Error-bounded volumetric constraints on Antarctic ice residence times

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24 January 2026 (updated 10 February 20026)

Abstract

The age structure of the Antarctic Ice Sheet is commonly inferred from localized ice-core records, yet the volumetric distribution of long-residence-time ice remains poorly quantified. Here we construct a continent-scale, dynamics-informed proxy for ice residence time based on ice thickness and observed surface velocity, and use it to estimate error-bounded volumetric proportions of Antarctic ice exceeding millennial-scale persistence thresholds. By combining BedMachine ice thickness with satellite-derived surface velocities, we derive residence-time exceedance maps and volume-weighted statistics for Antarctica as a whole and for its major ice-sheet components. We find that only a small fraction of Antarctic ice volume is dynamically constrained to exceed Holocene-scale residence times, with a central estimate of approximately 1% exceeding 10 kyr and a conservative uncertainty envelope of 0.6–2.5%. These results provide a lower bound on dynamically persistent ice volume and reconcile the existence of extremely old ice at isolated dome sites with the predominantly transient character of Antarctic ice at continental scale.

1 Introduction

The Antarctic Ice Sheet contains the largest reservoir of freshwater ice on Earth and preserves a unique archive of past climate variability. Deep ice cores recovered from a small number of interior dome sites have demonstrated that Antarctic ice can exceed ages of several hundred thousand years, and in some locations may approach or exceed one million years. However, such records provide pointwise constraints and do not directly inform the volumetric or spatial distribution of long-lived ice across the continent.

At continental scale, ice age is not determined solely by accumulation history but by the combined effects of ice thickness, flow velocity, and geometry. Ice that is thick but dynamically mobile may be replaced on millennial timescales, whereas thinner ice in regions of extremely slow flow may persist far longer. This distinction motivates a dynamics-informed approach to assessing the persistence of Antarctic ice that complements traditional stratigraphic methods.

In this study we estimate the large-scale residence-time structure of Antarctic ice using a simple but physically interpretable proxy: the ratio of local ice thickness to observed surface flow speed. While this quantity does not represent the true age of ice at depth, it provides a conservative estimate of the characteristic timescale over which a vertical ice column would be evacuated under present-day dynamics. By evaluating exceedance of millennial-scale thresholds in this proxy and integrating over ice volume, we derive error-bounded estimates of the fraction of Antarctic ice that is dynamically constrained to exceed Holocene-scale residence times.

2 Background and Prior Art

Understanding the age structure of the Antarctic Ice Sheet historically stems from a combination of deep ice-core stratigraphy, radar-echo sounding (RES) interpretations, and numerical ice-flow modelling. Each approach provides partial insight into the age and internal architecture of ice, but none so far has yielded a purely observational, continent-wide quantitative estimate of the volumetric prevalence of long-lived ice.

Deep ice cores from interior sites such as Vostok, EPICA Dome C, Dome Fuji, and the West Antarctic Ice Sheet Divide have demonstrated multi-glacial age ice exceeding several hundred thousand years [2, 3, 5]. Complementary to cores, RES imaging reveals englacial internal reflecting horizons — the 'internal architecture' — with substantial spatial coverage and retention of isochronal information far beyond individual boreholes. Internal stratigraphy can be tied to core chronologies to extend age inference away from drilling sites [6, 7, 8].

In addition to deep interior cores and radiostratigraphy, localized ablation environments known as blue-ice areas (BIAs) provide an important and complementary archive of very old ice. In such regions, strong katabatic winds and low net accumulation expose deep, ancient ice at or near the surface, allowing direct sampling of ice that has been preserved under near-stagnant flow conditions. Recent work from the Allan Hills blue-ice area in East Antarctica has identified ice dating to the Miocene–Pliocene, demonstrating that ice substantially older than the Quaternary can survive in highly specialized dynamical settings [19]. These discoveries extend the known temporal range of Antarctic ice preservation, while simultaneously highlighting the spatially restricted and topographically controlled nature of such environments.

