

We thank the reviewer for his careful and helpful comments.

In the response, referee comments are in *italics*, our replies are in normal font, and the revised text is highlighted in light blue relative to the preprint version.

5 *Dear authors,*

I appreciated reading your paper on simulated evidence for ice over 1 Ma in the Dome A region, East Antarctica. This paper provides inputs on the search for the oldest-ice quest ; as we know multiple drilling sites are needed to resolve the puzzle: Dome C, Dome F, South Pole, ... and Dome A are potential candidates. This paper is an increment in the research even if it is not adding a lot of new knowledge since Zhao et al. (2018), the use of radar transect constraints in addition to the 1D model results to delineate promising oldest ice sites is interesting as an approach.

I would suggest the following general and major changes:

1. The GHF parameter, even if not used in the specific 1D model, has to be introduced and discussed, especially since it is used in Zhao et al (2018), this reference being widely used in this manuscript (e.g. figure 7).

15 We have introduced and discussed GHF in the revised manuscript. The importance of GHF is introduced in the Introduction, and its different treatment in the 1D and 3D models is discussed in Sect 5.4. The specific additions are inserted below.

In introduction:

“

20 ...factors that favor the preservation of old ice. Previous studies by Sun et al. (2014) using a full Stokes model showed that, in the absence of basal melting, ice ages at 95% depth in the Dome A region could be constrained to less than 1.5 Ma. Meanwhile, ice with ages of approximately 600-700 ka and low age density may exist near Kunlun Station. Using the same methodology and the best available ice fabric, Zhao et al. (2018) found that within 400 m of Kunlun Station, 1 Ma ice could exist 200 m above the bedrock. Their models are constrained by surface velocity measurements and prescribed GHF. However, surface
25 velocity observations across Dome A are sparse, and GHF exhibits strong spatial variability (Schroeder et al., 2014; Yang et al., 2014). Both ice fabric and GHF were identified as key controllers of deep ice age, with the influence of fabric being comparable to uncertainties associated with GHF (Sun et al., 2014). Different GHF values (50–60 mW m⁻²) produced basal age ranging from 650–830 ka (Zhao et al., 2018). Despite its importance, direct GHF measurements remain extremely limited
30 in East Antarctica. Existing GHF datasets rely on indirect geophysical inversions or glaciological inferences and therefore carry substantial uncertainties (Lösing et al., 2020; Martos et al., 2017). Consequently, the treatment of GHF represents an important source of model uncertainty, which is discussed in Sect 5.4. In contrast, the approach adopted here offers three advantages: (1) the 1D pseudo-steady-state model does not explicitly include parameters for GHF and surface velocity, avoiding the uncertainties inherent in their estimation; (2) it is constrained by dated internal reflecting horizons (IRHs), which

provide a stronger constraints on age-depth structure; and (3) The model has been successfully applied in multiple regions, especially at EDC and LDC where it has been validated.

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In dicussion(Sect 5.4):

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40 Fujita et al. (1999) demonstrated that highly anisotropic fabric structures are widespread in Antarctic ice, and Sun et al. (2014) showed that anisotropy exerts a dominant control on the vertical velocity distribution, particularly at depth, and has an influence comparable to uncertainties in GHF. Zhao et al. (2018) combined different ice fabric configurations with varying GHF values in a 3D model to simulate multiple age–depth profiles at Kunlun Station. Their results show that, across the tested GHF values tested, the reasonable ice age at bedrock spans 650–830 ka. The simulated age-depth profiles diverge minimally in the upper ice column, where they are constrained by surface velocities, but diverge substantially with depth as a function of GHF (Fig. 6 A). Higher GHF increases basal temperatures, reduces the effective viscosity of ice, and enhances the nonlinearity of the vertical velocity profile, resulting in younger basal ages. This results demonstrate the strong sensitivity of deep ice age to both GHF and ice fabric.

45 The 1D model employed in the present study does not explicitly incorporate GHF or ice fabric parameters. Both factors influence the vertical velocity profile and thus affect the simulated age. GHF affects basal temperature and ice rheology, whereas ice fabric controls the ice anisotropic and therefore influences viscosity. Within the 1D inversion, the shape parameter p is optimized to match the observed dated isochrones, and the effects of GHF and ice fabric are partly absorbed into the optimized value of p . However, p simultaneously compensates for the combined effects of neglected horizontal advection, GHF, ice anisotropy, and other model simplifications, and thus cannot be uniquely attributed to GHF or ice fabric alone. Consequently, the present study cannot quantitatively isolate the contribution of GHF to deep ice age as in Zhao et al. (2018) by explicitly varying GHF or ice fabric. This represents an inherent limitation of the simplified physical framework of the 1D model and contributes to the structural discrepancy between 1D and 3D models in this study.”

2. *The use of the SMB parameter of Vostok has to be clarified, I still don't understand why you use it.*

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We thank the reviewer for this comment. We have revised the sentence to clarify that the input is the ice chronology (including both the age–depth relationship and the temporal relative accumulation variations) from the Vostok Ice Core, rather than the surface accumulation rate at Vostok itself. Because Dome A lacks a deep ice core, we need to account for temporal variations in accumulation rates to model the depth–age relationships. For that, we used the temporal variations of accumulation recorded at Vostok, assuming the pattern of accumulation changes over time is similar in the two regions (just with a different scaling factor).

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The revised sentence now is “... , $r(t)$ is derived from ice chronology inputs from the Vostok Ice Core (Bouchet et al., 2023), including both the age–depth relationships and the accumulation profile”.

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3.The comparison with Zhao et al (2018) should be more explicit and quantified: e.g overlap maps, ...

We have substantially expanded the comparison with Zhao et al. (2018) to make it more explicit and quantified. In the Discussion (Section 5.1), we now provide:

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(1) A direct comparison of the 1D and 3D vertical velocity profiles, with a quantitative explanation of the observed discrepancies (Section 5.1.1).

(2) A spatial map of the 1D–3D age differences at 200 m above the bed along the transect, identifying where the two models agree best and where discrepancies are larger (Section 5.1.2, Fig. 7).

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(3) A comparison of the magnitudes of the 1D–3D structural discrepancy against the uncertainties from the 1D model inputs (Section 5.1.3).

The corresponding additions are provided below.

