap2 ice thickness compilation (Fretwell et al., 2013), which included ice thickness data collected up to 2009. Several of the predicted sites (here known as Candidates A, B, C, D, and E) were clustered within 50 km of the existing joint Italian/French Concordia Station.

A European-led group identified these sites as being of significant interest for old ice access, and requested the ongoing ICECAP (International Collaborative Exploration of the Cryosphere through Airborne Profiling) project survey these sites in January 2015. After logistical delays and further planning, the US-Australian ICECAP II project was successful in conducting a systematic aerogeophysical survey of these sites in late January 2016. This paper reports on the preliminary results of this survey.

2 The Dome C region

Dome C (Figure 1) is a local topographic high in the East Antarctic Ice Sheet (EAIS), rising to 3250 m above sea level, located 1100 km from the East Antarctic coast. Dome C separates ice flowing to Totten Glacier to the northwest from ice flowing to the George V Coast to the east and to Byrd Glacier to the south. A topographic saddle connects Dome C to the higher ice overlying Subglacial Lake Vostok to the south, through Ridge B and Dome A, the highest part of the EAIS.

2.1 Previous datasets

The topographic form of Dome C was first defined from the joint SPRI/NSF/TUD airborne surveys of the 1970's (Drewry and Jordan, 1983). This crude airborne radar altimetry predated GPS, and were constrained from pressure and INS measurements with large uncertainties; however, subsequent ground-based traverses and satellite radar altimetry (Bamber and Bentley, 1994) confirmed the presence of the Dome. As a site of thick ice, low accumulation, and slow ice flow, it was a promising site for ice coring, with the first cores in the region acquired in 1977-78 (Lorius et al., 1979). These early surveys also revealed the presence of an extensive population of subglacial lakes in this region (Oswald and Robin, 1973; Wright and Siegert, 2012), which would become known as the 'Dome C Lake District'.

Site selection work for the EPICA Dome C ice core took place in the mid 1990's with an Italian survey grid covering the Dome C region (Tabacco et al., 1998). This work, a combination of ground and airborne (Twin Otter) based surveys using a 60 MHz incoherent radar system with a 1 μsec pulse-width, covered most of the Dome C region with a 10 km line spacing. Ice thickness measurements from these surveys form the bulk of the data coverage for this region in the Bedmap2 compilation (Fretwell et al., 2013). The coarse subglacial geography revealed by the Italian survey is comprised of a deep subglacial trough to the north of Dome C, with indications of a flat subglacial plateau near mean sea level under the center of the primary Dome, and a series of mountains to the south along the line of northward ice flow. EPICA Dome C targeted the center of the Dome on

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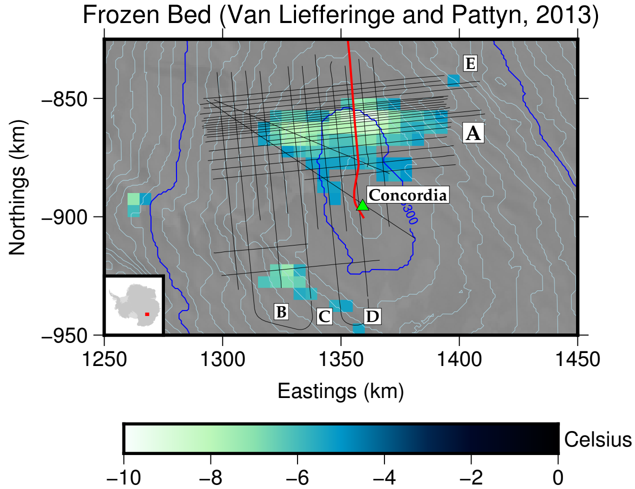

Figure 1. Dome C and the OIA survey flight lines (black, transit lines are not shown), in the context of the Van Liefferinge and Pattyn (2013) frozen bed candidates and Concordia Station. The older profile show in Figure 3 is in red, and follows the ice divide. A threshold of -5°C was used for selecting candidates. 10 m surface elevation contour lines from Fretwell et al. (2013) are in blue; the background is the MODIS Mosaic of Antarctica (Scambos et al., 2007). Projection is Antarctic Polar Stereographic.

the basis of apparently flat topography and its isolation from surrounding ice flow (Tabacco et al., 1998). Additional analysis (Rémy and Tabacco, 2000), however, revealed broad channels trending north-south underlying the target region.

The final EPICA Dome C ice core succeeded in obtaining ice dated as old as 800 ka; however, the lower 75 m of the ice column was either undatable, or not drilled to prevent contamination of a wet bed (Tison et al., 2015), and extrapolation of the borehole temperatures indicated that melting was likely occurring at the bed (Lefebvre et al., 2008). Analysis of the composition and structure of the lower portion of the ice core showed that focusing of ice flow by the broad channels on this plateau may have resulted in stretching and recrystallization of the lower part of the ice column, implying that an ideal old ice target may require a very flat ice-bed interface, characterized by a horizontal size of several ice thicknesses (Tison et al., 2015).

