Glaciological characteristics in the Dome Fuji region and new assessment for 1.5 Ma old ice

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Abstract. A key objective in palaeo-climatology is the retrieval of a continuous Antarctic ice-core record dating back 1.5 Ma. The identification of a suitable Antarctic site requires sufficient knowledge of the subglacial landscape beneath the Antarctic Ice Sheet. Here, we present new ice thickness information from the Dome Fuji region, East Antarctica, based on airborne radar surveys conducted during the 2014/15 and 2016/17 southern summers. Compared to previous maps of the region, the new dataset shows a more complex landscape with networks of valleys and mountain plateaus. We use the new dataset as input in a thermokinematic model that incorporates uncertainties in geothermal heat flux values in order to improve the predictions of potential ice-core sites. Our results for obtaining an old ice core show that especially the region immediately south of Dome Fuji station persists as a good candidate site. An initial assessment of basal conditions revealed the existence several wet-based areas. Further radar data analysis shows overall high continuity of layer stratigraphy in the region. This indicates that extending the age–depth information from the Dome Fuji ice core to a new ice-core drill site is a viable option.

1 Introduction

To better constrain the response of the Earth's climate system to continuing emissions, a better understanding of past climate change is essential. A key advance would be to understand the transition in the climate response to changes in orbital forcing during the 'mid-Pleistocene transition' (900 to 1200 thousand years ago). Marine records indicate that during this time the periodicity of the glacial cycles changed from 40 ka to our current 100 ka (e.g. Lisiecki and Raymo, 2005). The driver of this change is not well understood and in particular the role of the atmospheric CO_2 and other greenhouse gases is of great interest. Therefore a key goal in the ice-core community is to retrieve a continuous climate record of this transition since only ice cores contain the unique quantitative information about past climate forcing and atmospheric responses (Wolff et al., 2005). An Antarctic ice core extending 1.5 Ma back in time (termed the "Oldest Ice" core) would provide not only a local Antarctic
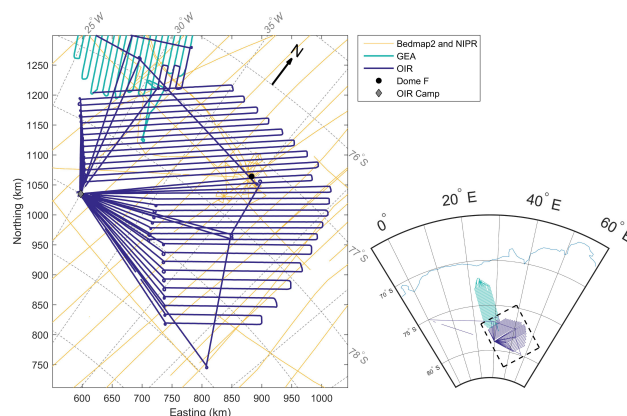
Figure 1. The Dome Fuji region in East Antarctica (using WGS84 and for the left-hand figure a polar stereographic projection with standard parallel of -70°). The map shows the coverage of the new radar survey flightlines in 2014/15 (green) and 2016/17 (blue), and the yellow lines show the Bedmap2 data (Fretwell et al., 2013). Dome Fuji station and the OIR field camp are marked with a black dot and a grey diamond respectively.

climate history but also global greenhouse gas concentrations (Fischer et al., 2013). This would be key to unravel the linkages between the carbon cycle, ice sheets, atmosphere and ocean behaviour. However, so far continuous ice-core records that may provide essential evidence about past mechanisms of climate change more than 1 Ma ago, have not been retrieved.

