



An improved parameterisation of basal processes for age of ice modelling in the Dome C region, Antarctica

Yéva Jeumot ¹, Frédéric Parrenin ¹, Ailsa Chung ^{1, 2, 3}, Olaf Eisen ^{4, 5}, Daniel Steinhage ⁵, Robert Mulvaney ⁶, Marie G. P. Cavitte ⁷, David A. Lilien ⁸, and Emilie Capron ¹

¹Université Grenoble Alpes, CNRS, INRAE, IRD, Grenoble INP, IGE, 38000 Grenoble, France

²Climate and Environmental Physics, Physics Institute, University of Bern, Bern, Switzerland

³Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland

⁴Fachbereich Geowissenschaften, Universität Bremen, Bremen, Germany

⁵Alfred-Wegener-Institut Helmholtz-Zentrum für Polar-und Meeresforschung, Bremerhaven, Germany

⁶British Antarctic Survey, Cambridge, UK

⁷Earth and Life Institute (ELI), Université catholique de Louvain-La-Neuve (UCLouvain), Louvain-la-Neuve, Belgium

⁸Department of Earth and Atmospheric Sciences, Indiana University, Bloomington, USA

Correspondence: Yéva Jeumot (yeva.jeumot@gmail.com) and Frédéric Parrenin (frederic.parrenin@univ-grenoble-alpes.fr)

Abstract. Accurate age–depth models are essential both for selecting suitable drill sites and for providing age constraints once the ice has been extracted. Such models rely on inverse ice flow methods constrained by dated radar internal reflecting horizons (IRHs) and on the parameterisation of several processes including the accumulation rate, the vertical velocity profile, and basal conditions. In particular, the treatment of basal processes, basal melting or stagnant ice, has an impact on the age of the deepest ice. Previous implementations parameterised basal conditions through a mechanical ice thickness, which truncated the shear layer in the melting regime, leading to an underestimation of basal melt rates and an overestimation of basal age. Here we introduce a dimensionless parameter Δ that unifies the treatment of basal melting and stagnant ice, and we implement it in both a 1D and a 2.5D pseudo-steady-state inverse model. The 1D model was applied to three independent radar datasets covering the Dome C region. The 2.5D model was applied to an EDC–BELDC radar transect superimposed onto a flow line along which the Beyond EPICA Oldest Ice Core project aimed to retrieve a continuous ice core of up to 1.5 Ma from Little Dome C (LDC), Antarctica, referred to as the Beyond EPICA–Little Dome C (BELDC) ice core. The 2.5D model produces the bottom age of ~ 800 ka for the EDC ice core which is in good agreement with measurements, confirming the validity of our methodology. The complete absence of accreted ice in the modelled particle trajectories is in contrast to the previous implementations. At the BELDC site, the model finds a 194 m thick layer of stagnant ice, consistent with the ~ 200 m thick basal unit identified in radar surveys. The modelled maximum age for meaningful palaeoclimatic reconstructions is 1.17 Ma (age at which the age density reaches the 20 kyr m^{-1} threshold). At the new Million Year Ice Core (MYIC) drill site at Dome C North, the 1D model predicts a maximum resolvable age of 2.07 Ma with an age density of 6.5 kyr m^{-1} at 1.5 Ma, confirming the potential of this site for recovering ice over the full Mid-Pleistocene Transition (about 1.25 to 0.7 Ma). The framework presented here is general and can be applied to any region in Antarctica and Greenland where high-quality dated radar isochrones are available.



20 1 Introduction

The Mid-Pleistocene Transition (MPT), which occurred between 1250 ka and 700 ka, is characterised by the change in glacial-interglacial cycles from the low amplitude around 41-ka periodicity to the low-frequency, high-amplitude, quasi-periodic (~ 100 -ka) glacial variability (Clark et al., 2006), despite the absence of significant changes in orbital forcing. The reconstruction of Earth's climate history over the Quaternary period relies heavily on the analysis of deep ice cores. The EPICA Dome C (EDC) ice core was drilled in Antarctica between 1996 and 2004 at Dome C (75.10° S, 123.35° E, 3233 m above sea level, mean annual temperature -54.5° C, mean annual accumulation rate ~ 0.025 m a $^{-1}$ ice equivalent) (EPICA community members et al., 2004). The EDC ice core has provided a continuous record of atmospheric composition and temperature over the last 800 ka (Jouzel et al., 2007; Lüthi et al., 2008; Bouchet et al., 2023). The Beyond EPICA Oldest Ice Core (BE-OIC) project, a European initiative, aimed to retrieve a continuous ice core spanning up to 1.5 Ma through deep drilling at Little Dome C (LDC), a secondary dome located approximately 35 km south-east of Concordia (Parrenin et al., 2017; Chung et al., 2023, 2025; Parrenin et al., 2025). An almost 2800 m long ice core (Westhoff et al., 2026) has been retrieved at the BELDC site (75.29917° S, 122.44516° E, surface elevation ~ 3230 m a.s.l, mean annual accumulation rate ~ 0.02 m a $^{-1}$ ice equivalent) (Lilien et al., 2021; Chung et al., 2023). The ice core is currently being analysed in European laboratories. The Australian Antarctic Division (AAD) has also selected a new drill site at Dome C North (DCN, referred to as North Patch (NP) in Chung et al. (2023)) for their Million Year Ice Core (MYIC) project (75.04220° S, 123.63120° E, ice depth of 3064 m, 3239 m a.s.l) located approximately 9 km NE of Concordia Station and 45 km NE of BELDC site (Pedro and Million Year Ice Core Project Team, 2026). The MYIC–DCN drilling is on-going.

Age–depth models are invaluable for both selecting promising ice core drill sites and providing age constraints once the ice has been extracted. Using radar internal reflecting horizons (IRHs) to constrain age–depth models is a well-established approach that has been applied across many regions of Antarctica (Parrenin et al., 2017; Lilien et al., 2021; Chung et al., 2023, 2025; Waddington et al., 2007; Wang et al., 2023; Obase et al., 2023; Bingham et al., 2025). By linking the depth of IRHs at an ice core site to existing chronologies, isochronal layers can attribute ages throughout the ice sheet (Cavitte et al., 2020) and be used as direct constraints on modelled age–depth profiles.

A challenge for age modelling in the Dome C region is the treatment of basal processes, which have a strong impact on the age of the deepest ice. At LDC, a basal unit approximately 200–250 m thick has been identified directly above the bedrock in radar surveys, in which no continuous IRHs are visible (Cavitte, 2017). Subsequent measurements with newer radar systems indicate that this unit is caused by physical properties of the ice rather than a system detection limit (Lilien et al., 2021). Vertical velocity measurements from an autonomous phase-sensitive radio-echo sounder (ApRES) further suggested that this layer is not deforming vertically (Chung et al., 2023). This interpretation is further supported by past age–depth modelling tuned to IRHs (Lilien et al., 2021; Chung et al., 2023, 2025). The properties of this basal unit remain debated, with proposed hypotheses including shear at the interface between stagnant and dynamic ice with refrozen basal ice in the basal unit (Bell et al., 2011), anisotropic crystal fabric resistant to vertical compression (Drews et al., 2009), or other physical properties such as entrained debris (Holschuh et al., 2026).



Basal processes play an important role in determining the age of the deepest ice and must therefore be considered in
 55 age–depth models, e.g. through parameterisations. In previous work, we inferred a mechanical ice thickness H_m to represent
 either stagnant ice ($H_m < H_{obs}$) or basal melting ($H_m > H_{obs}$) where H_{obs} is the observed thickness (Chung et al., 2023, 2025).
 However, the limitation of this method was that the range of depths through which the model hypothesized significant vertical
 shear, hereafter referred to as the “shear layer”, was truncated in the case of melting, leading to an underestimation of basal
 melting and an overestimation of basal age (Chung et al., 2023). Moreover, in some cases, ice particle trajectories were found
 60 to emerge from the bedrock Chung et al. (2025) inconsistent with the absence of refrozen basal ice reported in stratigraphic
 observations (Westhoff et al., 2026).

In this study we use a one-dimensional model that considers only vertical flow of ice named IsoInv1D (Chung et al., 2023)
 and a 2.5 dimensional model that considers a flow tube width with variable width, named age_flow_line (Parrenin et al., 2025)
 with its inverse version IsoInv2.5D (Chung et al., 2025). These are pseudo-steady state numerical models, meaning that the
 65 geometry and velocity profiles are assumed steady, and the accumulation rate is allowed to vary temporally. We introduce a
 dimensionless Δ parameter in both IsoInv1D and IsoInv2.5D models, keeping $H_m = H_{obs}$ in the melting case and reducing H_m
 when stagnant ice is present. This parameterisation eliminates the truncation of the shear layer of the previous approach and,
 in 2.5D, prevents trajectories from emerging from the bedrock. We apply the updated models to three radar surveys covering
 the Dome C and LDC region for the 1D model and to the DC–LDC flow line for the 2.5D model. Results show that the new
 70 parameterisation is more consistent with observations, and provide new age estimates at BELDC and MYIC.

2 Method

2.1 Models

In this study, we use modified versions of two numerical age–depth models: the 1D inverse model IsoInv1D, first presented in
 Chung et al. (2023), and the 2.5D inverse model IsoInv2.5D, first presented in Chung et al. (2025). Here we summarise the
 75 aspects common to both models and refer the reader to these studies for more detailed descriptions.

Both models are based on a pseudo-steady-state assumption, meaning that the ice geometry and vertical velocity profile
 are assumed to be steady in time, while a temporal factor is applied to both the surface accumulation and basal melting rates
 (Parrenin et al., 2017, 2025) :

$$a(x, t) = \bar{a}(x) R(t) \qquad m(x, t) = \bar{m}(x) R(t) \qquad (1)$$

80 where $\bar{a}(x)$ is the temporally averaged accumulation rate and $\bar{m}(x)$ is the temporally averaged basal melt rate at position x
 along the flow line. $R(t)$ is a positive temporal factor derived from the AICC2023 chronology (Bouchet et al., 2023) for the
 EDC ice core, defined as the ratio of the accumulation at time t to its temporally averaged value over the last 800 ka.

The horizontal flux shape function is described by the Lliboutry profile (Lliboutry, 1979):

$$\omega(\zeta) = 1 - \frac{p+2}{p+1}(1-\zeta) + \frac{1}{p+1}(1-\zeta)^{p+2}, \qquad (2)$$



85 where ζ is the normalised vertical coordinate, equal to 0 at the bedrock and 1 at the surface, and p is the Lliboutry exponent. Increasing p makes the vertical velocity profile more linear, while lower values of p concentrate thinning near the base of the ice column. Several assumptions are associated with this profile, including isotropic ice, smooth bedrock variations and non-zero horizontal velocity; however, varying p can approximate the effect of relaxing these assumptions (Lliboutry, 1979; Parrenin et al., 2017).

90 In the 1D model, the thinning function τ , which describes how annual layers thin with depth, takes the form (Parrenin et al., 2017):

$$\tau = (1 - \mu)\omega + \mu, \quad (3)$$

where $\mu = m/a$ is the ratio of the steady basal melt rate $\bar{m}$ to the steady surface accumulation rate a .

The 2.5D model uses an analogous but more complex thinning function because it additionally considers horizontal ice flow 95 along a flow line from Dome C (DC) to LDC, with lateral flow divergence accounted for through a flow tube width varying along the flow line (Chung et al., 2025; Parrenin et al., 2025).

