

In the reply, the referee's comments are in italics, our response is in normal text, and quotes from the manuscript are in blue.

Review of Where is the 1-million-year-old ice at Dome A? Liyun Zhao, John C. Moore, Bo Sun, Xueyuan Tang and Xiaoran Guo

The study aims to locate areas around Kunlun Station that contain ice older than 1Myr, and the manuscript describes results from simulations with the Elmer/Ice model, a 3D, thermomechanical, Full-Stokes, finite-element model. The model parameters are constrained by observations of surface velocity, ice fabric and radar isochrones. The authors test different ice fabrics and geothermal heat fluxes and conclude through the comparison with observations that the geothermal heat flux is likely between 55mW/m² and 60mW/m². From the model results, areas that potentially contain ice older than 1Myr are identified based on these two geothermal heat flux values. Overall, the manuscript is well written and is definitely of interest to the glaciological community especially those concerned with ice-core sites and the retrieval of "the oldest ice". I have some main points that I would like to see addressed, as well as some minor points that might improve readability.

Main points

I am missing a more thorough discussion of the uncertainties or rather the confidence the authors have in their results (Figs. 6 and 8). Firstly, a comparison with the results from van Liefferinge and Pattyn (2013) would be interesting in order to give insights into how coarse vs. fine grid, and shallow-ice vs. full-Stokes might affect results.

Reply: We add a discussion of the uncertainties in an extended **uncertainties** section, including comparison with Liefferinge and Pattyn (2013), and other assumptions and limitations:

Our approach here is relatively sophisticated in terms of ice models presently in use, but there are several limitations that almost certainly mean that details of the simulation will be wrong. We make the key assumption that the ice sheet is in steady-state, and the surface geometry is fixed, which means the surface accumulate rates balances the vertical velocity and it is also fixed in time. However, the basal thermal condition is sensitive to the ice thickness although other simulations of the whole Antarctic ice sheet suggest that elevation changes at Dome A have been less than 50 m over glacial cycles (Ritz et al., 2001; Saito and Abe-Ouchi, 2010.) Transient simulations with varying geometry and surface accumulation rate in the past 800 ka would improve the model result.

We used a spatially constant geothermal heat flux. Although geothermal flux may over kilometer scales, it seems unlikely in East Antarctica. For example, Carson et al. (2014) suggest heat flow may vary by a factor of >150% over 10–100 km length scales in East Antarctica. Passalacqua et al. (2017) explored variation in heat flux around Dome C using data from radar surveys, and prescribe uniform geothermal heat flux over 10 km

scales. Schroeder et al. (2014) similarly infer geothermal heat flux variability from radar surveys over Thwaites glacier in West Antarctica, which is proximal to the Mount Takahe volcano that was active during the Quaternary, finding heat fluxes could double over ranges of about 20 km. We do not expect any recent magmatic activity in the Gamburtsev Mountains, and the situation of Dome C is probably a reasonable analogue. However there is simply no data to constrain heat flux around Dome A, and hence modelled thermal structure, ice viscosity and age-depth profile. Liefferinge and Pattyn (2013) explored the uncertainty in existing geothermal heat flux data sets and their effect on basal temperature with a spatial resolution of 5 km. The basal temperature was calculated using the steady-state thermodynamic equation in which ice flow velocity is calculated from the shallow-ice approximation. The mean geothermal heat flux of the three existing datasets at Dome A is about 45 mWm^{-2} , with root mean square error of about 20 mWm^{-2} . Their modelled basal temperature at Dome A is about -10°C corrected for the dependence on pressure with a root mean square error of about 6°C . Due to the coarse resolution (5 km) used in the whole Antarctic simulations of Liefferinge and Pattyn (2013), the modelled basal temperature does not have obvious spatial variation across the Dome A region at scales of hundreds kilometers.