Under the umbrella of the International Partnerships in Ice Core Sciences (IPICS) the European "Beyond EPICA – Oldest
5 Ice" (BE-OI) consortium and its international partners aim to retrieve an ice core up to 1.5 Ma old. As part of the pre-site survey plan, several extensive airborne operations have already been carried out. Campaigns have been conducted in the Dome C region, revealing several sites of interest and pinpointing areas for targeted exploration (Young et al., 2017), and extending the known ages of the EPICA ice core to surrounding sites (Cavitte et al., 2016). Results from these surveys have provided additional constraints for modelling efforts to improve site predictions (Parrenin et al., 2017) or to estimate geothermal
10 heat fluxes (Passalacqua et al., 2017). In the region around Dome Fuji (Fig. 1), the subglacial topography has so far been undersampled. The latest compilation of Antarctic ice thicknesses (Bedmap 2, Fretwell et al., 2013) relies mainly on Soviet airborne data from the 1970s with a large navigational uncertainty, and on ground-based Japanese surveys with a limited spatial coverage. Here, we present an updated ice thickness dataset for the Dome Fuji region including new data from two radar surveys carried out by the Alfred Wegener Institute, Helmholtz-Centre for Polar and Marine Research (AWI). In this region,
15 there is a likely presence of old ice according to earlier evaluations (Fischer et al., 2013; Van Liefferinge and Pattyn, 2013). We use the new dataset to update this prediction and issue recommendations for future field campaigns in the region.

2 Ice Thickness

2.1 Observations and Methods

The new topography relies primarily on datasets from two field campaigns, conducted during the Antarctic seasons 2014/15 and 2016/17 (Fig. 1 green and blue lines, respectively). In both cases the radar instrument was mounted on AWI's Basler BT-67 aircraft. The data from the 2014/15 season were collected as part of the GEA (Geodynamic Evolution of East Antarctica) project, a collaboration between AWI and the Federal Institute for Gesoscience and Natural Resources, Germany (Eagles et al., 2017). In that earlier survey, close to 40,000 km of flightlines were conducted but here we include only the 10 flights that directly intersect our area of interest corresponding to 12,000 km. The more recent survey is part of the Oldest Ice Reconnaissance (OIR) project, a contribution to BE-OI. During this field campaign, measurements were conducted from a temporary camp (located at 79°S, 30°E) 290 km from the Dome Fuji station. A total of 19,000 km of radar data were collected in 26 flightlines. The radar data in both campaigns were collected using AWI's EMR (Electromagnetic Reflection) system (Nixdorf et al., 1999). Radar waves were emitted with a centre frequency of 150 MHz and an amplitude of 1.6 kW as a 600 ns long pulse aiming to return a clear signal from the ice/bedrock interface as well as capturing information on the englacial properties of the ice. The system rectifies the returned energy and applies a logarithmic amplification.

To determine the ice–bed interface, only moderate processing was applied to the data, mainly 7-fold horizontal stacking and modest filtering to decrease noise. The bed returns were picked manually using the seismic software package ECHOS (2014/15 data) or semi-automatic detection routines developed in MATLAB (2016/17 data). The surface returns were automatically determined from the radar altimeter-reading simultaneously operated on the plane, filtered for outliers and smoothed. Subglacial lakes and locations of basal melt were identified based on a manual assessment of the reflection strength of the basal signal. For the calculation of the internal layer continuity index (cf. Karlsson et al., 2012) the logarithmic value of the stacked data was used. The top and bottom 20% of the ice column was discarded in the calculation to avoid surface noise and the reduced signal from the echo-free zone (e.g., Drews et al., 2009).

In addition to the two datasets described above, the new ice thickness dataset also includes the data from the Japanese and German surveys that are part of the Bedmap2 compilation. We have not included the Soviet data from the Bedmap2 data in our compilation due to the high associated uncertainty in location. The ice thickness was constructed in the following way: The difference between the surface and the bed signal was converted from two-way travel time to distance assuming a signal velocity in ice of $1.67 \cdot 10^8$ m/s with a firn correction of +10 m following Fretwell et al. (2013). We assume that the thickness has not changed between time of data acquisition – a reasonable assumption given that elevation changes at Dome Fuji are less than 0.25 m/a (e.g. Helm et al., 2014), too small to be detectable since the pulse length of the system is about 50 m. The data were subsequently regridded to a 500 m resolution grid using a kriging interpolation scheme and merged with the Bedmap2 topography. The merging of the datasets was carried out by interpolating the Bedmap2 data to a 500 m grid. A weighed mask was then constructed wherein grid points more than 50 km from our survey points were assigned the Bedmap2 value, and grid points less than 20 km from our survey were assigned values from our newly interpolated data. Finally, the grid points

in-between were assigned a linear combination of the two datasets with decreasing weight on OIR data with increasing distance from the OIR data points.