In 2008, 2009, and 2011, the ICECAP project conducted survey flights using the HiCARS family of radar sounders (Young et al., 2015b), mounted on a DC-3T Basler. These radar systems provided coherent, focusable 60 MHz data with a 0.08 μsec pulse-width. The goal of these flights was improving the radar stratigraphy between the EPICA Dome C and Vostok ice core sites (Cavitte et al., 2016). Included in these ICECAP flight lines was a transect along the Dome C to Subglacial Lake Vostok ice divide, which was also flown by a range of other radar sounders, as well as number of sparse lines of the Vostok/Concordia/DDU corridor (VCD), typically 20 to 40 km apart, parallel to the ice divide.

2.2 Candidate Site A

Van Liefferinge and Pattyn (2013) have developed an ensemble model for predicting regions of frozen bed using a combination of remote sensing and telesesimic estimates for geothermal heat flux combined with a thermomechanical ice sheet model

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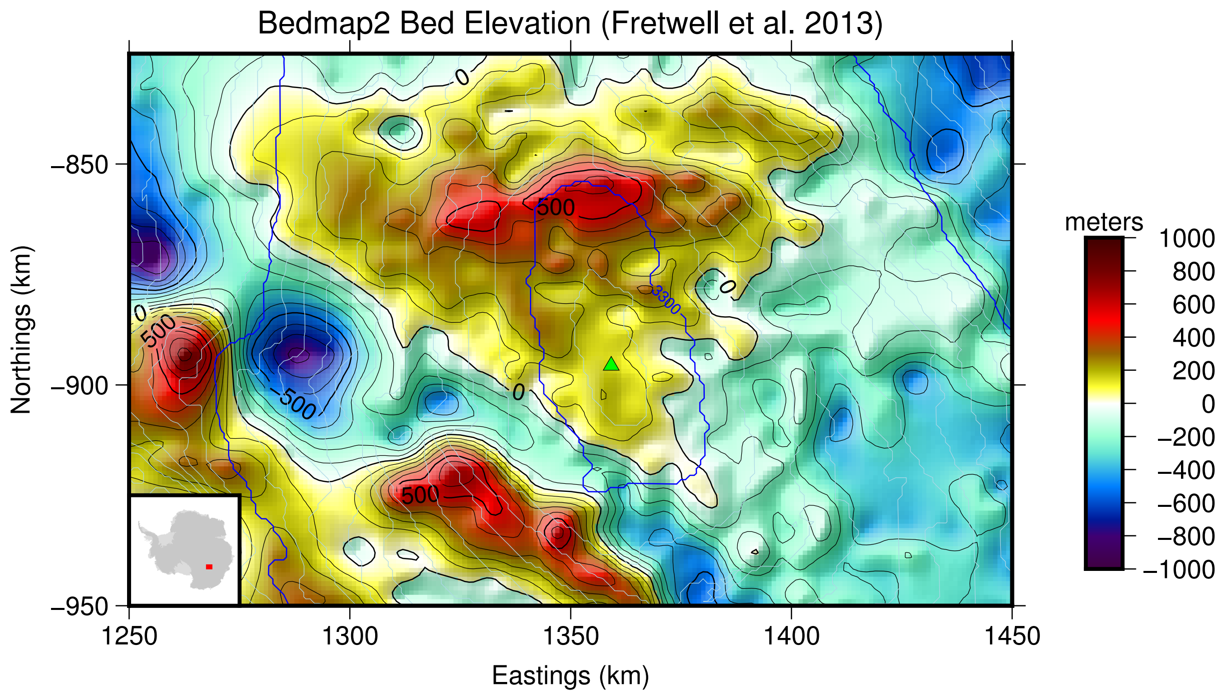

Figure 2. Bedmap2 bed elevations (WGS-84) from Fretwell et al. (2013). Concordia Station is the green triangle. North is toward the right. 10 m surface elevation contour lines from Fretwell et al. (2013) are in blue. Projection is Antarctic Polar Stereographic.

calibrated by observations of subglacial lakes. When thresholds for ice thickness (>2000 m) and of the horizontal component ice velocity (< 2 m/yr) were applied, a map of possible old ice candidates was produced.

In the Dome C region, five candidate sites exist: A, B, C, D, and E (Figure 1). Notably, none of these sites overlap with EPICA Dome C ice core – consistent with the likely basal melting implied by extrapolation of borehole temperatures. Sites B, C, and D are located on the steep and poorly sampled peaks on the northern side of the Concordia Subglacial Trench (CST); basal ice in this region likely traverses the deep, wet CST and is unlikely to be stratigraphically intact. Site E lies on a small subglacial high downstream on the Totten Glacier side of the Dome; this site also lies down flow of a deep subglacial trough, thus raising substantial doubt to its suitability as an old ice coring site.