Recently, Bingham *et al.* provided a comprehensive review of Antarctic internal architecture and the prospects for constructing continent-wide age–depth models from RES radiostratigraphy [1]. This 'AntArchitecture' framework synthesises decades of RES data and crystallises the potential for radar-based age inference at scales previously unattainable, including the identification of optimal drilling sites, palaeo accumulation reconstructions, and constraints on basal processes. Their review highlights both the richness of the RES archive and the technical challenges that remain in standardising, dating, and modelling these datasets across the entire ice sheet — a gap that motivates complementary approaches such as dynamics-informed residence-time proxies.

Numerical modelling studies have also explored ice age fields by integrating physics-based ice-sheet simulations with climatic forcing, though such models are subject to substantial uncertainties related to basal conditions, accumulation histories, and model parameterisations [9, 10, 11]. These modelled age fields have been used to evaluate candidate locations for old ice and to inform theories of long-term ice-sheet evolution, but they rely on assumptions about past climate and ice dynamics that are difficult to validate universally.

By contrast, the present work seeks a **dynamics-based lower bound** on the volumetric prevalence of long-lived ice by exploiting only present-day thickness and velocity fields, avoiding assumptions about past states. This framing aligns with conceptual interpretations of ice flow and divide persistence [14, 15], and provides a quantitative complement to the stratigraphic and modelling perspectives emphasised in the prior art.

3 Data and Methods

3.1 Datasets

Ice thickness and grounded–floating mask information were obtained from the BedMachine Antarctica v4 dataset [16], provided on a polar stereographic grid with nominal horizontal resolution of

500 m. Surface ice velocities were taken from the MEaSUREs InSAR-based Antarctic Ice Velocity Map [17], representing multi-year averaged horizontal surface flow speeds derived primarily from satellite interferometry.

The velocity and thickness datasets were reprojected onto a common grid and aligned using nearest-neighbour interpolation. Given the multi-year averaging of satellite velocity products and the millennial timescales considered here, the datasets are treated as representative of a quasi-steady present-day dynamical state.

3.2 Residence-time proxy

We define a residence-time proxy

$$\tau = \frac{H}{u}, \tag{1}$$

where H is local ice thickness and u is horizontal surface velocity magnitude. This quantity represents an evacuation timescale: the time required for ice at a given location to be advected out of that position under present-day flow conditions.

Importantly, τ is *not* interpreted as the true age of ice. Rather, it provides a conservative lower bound on ice persistence under current dynamics. Ice may be older than implied by τ if past flow velocities were lower or geometry differed, but ice cannot remain in place longer than τ without violating present-day flow constraints.

3.3 Interpretation and scope of the residence-time proxy

The residence-time proxy employed here, defined as the ratio of ice thickness to observed horizontal surface velocity, is intentionally conservative in scope. It represents a characteristic evacuation timescale under present-day flow, rather than a full three-dimensional age model. In particular, the proxy does not incorporate vertical strain rates, basal melting, or time-varying flow histories.

This omission is deliberate. Vertical velocities and strain thinning rates are not directly observed at continental scale and must be inferred from mass continuity, accumulation estimates, and assumptions regarding basal conditions. Incorporating such terms would introduce additional model dependence and, in nearly all plausible cases, would act to *reduce* inferred residence times, especially in thick interior regions. As such, the present formulation should be interpreted as defining an upper envelope on dynamically plausible ice persistence under current geometry and flow.

The volumetric exceedance fractions reported here therefore constitute strict lower bounds on the amount of ice that is demonstrably long-lived in a dynamical sense, rather than comprehensive estimates of absolute ice age.

3.4 Velocity floor and masking

Observed surface velocities in the slowest-flowing regions approach the noise floor of satellite-derived products. To prevent numerical divergence and to avoid assigning unphysical residence times, a minimum velocity threshold of

$$u_{\min} = 0.01 \text{ m yr}^{-1} \tag{2}$$

was imposed. Velocities below this threshold are treated as dynamically indistinguishable from stagnation at the resolution of the observations.

This choice imposes a conservative upper bound on τ (e.g. $\sim$400 kyr for 4 km thick ice) and therefore biases results toward underestimating the prevalence of long-residence-time ice. Lowering $u_{\min}$ would monotonically increase exceedance fractions.

Only grounded ice cells with non-zero thickness were included in the analysis. Floating ice shelves were analysed separately where indicated.