2.2 Uncertainties

Analysis of values at crossover points gives an insight into the uncertainty in the picked bedrock topography. We consider all
5 points within 50 m of each other to be crossover points following Fretwell et al. (2013). The mean difference in crossover points for the GEA-OIR surveys is -5 m, although for 17% of the crossover points this difference exceeded 100 m. We ascribe this difference to geometrical effects of flightline orientation since we observe that flightlines intersecting each other at oblique angles have a larger thickness difference than those that are almost parallel. The standard deviation is 80 m although we note that only the same 17% of crossover points lie outside the standard deviation. The mean difference between the gridded ice
10 thickness and the individual data points from the German and the Japanese surveys is -5 m indicating that the gridded data underestimate the ice thickness compared to the flightlines. The standard deviation is 142 m. The high value for the standard deviation is an inevitable result of the smoothing introduced by the kriging interpolation scheme.

The difference between GEA-OIR and Bedmap2 is upwards of ± 800 m in some areas, with a mean difference of 20 m, a mean absolute difference of 136 m, and a standard deviation of 177 m. This difference is undoubtedly due to the Soviet data included
15 in Bedmap2. Comparison between the Soviet flightlines and the OIR and GEA surveys shows that only slightly more than 100 points qualified as crossover points. For these points, the mean difference in ice thickness between the points is -5 m with a standard deviation of 193 m. This larger standard deviation is likely due the poorly resolved bed rock and the large navigational uncertainty in the Soviet flightlines. This fact formed part of the reason for our decision to exclude the Soviet data from our final data product.

20 We performed a similar crossover analysis of the surface elevation measured in the GEA-OIR surveys. Here, we find a mean difference of less than 1 m with a standard deviation of 2.5 m. Thus, the uncertainties in the surface reflection measurements are negligible compared to uncertainties in the bed picking. Based on this we assign an uncertainty of 142 m to the OIR ice thickness.

2.3 Results and Characteristics

25 The resulting ice thickness is displayed in Fig. 2A and in the following we refer to this dataset as the OIR (ice thickness) data. The difference between the OIR and the Bedmap2 datasets is shown in Fig. 2B. The largest differences are to the west of Dome Fuji between 30°W and 35°W, and 77°S. In the immediate vicinity of the station, differences are smaller due to the high resolution data from Japanese ground-based surveys that were included both in the Bedmap2 and the OIR compilations. The improved horizontal resolution of the OIR survey reveals a landscape with ice thicknesses varying between 2000 m and 4000 m
30 with an average ice thickness of 3021 m. Immediately south of the Dome Fuji there is an area with shallow ice thicknesses while the ice further to the south and to the southeast and are significantly thicker. North and west of Dome Fuji a complex terrain with a patchwork of thick and shallow ice becomes visible. Since the surface topography in this part of Antarctica
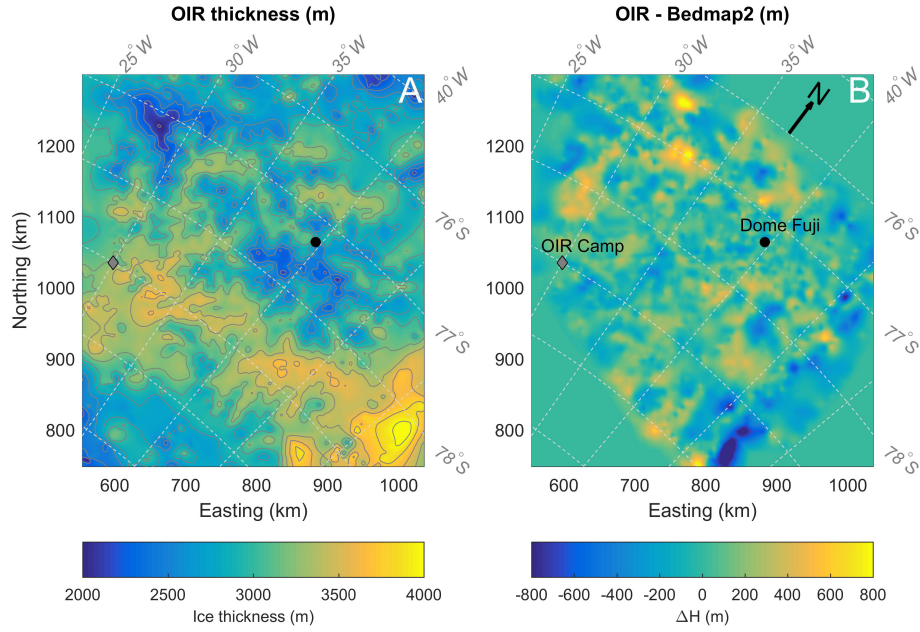
Figure 2. (A) OIR ice thickness on grid (500 m horizontal resolution) and (B) the difference between the OIR ice thickness grid and the interpolated 500 m Bedmap2 ice thickness. Positive values indicate that the OIR data show larger ice thicknesses in an area.