The inverse models optimise three inferred parameters at each horizontal position: the steady accumulation rate $\bar{a}$, the Lliboutry parameter p , and the basal processes parameter Δ that we describe in the next section. The model is constrained by dated radar IRHs. A cost function evaluates the misfit between modelled and observed isochrone ages, which the inversion 100 minimises using a least-squares optimisation with the Trust Region Reflective algorithm (Chung et al., 2025).

2.2 Implementation of the basal parameter Δ

Previous implementations of IsoInv1D and IsoInv2.5D parameterised basal conditions through the mechanical ice thickness H_m relative to the observed ice thickness H_{obs} (Chung et al., 2023, 2025), while Parrenin et al. (2017) instead prescribed a geothermal flux to infer basal melt rates. In the H_m approach, two regimes are possible: where $H_m < H_{\text{obs}}$, a stagnant ice 105 layer of thickness $H_{\text{obs}} - H_m$ is inferred; where $H_m > H_{\text{obs}}$, a basal melt rate is inferred from the value of the vertical velocity at the observed bedrock interface, thereby coupling the mechanical ice thickness to the melt rate. However, this formulation truncates the shear layer in the melting case due to the correspondence between vertical and horizontal shear in the Lliboutry model (Fig. 1), leading to an underestimation of the melt rate and an overestimation of the basal age, with unphysical ice particle trajectories possibly emerging from the bedrock in the 2.5D model.

110 To address these limitations, we introduce a dimensionless parameter Δ in both models to describe basal melting and stagnant ice within a continuous framework (Fig. 1). The two regimes are defined as follows.

Basal melting ($\Delta \geq 0$): The mechanical ice thickness is kept equal to the observed ice thickness ($H_m = H_{\text{obs}}$), preserving the full extent of the shear layer, and the basal melt rate m is inferred as:

$$\Delta \geq 0 : \begin{cases} H_m = H_{\text{obs}} \\ m = \bar{a}\Delta \end{cases} \quad (4)$$

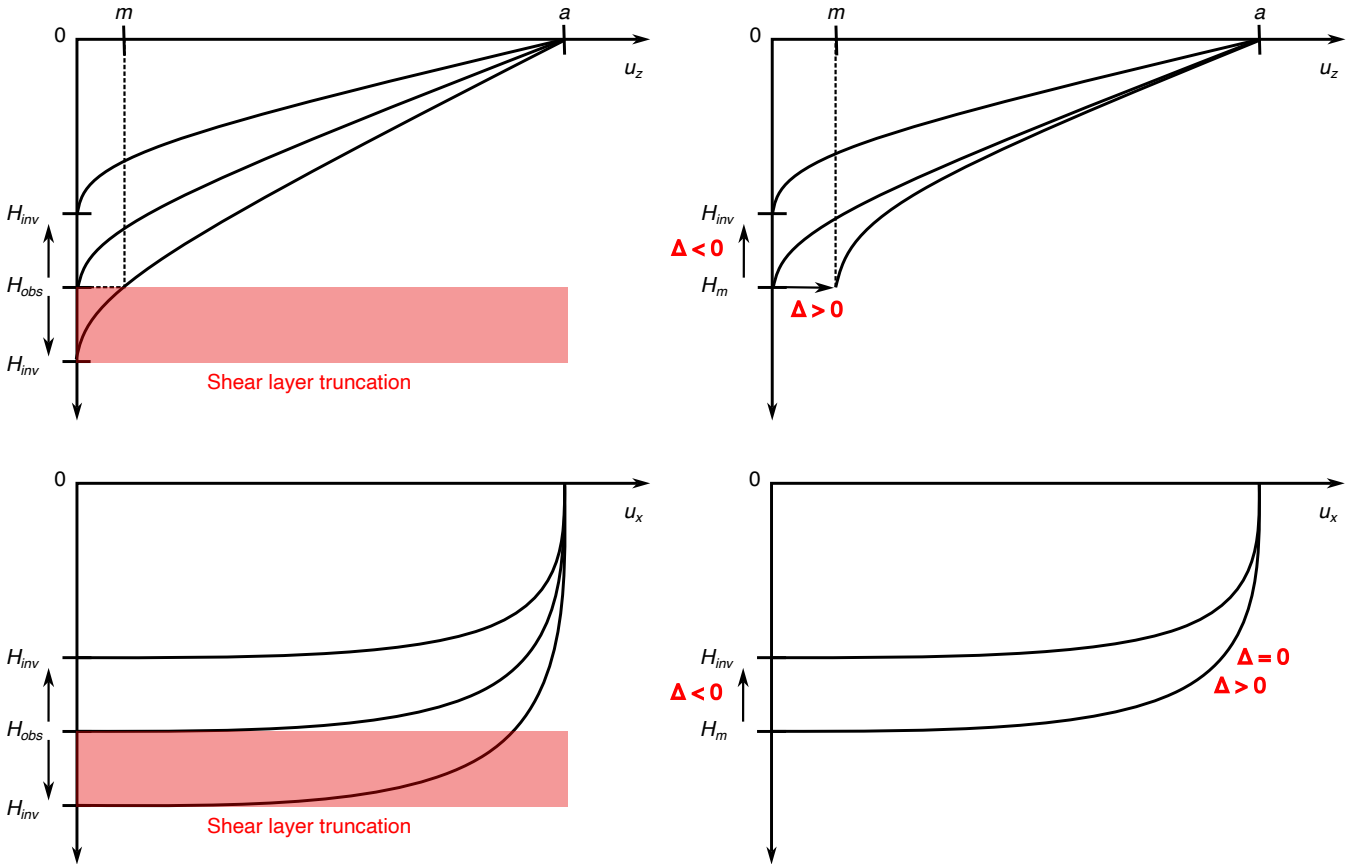


Figure 1. Schematic comparison of basal condition parameterisations in the IsoInv1D and IsoInv2.5D models, where the vertical axis represents the depth increasing downwards and the horizontal axis represents the vertical velocity (top) or the horizontal velocity (bottom). Previous approach (left): Parameterisation via the mechanical ice thickness H_m relative to the observed ice thickness H_{obs} . New approach (right): the newly introduced framework using the parameter Δ .

115 Stagnant ice ($\Delta < 0$): A stagnant ice layer is inferred at the base, the melt rate is set to zero, and the mechanical ice thickness is reduced accordingly:

$$\Delta < 0 : \begin{cases} H_m = H_{obs}(1 + \Delta) \\ m = 0 \end{cases} \quad (5)$$

This parameterisation allows the model to transition dynamically between the two regimes during the inversion process. By decoupling the melt rate from H_m when basal melting occurs, it preserves the physical integrity of the shear layer and
 120 eliminates the unphysical particle trajectories produced by the previous formulation, providing a more physically consistent estimation of the basal age.



2.3 Data

The two models used in this study are constrained by different radar datasets, reflecting their different spatial requirements: the 1D model is applied pointwise along multiple radar transects covering Dome C and LDC region, while the 2.5D model uses a single continuous radar transect along the DC–LDC flow line.

2.3.1 Radar dataset for 1D model

In this study, we use three radar surveys collected in the Dome C region during the Antarctic field seasons from 2016 to 2020, the UTIG HiCARS airborne survey (2016), the BAS DELORES ground-based survey (2016–2018), and the UA LDC-VHF high resolution ground-based survey (2019). Here we summarise the characteristics most relevant to our age modelling approach. The reader is referred to (Chung et al., 2023) for a comprehensive description of each dataset.

Internal reflecting horizons (IRHs) were traced in each dataset and dated by linking them to the EPICA Dome C (EDC) ice core using the AICC2023 timescale (Bouchet et al., 2023). The HiCARS dataset covers a large area of approximately $100 \times 100 \text{ km}^2$ around LDC and Dome C, with 19 dated IRHs spanning depths of 308–2644 m and ages of $10.0 \pm 0.3 \text{ ka}$ to $366.5 \pm 7.9 \text{ ka}$ (Cavitte et al., 2016, 2018, 2020, 2021; Young et al., 2017). The DELORES dataset provides a dense grid of transects over LDC and the neighbouring DCN area, with 20 traced IRHs reaching depths of 317–2740 m, the deepest isochrone being dated at $414.6 \pm 10.5 \text{ ka}$ (Cavitte et al., 2021; Mulvaney et al., 2023). The LDC-VHF dataset covers Patches A and B (Lilien et al., 2021; Yan et al., 2020), the candidate sites for the Beyond EPICA drill site (BELDC), with 19 IRHs spanning depths of 1079–2826 m and ages up to $476.4 \pm 14.7 \text{ ka}$ (Chung et al., 2023). In all three datasets, IRH depths are computed using an electromagnetic wave speed in ice of $168.5 \text{ m } \mu\text{s}^{-1}$ and a firm air correction of $10 \pm 3 \text{ m}$ (Lilien et al., 2021).

2.3.2 Radar for DC-LDC flow line

The radar data used to constrain the 2.5D ice flow model are drawn from Chung et al. (2025) and consist of 19 IRHs traced along the EDC–LDC radar transect from the LDC-VHF dataset (Chung et al., 2023). Since no radar transect follows the DC–LDC flow line exactly, the IRHs are mapped onto the flow line by taking the point of intersection between the radar transect and a line perpendicular to the local direction of flow. The IRHs span depths from 1079 to 2826 m at EDC, with ages ranging from 73.2 ± 1.5 to $475.3 \pm 17.9 \text{ ka}$. These IRHs were originally dated by Chung et al. (2023) using the AICC2012 timescale (Bazin et al., 2013), and were subsequently re-dated by Chung et al. (2025) using the newest EDC ice core chronology AICC2023 (Bouchet et al., 2023). The adoption of AICC2023 reduced the age uncertainties of the shallower isochrones, while absolute ages changed by no more than $\pm 2.3 \text{ ka}$ compared to those obtained with AICC2012.

For this study, we used the depths from Chung et al. (2023) and ages from Chung et al. (2025), ensuring consistency between the radar stratigraphy and the chronological framework used in the present study.



3 Results

3.1 1D age-depth model results

Here, we present the results when the 1D model was applied to the three radar surveys described in Sect. 2.3.1. As the DELORES survey covers two distinct areas : LDC and DCN, results are presented separately for each. We show the bottom ice age, the basal melt rate and stagnant ice and we also take a detailed look at the modelled age scales for past and ongoing deep ice core projects in the region : BELDC and MYIC-DNC.

3.1.1 Model results at EDC

To evaluate the accuracy of the 1D model, we compared the modelled age–depth profiles to those obtained from the EDC ice core record. Three radar transects from the LDC DELORES dataset, one transect from the DCN DELORES dataset, and one transect from the LDC-VHF dataset pass near the EDC drill site. Table 1 summarises the total ice thickness and the modelled age at the closest points to the EDC drill site for each radar dataset.

Table 1. Results at the closest points to the EDC drill site for different radar transects for the 1D model and for the 2.5D model flowline. Values for corresponding modelled age at 3192 m depth (ka) from Chung et al. (2023, 2025) are indicated in italics. The final column shows values from the EDC ice core chronology (AICC2023) from Bouchet et al. (2023). Note that Chung et al. (2023) originally reported this depth as 3189 m under the AICC2012 timescale; here we use 3192 m, consistent with the AICC2023 chronology. The total ice thickness for the DCN DELORES radar transect is shallower than 3192 m; therefore, no age estimate is provided.