Candidate A is by far the largest site in the Dome C area and lies under the ice divide on a subglacial massif, minimizing both ice thickness and ice velocity. The ice surface above Candidate A forms a topographic extension to the south of Dome C informally termed 'Little Dome C'. The central part of Candidate A lies 40 km south from Concordia Station. Because of its characteristics, Candidate A represents a near term primary goal of European and Australian old ice site selection.

The 2011 airborne survey line (VCD/JKB2g/DVD01a; Figure 3) crossed the core of the Candidate A site. Focusing of the radar data showed that the southern flank of the Candidate A massif ended in a steep cliff over which englacial layers dive. Coherent, continuous englacial reflectors are present in the upper 80% of the ice column (Cavitte et al., 2016), while in the

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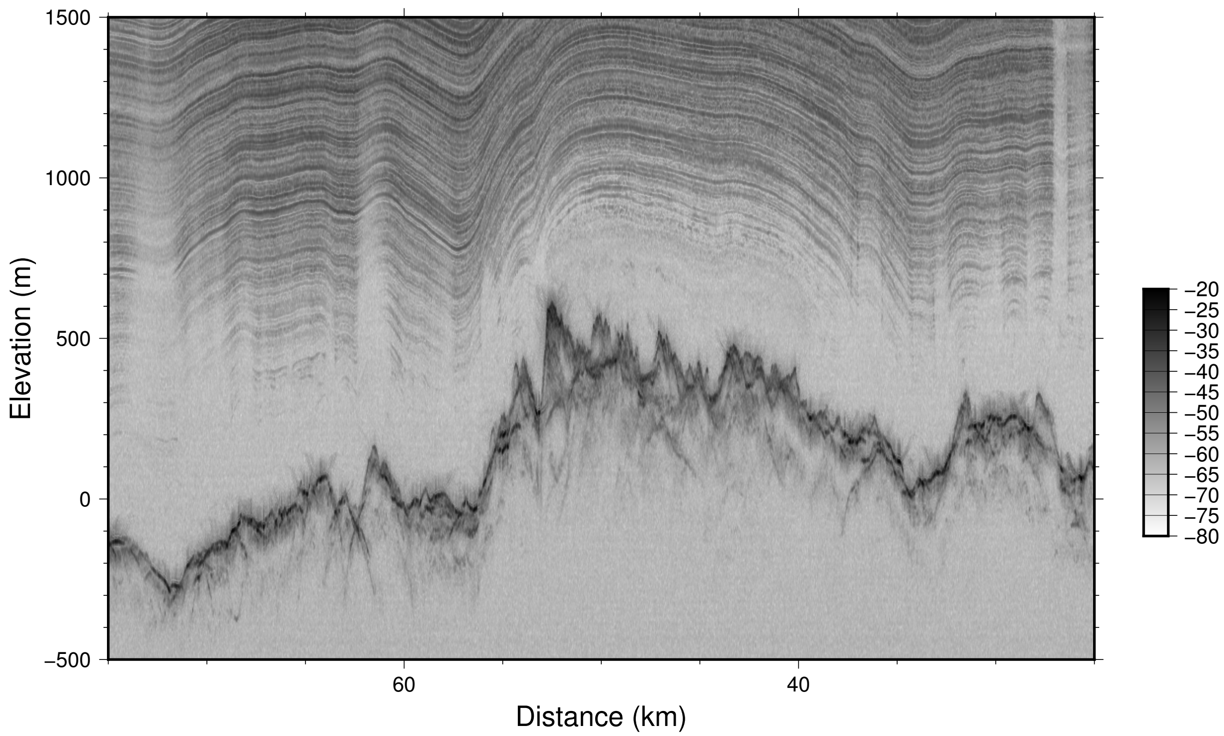

Figure 3. HiCARS2 2D focused and depth corrected radargram alone the ice divide across the Candidate A target; (line VCD/JKB2g/DVD01a from Blankenship et al. (2014)). South is to the left, Dome C is to the right, color scale is relative power in dB.

bottom 500 m, a region of more diffuse englacial scattering is present. This distinct zone of basal ice is also apparent in McCoRDS radar data that operates at a higher frequency (Cavitte et al., 2016; Leuschen and Allen, 2011a).

3 The OIA survey

Key objectives of the survey were to define the ice thickness at high resolution, infer basal roughness across the target region and map the distribution of subglacial water. Improving the englacial stratigraphy (especially deep layers) and correlating it to the existing EPICA Dome C core site were also high priorities. In addition to the radar data, we acquired laser altimetry, gravity and magnetics data, along with complementary Global Positioning System (GPS) and Inertial Measurement Unit (IMU) data. Instruments are detailed in Table 1.