is relatively flat, ice thicknesses is a good indicator of bed topography, thus thick ice indicates valleys while shallower ice indicates mountains or highlands. The OIR dataset shows a system of valleys surrounded by high plateaus.
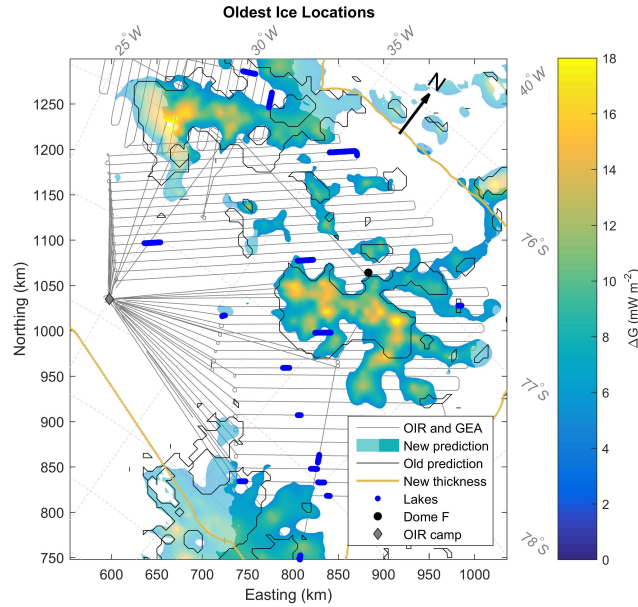
3 New Prediction of Oldest Ice Locations: Method and results

We apply the one-dimensional thermokinematic model described in Van Liefferinge and Pattyn (2013) to the OIR data. The model calculates the minimum required geothermal heat flux that will cause the bed to reach the pressure melting point. It is based on the simplified model of Hindmarsh (1999), wherein the one-dimensional temperature equation is solved while neglecting horizontal advection caused by ice-flow and further assuming steady-state conditions.

$$\kappa\frac{\partial^2 T}{\partial z^2} - w\frac{\partial T}{\partial z} = 0 \quad , \tag{1}$$

where w is the vertical velocity, and $\kappa = K/(\rho c)$, where K is the thermal conductivity, ρ is the density and c the heat capacity of ice.

In the original study by Van Liefferinge and Pattyn (2013), the model was applied to the entire Antarctic Ice Sheet on a 5 km resolution grid. The input parameters were horizontal ice velocities (assumed to be equal to balance velocities in our region of interest), surface mass balance (van de Berg et al., 2006; van den Broeke, 2008) and surface temperature (van den Broeke et al., 2006). The geothermal heat fluxes are from three different studies (Shapiro and Ritzwoller (2004); Fox Maule et al. (2005) and Purucker (2013)). In our study, all above-mentioned parameters with the exception of ice thicknesses are identical to the fields

Figure 3. Updated predictions of possible Oldest Ice locations in colours compared to the prediction of Van Liefferinge and Pattyn (2013) outlined in black. The colour scale show the values of ΔG, semi-transparent colours show areas with a threshold horizontal ice-flow velocity of <2 m/a, fully saturated colours show areas where the threshold is <1 m/a. Blue dots show lake locations identified from the radar data, the extent of the OIR dataset is outlined with a yellow line, i.e., predictions outside the line are based on Bedmap2 values (cf. Fig. 2B).

used in Van Liefferinge and Pattyn (2013) but regridded to 500 m resolution using nearest neighbour interpolation.