The Gamburtsev Mountain is characterized by large spatial variability in bedrock topography, which means that a full-Stokes model that considers the all the stress components is better able to capture the ice dynamics than does the shallow-ice approximation (e.g., Zhao et al., 2013). In our study, large variations in basal temperature are simulated using a full-stokes model run at around 500 m resolution. The basal thermal state is then very sensitive to geothermal heat flux (Sun et al., 2014), which we explored using 45, 50, 55 and 60 mWm^{-2} , and which spans the broad range suggested by Liefferinge and Pattyn (2013).

We also use a spatially constant fabric across all our model domain, with transitions between fabrics at two fixed depths taken from those measured at Kunlun station by Wang et al. (2017). As discussed in Section 4.2, this leads to lower confidence in the age of the basal ice in the region south of Kunlun than to the north. This further means that we have more confidence in finding very old ice in the slightly further away northern region of Fig. 6 than to the south of Kunlun.

Our results suggest spatial variability in basal melting, and this may introduce basal accretion in places (Bell et al., 2011), though there is no radar evidence of any basal accretion features in the vicinity, the model could be improved by adding basal hydrology. Basal melting may also introduce sliding at the ice/bed interface, which we explicitly excluded in the model, however, comparison with observed horizontal velocities suggests that this is not an issue. Indeed extraction of sliding rates from inverse modeling using observed velocities would be extremely difficult at Dome A given the very low speeds making satellite interferometry impossible, and the sparse network of GPS locations.

Surface measurements of horizontal velocity do not constrain fabric information in the ice sheet. The influence of fabric is felt in the deeper ice not near the surface. Hence accurate estimates of fabric must rely on observations from the deeper layers, such as radar isochrones, or potentially vertical velocity profiles from phase sensitive radar. These observations together with a flow model allow geothermal heat flux and thence basal temperatures to be estimated over extended regions where assumptions of unchanging heat flux and fabric hold. Testing this hypothesis by tracking the depths of a 150 ka isochrone with the model suggests that fabric and heat flux variations are not very fast on 10 km horizontal scales, but that localized basal melt may complicate this diagnostic method.

The special ice flow conditions at ice divides often leads to the presence of Raymond arches (Raymond, 1983), where older ice is at shallower depth than it is several ice thicknesses away from the divide. These features are visible as uplifted radar internal reflections in profiles across the divide. The strongest Raymond arches show up in high-accumulation coastal domes where the bed is cold and flat and the ice column is closer to isothermal (e.g. Hindmarsh et al., 2011). However, bed topography is complex at Dome A and Raymond arches are not seen in the observed radar profiles. Furthermore, our ice dynamics package, Elmer-ice, includes all the physics needed to produce the Raymond effect, but we also detect no such feature in transects across the flow divide. We explain this by the Raymond arch being obscured by a combination of rugged basal topography and thermal structure. The strong thermal gradient in the ice sheet tends to reduce the Raymond effect: the tendency of the non-Newtonian rheology to produce a stiff layer near the bed where strain rates are low is counteracted by the tendency of warm temperatures to produce softer ice at depth. The viscosity of the basal ice under the dome was softer than the viscosity of the super cold ice near the surface, but it was still much stiffer than the basal ice away from the dome, causing the old ice to be up-warped somewhat under the ridge. Moreover, the high basal melt rates of 2-3 mm a⁻¹ at Kunlun station draws down ice and obscure the Raymond effect.

Very old and deep ice near bedrock is likely to have experienced vertical mixing via various mechanisms: boudinage between layers with different rheology, small scale non-laminar flow, or regelation around any bed irregularities (Taylor et al., 1993). Although in central Greenland mixing was limited to areas closer than 200 m above the bed, mixing may scale with the vertical relief in the area, which would be very large in the case of the Kunlun site if the ice dome location has migrated by 10 km or more over history. However, the coherence of the radar isochrones to at least 2/3 ice depth from Vostok through Gamburtsev mountains to Dome A suggests that vertical mixing to the topographic scale of the mountains has not occurred. Furthermore analysis of the Epica Dome C ice core revealed continuous stratigraphy to within 60 m of bedrock (Tison et al., 2015), and Parrenin et al. (2017) use that as a basis for locating ice up to 1.5 Ma old in the Dome C region. Comparing our Fig. 6 with the analysis in Parrenin et al. (2017) shows far more locations having ice at least 1.5 Ma further than 200 m from the bed in the vicinity of Dome A than at Dome C. The nearest such ice to the Concordia station

is about 10 km away, compared with 0.5-5 km from Kunlun station.