3.1 Survey Design

The Old Ice A (OIA) survey was designed to sample Candidate A at high resolution, with 110 km long 'Y' survey lines at separations of down to 1 km cutting across the ice divide, and $\sim$ 65 km 'X' tie lines with separations of 5 km parallel to the

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Table 1. ICECAP II instrument suite

Instrument	Type	Flights	Reference
MARFA	Coherent Ice Penetration Radar	F11-F14	Young et al. (2015b); Castelletti et al. (2015)
Geometrics G823A	Scaler Magnetometer	F11-F14	Aitken et al. (2014)
CMG GT-2A	Airborne Gravity Meter	F12-F14	Greenbaum et al. (2015)
Riegl LD90	Laser Distance Meter	F11-F14	Young et al. (2015a)
Sigma Space ALAMO	Photon Counting Lidar	F11-F14	Young et al. (2015a)
Javad Delta	4-Antenna GPS	F12-F14, partial F11	
Novatel SPAN	Integrated IMU/GPS	F12-F14, partial F11	Young et al. (2015a)

ice divide (Figure 1). Some of the X lines extend north to cross the Concordia Subglacial Trench and candidates B, C, and D, while the Y lines extend far enough to the west to cover Candidate E.

Two lines were added to cut obliquely across the grid: one that tracked over the EPICA Dome C site in order to connect the ice chronology to the grid and a second line to better constrain an oblique topographic ridge crossing the divide. Flight lines were designed to avoid Concordia's clean air sector to the south of the station, as well as to allow the aircraft to make VHF communications with the station before landing.

3.2 Survey Implementation

After setup at Casey Station in late December 2015, the ICECAP II project operated in a number of different East Antarctic locations including Concordia Station. Four flights were carried out from Concordia Station in late January 2016 - the first two (F11 and F12) focused on 2 km line spacing Y lines over Candidate A, followed by one flight (F13) targeting X lines extending past Concordia to Candidate A, and lastly one flight (F14) focused on increasing the line density over the primary target to 1 km line spacing. Initial interpretation of the radar data was performed during the field program, and helped refine the later flight plans. GPS base station data was collected during the survey flights, while the existing Dome C magnetic base station (Di Mauro et al., 2015) was used to correct diurnal effects in the magnetics data. Elevation differences between survey lines at crossovers were minimized to obtain laser altimeter pointing biases (after Young et al. (2015a)). The airborne gravity meter (GT-2A sn 18) was successfully operated for F12, F13 and F14 and gravity ties were performed with a hand held gravity meter between Concordia Station and reference sites at Casey Station.

4 Data Processing

4.1 GPS processing

After the field season, GPS data were processed using Waypoint Inertial Explorer, using Precise Point Positioning (PPP) loosely coupled to the acceleration and rate data from the SPAN IMU system. Internal estimates of uncertainty for these data have 2 cm height standard deviation.

4.2 Radar processing

Range compression of the raw radar resulted in a range resolution in ice of 8.4 meters (Cavitte et al., 2016). The radar data was first processed using a very short synthetic aperture (Holt et al., 2006; Young et al., 2011) to extract the surface return and for initial quality control. This processing (called "pik1") retains the unmigrated along track hyperbolae that characterizes many earlier radar sounding datasets. The data was then processed using the "1-D" focused SAR approach of Peters et al. (2007), where focusing of the along track Doppler phase variations within each range resolution cell was employed to improve the along track resolution to approximately 10-20 meters for scattering targets. The data was resampled to 4 Hz along track sampling (~22 m) for manual interpretation.

4.3 Radar ice thickness and bed elevation extraction

To obtain ice thicknesses, we systematically select a window around the earliest bed return, and then automatically select the best fitting pulse waveform within that window (assumed to be a paraboloid power profile), for both the surface and the bed. The surface time delay is subtracted from the bed time delay to obtain the two way travel time in the ice column, and using an appropriate refractive index for ice ($\sqrt{3.15}$), we convert to ice thickness. We choose to not apply a firn correction. Bed elevations are derived by subtracting the ice thickness from concurrently collected laser or radar altimetry; all elevations are referenced to the WGS-84 ellipsoid.

We do not attempt to reconcile ice thickness interpretations at crossover points, and maintain a strict first return policy. As detailed in the next section, preserving crossover differences provide important information on understanding the interactions between radar geometry, processing, and bedrock roughness, and allows us to extrapolate these statistics to intervals without crossover constraints.

5 Radar ice thickness and bed elevation uncertainties

Crossover differences in ice thickness (or equivalently bed elevation) between radar lines are often reported as a metric of uncertainty in the quality of the ice thickness data. However, given the geometry and processing of radar sounding data, the information contained in these crossovers must be carefully considered. As well as the inherent science interest in the uncertainties in the data, the density of orthogonal lines over thick ice and a rough bed target presents an opportunity to better

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Table 2. Crossover difference for the OIA survey, as a function of processing. N is the number of crossovers used.