The result from the calculation of the minimum geothermal heat flux is denominated G_{min}. It is compared to the three different geothermal heat flux datasets, as well as G_{mean} the average of the three datasets and σ_G their standard deviation. The difference ΔG is then defined as

$$\Delta G = G_{min} - G_{mean} \quad .$$

Potential candidate sites for Oldest Ice are assumed to be areas where ΔG is larger than 5 mW/m^2 and the standard deviation between the different geothermal heat flux datasets is low ($\sigma_G < 25$ mW/m^2). The number of sites is further constrained by only considering areas where the ice thickness is above 2000 m and the horizontal ice-flow velocities are <2 m/a. We refer readers to Van Liefferinge and Pattyn (2013) for an in-depth discussion about the choice of these parameter values.

5   The result of the model applied to the OIR data is shown in Fig. 3 in colours with black lines outlining the prediction of Van Liefferinge and Pattyn (2013) using Bedmap2. The colours of the figure show the value of ΔG. Larger values of ΔG indicate that based on current observations it is likely that the geothermal heat flux is so low that the temperature of the bed is below the pressure melting point. Note that the old prediction is based on both the simple model presented above and results from an ensemble of runs with a more advanced three-dimensional ice-flow model. The new prediction roughly outlines the one based

10 on Bedmap2. The areas of high likelihood of Oldest Ice fall into the same three areas: one approximately 250 km to the west of Dome Fuji, one in a large sector immediately south of Dome Fuji and one approximately 200 km further to the south. Notably,
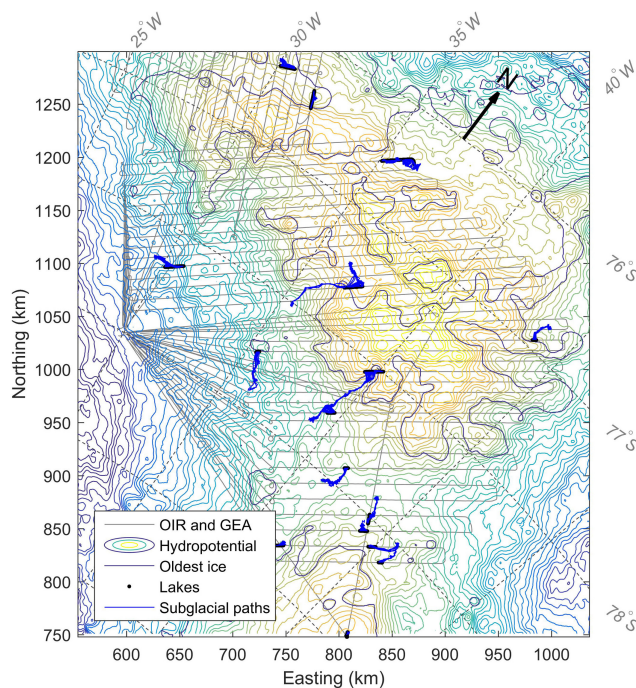
Figure 4. The hydropotential (coloured contours) with the new Oldest Ice prediction outlined in black. The identified water-filled areas are shown with black dots and the drainage routes of the water with blue lines.

the area to the west has decreased in size and areas that were considered likely to contain old ice are now no longer probable candidates for the chosen conditions. The two other areas have increased slightly in size. However, repeating the ensemble runs with the OIR dataset might modify this prediction but that is beyond the scope of this study.

4   Basal conditions and internal layering

5   In order to make the best informed decision on the optimum drill site for retrieving Oldest Ice, we now return to the radar data for additional information. Based on a manual assessment of basal signal reflection strength and specularity of the signal (cf., Siegert et al., 2005), we have identified several areas that exhibit signs of basal melt and/or the presence of a subglacial lake (blue dots, Fig. 3). Previous studies have also identified lakes in the region (Siegert et al., 2005; Fujita et al., 2012) but our analysis adds several new locations. The identification of these "wet areas" is somewhat subjective and probably