“

5.1 Results Comparison:1D vs 3D

85 5.1.1 Results at Kunlun Station

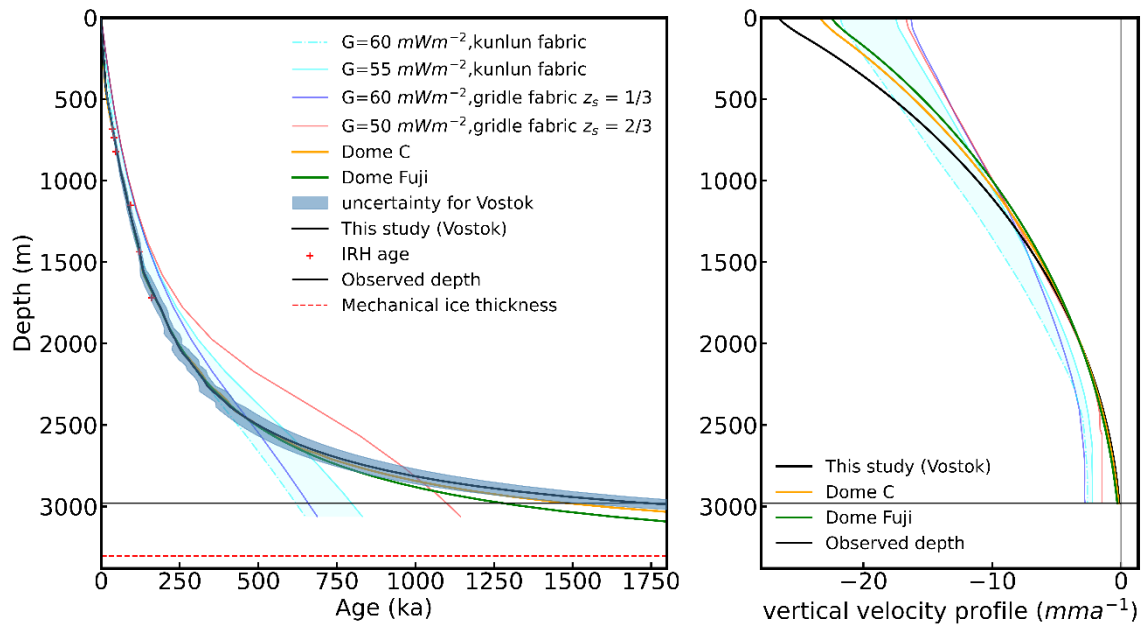


Figure 1. Modeled results at Kunlun Station. The left and right panels show the age–depth and vertical velocity profiles, respectively. Thick lines denote 1D model outputs: black thick lines are from this study, and other thick lines are sensitivity test results for different ice chronologies (Dome Fuji and Dome C), while thin lines represent those of Zhao et al. (2018). Light blue shading indicates the recommended range of age–depth estimates from Zhao et al. (2018), while dark blue shading represents uncertainty in this study (Vostok), arising from uncertainties in input dated IRHs. Black and red horizontal lines denote bedrock and mechanical ice thickness, respectively. Red crosses indicate dated IRHs.

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Among existing studies of ice ages in the Dome A region, Sun et al. (2014) used a three-dimensional full-Stokes model to demonstrate that Kunlun Station provides a high-resolution ice core record of 600-700 ka. However, approximately 5 km north of Kunlun Station, an older but lower-resolution ice core record exists. Our simulations also reflect this result. Zhao et al. (2018) used the same methodology as Sun et al. (2014) to estimate the age of the Dome A region, using data from the C21 radar survey as this study within a 30 × 30 km² area at Dome A. By varying ice fabric and geothermal flux, their simulated basal maximum ice age ranges from 650 to 830 ka, with melt rates of 2-3 mm yr⁻¹.

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Compared with the age–depth curve simulated by Zhao et al. (2018) at Kunlun Station, the age ranges of the curve (Vostok) are similar. Our simulated curve agrees well with the curve (G=60 mWm⁻², Kunlun fabric) at depths above 2500 m (Fig. 6). Below 2500 m depth, our simulated ages increase strongly with depth, significantly exceeding the age of the curve (G=60 mWm⁻², Kunlun fabric). At the bottom of Kunlun, our simulations yield an age of 1737 ± 223 ka and a relatively low melt rate of 0.14 mm yr⁻¹. This differs significantly from the simulations of Zhao et al. (2018). This discrepancy likely arises from the

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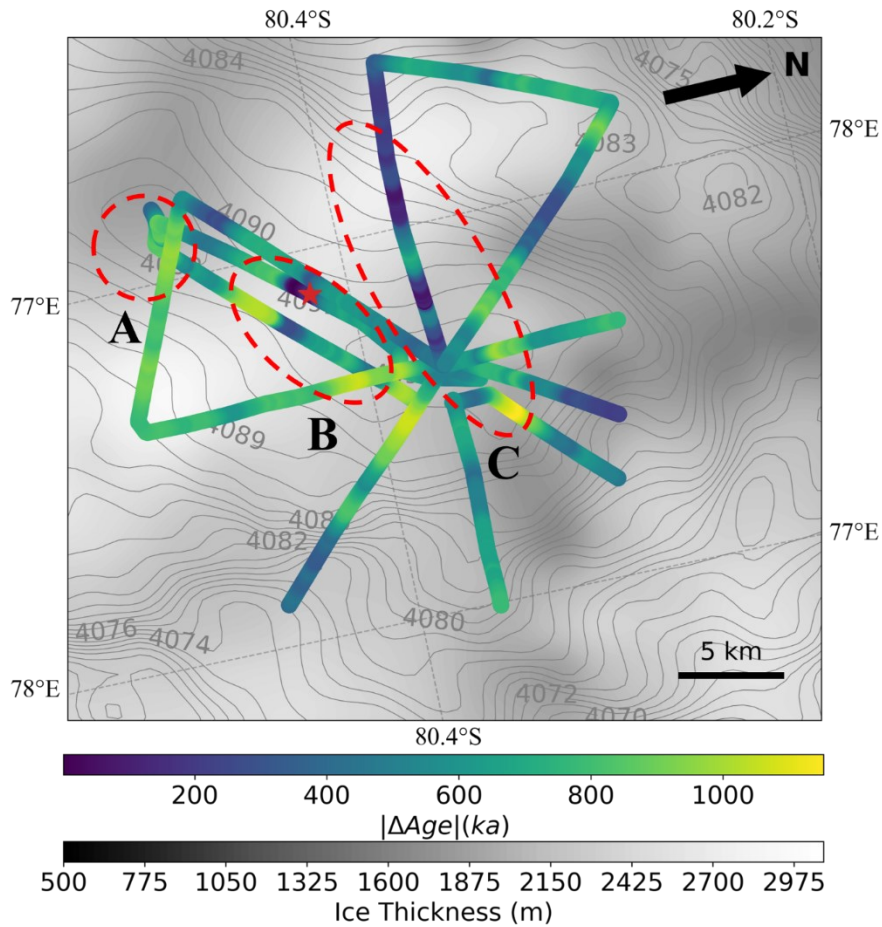
105 lack of IRH constraints at the base of the ice sheet. The best IRH is less than 60% of the ice-sheet thickness at Kunlun Station
with an age of 161 ka. This is significantly shallower and younger than IRHs used in other studies with this model (Chung et
al., 2023; Wang et al., 2023). Due to basal melting, it is generally difficult to preserve old ice at the bedrock. In ice cores drilled
at Dome C, the oldest ice is found 60 m above the bedrock, while in the Greenland Ice-core Project (GRIP), this value is 200m.
Although our simulated age for the oldest ice at Kunlun Station differs significantly from that of Zhao et al. (2018), our
simulated age of 909 ± 113 ka at a depth of 200 m above the bedrock at Kunlun is considered a conservative estimate of the
110 maximum ice age and is relatively consistent with the maximum ice age simulated by others (Sun et al., 2014; Zhao et al.,
2018).