(2) Secondly, the vertical distribution of ice fabric is not in line with the findings of Wang et al. The authors state that they obtain the same results for two or four layers of fabric but the same what? Age-depth distribution? Surface velocity? 153.3kyr isochrone depth?

Reply: Actually the data in Wang et al. (2017) are problematic in some parts of the survey they do detect coherent signals from 6 or even 4 layers. Experiments with 4 layers T1:T4 show a slightly larger vertical velocity at Kunlun station and deeper depth of 153.3ka isochrones, and almost the same horizontal flow velocity than as with just the top two layers T1 and T2 in our simulations.

We note this in Section 3.3:

The Wang et al. (2017) lowermost T5 and T6 layers are rather weak and indistinct in most of the survey grid. The layer T1 is relatively flat, T2 are relatively flat in half region and has large spatial variation of depth in the other half, while the T3 and T4 layers have large spatial variation of depth and are even missing in some locations around their survey grid. Experiments with 4 layers T1:T4 show a slightly larger vertical velocity at Kunlun station and deeper depths for the 153.3ka isochrone (Section 4.2), and almost the same horizontal flow velocity as with just the top two layers T1 and T2 in our simulations. So here we present simulation results based on a fabric model using just the two upper layers.

Based on the figures in Wang et al. (2017), I would say that an assumption of two layers is fine around Kunlun station but does not appear to be valid further away from the station. Could the variability of T3 and T4 explain the variation in fit with the isochrone? Finally, the fact that the model has a tendency to underestimate the depth of the 153.3kyr isochrones indicates that the model could be overestimating the amount of 1Myr old ice (with the possible exception of triangle 4). Especially triangle 3 is problematic and perhaps by extension the age of the valley.

Reply: Yes we agree this needs emphasizing in the paper. In fact, the variability of T2, T3 and T4 explains all.

Wang et al. (2017) shows that the depth of T2 layer is relatively constant in most of the region to the north of Kunlun Station, but is much deeper to the south. As does the depth of T3.

A deeper depth for T2 would result in larger vertical ice velocity, hence a deeper depth of the 153.3ka isochrones. Triangle 4 is well inside the north part, moreover, it is closest in depths of the T2-T4 layers to those at Kunlun station (see Fig. 9 in Wang et al., 2017). Therefore, the modeled depths of the 153.3ka isochrones in triangle 4 is as most confidence among the four triangles (Fig. 4). In contrast, triangles 2 and 3 are in the southern region, therefore, the modeled depths of the 153.3ka isochrones are underestimated (Fig. 4). This magnitude of this underestimation depends on the ice

thickness. The underestimation is larger where the ice is thicker (triangle 3) and smaller in triangle 2 where the ice is thinner. This explains why triangle 3 is problematic.

In the text, we add this in section 4.2:

Wang et al. (2017) observed large spatial variability of the depth of the ice fabric layers T2:T4. As noted in Section 3.3, we applied the depth of the top two fabric layers T1:T2 at Kunlun station to the whole region. Wang et al. (2017) show that the depth of the T2 layer is relatively constant in the region to the north of Kunlun Station (which includes triangle 4 in Fig. 4A), but is much deeper in the southern region (including triangles 2, and 3). Smaller T2 layer depth would result in slower simulated ice vertical velocity, hence older ice. Therefore, the modeled depths of the 153.3ka isochrones to the south of Kunlun are underestimated. The underestimation is larger where the ice is thicker (triangle 3) and smaller in triangle 2 where the ice is thinner, see Fig. 4B.