Processing	N	RMS difference
incoherent pik1 (Young et al., 2011)	204	54 m
"1D" focused SAR (Peters et al., 2007)	214	80 m

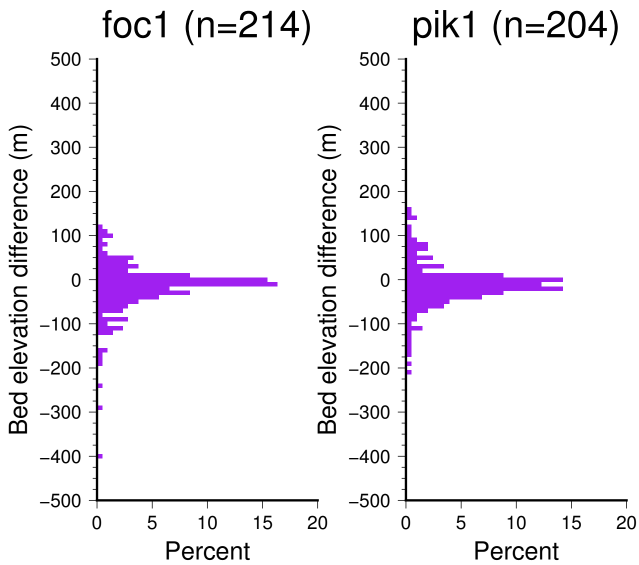

Figure 4. Histogram of bed elevation differences for orthogonal OIA survey line crossovers; the Y line bed elevations is subtracted from the X line bed elevations. The much larger RMS difference for focused data (left, see Table 2) is driven by the large negative outliers below -200 meters difference. This is consistent with the Y lines being parallel to the large cliffs in the area, which are better resolved in the orthogonal X lines.

understand the nature of uncertainties in this kind of dataset in general. Crossover bed elevation statistics are presented in Table 2, using just the orthogonal X and Y lines of the OIA survey.

The result of Table 2 and Figure 4 is counterintuitive; the more intensive processing has higher crossover differences. This difference can be explained by understanding the geometric controls on the radar signal and the interactions with bed rock roughness.

In the case of the incoherent pik1 processing, the beam pattern is effectively limited by the critical angle of refraction of the air-ice interface (34°), in both the along track and across track directions. The processed radargram in this case effectively shows the range to the nearest bed interface, and the direction of travel does not affect that range. Approaching the crossover point from either direction, a similar range is seen, even if the reflecting target is not under the aircraft. If the first return is coming from an off track target, an incorrect (and likely too thin) ice thickness will be inferred; this is an error that will not be

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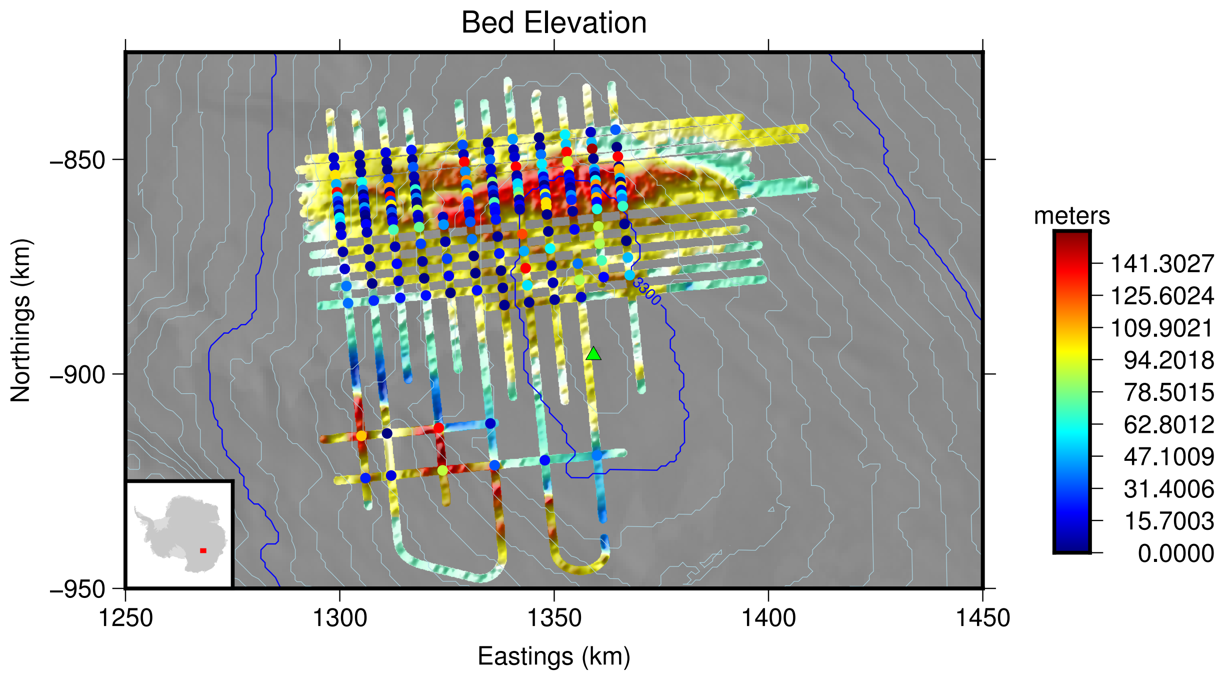