1D model						2.5D model	Ice core
LDC DELORES				DCN DELORES	LDC-VHF	DC-LDC	AICC2023
Distance of closest point to EDC (m)	338	338	368	404	178	0	0
Total ice thickness (m)	3239	3213	3239	3141	3238	3235	3273
Age at 3192 m depth (ka)	817 ± 55	797 ± 49	827 ± 89	–	806 ± 111	820	813 ± 5.8 ^c
	1015 ± 87 ^a	1013 ± 86 ^a	1016 ± 86 ^a	–	1096 ± 178 ^a	1035 ^b	

^aChung et al. (2023) ^bChung et al. (2025) ^cBouchet et al. (2023)

We compare the modelled bottom age at the closest point to EDC against the AICC2023 chronology (Bouchet et al., 2023), in which the deepest dated ice is at 3192.75 m depth, with an age of 813 ± 5.8 ka. For the LDC DELORES dataset, the modelled age at this depth ranges from 797 ± 49 ka to 827 ± 89 ka across the three transects. For the LDC-VHF dataset, the modelled age is 806 ± 111 ka, which is only 7 ka younger than the AICC2023 value and well within the model uncertainty. The 2.5D model predicts an age of 820 ka at this depth, also consistent with the AICC2023 chronology within uncertainties. The DCN DELORES transect has a shallower total ice thickness of 3141 m, likely reflecting the greater distance of the closest point



to EDC (404 m), as well as the fact that it approaches EDC from a different direction than the LDC DELORES transects, which are relatively close to one another. As the base of the ice column does not reach 3192 m depth, no comparison with the AICC2023 chronology is possible for this transect.

3.1.2 Modelled age and age density at BELDC and MYIC

Table 2 shows the 1D modelled results for the BELDC and MYIC-DCN drill sites. Close to the BELDC, there is one transect from the LDC DELORES dataset and one from the LDC-VHF dataset and for MYIC-DCN there is one transect from the DCN DELORES dataset.

Table 2. 1D and 2.5D modelling results for the BELDC and MYIC-DCN drill sites. Corresponding values from previous studies are indicated in italics.

	BELDC		MYIC	
	1D model		2.5D model	1D model
	LDC DELORES	LDC-VHF	DC-LDC	DCN DELORES
Distance of closest point to drill site (m)	21	37	–	0.18
Total ice thickness H_{obs} (m)	2756	2757	2735	3064.6
Stagnant ice thickness (m)	220 ± 31	195 ± 43	194	0
	<i>210 ± 35^a</i>	<i>186 ± 3^a</i>	<i>212.8^b</i>	
Depth of 1.2 Ma ice (m)	2464	2484	–	2935
	<i>2469^a</i>	<i>2486^a</i>		<i>2911.2^a</i>
Age density at 1.2 Ma (kyr m^{-1})	13.9	12.8	–	4.8
	<i>13.2^a</i>	<i>12.2^a</i>		<i>6.0^a</i>
Depth of 1.5 Ma ice (m)	2480	2502	–	2988
	<i>2487^a</i>	<i>2506^a</i>		<i>2950.7^a</i>
Age density at 1.5 Ma (kyr m^{-1})	–	–	–	6.5
				<i>9.5^a</i>
Maximum age at 20 kyr m^{-1} (Ma)	1.39 ± 0.18	1.45 ± 0.25	1.17	2.07 ± 1.10
	<i>1.43 ± 0.16^a</i>	<i>1.47 ± 0.13^a</i>	<i>1.12^b</i>	<i>2.13 ± 0.19^a</i>
Depth of max age (m)	2475	2500	2517	3064.3
	<i>2484^a</i>	<i>2504^a</i>	<i>2453.1^b</i>	<i>2996.8^a</i>
Modelled p value above stagnant ice or base	6.5	6.9	10.7	2.7
	<i>7.1^a</i>	<i>6.4^a</i>	<i>13.6^b</i>	<i>2.6^a</i>
Temporally averaged accumulation rate (mm yr^{-1})	19.1	19.0	20.3	20.2
	<i>19.0^a</i>	<i>19.1^a</i>	<i>19.3^b</i>	<i>20.1^a</i>

^aChung et al. (2023) ^bChung et al. (2025)



175 At the BELDC drill site, we report the depth at which the age density reaches the threshold of 20 kyr m^{-1} , considered the minimum required for meaningful palaeoclimatic reconstructions (Fischer et al., 2013; Van Liefferinge and Pattyn, 2013). The depths of maximum resolvable age are 2475 m for LDC DELORES and 2500 m for LDC-VHF, with corresponding maximum resolvable ages of $1.39 \pm 0.18 \text{ Ma}$ (LDC DELORES) to $1.45 \pm 0.25 \text{ Ma}$ (LDC-VHF). The modelled stagnant ice thickness at BELDC is $220 \pm 31 \text{ m}$ (LDC DELORES) and $195 \pm 43 \text{ m}$ (LDC-VHF). The LDC DELORES estimate, obtained from the
 180 transect closest to BELDC (21 m) and is therefore considered the most reliable of the two datasets.

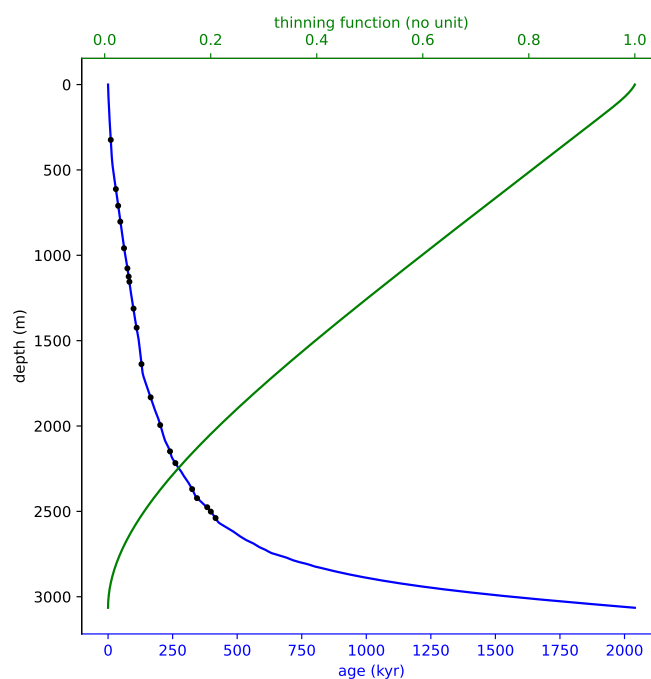


Figure 2. The modelled age–depth profile is shown as solid blue line and the thinning function τ is shown in solid green line at the MYIC-DCN drill site. Black dots indicate the ages of the 20 observed radar isochrones used to constrain the model.

At the MYIC-DCN drill site, located at DCN, the closest radar transect from the DCN DELORES dataset passes only 4 m away. Figure 2 shows that the modelled isochrones fit the observed ages at isochrones well. The total ice thickness at this location is 3064 m, significantly greater than at BELDC ($\sim 2757 \text{ m}$), reflecting the thicker ice sheet at DCN compared to the LDC region. In this location, a basal melt rate of $0.13 \pm 0.14 \text{ mm yr}^{-1}$ and no stagnant ice is inferred. Despite the presence of
 185 basal melting, the modelled age predictions at MYIC-DCN are remarkably old. Ice of 1.2 Ma is found at 2935 m depth with an age density of only 4.8 kyr m^{-1} , well below the 20 kyr m^{-1} threshold. Ice of 1.5 Ma is predicted at 2988 m depth with an age density of 6.5 kyr m^{-1} , also far below the threshold. The maximum age at the 20 kyr m^{-1} threshold reaches 2.07 Ma at 3064 m depth, corresponding to the bedrock.

3.1.3 Modelled basal melting and stagnant ice

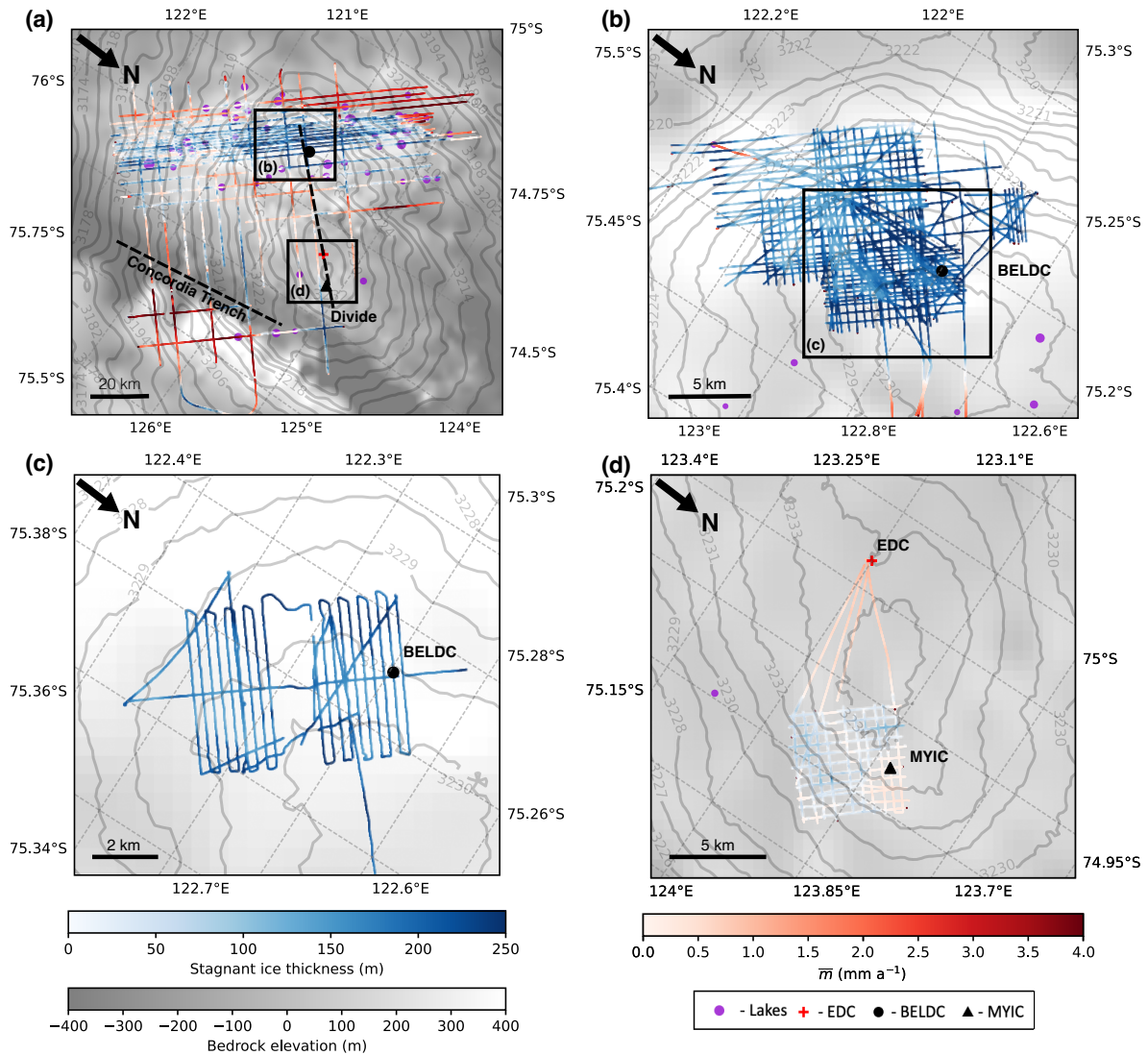


Figure 3. Modelled stagnant ice and basal melting for the four radar datasets. Transects in blue indicate the presence of a stagnant ice layer. Transects in red indicate basal melting. Stagnant ice thickness, melt rate and bedrock elevation colour bars are the same for all four maps, while the horizontal scale is different. The bedrock elevation is from BedMachine version 3 (Morlighem, 2022). (a) HiCARS airborne dataset, (b) LDC DELORES ground-based dataset, (c) LDC-VHF high resolution ground-based dataset and (d) DCN DELORES ground-based dataset. Drill sites EDC, BELDC and MYIC-DCN location are indicated by a red cross, black circle and black triangle, respectively. Purple dots indicate subglacial lakes (Young et al., 2017; Livingstone et al., 2022).