We also add this sentence in Section 4.3

As we discussed earlier in section 4.2, the age in triangle 3 are probably overestimated (Fig. 5C and D). The modeled age inside triangle 4 has the most confidence.
and

There is ice at least 1 million years old ice simulated on the side slopes of the valley below Kunlun station. The closest to Kunlun station being found directly below a point about 380 m away under 55 mW m^{-2} , and 1 km away under 60 mW m^{-2} heat fluxes. However this position is a less reliable part of the domain than the area to the north of Kunlun in triangle 4, where old ice is about 5 km away.

We add the four triangles in Fig.s 5 and 6. The modeled age inside triangle 4 is the most reliable.

We also note this in the Uncertainties

We also use a spatially constant fabric across all our model domain, with transitions between fabrics at two fixed depths taken from those measured at Kunlun station by Wang et al. (2017). As discussed in Section 4.2, this leads to lower confidence in the age of the basal ice in the region south of Kunlun than to the north. This further means that we have more confidence in finding very old ice in the slightly further away northern region of Fig. 6 than to the south of Kunlun.

And Conclusion

Using our favored values for geothermal heat flux and ice fabric, ice this ancient may be found by vertical drilling within 400 m of the present Kunlun drill site, indeed this location would contain much older ice since it seems to be frozen to the bed. However we have more confidence in our simulation of ancient ice about 5-6 km to the north of Kunlun station than the closer sites to the south. Near-basal ice this close to Kunlun may be accessible with a straight forward repositioning of the drilling site (Talalay et al., 2017) rather than the logistics base.

2 Most of the figures are small and hard to interpret. Please add legend and/or title so

that main points of the figures are understandable without consulting the figure caption. The symbol for Kunlun Station, the letters distinguishing the figures and the axes labels are hard to read.

Reply: Actually we followed the submission guidelines of The Cryosphere, but we try to improve the figures as much as we can. We change the size of some figures to make it larger to see in the revision. The figures are small also due to the format of TCD – it is not 100% occupied. We expect the figures will be larger and higher resolution in the final TC version. We add letters of “Kunlun” in Fig. 4b and Fig. 5-8, and distinguishing legends in Fig. 5-7. We make a new Fig. 1A.

3 The structure of the paper could be improved. For example, the introduction and the discussion/conclusion appear fragmented rather than cohesive sections (e.g., the introduction contains a section about Kunlun, then a section about ice fabric and vertical velocities and then another section about Kunlun). I am also missing an introduction to the datasets in Section 2. The surface velocity data, the polarimetric data and the isochrones depths should be mentioned in Section 2 before they are used in Section 4.

Reply: Yes, we agree. The introduction has been reorganized. We have also split and expanded the Uncertainties and Conclusions. We have expanded the Section 2 (Domain, Data and Mesh):

The surface and topography ice thickness in the Dome A region come from both airborne and ground based measurements. The Antarctic Gamburtsev Province Project (AGAP) surveyed the region with flight lines 5 km apart orientated in the north-south direction (Bell et al., 2011) with perpendicular lines every 33 km. Ground-based surveys were done by the 21st and 24th Chinese National Antarctic Research Expedition (CHINARE) in a 30×30 km square along lines typically a few km apart, the along-track radar resolution is 125 m (Sun et al., 2009; Cui et al., 2010). A stake network was also established for ice motion using differential GPS receivers, and data collected in 2008 and 2013 (Yang et al. (2014)). More recently polarimetric radar observations were also collected on 5 km-spaced ground-based survey grid (Wang et al., 2017) using a 179 MHz radar using orthogonal orientated antennae with 17 m along-track spacing. They deduced the existence of 4-6 layers of different ice fabric in their survey, and we make use of these data for the ice dynamics simulation.

The Vostok ice core provides absolute dates for radar internal reflections, and since these radar reflections are often continuous over hundreds of kilometers that can provide age-depth profiles over an extensive region of the ice sheet (e.g. Wang et al., 2017). Isochrones in two 150 MHz airborne radar transects collected by the Alfred Wegener Institute were tracked from Vostok to Dome A (Sun et al., 2014; Wang et al., 2017; Fig. 1A) providing 12 dated layers at Kunlun station. We select the 153.3ka isochrones for detailed analysis making use of polarimetric radar data collected in a set of 4 triangles centred on Dome A and 160 km in length.