10 underestimates the amount of liquid water present at the bed. Assuming that the subglacial water follows the steepest gradient in the hydropotential (Shreve, 1972), we estimate the potential drainage routes of the water. Fig. 4 shows the hydropotential (coloured contours), subglacial water-filled areas (black dots) and their drainage routes (blue lines). The updated Oldest Ice prediction is outlined in black. Although several water-filled areas are in the vicinity of sites that may contain Oldest Ice, the water is draining away from these regions, indicating that subglacial water is not easily introduced to the sites.
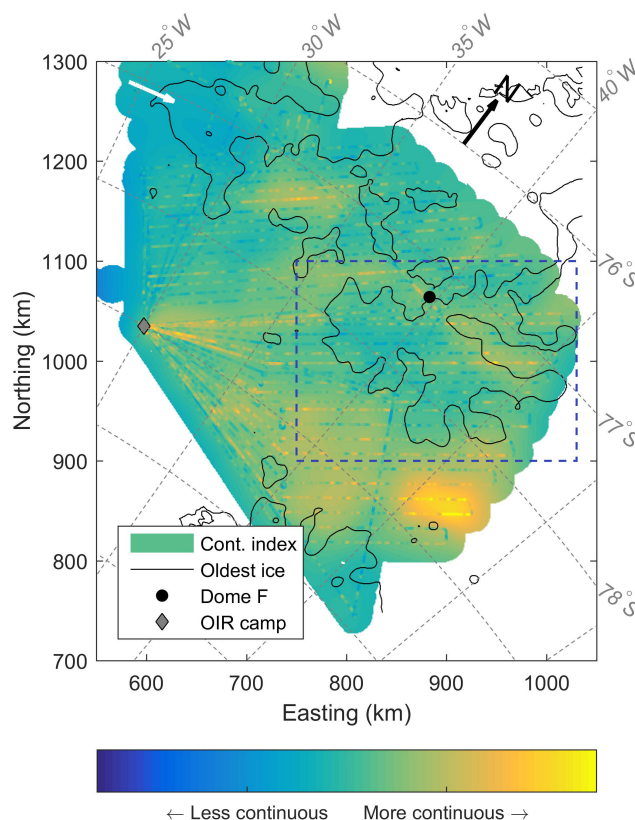
Figure 5. Continuity index of the internal layers in the OIR radar data. The index has been smoothed with a horizontal window of 100 samples (∼25 km), and gridded onto a 500 m resolution grid. Here, yellow colours indicate highest layer continuity. The dashed box shows the location of Fig. 6

One key priority for drilling for an Oldest Ice core is not just the existence of old ice but also a sequentially stacked and undisturbed ice column. The internal stratigraphy of the ice, as imaged by the radar data, may provide a valuable constraint. The radar data are therefore analysed for layer continuity using the method of Karlsson et al. (2012). This automatic method gives an indication of the continuity of the layers, i.e., how coherent and easily traceable they might be. The analysis was

5   conducted only on the OIR data collected during the 2016/17 field season since the method relies on consistency in the radar system settings and processing chain in order to be comparable between flightlines. Fig. 5 shows the continuity index smoothed by a moving window of 100 horizontal samples (∼25 km), and then gridded into a 500 m grid. Evidently, the layer stratigraphy southeast of Dome Fuji is markedly more continuous than layers north and west of the station. Indeed, the candidate sites for the Oldest Ice do not have lower layer continuity compared to some of the regions outside of the candidate sites. However,

10   it should be emphasised that this does not preclude tracing of the layer. The continuity index merely indicates that there are potentially fewer well behaved layers, or that in order to resolve the layers a survey would be needed with higher vertical or horizontal resolution on the order of metres and kilometres, respectively, for example, by ground-based radar.

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5   Implication for ground-based Oldest Ice surveys

Based on the OIR ice thickness dataset, we identify two regions with the best potential for containing Oldest Ice. The most promising is also the most easily accessible region: the region immediately south and southeast of Dome Fuji (blue box, Fig 5). For this region, we favour two areas outlined with white rectangles in Fig. 6. According to the thermokinematic model (cf. Fig. 3), the value of ΔG is large here, thus the uncertainty in geothermal heat flux is less important for the robustness of the prediction. The proximity to the ice core site also implies that extending the age–depth information from the ice core to a new drill site would be relatively straightforward. Especially the area "II" where the distance is small and the bed topography relatively smooth is a promising site.