190 Figure 3 shows the spatial distribution of the 1D modelled basal conditions, stagnant ice thickness or basal melt rate, for the four radar datasets.

At the large scale, the HiCARS dataset (Fig. 3a) reveals a heterogeneous pattern, with significant basal melting predicted along several transects, particularly in areas of deeper or rougher bedrock away from the LDC ridge. Melt rates reach up to 4 mm yr^{-1} in the most active regions. Stagnant ice is also present in the HiCARS dataset, predominantly in the LDC region, 195 where the bedrock topography provides a favourable configuration for cold basal conditions.

At the LDC scale, both the DELORES (Fig. 3b) and LDC-VHF (Fig. 3c) datasets consistently predict a thick stagnant ice layer across the majority of the surveyed area, with no significant basal melting. The stagnant layer thickness reaches up to $\sim 250 \text{ m}$ in places,

In the DCN area (Fig. 3d), the pattern differs from LDC, with basal melting predicted along most transects and melt rates 200 reaching up to $\sim 1.0 \pm 0.3 \text{ mm yr}^{-1}$. There is an area of stagnant ice on the east side of DCN, but its thickness is generally below 60 m . The absence of a thick stagnant layer at DCN is consistent with the deeper bedrock at this location and suggests a warmer basal thermal regime, at the limit between melting and frozen base.

3.1.4 Oldest ice around Dome C

Figure 4 shows the spatial distribution of the 1D modelled maximum age for each of the four radar datasets. At the large scale 205 (Fig. 4a), the HiCARS dataset reveals a strong contrast between LDC, where maximum ages reach more than $\sim 1.4 \text{ Ma}$, and the surrounding regions. Along the DC–LDC divide and over the Concordia trench, where basal melting dominates (Fig. 3a), the maximum age drops considerably to below $\sim 0.9\text{--}1.0 \text{ Ma}$,

Over the LDC relief, both the DELORES (Fig. 4b) and LDC-VHF (Fig. 4c) datasets show a homogeneous spatial distribution of maximum ages around $1.2\text{--}1.5 \text{ Ma}$, reflecting the presence of thick stagnant ice across this area.

210 The DCN area (Fig. 4d) has a different pattern, characterised by strong gradients in maximum age across the area. Modelled maximum ages range from $\sim 0.9 \text{ Ma}$ in the regions where basal melting is modelled, to over 2.0 Ma in the central part of the DCN relief.

3.2 2.5D ice flow model results

In this subsection, we present the results for the 2.5D model applied to the DC-LDC flow line. The line goes from Dome C 215 passing through the EDC ice core site at 6.3 km and ending at the BELDC site at 39.8 km .

3.2.1 DC–LDC flow line and flow tube geometry

The flow tube geometry between LDC and DC was calculated based on the surface velocity field following Chung et al. (2025), with an exponential extrapolation applied near the dome summit. The resulting flow line extends 40.7 km from the high point of DC (0 km) to LDC, with BELDC located 39.8 km along the flow line. As radar isochrones are only available from

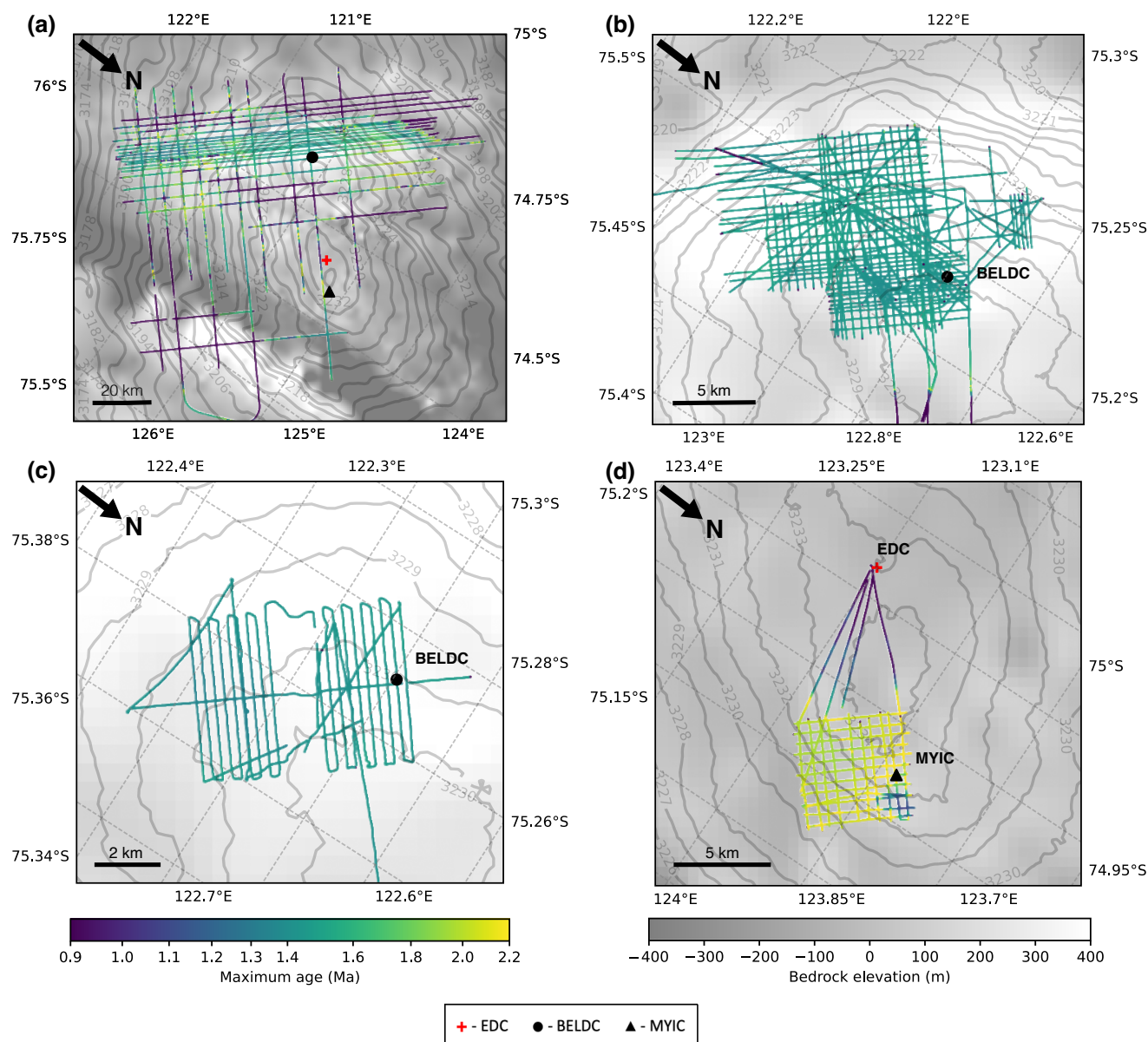


Figure 4. Maximum age with a maximum acceptable age density of 20 kyr m^{-1} , colour bars correspond to all four panels. (a) HiCARS airborne dataset, (b) LDC DELORES ground-based dataset, (c) LDC-VHF high resolution ground-based dataset and (d) DCN DELORES ground-based dataset.



EDC onwards, model results are presented starting from EDC, which lies 6.3 km downstream of the DC summit. The radar isochrones were mapped onto this flow line following the procedure detailed in Chung et al. (2025) and Sect. 2.3.2.

3.2.2 Ice particle trajectories

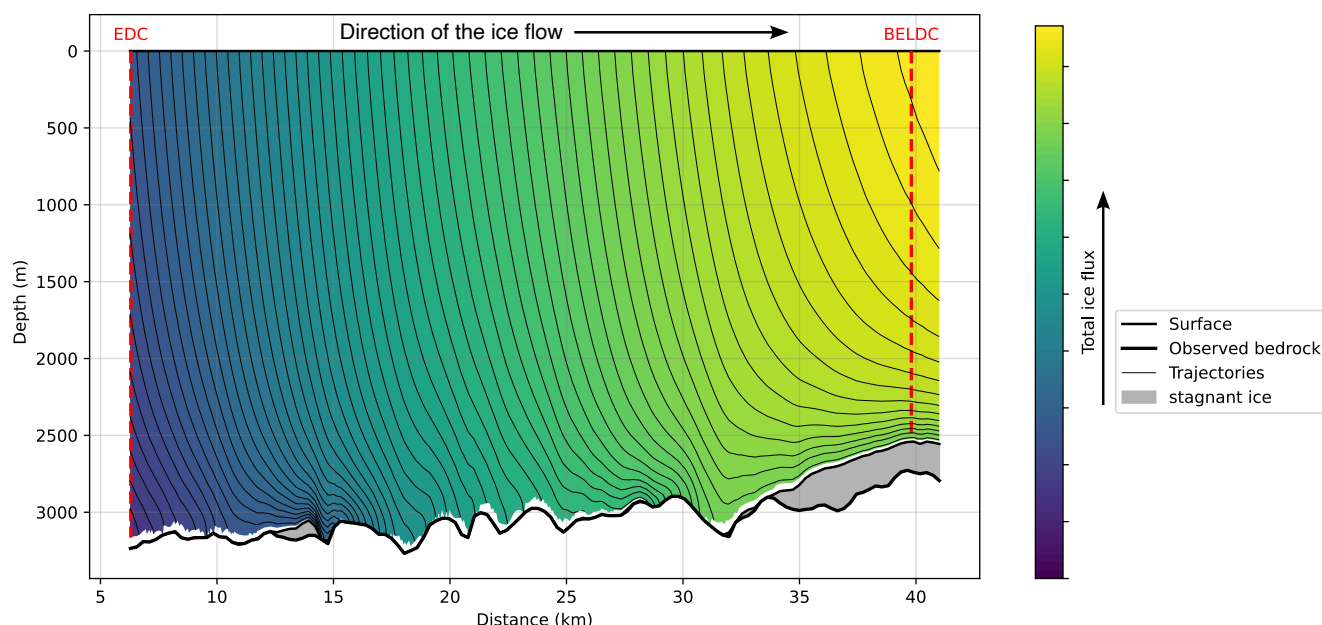


Figure 5. Ice particle trajectories along the DC–LDC flow line, coloured by total ice flux. Black thin lines show individual particle trajectories from the surface to the bedrock. The thick black line shows the observed bedrock and the grey area shows the stagnant ice layer (grey area). Red dashed vertical lines indicate the positions of EDC (6.3 km) and BELDC (39.8 km) along the flow line.

Figure 5 shows the ice particle trajectories along the DC–LDC flow line as determined by the 2.5D inverse model. The trajectories illustrate how ice deposited at the surface near the DC summit is advected horizontally and compressed vertically as it flows downstream towards LDC. The total ice flux, shown by the colour scale, increases progressively from the dome towards LDC, reflecting the accumulation of ice along the flow line and the divergence of the flow tube.