Minor points

Lines 13-33: The abstract should also state the aim of the study.

Reply: We add to the abstract:

To investigate the age-depth profile to be expected of the on-going deep ice coring at Kunlun station, Dome A

Line 13 (and other places): age/depth or age-depth?

Reply: we use age-depth uniformly in the revision.

Line 25 and 313: Typo “polarimetric”

Reply: We corrected them.

Lines 35-42: This part of the introduction needs a few more sentences about the background for the search a 1Myr ice, for example, with references to the IPICS white paper and to Fisher et al., 2013 (<https://www.clim-past.net/9/2489/2013/>)

Reply: Thank you. We change this part of introduction as

Finding a continuous and undisturbed million-year old ice core record in Antarctic has been identified by the International Partnership for Ice Core Sciences (IPICS) as one of the most important scientific challenges in ice core research in the near future (<http://www.pages.unibe.ch/ipics/white-papers>). This is because the last 8 glacial cycles are characterized by irregular cycles of roughly 100 ka in length. Both climate and greenhouse gases co-vary closely. Between 900 ka and 1.2 Ma BP glacial cycles are more regular and are paced at significantly higher frequencies (Lisiecki and Raymo, 2005). The relationship between greenhouse gases and ice sheet growth and decay during these times is presently unknown since it can only be derived from the atmospheric record archived in an Antarctic ice core covering this time interval.

The search for a continuous and undisturbed stratigraphic record containing 1 million-year old ice has also interested and challenged the ice modeling communities for several decades (e.g., Van Liefferinge and Pattyn, 2013).

References:

Lisiecki, L. E. and Raymo, M. E.: A Pliocene-Pleistocene stack of globally distributed benthic $\delta^{18}\text{O}$ records, *Paleoceanogr.*, 20, PA1003, doi:10.1029/2004PA001071, 2005.

Lines 56-62: There is no information about the Dome A ice core. Since an ice core has been drilled, is there no information about ice fabric, age-depth profile or temperature from that?

Reply: There is no results or publications from the deep ice core at all as yet, drilling is far from completed, in fact they have not gone very deep so far.

Line 69: Is Parrenin et al., 2017, the correct reference here?

Reply: No, we made a mistake here. We replace it with Van Liefferinge and Pattyn, 2013.

Lines 96-107: What is the original resolution of the AGAP data and the Chinese data? How does the resolution compare to that of the model?

Reply: We add this in the revision (section 2)

The surface and topography ice thickness in the Dome A region come from both airborne and ground based measurements. The Antarctic Gamburtsev Province Project (AGAP) surveyed the region with flight lines 5 km apart orientated in the north-south direction (Bell et al., 2011) with perpendicular lines every 33 km. Ground-based surveys were done by the 21st and 24th Chinese National Antarctic Research Expedition (CHINARE) in a 30×30 km square along lines typically a few km apart, the along-track radar resolution is 125 m (Sun et al., 2009; Cui et al., 2010).

In the model, the inner 30×30 km² region centred on Kunlun station has 300 m resolution, and the outer region 3 km resolutions. So the resolution of the model is comparable with the radar data in the central part of the domain that we focus on.

Line 130: Word missing?

Reply: We add the word “that”. Now it reads

where τ is the deviatoric stress tensor that has a non-linear constitutive relationship with the strain rate tensor

Line 131: Add that the strain rate tensor will be discussed in more detail below.

Reply: Done.

Line 145: Typo: “Gudmundsson”

Reply: Done.

Line 157: what is n equal to?

Reply: n equal to 3. We add it in the revision.

Lines 160-165: These values might be better summarized in a table

Reply: Actually we tested this, but we think that it is more convenient for the readers if the values are shown in the text.

Section 4: I would like a table in this section where different simulations are listed with least-square age error, vertical surface velocity, age at the bedrock and the magnitude of the difference between measured and modelled horizontal velocity. This would allow readers to judge the difference between the model results and how well they agree with observations.