Figure 5. Crossovers (circles) superimposed on focused bed elevations (color scale is for cross over difference absolute value; bed elevation color scale same as for Figure 2). Large cross overs correlate with scarps in the bed rock topography. Concordia Station is the green triangle. North is toward the right. 10 m surface elevation contour lines from Fretwell et al. (2013) are in blue. Projection is Antarctic Polar Stereographic.

indicated by the cross over difference. In general, in rough terrain unfocused data will provide a considerable underestimate of ice thickness.

In focused radar data, discontinuities are often seen in crossovers, especially where terrain is rough or steeply sloping (Figure 5. These discontinuities are due to the asymmetry in resolution between the fine along track resolution (10-20 meters), determined by the synthetic aperture generated by motion of the radar, and the coarser across track field of view, determined by the real aperture of the two underwing dipoles. The across track beam at the bed covers approximately 1 km either side of the nadir point. Due to the refraction of ice, the wavefronts propagating to the bed are wide parabolas, meaning that small scale topography projecting above the nadir bed can lay over the nadir return. The result is the first return will tend toward the minimum ice thickness within the aircraft beam pattern, however the measured thickness at this site will be slightly overestimated. The primary uncertainty will be in the cross track position of the bed echo.

The horizontal area on the bed simultaneously illuminated by the range compressed pulse is termed the "pulse limited footprint". If the vertical roughness on the length scale of the pulse limited footprint (radius of ∼250 m) is similar to that of the range resolution, we would expect low crossover difference in ice thickness.

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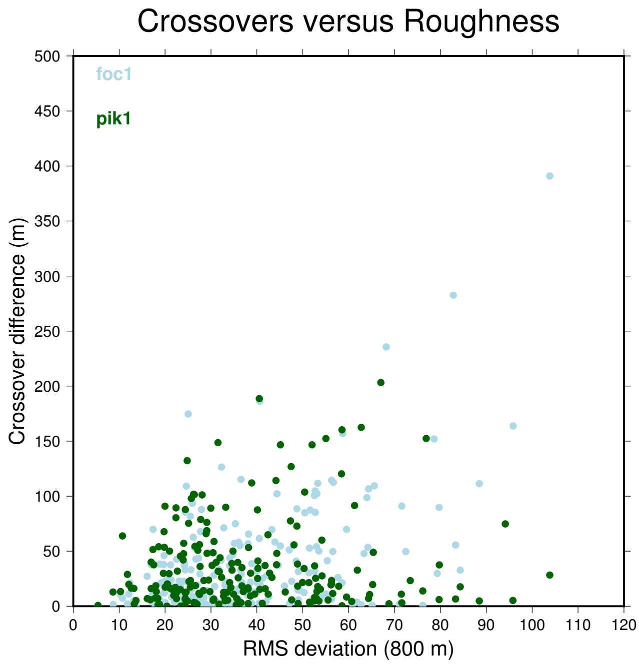

Figure 6. Relationship between RMS deviation at 1600 m length scale (as measured in the focused bed elevation data) and crossover difference in bed elevation.

The apparent large scale roughness of a radar profile will be dominated by along track roughness, but smoothed by layover contributions from the side. We can estimate along track roughness by obtaining the root mean squared (RMS) deviation in elevation as a function of a characteristic distance between points after detrending the data to remove the effect of large scale slopes.

The uncertainty in ice thickness (and hence bed elevation) for a given survey line will be a function of bedrock roughness. The roughness of landscapes can be expressed as a function of RMS deviation for a given horizontal distance; the ratio of the two gives the RMS slope. For fractal landscapes, how roughness will scale will be a function of the Hurst exponent (H, Shepard et al. (2001)). Typical landscapes are self-affine, having an H of $\sim$0.5 (i.e. they get smoother as a function of increasing length scale). At typical ice thicknesses (2500 m) and survey heights above the surface (600 m) for this survey, the first return of the bed echo will likely lie within the inner half of the beam pattern for the RMS roughnesses of 10-20 meters (RMS slopes of $\sim 1^{\circ}$) at hundreds of meters length scale. For landscapes with hundreds of meters of relief at these length scales (RMS slopes of $\sim 5^{\circ}$), the first return is much more likely to come from the outer part of the field of view.