At EDC, ice found at the bedrock originates from approximately 3.5 km upstream of the drill site, indicating that horizontal advection is almost vertical at this location, close to the dome summit. At BELDC, however, the basal ice originates from approximately 14 km upstream, highlighting that horizontal advection plays a significant role in determining the provenance of the deepest ice at this site.

3.2.3 Age of ice

Figure 6 shows the 2.5D modelled age–depth relationship along the DC–LDC flow line. The modelled isochrones (black lines) agree well with the observed isochrones (white lines), which are almost entirely covered by the modelled contours, indicating a

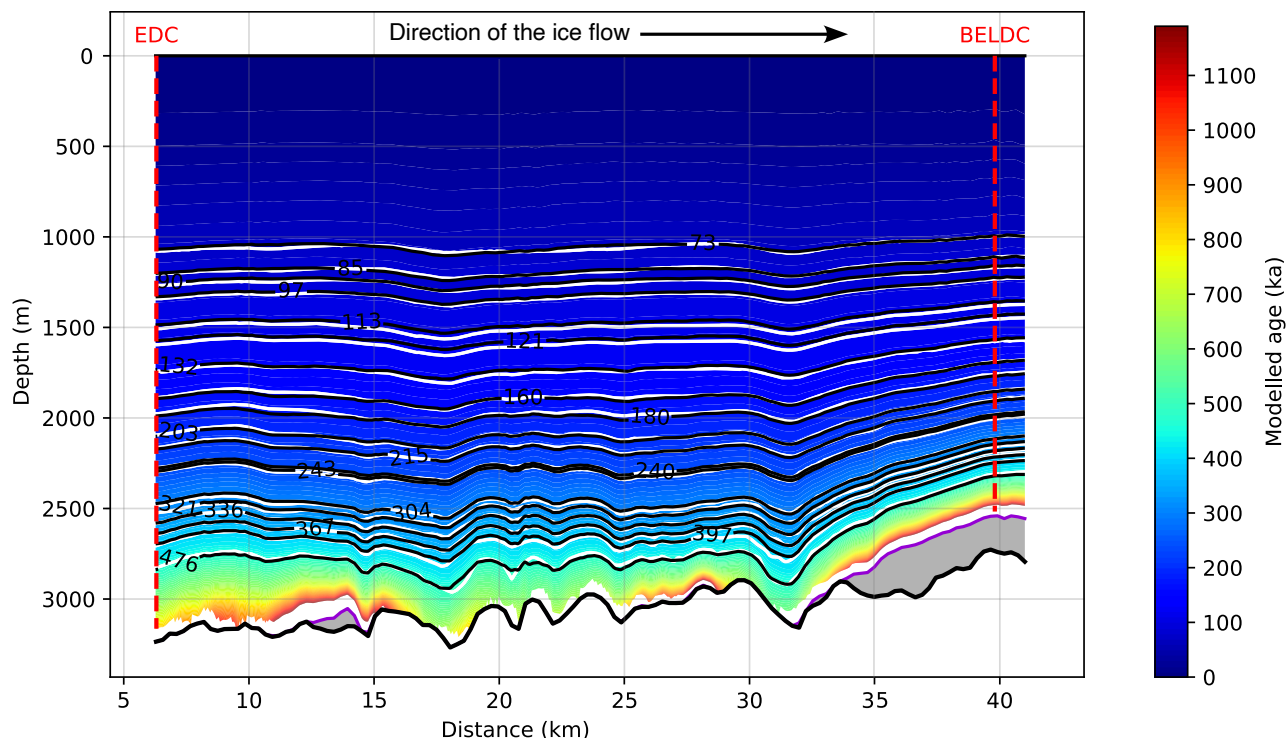


Figure 6. Modelled age–depth relationship along the DC–LDC flow line. The colour scale shows the modelled ice age in ka. Black lines show the modelled isochrones, with their ages labelled in ka, and white lines show the observed isochrones. The thick black line shows the observed bedrock in the radar transect, the purple line shows the mechanical ice thickness H_m , and the grey area indicates the stagnant ice layer. Red dashed vertical lines indicate the positions of EDC (6.3 km) and BELDC (39.8 km) along the flow line.

good fit. The 19 isochrones span ages from 73 to 476 ka and depths from 1079 to 2826 m at EDC (Chung et al., 2025; Bouchet et al., 2023).

Between approximately 18 and 25 km along the flow line, the age of ice near the bed is relatively young (<700 ka), reflecting the presence of basal melting in this region (Fig. 3). In contrast, stagnant ice is predicted between approximately 34 and 41 km along the flow line, encompassing the BELDC drill site, as well as a smaller patch at around 14 km. In these regions, there is no basal melting and the age of the ice increases rapidly with depth, reaching values over 1 Ma.

240 3.2.4 Inferred parameters

Figure 7 shows the three inferred parameters from the 2.5D model, the steady–state accumulation $\bar{a}$, the Lliboutry parameter p and the Δ parameter along the DC–LDC flow line, as well as the basal melt rate and stagnant ice thickness. The steady–state accumulation rate $\bar{a}$ (Fig. 7a) is uniform along the flow line, with values close to 0.02 m yr^{-1} . Near BELDC (>35 km), the inferred accumulation rate becomes more variable, while its uncertainty remains similar and increases over the last 4 km of the line. This reflects the absence of IRHs downstream of this point, which limits the constraint on accumulation

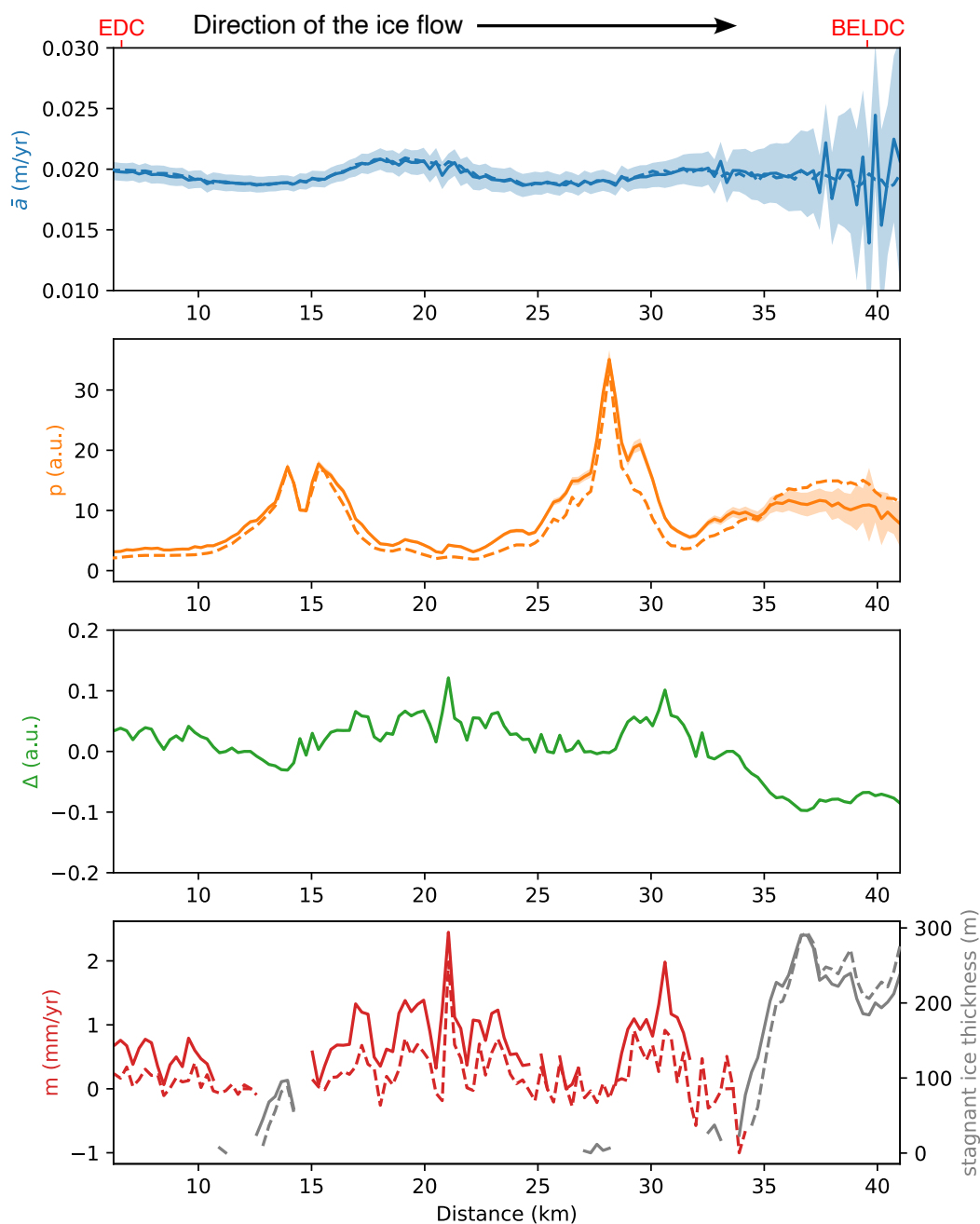


Figure 7. Inferred parameters along the DC–LDC flow line from the 2.5D inverse model are shown in solid lines with uncertainties in shaded areas compared to the previous 2.5D modelled results from Chung et al. (2025) shown in dashed lines. From top to bottom: (a) steady-state accumulation rate $\bar{a}$ (m yr⁻¹); (b) Lliboutry parameter p ; (c) basal parameter Δ ; (d) basal melt rate m (m yr⁻¹, red, left axis) and stagnant ice thickness (m, grey, right axis).



The Lliboutry parameter p (Fig. 7b) shows significant variability along the flow line, with a background value of $p \approx 3$ near EDC. Two prominent peaks are visible at approximately 14 km and 28 km, where p reaches values of ~ 18 and ~ 33 , respectively.

The Δ parameter (Fig. 7c) remains close to 5% along most of the flow line, indicating that there is basal melting along the DC–LDC transect. Near BELDC (>34 km), Δ becomes slightly negative (-10%), consistent with the presence of a stagnant ice layer in this region.

The derived basal melt rate m and stagnant ice thickness are shown in Figure 7d. The modelled melt rate is ~ 0.68 mm yr $^{-1}$ at EDC. Localised patches of stagnant ice are present around 14 km and between 34 and 42 km, with the stagnant layer reaching a maximum thickness of ~ 300 m. At the BELDC drill site specifically, the modelled stagnant ice thickness is 194 m.