The second region with a potential for Oldest Ice is the site west of Dome Fuji (white arrow, Fig. 5). In the western part of this area, values of ΔG are also high. However, two properties make it less favourable: Firstly, the horizontal surface velocities approach and exceed 2 m a^{-1} in this area, increasing the travel distance of the particles and thus making interpretation of an ice core more complicated; secondly, the ice is relatively thin in the region (typically less than 2.5 km) which may prove problematic for obtaining an adequate age resolution in an ice core. Finally, the distance from Dome Fuji station is several hundreds of kilometres, crossing an area of thick ice and rough bed topography. This makes tracing internal layers from Dome Fuji challenging. A targeted campaign with radar systems optimised for layer clarity would be necessary to improve transfer of age–depth information. Even so, layer tracing has been achieved across equal or longer distances in this part of Antarctica (e.g., Fujita et al., 2011; Steinhage et al., 2013) although not for very deep layers. To verify that the two regions could indeed provide a suitable drilling target for IPICS Oldest Ice objectives, we recommend first further investigations in these two regions. High-resolution radar measurements, ideally from the ground, are needed to identify the layer integrity especially in the basal region, i.e. the lowermost 20% of the ice. Temperature measurements in boreholes in the upper ∼600 m of the ice column need to be merged with measurements of the vertical velocity by phase-sensitive radar systems (e.g., Nicholls et al., 2015). Using those data sets with ice-flow modeling and the age–depth distribution extrapolated from the Dome Fuji ice core would provide better estimates of the age near the bed as well as the respective annual layer thickness, which constrains the applicability of currently available ice core analytics (Fischer et al., 2013). This would provide further constraints to localize areas suitable for rapid access drilling (e.g., Schwander et al., 2014) to be deployed in a second step, which would enable a preliminary analysis of climate proxies and thereby constrain the age of the ice at the sample site by comparing directly with marine climate records.

6   Conclusions

A new ice thickness dataset for the Dome Fuji region has been constructed from airborne radar data with the aim to improve predictions of sites that may contain ice that is older than 1.5 Ma. The new data resolve the topography in substantially higher detail than previously published data, revealing a landscape of valleys and highlands. A manual assessment of the data also identified several areas exhibiting signs of the presence of subglacial water, and our analysis indicates that any subglacial water drains away from potential Oldest Ice sites.
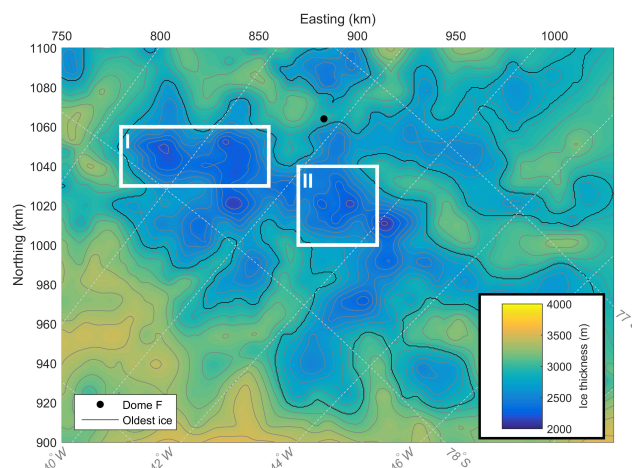
Figure 6. Ice thickness in the area close to Dome Fuji station. The updated Oldest Ice prediction is outlined with black. The white boxes indicate the two most favourable Oldest Ice spots according to our analysis (cf. Fujita et al., 2012).

We use the new data to force a thermokinematic model and update the prediction for candidate sites. Based on the model results, we presented a new assessment of areas in the Dome Fuji region where the presence of ice older than 1.5 mio. year is likely. We identified two regions where the available margin for geothermal heat flux uncertainties is large enough to sustain old ice over several glacial-interglacial cycles. One such region is south of the Dome Fuji station, and within this region especially two areas are of substantial interest. We recommend further targeted investigations to these areas to ascertain layer continuity and to establish approximate age–depth information.

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