To provide a more comprehensive comparison of the simulation results, we further compared the vertical velocity profiles
derived from the 1D and 3D models. Overall, systematic differences in vertical velocity are observed throughout the entire
depth range, with substantially larger discrepancies in the shallow layers than in the deeper ice. Notably, even within the depth
115 interval constrained by dated IRHs, the two models exhibit significant differences in vertical velocity, whereas their age–depth
relationships remain largely consistent within the same interval (Fig. 6).

The apparent contradiction of significant velocity differences but consistent ages where isochrone constraints exist, can
be explained by two factors. First, the two models are constrained by fundamentally different target variables. The 1D model
directly fits the ages of dated isochrones, and age represents the integral of the inverse vertical velocity. Consequently, the 1D
120 model inversion problem is inherently non-unique: different shapes of the vertical velocity profile can produce the same
cumulative age within the interval constrained by isochrones. In contrast, the steady-state 3D inversion directly constrains the
surface velocity field and obtains a physically self-consistent three-dimensional velocity field through solving the Stokes
equations. The difference in inversion targets implies that the vertical velocity profile inferred from the 1D model may deviate
from a physically self-consistent velocity field, because the inversion only requires agreement in the integrated age signal
125 rather than in the velocity field itself. Second, the integral nature of age reduces the impact of velocity differences in the
shallow layers. The shallow ice constitutes the initial segment of the age integration path, where the integration length is
relatively short. As a result, the cumulative age uncertainty induced by differences in vertical velocity remains limited.
Therefore, within the shallow interval constrained by dated isochrones, the 1D model can reproduce the observed ages by
adjusting the shape of the vertical velocity profile without introducing substantial age discrepancies.

130 In the deeper ice, however, the influence of vertical velocity differences on age becomes more pronounced. Because no
dated isochrone constraints are available at depth, biases in vertical velocity can no longer be compensated for through
adjustments to the profile shape. Instead, these biases accumulate and amplify over the long integration path, causing the ages
simulated by the 1D model to become systematically older. At 200 m above the bed at Kunlun Station, the age difference
between the 1D simulation (Vostok) and the 3D simulation ($G = 60 \text{ mW m}^{-2}$, Kunlun fabric) reaches approximately 261 ka.
135 This offset reflects the structural discrepancy between the two models, which comprises two main components: (1) differences
in model assumptions, particularly the neglect of horizontal advection by the 1D model; and (2) differences in parameter
treatment, including the handling of GHF and ice fabric, which are discussed in Sect. 5.4.

5.1.2 Results along the transect



140 **Figure 2. Ice age difference (1D vs 3D).** This figure shows the absolute ice age difference at 200 m above bedrock between 1D and 3D simulations. Our comparison is confined to the $30 \times 30 \text{ km}^2$ rectangular area centred on Kunlun Station. Within this area, Zhao et al. (2018) adopted a grid resolution of 300 m at the bed, whereas outside this area the resolution is on the order of kilometres.

To evaluate the spatial distribution of the structural discrepancy between the 1D and 3D simulations, we extracted the simulated ages at 200 m above the bed from the 3D simulation ($G = 55 \text{ mW m}^{-2}$, Kunlun fabric) and the 1D simulation (Vostok) along the transect, and calculated the absolute age differences between them (Fig. 7). Overall, the age differences in Areas B and C are significantly smaller than those in the surrounding areas, indicating that the 1D model assumptions are better suited to these two regions. Notably, Areas B and C were also identified as candidate 1Ma old ice sites (Sect. 4.2), which provides additional independent support for the reliability of the simulated ages at these locations. Outside these two regions, the age discrepancies are substantially larger, and their spatial distribution shows no systematic relationship with either surface topography or ice thickness. This spatial pattern likely reflects differences in model assumptions: the 1D model neglects horizontal advection, whereas the 3D model fully resolves the three-dimensional velocity field.

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5.1.3 Sensitivity test at Kunlun Station

In this section, we assess the sensitivity of the 1D simulated ages to two input-related factors: uncertainties in dated isochrone ages and the choice of ice chronology input. For the dated isochrones, the influence of age uncertainty on the simulated results is represented by the shaded region labelled "uncertainty for Vostok" (Fig. 6). The resulting age differences are relatively small in the upper ice column but increase with depth. At 200 m above the bed, the uncertainty range reaches 113 ka, increasing to 223 ka at the bed.

We adopted the Vostok ice chronology as the reference input and also tested other ice chronologies, shown in Fig. 6 as Dome C in yellow and Dome Fuji in green. In these tests, only the accumulation variations (Bouchet et al., 2023; Oyabu et al., 2022) applied to the age-depth profile were changed; the isochrone ages remain tied to the Vostok chronology and cannot be independently re-dated from the other ice cores. The test results show that the simulated age–depth profiles remain broadly consistent in the upper part of the ice column (Fig. 6). Below approximately 2600 m depth, however, the differences become dependent on the selected ice chronology and increase progressively toward the bed. At 200 m above the bed beneath Kunlun Station, switching the ice chronology introduces age differences of up to 104 ka, while at the bedrock the differences reach as much as 459 ka. The Vostok chronology produces older ages in deep ice than the other chronologies. This may reflect the greater uncertainty in the Vostok accumulation-rate history, as it was derived from a flank ice core that is more difficult to model than dome-site records.