255 3.2.5 2.5D model results at EDC and BELDC

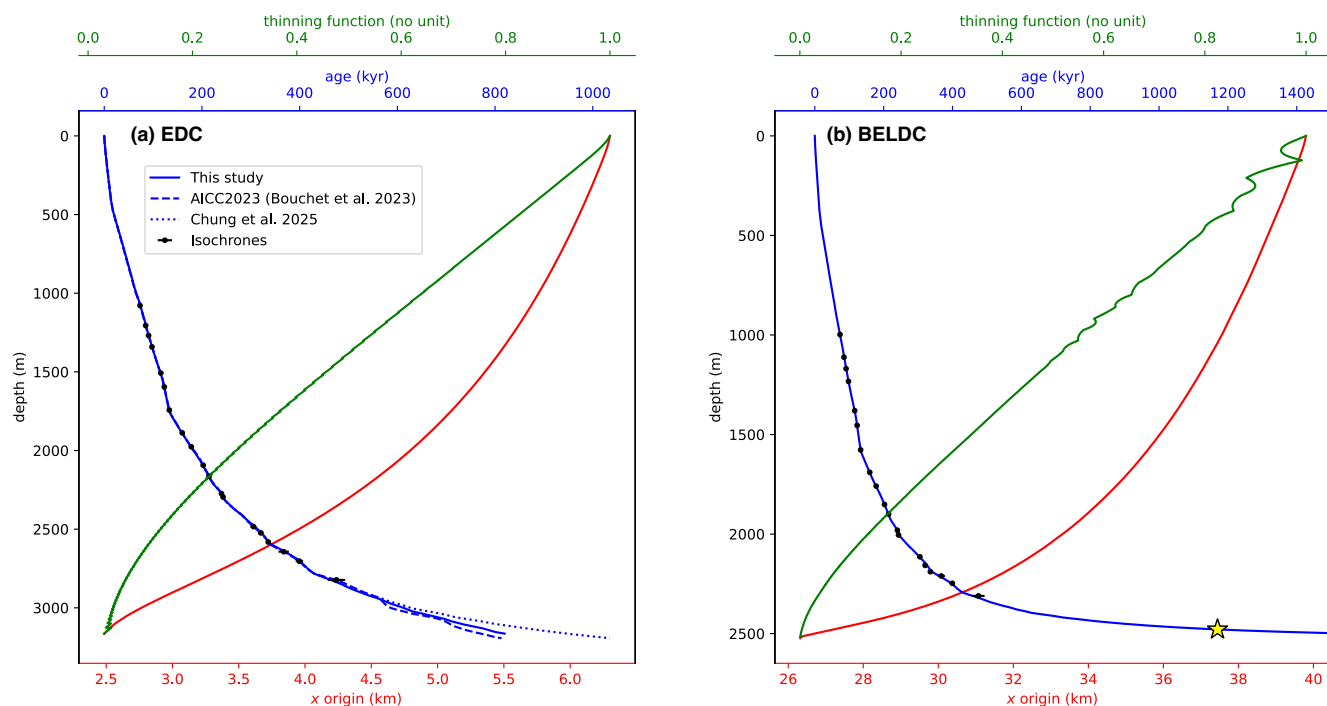


Figure 8. The solid blue line shows the modelled age–depth profile, the solid green line shows the thinning function τ and the red line shows the horizontal distance origin of ice particles (a) at EDC and (b) BELDC from the 2.5D model. Black dots indicate the ages of the 19 observed radar isochrones used to constrain the model. The dashed blue line at EDC shows the AICC2023 ice core chronology (Bouchet et al., 2023) for comparison. The yellow star shows the 20 kyr m $^{-1}$ threshold at BELDC.

Figure 8 shows the 2.5D modelled age–depth profiles at EDC and BELDC, with the corresponding thinning function τ and the upstream origin of ice particles. At EDC, the modelled age–depth profile agrees well with the AICC2023 chronology



(Bouchet et al., 2023) throughout the full depth range constrained by the radar isochrones. The thinning function decreases smoothly with depth, reflecting the progressive compression of annual layers towards the bed. The upstream origin of basal ice particles is approximately 3.5 km. At the depth of 3192 m, the modelled age is 820 ka, compared to 813 ka (Table 1) in the AICC2023 chronology (Bouchet et al., 2023), a difference of only 7 ka.

At BELDC, the modelled age–depth profile shows a much more rapid increase in age with depth at the base of the ice sheet, a consequence of the strong thinning of annual layers and the presence of the stagnant ice layer below $H_m = 2527$ m. The upstream origin of basal ice particles reaches approximately 14 km. At a depth of 2517 m, the modelled age density of ice becomes $> 20 \text{ kyr m}^{-1}$. At this depth, the ice is $1.17 \pm 0.39 \text{ Ma}$,

4 Discussion

4.1 Improvements brought by the Δ parameter

While the overall model framework remains that of Chung et al. (2023) and Chung et al. (2025), the introduction of the dimensionless parameter Δ constitutes the central methodological contribution of this study, with measurable consequences on the modelled basal age.

In the melting regime, the previous approach inferred a melt rate from the excess of H_m over H_{obs} , which truncated the shear layer above the observed bedrock. This led to an underestimated melt rate and an overestimated basal age. By keeping $H_m = H_{\text{obs}}$ and parameterising the melt rate directly as $m = a\Delta$, this formulation preserves the full shear layer and produces a more consistent age–depth profile in the deepest ice. The effect is visible in the age–depth profile along the DC–LDC flow line (Fig. 6), where the modelled bottom age is systematically lower than in Chung et al. (2025) in regions of basal melting. Furthermore, the spatial variations of the inferred Δ parameter (Fig. 7c) show the transitions between different basal regimes along the transect. This demonstrates that Δ is effective and capable of separating basal melting area from stagnant ice area.

The most direct validation of this improvement comes from the comparison with the EDC ice core, the 2.5D modelled age at $H_m = 3192$ m is 820 ka, compared to 813 ± 58 ka in the AICC2023 chronology (Bouchet et al., 2023), a difference of only 7 ka that lies well within the chronology uncertainties. This tight agreement represents a clear improvement over the previous simulation configurations by Chung et al. (2025). This highlights the strong sensitivity of age estimates to the basal parameterisation in the lowermost ice, where annual layers are extremely thin and age increases rapidly with depth. The correction of the shear layer truncation brought by Δ therefore has a meaningful impact on the age predictions even when the depth of ice thickness barely changes. Similarly, at BELDC (Fig. 8b), our calculated age of $1.17 \pm 0.39 \text{ Ma}$ at the 20 kyr m^{-1} age-density threshold is older than the estimate proposed by Chung et al. (2025). This improvement carries direct implications for the interpretation of the deepest part of the Beyond EPICA ice core, demonstrating that the Δ parameterisation improves the accuracy of basal age estimates at drill sites without degrading the fit to the observed isochrones.

The relocation of the MYIC-DCN drill site from Little Dome C to Dome C North (Pedro and Million Year Ice Core Project Team, 2026) gives new relevance to the DCN DELORES results presented in this study. While Chung et al. (2023) noted that the DCN area showed strong lateral gradients in maximum age and a relative lack of stagnant ice, our results with the Δ



parameterisation refine these predictions at MYIC: a maximum age of 2.07 Ma with an age density of 6.5 kyr m^{-1} suggests that MYIC-DCN is a highly promising site for recovering ice older than 1.5 Ma at excellent temporal resolution. These predictions are consistent with the results of Chung et al. (2023), who found maximum ages potentially reaching 2 Ma in the DCN area. The low age density values at 1.2 and 1.5 Ma (4.8 and 6.5 kyr m^{-1} respectively) are notably better than those predicted at
 295 BELDC, reflecting the larger ice thickness and lower thinning rate at DCN. Given the uncertainty on the basal melt rate of $0.13 \pm 0.14 \text{ mm yr}^{-1}$, a thin layer of stagnant ice with no basal melting cannot be excluded. These predictions provide model-based support for the choice of MYIC-DCN as a drill site for the recovery of ice during the Mid-Pleistocene Transition. However, it should be noted that the DCN DELORES radar dataset provides IRH constraints only down to $\sim 2600 \text{ m}$ depth (Fig. 2), leaving the lowermost section of the ice sheet unconstrained by isochrones. This limits the accuracy of the age predictions
 300 at MYIC, particularly for ice older than 1.5 Ma. As noted by Chung et al. (2023), a higher-resolution radar survey over the DCN area, similar to the LDC-VHF survey conducted at LDC, may allow deeper IRHs to be traced and possibly confirm the presence or absence of a basal unit.

4.2 Correction of accreted ice and ice particle trajectories

In Chung et al. (2025), a layer of potentially accreted ice was identified along the DC–LDC flow line, arising from ice particle
 305 trajectories that crossed below the observed bedrock where $H_m > H_{\text{obs}}$. This layer reached up to 120 m in thickness at 34 km along the flow line and decreased to $\sim 40 \text{ m}$ near BELDC (Chung et al., 2025). Its presence was an artefact, leading to an unphysical layer of inferred H_m in the case of basal melting, as it implied that ice particles originated from below the bedrock. The introduction of Δ resolves this issue entirely. A key improvement over these previous implementations (Chung et al., 2023, 2025) is that no ice particle trajectories originate from or cross the bedrock. By keeping $H_m = H_{\text{obs}}$ in the basal melting
 310 case (Sect. 2.2), the shear layer extends to the observed ice thickness H_{obs} and no trajectory is allowed to cross the bedrock.

The lack of an accreted ice layer in our results (Fig. 5) constitutes a direct validation of the improved physical consistency of the new parameterisation. Furthermore, it suggests that basal melt rates inferred in previous studies using the H_m approach may have been underestimated in regions where this layer was present without a stagnant ice layer, as part of the available ice flux was effectively misattributed to a sub-bedrock disturbed layer rather than to basal melting.

315 4.3 Comparison with Chung et al. (2023) and Chung et al. (2025)

When the Δ parameterisation is applied to the 1D model, the maximum ages of paleoclimatically resolvable ice are younger compared to Chung et al. (2025) at the EDC and BELDC drill sites. At BELDC, the depths at which these maximum ages are reached, are also shallower than those of Chung et al. (2025); for the DELORES dataset (2475 m vs 2484 m) and for the LDC-VHF dataset (2500 m vs 2504 m). Both differences lie within the respective model uncertainties. The spatial distribution
 320 of basal conditions across the four radar datasets (Fig. 3) agrees well with the results from Chung et al. (2023): stagnant ice dominates over the LDC area (LDC DELORES, Fig 3b and LDC–VHF, Fig 3c datasets) while basal melting is predicted along the DC–LDC divide and over the Concordia trench. At BELDC, the 1D and 2.5D modelled stagnant ice thickness of 220 m and 194 m, respectively, remains in good agreement with Lilien et al. (2021) and Chung et al. (2023), confirming the robustness of



this estimate at the drill site. However, quantitative differences are significant in regions of basal melting. At the large scale, the HiCARS dataset (Fig. 3a, 4a) shows higher inferred melt rates and lower bottom ages compared to Chung et al. (2023). The most striking differences are observed in the DCN area (Fig. 3d, 4d), where the Δ parameterisation produces higher gradients in maximum age than previously reported. This reflects the higher sensitivity of the DCN results to the basal melting parameterisation and to local bedrock topography where even small variations in bed elevation translate into significant changes in the basal thermal regime and therefore in the age of the deepest ice. This high spatial variability makes DCN a significantly riskier candidate for retrieving a continuous, undisturbed oldest ice record compared to the spatially uniform age distribution at LDC (Parrenin et al., 2017; Chung et al., 2023). The introduction of Δ therefore does not fundamentally alter the pattern of basal conditions, but meaningfully changes the quantitative basal estimates in the melting regime, with implications for the identification of sites where ice older than 1.2 Ma could be preserved.