Reply: OK. We add this table (Table 1) in the revision.

Table 1. Modeled and observed isochrones ages and surface velocities at Kunlun.

Simulation	Isochrone RMS error	age (ka)	Modeled-observed surface velocity (mm a ⁻¹)	vertical Horizontal speed error (cm a ⁻¹)	RMS	Modeled age at bedrock (ka)
Kunlun fabric, G=55 mW m ⁻²	10.85	-0.1		4.9		831
Kunlun fabric, G=60 mW m ⁻²	26.00	4.2		2.7		649
Girdle fabric $z_s = 1/3$, G=60 mW m ⁻²	6.88	-1.2		3.9		687
Girdle fabric $z_s = 2/3$, G=50 mW m ⁻²	27.18	-0.9		6.9		1143

Lines 360-364: explicitly refer to the figure that is being discussed (5C, 5D etc.) otherwise it is hard to follow.

Reply: Done.

Line 402: I agree with reviewer #1 re. the comparison with accumulation + basal melt rate.

Reply: We agree with the referee. We made a mistake here. At steady-state, surface vertical velocity equals surface accumulation rate, while vertical velocity at the bottom equals the basal melting rate. We correct it in the revision.

The modeled surface vertical velocity distribution is shown in Fig. 7B and, as discussed earlier (section 4.1), may be compared with local accumulation.

Line 442: please indicate on a figure where this valley is.

Reply: We add the outline of the valley (the contour of 1500 m in bedrock elevation) in Fig. 8A&B – the modeled basal temperature plot.

Line 455: The hydraulic potential should be shown on a figure or in the supplementary material. The description here does not help the reader.

Reply: OK. We add this plot in the Fig. 8C in the revision.

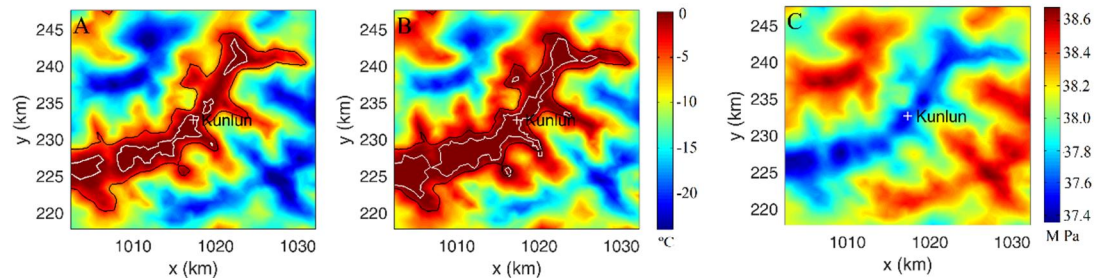


Fig. 8 Basal temperature relative to pressure melting point using Kunlun fabric and a geothermal heat flux of 55 (A) and 60 (B) mW m^{-2} , and the hydraulic potential (C). The bedrock areas at pressure-melting point in A and B are surrounded by a white contour. Kunlun station is marked as white plus sign. The black curve in A and B shows the outline of the valley defined as the 1500 m contour in bedrock elevation.

Line 522: Considering that Dome A has very low accumulation rates, how can an ice core from the area provide the highest resolution record?

Reply: We are comparing to other stratigraphic records such as sediment cores.

However, we delete “and highest resolution” in this sentence

Thus the Kunlun station is well suited to provide the longest continuous stratigraphic record from Antarctica.

Fig. 1: Both figures appear pixelated and especially 1A is not very informative.

Reply: The other referee also complained about Fig. 1. We revised Fig. 1A to show more useful information such as the radar lines connecting to Vostok. The pixilation issue is probably something to do with how TC makes the pdf. In fact when we tested it we see no issues zooming to 500%, but anyway it should be improved in the publication version.

Fig. 2: this figure is hard to read, why not split it into two figures?

Reply: OK. We split it into two plots.