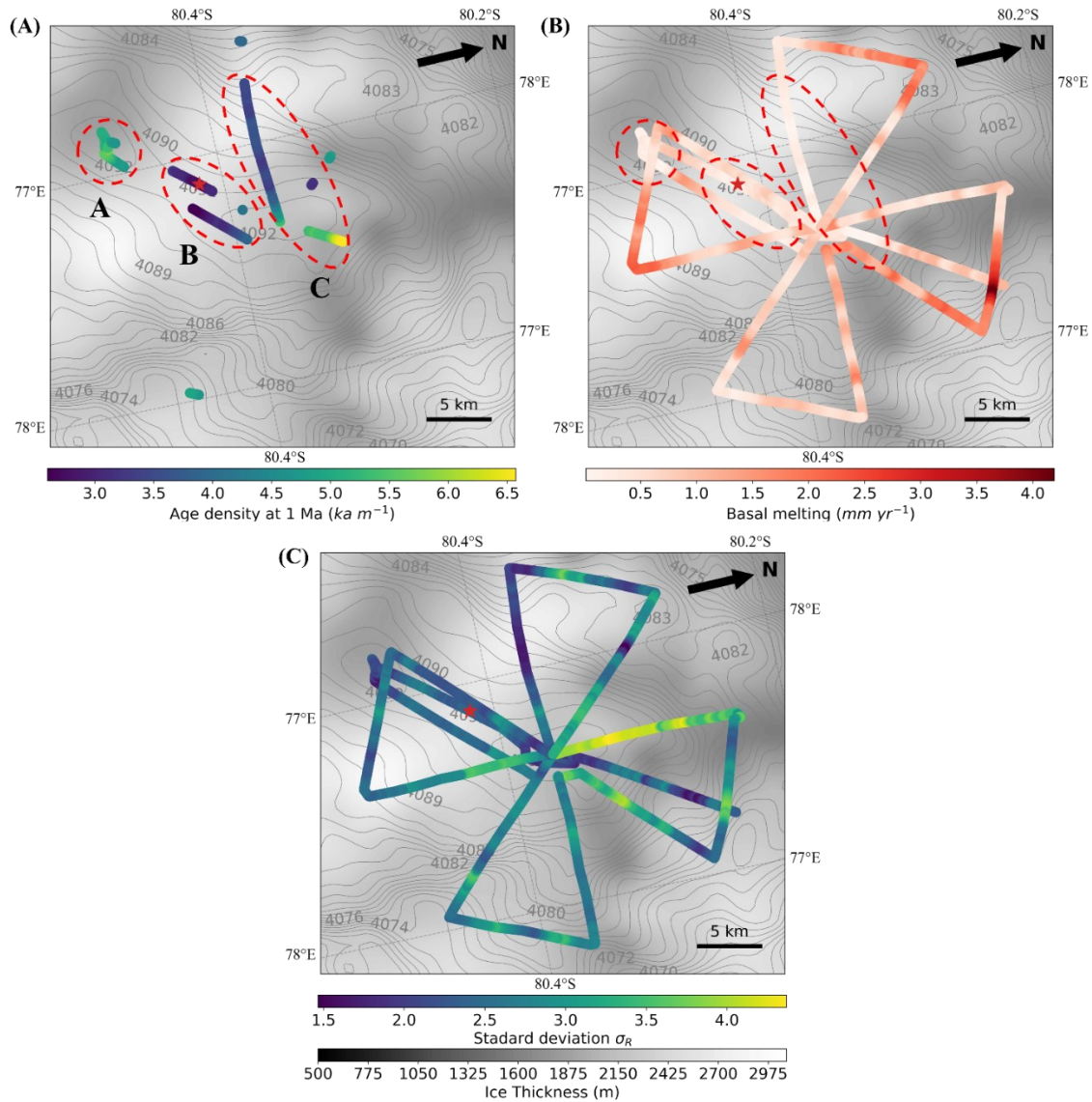
In contrast to the age–depth relationship, the vertical velocity profiles are more sensitive to the choice of ice chronology in the upper ice column, while showing only minor variations in the deeper part. This opposite behaviour arises because the 1D model is constrained primarily by age rather than velocity, and because age represents the integral of the inverse vertical velocity. As discussed in Sect. 5.1.1, variations in shallow vertical velocity have only a limited influence on cumulative age, whereas age becomes highly sensitive to velocity changes at depth.

Among the above factors, the uncertainty associated with dated isochrone ages was propagated into the simulated age envelope and is therefore already included in Fig. 6. The effects associated with ice chronology input differences are not included in the envelope, but are listed here as an independent reference magnitude. For comparison, the structural discrepancy between the 1D and 3D models introduces an age difference of ~261 ka at 200 m above the bed (Sect. 5.1.1). At this depth, the relative magnitudes of the three sources are, from largest to smallest: structural differences between the 1D and 3D models (~261 ka) > isochrone-derived age uncertainty (113 ka) > ice chronology input differences (104 ka).

180 ”

4. All figures need to be revised for clarity (see attached pdf). And in particular; it would be much more interesting to zoom into the area of interest. Locations mentioned in general are too vague in the text, make sure to highlight them on figures as well.

We have revised all figures for clarity. An example of revised Figure. 4 is attached below.



190 **Figure 3.** (A) Age density at 1Ma, (B) Basal melting rate, (C) Standard deviation. The dashed circle marks the potential area for preserving old ice. Area A is 2.5 km around the point ($76.89^{\circ}E, 80.47^{\circ}S$), Area B is 3 km around the point ($77.12^{\circ}E, 80.42^{\circ}S$) and Area C is 8 km around the point ($77.14^{\circ}E, 80.37^{\circ}S$).

195 5. The discussion should include a comparison with other oldest ice sites where we already have studies, data, and in particular Dome C, Dome F.

We have added a comparison with Dome C and Dome Fuji in Section 5.5.

200 This section compares the measured and 1D-simulated oldest ice ages at the three sites, and discusses the inter-site ordering under a consistent modelling framework. The added text is inserted below.

“

5.5 The oldest ice: comparison with Dome C and Dome Fuji

205 Dome A, Dome C, and Dome Fuji are all situated at the summits of the East Antarctic plateau and are considered prime candidates for preserving the oldest ice (Van Liefferinge and Pattyn, 2013). The oldest ice recovered from the EDC core is approximately 800 k(Jouzel et al., 2007), and from Dome Fuji approximately 720 ka (Dome Fuji Ice Core Project Members: et al., 2017). Applying a similar 1D modeling approach, Chung et al. (2023) obtained a maximum simulated age of ~1500 ka at LDC, and Wang et al. (2023b) ~1350 ka at Dome Fuji. At Dome Fuji and EDC, the Lliboutry profile has been shown to significantly overestimate the ice age in deepest part of the ice sheet (Chung et al., 2025).