3.5 Exceedance analysis and uncertainty bounds

Rather than assigning absolute ages, we compute volumetric exceedance fractions for specified residence-time thresholds (1, 5, 10, 20, 50, and 100 kyr). For each threshold T, we calculate the fraction of total Antarctic ice volume for which $\tau \geq T$.

Uncertainty is represented structurally rather than statistically. A central estimate at 10 kyr is bracketed by neighbouring thresholds at 5 kyr and 20 kyr, yielding conservative lower and upper bounds on the inferred volumetric fraction. This approach avoids false precision and reflects dominant uncertainties associated with slow-flow dynamics rather than measurement noise.

3.6 Regional partitioning

East and West Antarctic Ice Sheets (EAIS and WAIS) are delineated using IMBIE2 drainage basin definitions [18]. While basin boundaries introduce some geometric artefacts near the divide, they provide a standard and reproducible partitioning consistent with prior mass-balance and dynamical studies.

3.7 Qualitative validation against ice-core constraints

Although the residence-time proxy is not calibrated to ice-core chronologies, its spatial patterns can be qualitatively compared with well-established deep ice-core sites. Regions exhibiting the highest residence-time exceedance values coincide with interior East Antarctic domes, including Dome C, Dome A, and Vostok, where ice-core records demonstrate multi-glacial ice exceeding several hundred thousand years in age [2, 3].

Conversely, regions of West Antarctica characterised by high surface velocities correspond to low residence-time values, consistent with the relatively young ice recovered at WAIS Divide [5]. This qualitative agreement supports the physical interpretability of the proxy while reinforcing that it provides a lower bound on ice persistence rather than a direct age estimate.

4 Results

4.1 Spatial distribution of residence-time structure

Figure 1 shows the continent-scale distribution of the residence-time proxy. Regions of long inferred residence time are confined primarily to the interior of East Antarctica, with especially pronounced maxima near known dome sites. In contrast, West Antarctica is dominated by shorter residence times associated with faster flow and thinner ice.

4.2 Residence-time exceedance

To visualize the spatial extent of dynamically persistent ice, we compute exceedance maps for residence-time thresholds of 1 kyr, 10 kyr, and 100 kyr (Figure 2). Exceedance of the 1 kyr threshold spans much of the grounded ice sheet, whereas exceedance of the 10 kyr threshold is restricted to compact interior regions. At 100 kyr, exceedance is confined to small cores within East Antarctica.