In the 2.5D model, the effect of Δ is more pronounced, as the horizontal advection of ice along the flow line amplifies the impact of basal processes on the age–depth profile. This upstream origin must be taken into account when interpreting the palaeoclimatic signal recorded in the deepest part of the ice core, as the ice was deposited under surface conditions prevailing further upstream rather than directly above the drill site. The modelled ice particle trajectories along the DC–LDC flow line are consistent with the findings of Chung et al. (2025). The steady-state accumulation rate of $\sim 0.02 \text{ m yr}^{-1}$ is in excellent agreement with modern surface data and historical estimates at Dome C (Parrenin et al., 2017; Cavitte et al., 2018; Chung et al., 2023, 2025). The high variability observed in the Llibouty parameter p , particularly the sharp peaks at 14 km and 28 km, reflects a localized response to bedrock features. These increases indicate a more linear vertical velocity profile arising from variations in basal drag over subglacial topography; notably, the peak at 28 km directly coincides with a bedrock dip noted by Chung et al. (2025). More generally, Fig. 7b shows that in areas of basal melting, p is systematically higher with the Δ parameterisation than with the previous model. This is expected, as the earlier approach truncated the thinning function where melting occurred, restricting the optimisation of p to a shorter, less representative section of the profile and biasing it towards lower p . Removing this truncation allows p to better reflect a more linear shape of the velocity profile. The Δ parameter remains close to 5% over most of the DC–LDC flow line (Fig. 7c), indicating that the previous results of Chung et al. (2025) were slightly affected by the shear layer truncation over the flow line. However, in the melting zone between 18 and 25 km (Fig. 7d), the correction is significant: the modelled bottom age is reduced and the melt rate is increased relative to Chung et al. (2025), consistent with the expected effect of restoring the full shear layer. The increase in uncertainty on Δ near BELDC reflects the inherent difficulty of constraining basal processes in the deepest and most compressed part of the base of the ice sheet, where the sensitivity of the isochrone geometry to basal conditions is highest and small changes in Δ translate into large changes in basal age. We note that Chung et al. (2023) and Obase et al. (2023) reported deviations between modelled and observed age–depth profiles in the lowermost ice at EDC and Dome Fuji; however, at EDC our model agrees with AICC2023 within 7 ka, suggesting suggesting the Δ parameter resolves this inconsistency.



4.4 Limitations specific to the Δ parameter

While Δ represents a methodological improvement over the H_m inverse approach, several limitations specific to this parameterisation should be noted. We emphasise that the general limitations of the pseudo-steady-state assumption, the Liboutry velocity profile, and the isochrone-based inversion framework are discussed in detail in Chung et al. (2023) and Chung et al. (2025) and remain unchanged here.

First, the relation $m = a\Delta$ assumes a linear dependence of the melt rate on the accumulation rate. At Dome C, basal melting is primarily driven by the geothermal heat flux, which is poorly constrained under the East Antarctic ice sheet (Passalacqua et al., 2017). Using a 1D heat model constrained by radar reflectivity, Passalacqua et al. (2017) inferred geothermal heat flow (GF) values ranging from 48 to 60 mW m⁻² across the Dome C region, deriving a time-averaged basal melt rate of 0.32 ± 0.25 mm yr⁻¹ at EDC, broadly consistent with the 0.22 mm yr⁻¹ found by Chung et al. (2023). However the value of 0.56 ± 0.19 mm yr⁻¹ previously inferred by Parrenin et al. (2007) is more consistent with our modelled melt rate at EDC of 0.68 mm yr⁻¹, which is slightly higher than these estimates.

Second, the range of Δ is bounded by $[H_{iso}/H_{obs} - 1, 1]$, which limits the maximum melt rate to $m = a$. In regions of very high geothermal heat flux, this upper bound may be reached and the model would be unable to represent the true melt rate. Passalacqua et al. (2017) showed that melt rates can exceed 0.6 mm yr⁻¹ in thick-ice regions around Dome C, and noted that local geothermal flux anomalies at the scale of a few tens of kilometres cannot be excluded. At the Dome C drill sites, where melt rates are generally low, this limitation is unlikely to be binding.

4.5 Possible applications and outlook

The Δ parameterisation is formulated in a general way and can be readily applied to other oldest ice candidate sites beyond Dome C, such as Dome Fuji in East Antarctica, where similar 1D (Wang et al., 2023; Obase et al., 2023) and 2.5D inverse modelling has been carried out. In these regions, the presence of a basal unit analogous to that observed at LDC has been suggested (Wang et al., 2023), and the improved treatment of the transition between the melting and stagnant regimes offered by Δ could lead to more accurate basal age estimates.

With the Δ parameterisation validated at both EDC and BELDC, a promising future outlook consists of incorporating this formulation into larger-scale, three-dimensional ice sheet models. This would allow for a more realistic representation of basal layers across the entire Antarctic plateau, improving the regional mapping of potential old ice.

5 Conclusions

In this study, we introduced a Δ parameter into both the 1D inverse model IsoInv1D (Chung et al., 2023) and the 2.5D inverse model IsoInv2.5D (Chung et al., 2025), providing a parameter for basal melting and stagnant ice in the pseudo-steady-state ice flow models. By keeping $H_m = H_{obs}$ in the melting regime, Δ preserves the full shear layer down to the observed bedrock,



correcting a fundamental truncation artefact that affected both previous models and led to an underestimation of basal melt rates and an overestimation of basal age.

This correction is reflected consistently across both models: results from the 1D and 2.5D models alike show higher basal melting and lower basal ages than previously estimated. In the 2.5D model, the results confirm that the deepest ice at BELDC originates from approximately 14 km upstream of the drill site, consistent with Chung et al. (2025) with a maximum modelled age of 1.17 Ma at an age density of 20 kyr m^{-1} . At EDC, the modelled age at $H_m = 3192 \text{ m}$ is 820 ka, within 7 ka of the AICC2023 chronology (Bouchet et al., 2023) and representing an improvement over the previous 2.5D estimate. The modelled basal age along the DC–LDC flow line is systematically lower than in Chung et al. (2025) in regions of basal melting, a direct consequence of the corrected shear layer and of a higher basal melting. Most notably, the layer of potentially accreted ice identified by Chung et al. (2025), up to 120 m thick at 34 km along the flow line and $\sim 40 \text{ m}$ near BELDC, is entirely absent from our results, confirming that this layer was an unphysical artefact of the previous H_m parameterisation rather than a physical feature of the ice sheet (Westhoff et al., 2026). At the MYIC-DCN drill site, the 1D model predicts a maximum resolvable age of 2.07 Ma and confirming the potential of this site for recovering ice spanning the full MPT.

Taken together, these results demonstrate that the Δ parameterisation offers a meaningful improvement over existing approaches: it corrects an identified physical inconsistency, produces more accurate basal age estimates at both EDC and BELDC, and eliminates unphysical model artefacts, while leaving the broad spatial pattern of basal conditions unchanged. The framework is general and transferable to any ice core site and could be integrated to 3D ice sheet models, offering an improved tool for basal age estimation at current and future Oldest Ice drilling targets.

Code availability. The codes for the 1D and 2.5D numerical models are available publicly from <https://github.com/yevajeaumot/IsoInv1D> and <https://github.com/yevajeaumot/IsoInv2.5D>.

Data availability. Once the manuscript is accepted, the results of the simulations will be uploaded to PANGAEA.

Author contributions. FP proposed the Delta parameterisation, funded the project and supervised YJ. AC provided the previous versions of IsoInv1D and IsoInv2.5D and guidance. YJ implemented the Delta parameterisation, carried out the IsoInv1D and IsoInv2.5D simulations and supervised the writing of the manuscript. OE, DS, RM, and DL provided the radar data. We thank Luca Vittuari for providing the GNSS-derived surface velocity field and flow-line information, and Carlos Martin for his contribution to the DELORES radar geophysical campaign. All co-authors read and commented on the manuscript.



Competing interests. The authors declare they have no competing interests.

Acknowledgements. This publication was generated in the frame of Beyond EPICA. The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 815384 (Oldest Ice Core). It is supported by national partners and funding agencies in Belgium, Denmark, France, Germany, Italy, Norway, Sweden, Switzerland, the Netherlands and the United Kingdom. Logistic support is mainly provided by ENEA and IPEV through the Concordia Station system. This publication was generated in the frame of the DEEPICE project. The project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Actions, grant agreement no. 955750. The research leading to these results has received funding from the French National Research Agency through the Towards Beyond EPICA (ToBE) project (ANR-22-CE01-0024). Ailsa Chung is funded by the Past to Future (P2F) project which has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101184070. EC acknowledges the financial support from the Agence Nationale de la Recherche through the MOPGA HOTCLIM project (grant no. ANR-19-MPGA-0001). The opinions expressed and arguments employed herein do not necessarily reflect the official views of the European Union funding agency or other national funding bodies. This is Beyond EPICA publication number ?. The radar shipment and personnel transportation to Antarctica were provided by the US NSF under grant 1921418, which also partly supported the development of the VHF radar. Radar development was further supported by internal funding from the University of Alabama. David A. Lilien and Dorthe Dahl-Jensen were partially supported by the Villum Foundation (grant number 16572).



References

- 430 Bazin, L., Landais, A., Lemieux-Dudon, B., Toyé Mahamadou Kele, H., Veres, D., Parrenin, F., Martinerie, P., Ritz, C., Capron, E., Lipenkov, V., Loutre, M.-F., Raynaud, D., Vinther, B., Svensson, A., Rasmussen, S. O., Severi, M., Blunier, T., Leuenberger, M., Fischer, H., Masson-Delmotte, V., Chappellaz, J., and Wolff, E.: An optimized multi-proxy, multi-site Antarctic ice and gas orbital chronology (AICC2012): 120dash;800 ka, *Climate of the Past*, 9, 1715–1731, <https://doi.org/10.5194/cp-9-1715-2013>, 2013.
- Bell, R. E., Ferraccioli, F., Creyts, T. T., Braaten, D., Corr, H., Das, I., Damaske, D., Frearson, N., Jordan, T., Rose, K., Studinger, M., and
435 Wolovick, M.: Widespread Persistent Thickening of the East Antarctic Ice Sheet by Freezing from the Base, *Science*, 331, 1592–1595, <https://doi.org/10.1126/science.1200109>, 2011.
- Bingham, R. G., Bodart, J. A., Cavitte, M. G. P., Chung, A., Sanderson, R. J., Sutter, J. C. R., Eisen, O., Karlsson, N. B., MacGregor, J. A., Ross, N., Young, D. A., Ashmore, D. W., Born, A., Chu, W., Cui, X., Drews, R., Franke, S., Goel, V., Goodge, J. W., Henry, A. C. J., Hermant, A., Hills, B. H., Holschuh, N., Koutnik, M. R., Leysinger Vieli, G. J.-M. C., MacKie, E. J., Mantelli, E., Martín, C., Ng, F. S. L.,
440 Oraschewski, F. M., Napoleoni, F., Parrenin, F., Popov, S. V., Rieckh, T., Schlegel, R., Schroeder, D. M., Siegert, M. J., Tang, X., Teisberg, T. O., Winter, K., Yan, S., Davis, H., Dow, C. F., Fudge, T. J., Jordan, T. A., Kulesa, B., Matsuoka, K., Nyqvist, C. J., Rahnemoonfar, M., Siegfried, M. R., Singh, S., Višnjević, V., Zamora, R., and Zuhr, A.: Review article: AntArchitecture – building an age–depth model from Antarctica’s radiostratigraphy to explore ice-sheet evolution, *The Cryosphere*, 19, 4611–4655, <https://doi.org/10.5194/tc-19-4611-2025>, 2025.
- 445 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., Legrain, E., Martinerie, P., Leuenberger, M., Jiang, W., Ritterbusch, F., Lu, Z.-T., and Yang, G.-M.: The Antarctic Ice Core Chronology 2023 (AICC2023) chronological framework and associated timescale for the European Project for Ice Coring in Antarctica (EPICA) Dome C ice core, *Climate of the Past*, 19, 2257–2286, <https://doi.org/10.5194/cp-19-2257-2023>, 2023.
- Cavitte, M. G. P.: Flow re-organization of the East Antarctic ice sheet across glacial cycles, Thesis, <https://doi.org/10.15781/T2TT4G891>,
450 accepted: 2017-11-13T16:37:08Z, 2017.
- 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, *Journal of Glaciology*, 62, 323–334, <https://doi.org/10.1017/jog.2016.11>, 2016.
- Cavitte, M. G. P., Parrenin, F., Ritz, C., Young, D. A., Van Liefferinge, B., Blankenship, D. D., Frezzotti, M., and Roberts, J. L.: Accumulation
455 patterns around Dome C, East Antarctica, in the last 73 kyr, *The Cryosphere*, 12, 1401–1414, <https://doi.org/10.5194/tc-12-1401-2018>, 2018.
- Cavitte, M. G. P., Young, D. A., Mulvaney, R., Ritz, C., Greenbaum, J., Ng, G., Kempf, S. D., Quartini, E., Muldoon, G. R., Paden, J., Frezzotti, M., Roberts, J., Tozer, C., Schroeder, D., and Blankenship, D. D.: Ice-penetrating radar internal stratigraphy over Dome C and the wider East Antarctic Plateau, U.S. Antarctic Program (USAP) Data Center [data set], <https://doi.org/10.15784/601411>, 2020.
- 460 Cavitte, M. G. P., Young, D. A., Mulvaney, R., Ritz, C., Greenbaum, J. S., Ng, G., Kempf, S. D., Quartini, E., Muldoon, G. R., Paden, J., Frezzotti, M., Roberts, J. L., Tozer, C. R., Schroeder, D. M., and Blankenship, D. D.: A detailed radiostratigraphic data set for the central East Antarctic Plateau spanning from the Holocene to the mid-Pleistocene, *Earth System Science Data*, 13, 4759–4777, <https://doi.org/10.5194/essd-13-4759-2021>, 2021.