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Using the same methodology, the present study yields a maximum simulated age of 1737 ± 223 ka at Kunlun Station, with a conservative estimate (at 200 m above the bed) of 909 ± 113 ka. At this depth, the isochrone-derived age uncertainty (± 113 ka) encompasses the spread induced by different ice chronology inputs (104 ka), indicating that the conservative estimate is robust with respect to the choice of ice chronology input. The structural discrepancy relative to the 3D model (~261 ka) is larger but is identified and discussed separately (Sect. 5.1.3).

215

Although the absolute ages are likely overestimated, the relative ordering of the three sites under a consistent framework remains informative: Kunlun Station yields the oldest maximum age, consistent with Dome A having the lowest surface accumulation among the three sites, which prolongs the vertical transit time and favours the preservation of older ice. Taken together, the physical conditions at Dome A and the consistent inter-site ordering of the 1D simulated ages indicate that Dome A has the greatest potential for preserving ice older than 1 Ma.

220

”

I attach a detailed point-by-point review of the paper.

Best,

225 *Brice Van Liefferinge*

-Line 19, remove comma

Done.

230 -Line 22, I recommend the use of "resolution" everywhere to be consistent with your co-authors' papers such as:
<https://tc.copernicus.org/articles/17/3461/2023/>

We have now made the wording more consistent with previous work.

In Line 25, we have rephrased to "...the maximum age density of 20 kyr m⁻¹ required for paleoclimate reconstruction."

In Line 69, we have rephrased to "Meanwhile, ice with ages of approximately 600-700 ka and low age density may exist near Kunlun Station."

235 -Line 42-43, Please add a link between the two sentences, as the link is not clear

We have added a sentence in the middle. The corrected sentence is "...1.2 million years old (Chung et al., 2023). It has also been suggested that there is a 200 m thick layer with different ice dynamic characteristics as the base of LDC, though comprehensive analysis of the LDC ice core is not yet available. Analysis of".

240 -Line 51, Please provide the full name (North Patch)

The revised sentence is "...old ice location, The North Patch (NP) (Chung et al., 2023)."

245 -Line 52, You mentioned 1D models (plural) in Line 50; here only one, please state which ones were used.
The revised sentence is "Wang et al.(2023) used the same model as Chung et al. (2023)...".

-Line 59, surface
We have added it.

250 -Line 60, please quantify the SMB
The revised sentence is "...and an extremely low surface mass balance of 25 mm yr⁻¹ ice equivalent."

-Line 62, also the SMB, see later comment
The revised sentence is "Van Liefferinge and Pattyn (2013) showed that the best locations to look for old ice are where the
255 heat flux is low and the ice thickness is relatively large (>2000m), ..."

-Line 69, The community decided to use "geothermal heat flow (GHF): White Paper Antarctic Geothermal Heat Flow: Future research directions <https://nora.nerc.ac.uk/id/eprint/527967/>

In Line 64, we changed "heat flux" to "geothermal heat flow (GHF)" as this is it's first appearance.

In Line 71, we have changed "geothermal flux" to "GHF".

260 -Line 70, please add references

Done. The revised sentence is "...and surface velocity observations are sparse (Schroeder et al., 2014; Yang et al., 2014)".

265 -Line 72, *It is not clear why the uncertainty will be lower because the model is well established, what is the link between the two ? The GHF, SMB, surface velocities, ... constraints are different from site to site*

We agree with the reviewer that a well-established model does not guarantee lower uncertainty, because GHF, SMB, and surface velocity constraints differ from site to site.

270 We have therefore removed the statement linking model validation to reduced uncertainty. Instead, we now expand the discussion of GHF and ice fabric in the Introduction to highlight their importance and their treatment as sources of model uncertainty, and direct the reader to Sect 5.4 for a detailed discussion.

-Line 73, *remove the "f"/ add a space/ please be consistent in the terms you use: 1D steady-state model or Isoinv1D model like in the abstract*

275 Done. We have used 1D-steady-state model.

-Line 74, *please add Parrenin and other (2006,2017).*

We have changed "Chung et al.(2023)" to "Chung et al.(2023) and Parrenin et al (2006, 2017)"

-Line 94, *please check the font of all subscript text of the document*

280 Done.

-Line 101, *First mentioned by Fujita and others; 2000: A summary of the complex dielectric permittivity of ice in the megahertz range and its application for radar sounding of polar ice sheets, in Physics of Ice Core Records*

285 *You can also cite: Cavitte and others; 2016: <https://www.cambridge.org/core/journals/journal-of-glaciology/article/deep-radiostratigraphy-of-the-east-antarctic-plateau-connecting-the-dome-c-and-vostok-ice-core-sites/1B82F2326F81986302EA370860086017> . This paper is clearly relevant for your study.*

The revised reference is "...0.168-0.1695 m/ns in ice sheet (Cavitte et al., 2016; Fujita et al., 2000; Winter et al., 2017) ."

-Line 107, *The map needs improvements for clarity:*

290 1) *add more lat and lon coordinates*

2) *the legend is meaningless (blue and dark blue ?)*

3) *use same terminology as in the text and the figure caption: C21DA, C21KL*

4) *in the "mini" map it should say Kunlun (or Dome A) and not Vostok*

5) *is the bedrock elevation or the ice-thickness the important parameter you should be showing here?*

295 We have corrected the issues raised in points (1)-(4). For point (5), They are all important, we have used the ice thickness in the Figure. 1 and bedrock elevation in others. All figures have been fixed.

-Line 119, Missing a dot

Done.

300

-Line 125, It is a big assumption that should be discussed in term of uncertainties, ...

We have performed sensitivity tests using different ice-core chronologies (Vostok, Dome C, and Dome Fuji) in Sect 5.1.3. We also have discussed its uncertainties and compared its magnitude with uncertainties caused by structural discrepancy in models and dated IRHs. The revised sentence are as follow:

305 “

5.1.3 Senseitivity test at Kunlun Station

In this section, we assess the sensitivity of the 1D simulated ages to two input-related factors: uncertainties in dated isochrone ages and the choice of ice chronology input. For the dated isochrones, the influence of age uncertainty on the simulated results is represented by the shaded region labelled "uncertainty for Vostok" (Fig. 6). The resulting age differences are relatively small in the upper ice column but increase with depth. At 200 m above the bed, the uncertainty range reaches 113 ka, increasing to 223 ka at the bed.