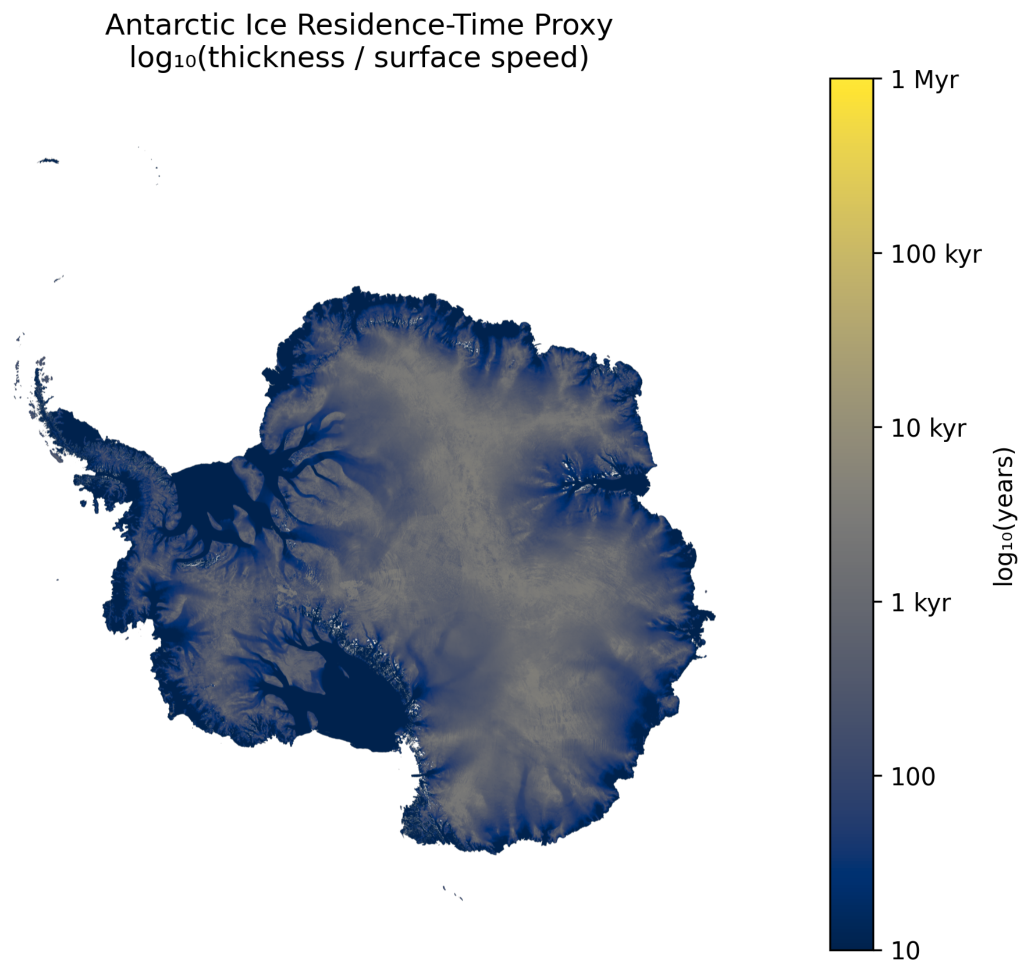

Figure 1: Antarctic ice residence-time proxy, expressed as $\log_{10}(H/u)$ in years. Long residence times are concentrated in the interior of East Antarctica, while West Antarctica is characterized by shorter evacuation timescales.

In this sense, the small volumetric footprint of long-residence-time regions inferred here is consistent with the observational record, which identifies very old ice primarily in localized interior divides and blue-ice ablation zones rather than across large portions of the ice sheet.

4.3 Error-bounded volumetric exceedance

Integrating exceedance over ice volume yields quantitative constraints on the fraction of Antarctic ice that is dynamically constrained to exceed millennial-scale residence times. Table 1 summarizes exceedance fractions for Antarctica, EAIS, and WAIS across multiple thresholds.

Figure 3 summarizes these results using an error-bounded envelope. The central estimate at 10 kyr is shown alongside a conservative uncertainty range defined by the 5–20 kyr thresholds.

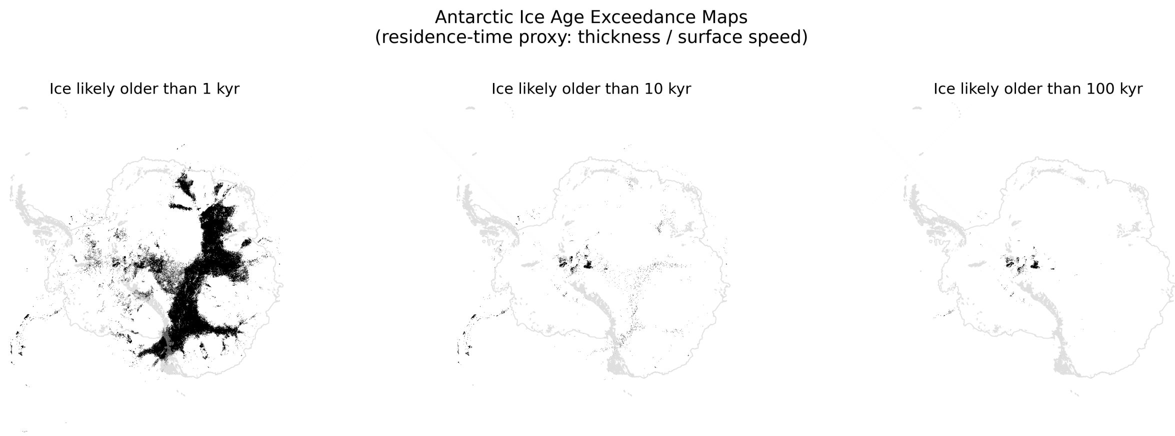

Figure 2: Residence-time exceedance maps based on the proxy $\tau = H/u$. Black regions indicate grid cells exceeding the specified threshold. Increasing thresholds isolate progressively smaller, dynamically persistent ice reservoirs.