Figure 6 shows the relationship between RMS deviation at 1600 m length scale (as measured in the focused bed elevation data) and crossover difference in bed elevation. In both processing approaches, there is a roughness correlation on maximum crossover difference. A stronger relationship is seen for the focused data than for the pik1 data, primarily due to the larger crossover differences seen in the focused data.

The key result of this analysis is that maximum crossover discontinuities may be predicted from along track roughness measurements, and assuming isotropic landscapes, the spatial variation in ice thickness uncertainty may be inferred from sparse, non-crossing lines. For areas of large roughness values, the horizontal position of the aircraft GPS cannot be assumed to represent the location of the ice thickness. This knowledge may help guide future data acquisition, as well as how ice sheet models ingest profile data.

6 Results

We combined the OIA results with older datasets (Tabacco et al., 1998; Steinhage et al., 2001; Blankenship et al., 2013; Leuschen and Allen, 2011b) and used a bicubic interpolation (Wessel and Smith, 1998) to grid the data for an initial examination.

While the outlines of the terrain at the 10 km length scale were visible in Bedmap2 (largely derived from the Tabacco et al. (1998) survey; Figure 2), the addition of the OIA dataset delineates the key features of this landscape. The CST is bound by a sharp, west-facing dissected escarpment approximately 2000 meters high that hosts Candidate B. In this new compilation, this escarpment is more continuous than conveyed in Bedmap2. Much of the base of the CST is very smooth.

The massif underlying Candidate A is bound by a south-west facing 200-300 meter high system of scarps to the south, which capture a system of perched lakes. The massif dips gently to the northeast, and is marked by a series of 200 m deep, 2-3 km wide valleys running toward the north, divided by occasionally large ridges. Under the divide, there is a local 300 m high peak where ice thickness is minimal. Typical RMS deviations at 800 meter length scale are 40 to 50 meters in this region (Figure 8), although locally smoother regions 3-5 km across exist in places. One of these locations is the EPICA Dome C ice core site.

To the southeast, a complex series of troughs with extensive water bodies emerges from the Candidate A massif and opens out into the CST.

7 Conclusions

1. An international program conducted a successful high resolution, multi instrument survey of a key old ice target.

2. Candidate A has some promising sites, including a shallow peak directly under the divide; however, a large number of subglacial lakes, generally rough terrain, and the presence of a distinct basal ice unit present challenges to site selection.

3. Candidates B, C and E either lie on extremely steep and rough topography, or lie downstream of deep, smooth and reflective troughs, implying transport and melt may have compromised the old ice record.

4. The OIA survey presents a useful tool for evaluating uncertainties in radar sounding measurements.

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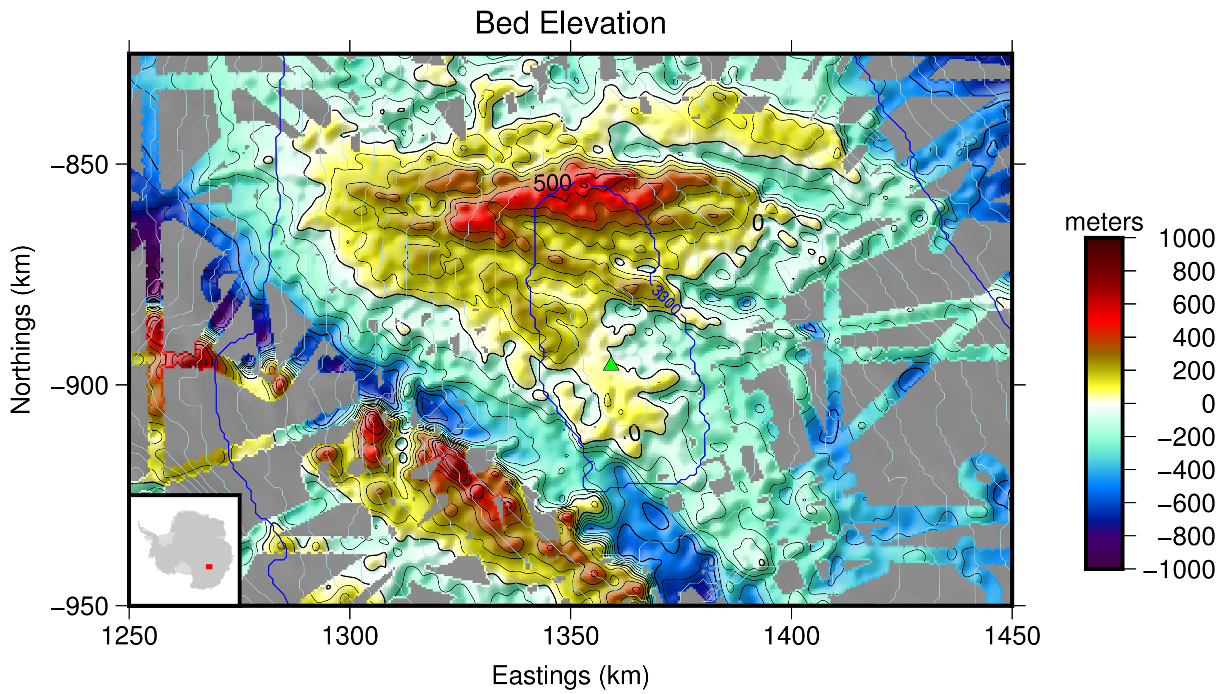