We adopted the Vostok ice chronology as the reference input and also tested other ice chronologies, shown in Fig. 6 as Dome C in yellow and Dome Fuji in green. In these tests, only the accumulation variations (Bouchet et al., 2023; Oyabu et al., 2022) applied to the age-depth profile were changed; the isochrone ages remain tied to the Vostok chronology and cannot be independently re-dated from the other ice cores. The test results show that the simulated age–depth profiles remain broadly consistent in the upper part of the ice column (Fig. 6). Below approximately 2600 m depth, however, the differences become dependent on the selected ice chronology and increase progressively toward the bed. At 200 m above the bed beneath Kunlun Station, switching the ice chronology introduces age differences of up to 104 ka, while at the bedrock the differences reach as much as 459 ka. The Vostok chronology produces older ages in deep ice than the other chronologies. This may reflect the greater uncertainty in the Vostok accumulation-rate history, as it was derived from a flank ice core that is more difficult to model than dome-site records.

In contrast to the age–depth relationship, the vertical velocity profiles are more sensitive to the choice of ice chronology in the upper ice column, while showing only minor variations in the deeper part. This opposite behaviour arises because the 1D model is constrained primarily by age rather than velocity, and because age represents the integral of the inverse vertical velocity. As discussed in Sect. 5.1.1, variations in shallow vertical velocity have only a limited influence on cumulative age, whereas age becomes highly sensitive to velocity changes at depth.

Among the above factors, the uncertainty associated with dated isochrone ages was propagated into the simulated age envelope and is therefore already included in Fig. 6. The effects associated with ice chronology input differences are not included in the envelope, but are listed here as an independent reference magnitude. For comparison, the structural discrepancy between the 1D and 3D models introduces an age difference of ~261 ka at 200 m above the bed (Sect. 5.1.1). At this depth, the relative magnitudes of the three sources are, from largest to smallest: structural differences between the 1D and 3D models (~261 ka) > isochrone-derived age uncertainty (113 ka) > ice chronology input differences (104 ka).

”
335 -Line 155, Please rewrite, I don't understand the distances mentioned !

The revised sentence is “Simulated ice ages near the bedrock are relatively old at distances of 4 km, 13 km, and 44 km along the C21 KL transect from its starting point (77.44 °E, 80.38 °S). These sites correspond to regions with low basal melt rates.”

340 -Line 159, The most important parameter is the Misfit and not the the absolute age error value. Please correct and describe in more detail.

We define the standard deviation (Eq. 8) as the misfit. The overall misfit of the model is 2.95. The revised sentence are as follow:

345 “The reliability index σ_R of the model (Eq. 9) is 2.95, and its distribution along the transect is shown in Fig. 4C. The maximum age error is 9.2 ka for IRH6, while the minimum is 0.1 ka for IRH1. The largest relative age deviation is 9.83% for IRH3, with all but the lagrest below 7.21%.”

-Line 160, Please avoid subjective words like "much, very, ...". ==> "less than 7.21%"
Done.

350 -Line 165, Please add locations on top and put axes / color bar, ... in bold or more readable (also for the other figures). The labelling is too small to read.
Done.

-Line 168, Use "basal conditions"? basal melting is not an ice state
355 Done. We have used “Basal conditions”.

-Line 175, It is difficult to read the figure: use thicker lines. Plotting ice thickness is more relevant than bed elevation with regards to your text discussion.
We have used thicker lines and ice thickness in the map.

360

-Line 181, On the figure you plot bed elevation, so it is hard to follow. I suggest you plot ice thickness data on the figures.

We will add ice thickness data as the background, as shown in the following figure.

All figures have been clarity, and we have replaced bedrock elevation with ice thickness.

365 -Line 185, please change "corresponding" to "indicates" an age density ... You cannot compare apples and pears, please check in the main document each time the word

The revised sentence is "...with an age density of 2.5 kyr m⁻¹".

-Line 189, remove

Done.

370

-Line 195, see comments on previous figures

Done.

-Line 202, see previous comments

375 Done.

-Line 203, Standard deviation

Done.

380 -Line 210, The accumulation rates values should be compared and discussed with the ones mentioned earlier (Vostok, Dome C, LDC)

We have added a comparison of accumulation rates at Dome A, Vostok, Dome C, and LDC, and we have also discussed its effect on the model. In Sect 4.3. The time-averaged accumulation rate simulated by our 1D model at Kunlun Station is now compared with published values from the other sites.

385 The revised sentence is "...the center of the survey line; the simulated average accumulation rate in the Dome C region ranges from 17 to 21 mm yr⁻¹ ice equivalent, while it is 19 mm yr⁻¹ at LDC (Chung et al., 2023). At Vostok Station, the average accumulation rate is 14 mm yr⁻¹ (Salamatin et al., 2004). Overall, these accumulation rates are of the same order of magnitude;"

-Line 216, 1) Emphasize your results. As is, it is difficult to read

390 2) The importance of the GHF should be discussed in more details in the introduction so that the comparison with Zhao (2018) is building on that knowledge

(choice of GHF values, importance of the parameters, ...).

We have responded to this comment in Major Comment 3 above in detail.

We have introduced the background of GHF in introduction and discussed it in Sect 5.4. We also have re-plotted the map for
395 clarity.

-Line 228, strongly

Done.

400 *-Line 233, at / Neem, GRIP?*

We changed “from” to “at”. The revised sentence is “...while in Greenland Ice-core Project (GRIP), this value is 200 m.”

-Line 245, As mentioned earlier, you should detail the implication of GHF. What do you mean by relatively low, what are the mean, min, max values at Dome A from different data sets, ...