Table 1: Volume fraction (%) of ice exceeding residence-time thresholds.

Threshold (yr)	Antarctica	EAIS	WAIS
1,000	28.8	33.2	6.7
5,000	2.5	2.6	2.0
10,000	1.0	0.9	1.8
20,000	0.6	0.4	1.8
50,000	0.4	0.3	1.7
100,000	0.4	0.2	1.6

5 Discussion

The results presented here offer a dynamics-based perspective on Antarctic ice persistence that complements stratigraphic and modelling approaches. The finding that only a small fraction of Antarctic ice volume is dynamically constrained to exceed millennial residence times reflects the rarity of conditions combining great thickness with exceptionally slow flow, rather than an absence of old ice per se.

Interior dome regions of East Antarctica dominate the longest residence-time exceedance classes. These settings are characterised by minimal horizontal flow and thick ice columns, allowing ice to persist over multiple glacial cycles [14]. Their limited volumetric footprint, however, implies that extremely old ice is spatially and volumetrically rare at continental scale, consistent with decades of ice-core and radar stratigraphic evidence.

At intermediate thresholds (10–50 kyr), West Antarctica contributes a non-negligible fraction of the exceedance volume despite lacking regions of extremely long residence time. This behaviour arises from volume weighting rather than spatial extent: thick marine-based basins with moderate flow speeds can satisfy intermediate residence-time thresholds while failing to exceed higher ones. As the threshold increases, these contributions collapse rapidly, leaving East Antarctica as the sole reservoir of very long-lived ice. This distinction reconciles the volumetric results with the established dominance of East Antarctica in preserving the oldest ice.

The present analysis deliberately adopts present-day dynamics as its sole constraint. During

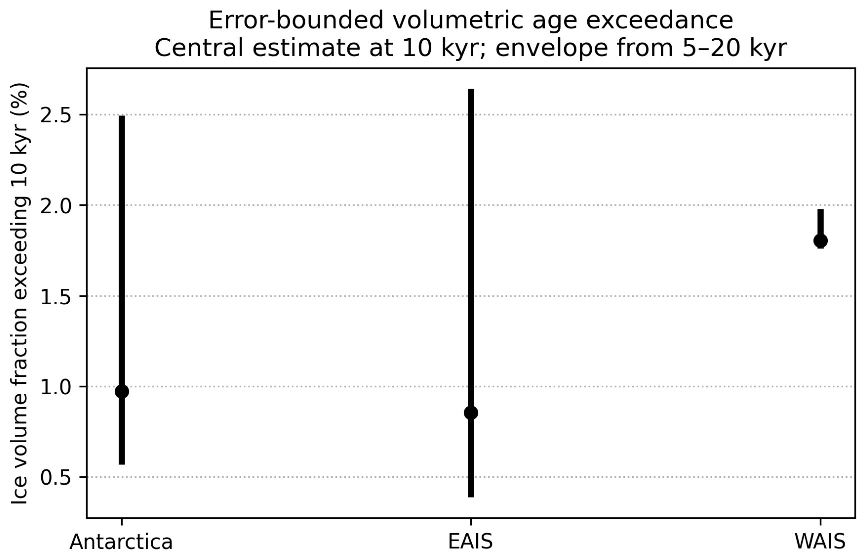

Figure 3: Error-bounded volumetric age exceedance. Points indicate the central estimate at 10 kyr; vertical bars indicate the uncertainty envelope defined by 5–20 kyr thresholds. Values represent strict lower bounds on dynamically persistent ice volume.

glacial maxima, ice-sheet geometry and flow patterns likely differed, potentially allowing longer persistence in regions that are currently more dynamic. For this reason, the exceedance fractions reported here should be interpreted strictly as lower bounds. Any departure from present-day conditions that reduced flow speeds would increase, rather than decrease, the true prevalence of long-lived ice.