- 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.,
 465 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., 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.: Internal reflecting horizons at Little Dome C, Antarctica,
<https://doi.org/10.1594/PANGAEA.957176>, 2023.
- 470 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.
- Clark, P. U., Archer, D., Pollard, D., Blum, J. D., Rial, J. A., Brovkin, V., Mix, A. C., Pisias, N. G., and Roy, M.: The middle Pleistocene
 transition: characteristics, mechanisms, and implications for long-term changes in atmospheric pCO₂, Quaternary Science Reviews, 25,
 475 3150–3184, <https://doi.org/https://doi.org/10.1016/j.quascirev.2006.07.008>, critical Quaternary Stratigraphy, 2006.
- Drews, R., Eisen, O., Weikusat, I., Kipfstuhl, S., Lambrecht, A., Steinhage, D., Wilhelms, F., and Miller, H.: Layer disturbances and the
 radio-echo free zone in ice sheets, The Cryosphere, 3, 195–203, <https://doi.org/10.5194/tc-3-195-2009>, 2009.
- EPICA community members, Augustin, L., Barbante, C., Barnes, P. R. F., Barnola, J. M., Bigler, M., Castellano, E., Cattani, O., Chappellaz,
 J., Dahl-Jensen, D., Delmonte, B., Dreyfus, G., Durand, G., Falourd, S., Fischer, H., Flückiger, J., Hansson, M. E., Huybrechts, P., Jugie,
 480 G., Johnsen, S. J., Jouzel, J., Kaufmann, P., Kipfstuhl, J., Lambert, F., Lipenkov, V. Y., Littot, G. C., Longinelli, A., Lorrain, R., Maggi, V.,
 Masson-Delmotte, V., Miller, H., Mulvaney, R., Oerlemans, J., Oerter, H., Orombelli, G., Parrenin, F., Peel, D. A., Petit, J.-R., Raynaud,
 D., Ritz, C., Ruth, U., Schwander, J., Siegenthaler, U., Souchez, R., Stauffer, B., Steffensen, J. P., Stenni, B., Stocker, T. F., Tabacco, I. E.,
 Udisti, R., van de Wal, R. S. W., van den Broeke, M., Weiss, J., Wilhelms, F., Winther, J.-G., Wolff, E. W., and Zucchelli, M.: Eight glacial
 cycles from an Antarctic ice core, Nature, 429, 623–628, <https://doi.org/10.1038/nature02599>, 2004.
- 485 Fischer, H., Severinghaus, J., Brook, E., Wolff, E., Albert, M., Alemany, O., Arthern, R., Bentley, C., Blankenship, D., Chappellaz, J., Creyts,
 T., Dahl-Jensen, D., Dinn, M., Frezzotti, M., Fujita, S., Gallee, H., Hindmarsh, R., Hudspeth, D., Jugie, G., Kawamura, K., Lipenkov,
 V., Miller, H., Mulvaney, R., Parrenin, F., Pattyn, F., Ritz, C., Schwander, J., Steinhage, D., van Ommen, T., and Wilhelms, F.: Where to
 find 1.5 million yr old ice for the IPICS "Oldest-Ice" ice core, Climate of the Past, 9, 2489–2505, <https://doi.org/10.5194/cp-9-2489-2013>,
 2013.
- 490 Holschuh, N., Christianson, K., Dienstfrey, W., Hills, B., Hoffman, A. O., Paden, J., Winter, K., and Zuraw, R.: Entrained debris records
 regrowth of the Greenland Ice Sheet after the last interglacial, Nature Geoscience, pp. 1–8, <https://doi.org/10.1038/s41561-026-01950-1>,
 2026.
- Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Minster, B., Nouet, J., Barnola, J., Chappel-
 laz, J., Fischer, H., Gallet, J.-C., Johnsen, S., Leuenberger, M., Loulergue, L., Lüthi, D., Oerter, H., Parrenin, F., Raisbeck, G., and
 495 Wolff, E.: Orbital and Millennial Antarctic Climate Variability over the Past 800,000 Years, Science (New York, N.Y.), 317, 793–6,
<https://doi.org/10.1126/science.1141038>, 2007.
- Lilien, D. A., Steinhage, D., Taylor, D., Parrenin, F., Ritz, C., Mulvaney, R., Martín, C., Yan, J.-B., O'Neill, C., Frezzotti, M., Miller, H.,
 Gogineni, P., Dahl-Jensen, D., and Eisen, O.: Brief communication: New radar constraints support presence of ice older than 1.5 Myr at
 Little Dome C, The Cryosphere, 15, 1881–1888, <https://doi.org/10.5194/tc-15-1881-2021>, 2021.



- 500 Livingstone, S. J., Li, Y., Rutishauser, A., Sanderson, R. J., Winter, K., Mikucki, J. A., Björnsson, H., Bowling, J. S., Chu, W., Dow, C. F., Fricker, H. A., McMillan, M., Ng, F. S. L., Ross, N., Siegert, M. J., Siegfried, M., and Sole, A. J.: Subglacial lakes and their changing role in a warming climate, *Nature Reviews Earth & Environment*, 3, 106–124, <https://doi.org/10.1038/s43017-021-00246-9>, 2022.
- Lliboutry, L.: A critical review of analytical approximate solutions for steady state velocities and temperatures in cold ice sheets, *Z. Gletscherkde. Glazialgeol.*, 15, 135–148, 1979.
- 505 Lüthi, D., Le Floch, M., Bereiter, B., Blunier, T., Barnola, J.-M., Siegenthaler, U., Raynaud, D., Jouzel, J., Fischer, H., Kawamura, K., and Stocker, T. F.: High-resolution carbon dioxide concentration record 650,000–800,000 years before present, *Nature*, 453, 379–382, <https://doi.org/10.1038/nature06949>, 2008.
- Morlighem, M.: MEaSUREs BedMachine Antarctica, Version 3, <https://doi.org/10.5067/FPSU0V1MWUB6>, 2022.
- Mulvaney, R., Frezzotti, M., Ritz, C., Martín, C., Rix, J., and Chung, A.: Internal reflecting horizons in the Dome C region of Antarctica, <https://doi.org/10.1594/PANGAEA.963470>, 2023.
- 510 Obase, T., Abe-Ouchi, A., Saito, F., Tsutaki, S., Fujita, S., Kawamura, K., and Motoyama, H.: A one-dimensional temperature and age modeling study for selecting the drill site of the oldest ice core near Dome Fuji, Antarctica, *The Cryosphere*, 17, 2543–2562, <https://doi.org/10.5194/tc-17-2543-2023>, 2023.
- Parrenin, F., Dreyfus, G., Durand, G., Fujita, S., Gagliardini, O., Gillet, F., Jouzel, J., Kawamura, K., Lhomme, N., Masson-Delmotte, V., Ritz, C., Schwander, J., Shoji, H., Uemura, R., Watanabe, O., and Yoshida, N.: 1-D-ice flow modelling at EPICA Dome C and Dome Fuji, East Antarctica, *Climate of the Past*, 3, 243–259, <https://doi.org/10.5194/cp-3-243-2007>, 2007.
- 515 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.
- 520 Parrenin, F., Chung, A., and Martín, C.: age_flow_line-1.0: a fast and accurate numerical age model for a pseudo-steady flow tube of an ice sheet, *Geoscientific Model Development*, 18, 8203–8216, <https://doi.org/10.5194/gmd-18-8203-2025>, 2025.
- Passalacqua, O., Ritz, C., Parrenin, F., Urbini, S., and Frezzotti, M.: Geothermal flux and basal melt rate in the Dome C region inferred from radar reflectivity and heat modelling, *The Cryosphere*, 11, 2231–2246, <https://doi.org/10.5194/tc-11-2231-2017>, 2017.
- Pedro, J. B. and Million Year Ice Core Project Team: The Million Year Ice Core Project at Dome C North, EGU General Assembly 2026, Vienna, Austria, 3–8 May 2026, EGU26-8488, <https://doi.org/10.5194/egusphere-egu26-8488>, 2026.
- 525 Van Liefferinge, B. and Pattyn, F.: Using ice-flow models to evaluate potential sites of million year-old ice in Antarctica, *Climate of the Past*, 9, 2335–2345, <https://doi.org/10.5194/cp-9-2335-2013>, 2013.
- Waddington, E. D., Neumann, T. A., Koutnik, M. R., Marshall, H.-P., and Morse, D. L.: Inference of accumulation-rate patterns from deep layers in glaciers and ice sheets, *Journal of Glaciology*, 53, 694–712, <https://doi.org/10.3189/002214307784409531>, 2007.
- 530 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.
- Westhoff, J., Ardoin, L., Weikusat, I., et al.: 316 m of ice beyond the stratified sections of the Beyond EPICA Little Dome C ice core, <https://doi.org/10.21203/rs.3.rs-9883712/v1>, pREPRINT (Version 1) available at Research Square, 2026.
- 535 Yan, J.-B., Li, L., Nunn, J. A., Dahl-Jensen, D., O'Neill, C., and Taylor, R. A.: Multiangle, Frequency, and Polarization Radar Measurement of Ice Sheets, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 13, 2070–2080, <https://doi.org/10.1109/JSTARS.2020.9086068>, 2020.



540 Young, D. A., Roberts, J. L., Ritz, C., Frezzotti, M., Quartini, E., Cavitte, M. G. P., Tozer, C. R., Steinhage, D., Urbini,
S., Corr, H. F. J., van Ommen, T., and Blankenship, D. D.: High-resolution boundary conditions of an old ice target
near Dome C, Antarctica, *The Cryosphere*, 11, 1897–1911, <https://doi.org/10.5194/tc-11-1897-2017>, 2017.