405 We analyzed a rectangular region centered at Dome A with a maximum dimension of approximately 80 km. The [mean, min, max] GHF values calculated for this area are: [53.2, 52.5, 54.1] mW m⁻² (Lösing et al., 2020); [55.3, 47.1, 58.6] mW m⁻² (Liu et al., 2025); [59.1, 52.8, 62.4] mW m⁻² (Stål et al., 2021). The revised paragraphs in Sect 5.2 is:

“

410 However, greater ice thickness does not necessarily imply increased basal melting. The thermal state of the ice sheet base depends on the competition between geothermal heating and the downward advection and diffusion of surface cold. In the East Antarctic interior plateau, where surface mean temperatures can drop below -50°C, the downward transfer of cold can effectively counteract or even exceed the effects of GHF and pressure melting. A prime example is Dome A, where the measured surface temperature is approximately -58 °C (Xiao et al., 2008) and GHF is relatively low compared to the West Antarctic average (Burton-Johnson et al., 2020). Based on different datasets, GHF at Dome A is estimated to range from 47.1
415 to 62.4 mW m⁻² (Liu et al., 2026; Lösing et al., 2020; Stål et al., 2021), a level of thermal input low enough to allow the ice sheet base to remain frozen despite its significant thickness. This may explain why our simulation along the C21KL transect (Fig. 2) did not exhibit the expected trend of higher basal melt rates with increasing ice thickness.

420 Unlike Full Stokes models that forward calculate velocity from explicit GHF, our approach infers the vertical velocity shape parameter p and mechanical ice thickness directly from observations. Thus, while GHF is not an explicit input, its physical impact on the basal thermal state is implicitly encapsulated in the optimized p and H_m , which acts as a data constrained proxy for the effective geothermal forcing. Specifically, by optimizing p and H_m , we effectively control whether the basal vertical velocity is zero (frozen bed) or positive (melting), a mechanism that is functionally equivalent to the role of GHF in determining the basal thermal regime.

.”

425

-Line 260, Please provide numbers

The revised sentence is "...radar accuracy. The age uncertainty we calculated for the deepest isochrone (IRH6) is 5.8 ka, surpassing the 1.5 ka estimated by Wang et al. (2016) and leading to an age uncertainty exceeding 200 ka at the bedrock of Kunlun Station."

430

-Line 276, isochrone

Done.

-Line 294, adapted from Parrenin, 2006

435 The revised sentence is "We applied the 1D pseudo-steady-state model adapted from (Chung et al., 2023; Parrenin et al., 2006, 2017) to simulate the age-depth profile along the C21 radar lines."

-Line 296, Here and in section 4 it is clear but I still don't understand why you mention the use of Vostok SMB (line 125 section 3), please clarify !

440 The original wording may have suggested a surface accumulation rate; in fact, it is the temporal relative variations of accumulation from the Vostok ice core. This has been clarified in our reply to Major Comment 2 above.

-Line 298, Maybe here and in the main text, you should provide precise locations ! e.g 2 km around the point x lat y lon, otherwise we get lost

445 We have fixed it throughout the manuscript. The revised sentence here is "Figure 4A shows that ice exceeding 1 Ma is concentrated in three regions: Area A is ~2.5 km around the point (76.89 °E, 80.47 °S); Area B is ~3 km around the point (77.12 °E, 80.42 °S); Area C is ~8 km around the point (77.14 °E, 80.37 °S)".

-Line 300, A map with ice thickness is more than welcome for ease of comprehension or as suggested put the ice thickness instead of bed elevation as your background map!

450

Done.

455

460

Reference

- Bouchet, M., Landais, A., Grisart, A., Parrenin, F., Prié, F., Jacob, R., Fourré, E., Capron, E., Raynaud, D., Lipenkov, V. Y., Loutre, M.-F., Extier, T., Svensson, A. M., Martinerie, P., Leuenberger, M. C., Jiang, W., Ritterbusch, F., Lu, Z.-T., and Yang, G.-M.: The Antarctic ice core chronology (AICC2023), <https://doi.org/https://doi.org/10.1594/PANGAEA.961017>, 2023.
- 465 Burton-Johnson, A., Dziadek, R., and Martin, C.: Review article: Geothermal heat flow in Antarctica: current and future directions, *The Cryosphere*, 14, 3843–3873, <https://doi.org/10.5194/tc-14-3843-2020>, 2020.
- Cavitte, M. G. P., Blankenship, D. D., Young, D. A., Schroeder, D. M., Parrenin, F., Lemeur, E., Macgregor, J. A., and Siegert, M. J.: Deep radiostratigraphy of the East Antarctic plateau: connecting the Dome C and Vostok ice core sites, *J. Glaciol.*, 62, 323–334, <https://doi.org/10.1017/jog.2016.11>, 2016.
- 470 Chung, A., Parrenin, F., Steinhage, D., Mulvaney, R., Martín, C., Cavitte, M. G. P., Lilien, D. A., Helm, V., Taylor, D., Gogineni, P., Ritz, C., Frezzotti, M., O’Neill, C., Miller, H., Dahl-Jensen, D., and Eisen, O.: Stagnant ice and age modelling in the Dome C region, Antarctica, *The Cryosphere*, 17, 3461–3483, <https://doi.org/10.5194/tc-17-3461-2023>, 2023.
- Chung, A., Parrenin, F., Mulvaney, R., Vittuari, L., Frezzotti, M., Zanutta, A., Lilien, D. A., Cavitte, M. G. P., and Eisen, O.: Age, thinning and spatial origin of the Beyond EPICA ice from a 2.5D ice flow model, *The Cryosphere*, 19, 4125–4140, <https://doi.org/10.5194/tc-19-4125-2025>, 2025.
- 475 Dome Fuji Ice Core Project Members:, Kawamura, K., Abe-Ouchi, A., Motoyama, H., Ageta, Y., Aoki, S., Azuma, N., Fujii, Y., Fujita, K., Fujita, S., Fukui, K., Furukawa, T., Furusaki, A., Goto-Azuma, K., Greve, R., Hirabayashi, M., Hondoh, T., Hori, A., Horikawa, S., Horiuchi, K., Igarashi, M., Iizuka, Y., Kameda, T., Kanda, H., Kohno, M., Kuramoto, T., Matsushi, Y., Miyahara, M., Miyake, T., Miyamoto, A., Nagashima, Y., Nakayama, Y., Nakazawa, T., Nakazawa, F., Nishio, F., Obinata, I., Ohgaito, R., Oka, A., Okuno, J., Okuyama, J., Oyabu, I., Parrenin, F., Pattyn, F., Saito, F., Saito, T., Saito, T., Sakurai, T., Sasa, K., Seddik, H., Shibata, Y., Shinbori, K., Suzuki, K., Suzuki, T., Takahashi, A., Takahashi, K., Takahashi, S., Takata, M., Tanaka, Y., Uemura, R., Watanabe, G., Watanabe, O., Yamasaki, T., Yokoyama, K., Yoshimori, M., and Yoshimoto, T.: State dependence of climatic instability over the past 720,000 years from Antarctic ice cores and climate modeling, *Science Advances*, 3, e1600446, <https://doi.org/10.1126/sciadv.1600446>, 2017.
- 485 Fujita, S., Maeno, H., Uratsuka, S., Furukawa, T., Mae, S., Fujii, Y., and Watanabe, O.: Nature of radio echo layering in the Antarctic Ice Sheet detected by a two-frequency experiment, *J. Geophys. Res.*, 104, 13013–13024, <https://doi.org/10.1029/1999JB900034>, 1999.
- Fujita, S., Matsuoka, T., Ishida, T., Matsuoka, K., and Mae, S.: A summary of the complex dielectric permittivity of ice in the megahertz range and its applications for radar sounding of polar ice sheets, 2000.
- 490 Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Minster, B., Nouet, J., Barnola, J. M., Chappellaz, J., Fischer, H., Gallet, J. C., Johnsen, S., Leuenberger, M., Loulergue, L., Luethi, D., Oerter, H., Parrenin, F., Raisbeck, G., Raynaud, D., Schilt, A., Schwander, J., Selmo, E., Souchez, R., Spahni, R., Stauffer, B., Steffensen, J. P., Stenni, B., Stocker, T. F., Tison, J. L., Werner, M., and Wolff, E. W.: Orbital and Millennial Antarctic Climate Variability over the Past 800,000 Years, *Science*, 317, 793–796, <https://doi.org/10.1126/science.1141038>, 2007.