Recent syntheses of Antarctic radiostratigraphy, notably the AntArchitecture review [1], highlight the promise and challenges of constructing continent-wide age–depth models from internal layering. While such efforts aim to recover absolute age structure, they depend on stratigraphic continuity, dating assumptions, and model integration. The residence-time framework presented here occupies a complementary niche: it identifies regions where long-term preservation is dynamically plausible without requiring explicit age calibration. Together, these approaches provide mutually reinforcing constraints on Antarctic ice-sheet evolution.

5.1 Relation to vertical strain and independent age proxies

A natural question arising from the residence-time framework concerns the role of vertical strain thinning and downward advection, which can limit the maximum age of ice even in regions of slow horizontal flow. While inclusion of vertical velocity terms would further constrain survivable age, such quantities are not directly observed and depend on assumptions regarding accumulation history, basal conditions, and long-term ice-sheet geometry. Importantly, the inclusion of realistic vertical strain rates would act to tighten the upper bound on persistence identified here, rather than relax it. In this sense, the present analysis should be regarded as conservative with respect to ice longevity.

Independent observational proxies are broadly consistent with this interpretation. Cosmogenic-nuclide exposure ages from nunataks and marginal bedrock commonly indicate extensive Holocene re-advance and limited survival of Last Glacial Maximum ice at the margins. This aligns with the residence-time results, which identify peripheral regions as dynamically young and unlikely to preserve long-lived ice by volume. Similarly, age constraints from basal ice, subglacial sediments, and subglacial lake environments often point to repeated reworking or young material beneath fast-flowing regions, consistent with short residence times inferred from surface velocity fields.

Conversely, the small number of sites known to preserve very old ice—primarily interior dome locations in East Antarctica—occupy precisely the slow-flow, thick-ice settings that persist as exceedance cores even under stringent residence-time thresholds. Thus, rather than conflicting with stratigraphic or geochemical observations, the residence-time framework provides a volumetric context that reconciles the existence of very old ice with its apparent spatial and volumetric rarity.

The discovery of multi-million-year-old ice in the Allan Hills blue-ice area provides an important additional perspective on Antarctic ice persistence. Blue-ice areas represent localized stagnation and ablation zones where very slow flow, low accumulation, and favourable topography allow ancient ice to survive and be brought to the surface. The presence of Miocene–Pliocene ice in such environments demonstrates that extremely old ice can persist under exceptional conditions. At the same time, these regions occupy only a small fraction of the Antarctic ice sheet and are dynamically distinct from the interior domes that host continuous stratigraphic records. In this context, the residence-time framework presented here does not contradict the existence of very old ice; rather, it provides a volumetric perspective indicating that such preservation is confined to rare dynamical niches, consistent with the limited spatial extent of blue-ice areas and interior divide environments.

6 Conclusions

By combining continent-scale ice thickness and velocity observations, we provide the first error-bounded volumetric constraints on Antarctic ice residence times. Our analysis reconciles the existence of multi-glacial ice at isolated dome sites with the predominantly transient nature of Antarctic ice at continental scale. The framework introduced here offers a physically interpretable and conservative complement to stratigraphic approaches and may be readily extended as observational constraints improve.

A Scope, limitations, and interpretation

The analysis presented here is not intended to replace stratigraphic age determination, radiostratigraphic reconstruction, or thermomechanical ice-sheet modelling. Instead, it addresses a narrower and previously unresolved question: how much of the Antarctic Ice Sheet is dynamically capable of persisting beyond millennial timescales under present-day geometry and flow.

Several limitations follow directly from this framing. First, the residence-time proxy does not capture past variations in flow or accumulation, and therefore cannot assign absolute ages to ice. Second, regions identified as dynamically long-lived are not guaranteed to contain old ice if advection or transient processes have recently supplied younger material. Third, regions identified as dynamically young may nevertheless contain isolated pockets of older ice, particularly at depth or near divides.

Despite these limitations, the approach offers a robust lower bound on ice persistence that is independent of palaeoclimate reconstruction and model tuning. Any additional physical processes omitted here—such as vertical strain thinning, basal melting, or episodic flow acceleration—would tend to reduce the volume of ice capable of long-term preservation. As a result, the volumetric exceedance fractions reported should be interpreted as conservative ceilings on Antarctic ice longevity rather than optimistic estimates.

B Source Code & Data

https://nobulart.com/media/age.zip

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