Figure 7. Bed elevation combining all available datasets, including SPRI/NSF/TUD, ICECAP, IceBridge, and unpublished data from Alfred Wegner Institute, British Antarctic Survey and Istituto Nazionale di Geofisica e Vulcanologia. Data has been binned every 1 km, interpolated using a bicubic spline, and filtered at 5 km wavelength. Concordia Station is the green triangle. The background is the MODIS Mosaic of Antarctica (Scambos et al., 2007). Projection is Antarctic Polar Stereographic.

Author contributions. D. Young wrote the manuscript. D. Young, J. Roberts, C. Ritz, E. Quartini and C. Tozer were involved in the ICECAP II data acquisition at Concordia Station. S. Uribani, D. Steinhage and H. Corr contributed older data. All authors helped conceive the experiment and design the flight plans.The authors declare that they have no conflict of interest.

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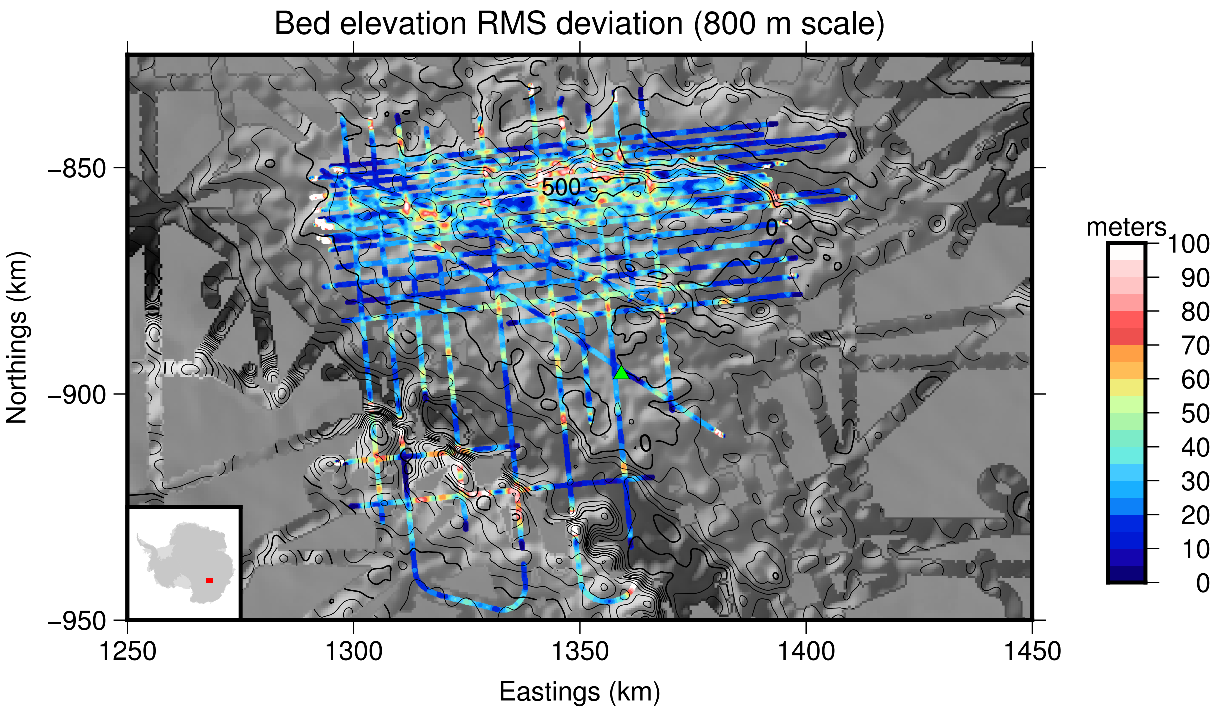

Figure 8. RMS deviation of the bed at 800 m length scale using OIA data only, superimposed on bed elevations (in grayscale) and contours from Figure 7. The region tends to be rougher toward the center of the Candidate A region, and smoother toward the edges and in the troughs. Concordia Station is the green triangle, and lies in a particularly smooth area. The background is the MODIS Mosaic of Antarctica (Scambos et al., 2007). Projection is Antarctic Polar Stereographic.

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