- 495 Liu, S., Tang, X., Yang, S., Wang, L., and Liu, J.: Mapping Antarctic geothermal heat flow with deep neural networks optimized by particle swarm optimization algorithm, *The Cryosphere*, 20, 1543–1558, <https://doi.org/10.5194/tc-20-1543-2026>, 2026.
- Löising, M., Ebbing, J., and Szwillus, W.: Geothermal Heat Flux in Antarctica: Assessing Models and Observations by Bayesian Inversion, *Front. Earth Sci.*, 8, <https://doi.org/10.3389/feart.2020.00105>, 2020.
- 500 Martos, Y. M., Catalán, M., Jordan, T. A., Golynsky, A., Golynsky, D., Eagles, G., and Vaughan, D. G.: Heat Flux Distribution of Antarctica Unveiled, *Geophysical Research Letters*, 44, 11,417–11,426, <https://doi.org/10.1002/2017GL075609>, 2017.
- Oyabu, I., Kawamura, K., Buizert, C., Parrenin, F., Orsi, A., Kitamura, K., Aoki, S., and Nakazawa, T.: The Dome Fuji ice core DF2021 chronology (0–207 kyr BP), *Quaternary Science Reviews*, 294, <https://doi.org/10.1016/j.quascirev.2022.107754>, 2022.
- 505 Parrenin, F., Hindmarsh, R. C. A., and Rémy, F.: Analytical solutions for the effect of topography, accumulation rate and lateral flow divergence on isochrone layer geometry, *J. Glaciol.*, 52, 191–202, <https://doi.org/10.3189/172756506781828728>, 2006.
- Parrenin, F., Cavitte, M. G. P., Blankenship, D. D., Chappellaz, J., Fischer, H., Gagliardini, O., Masson-Delmotte, V., Passalacqua, O., Ritz, C., Roberts, J., Siegert, M. J., and Young, D. A.: Is there 1.5-million-year-old ice near Dome C, Antarctica?, *The Cryosphere*, 11, 2427–2437, <https://doi.org/10.5194/tc-11-2427-2017>, 2017.
- 510 Salamatin, A. N., Tsyganova, E. A., Lipenkov, V. Y., and Petit, J. R.: Vostok (Antarctica) ice-core time-scale from datings of different origins, *Annals of Glaciology*, 39, 283–292, <https://doi.org/10.3189/172756404781814023>, 2004.
- Schroeder, D. M., Blankenship, D. D., Young, D. A., and Quartini, E.: Evidence for elevated and spatially variable geothermal flux beneath the West Antarctic Ice Sheet, *Proceedings of the National Academy of Sciences*, 111, 9070–9072, <https://doi.org/10.1073/pnas.1405184111>, 2014.
- 515 Stål, T., Reading, A. M., Halpin, J. A., and Whittaker, J. M.: Antarctic Geothermal Heat Flow Model: Aq1, *Geochemistry, Geophysics, Geosystems*, 22, e2020GC009428, <https://doi.org/10.1029/2020GC009428>, 2021.
- Sun, B., Moore, J. C., Zwinger, T., Zhao, L., Steinhage, D., Tang, X., Zhang, D., Cui, X., and Martín, C.: How old is the ice beneath Dome A, Antarctica?, *The Cryosphere*, 8, 1121–1128, <https://doi.org/10.5194/tc-8-1121-2014>, 2014.
- 520 Wang, Z., Chung, A., Steinhage, D., Parrenin, F., Freitag, J., and Eisen, O.: Mapping age and basal conditions of ice in the Dome Fuji region, Antarctica, by combining radar internal layer stratigraphy and flow modeling, *The Cryosphere*, 17, 4297–4314, <https://doi.org/10.5194/tc-17-4297-2023>, 2023.
- Winter, A., Steinhage, D., Arnold, E. J., Blankenship, D. D., Cavitte, M. G. P., Corr, H. F. J., Paden, J. D., Urbini, S., Young, D. A., and Eisen, O.: Comparison of measurements from different radio-echo sounding systems and synchronization with the ice core at Dome C, Antarctica, *The Cryosphere*, 11, 653–668, <https://doi.org/10.5194/tc-11-653-2017>, 2017.
- 525 Xiao, C., Li, Y., Hou, S., Allison, I., Bian, L., and Ren, J.: Preliminary evidence indicating Dome A (Antarctica) satisfying preconditions for drilling the oldest ice core, *Chin. Sci. Bull.*, 53, 102–106, <https://doi.org/10.1007/s11434-007-0520-6>, 2008.

Yang, Y., Sun, B., Wang, Z., Ding, M., Hwang, C., Ai, S., Wang, L., Du, Y., and E, D.: GPS-derived velocity and strain fields around Dome Argus, Antarctica, *J. Glaciol.*, 60, 735–742, <https://doi.org/10.3189/2014JoG14J078>, 2014.

530 Zhao, L., Moore, J. C., Sun, B., Tang, X., and Guo, X.: Where is the 1-million-year-old ice at Dome A?, *The Cryosphere*, 12, 1651–1663, <https://doi.org/10.5194/tc-12-1651-2018>, 2018.