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Evaluating marine dust records as templates for optical dating of Oldest Ice

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Abstract. The continuous ice core record extends 800,000 years into the past, covering the period of 100,000-year glacial cycles, but not the transition from 40,000-year glacial cycles (the Mid-Pleistocene Transition, 1.2-0.7 million years ago). A primary goal of the International Partnership in Ice Core Sciences is therefore to retrieve a 1.5-million-year-old continuous ice core, increasing our understanding of this major change in the climate system and thus of fundamental climate forcings and feedbacks. However, complex glacial processes, limited bedrock data, and surprisingly young basal ice in previous cores necessitate careful reconnaissance studies before extracting a full core.

Ice borehole optical logging reflects the ice dust content and may be used to date ice quickly and inexpensively if a reference record is known. Here we explore the relationship between ice dust records and well-dated marine dust records from sediment cores in the southern Atlantic and Pacific Oceans, which lie along paths of dust sources to Antarctica. We evaluate how representative these records are of Antarctic dust both through the existing ice core record and during the older target age range, suggesting that a newly published 1.5 million year record from site U1537 near South America is likely the most robust predictor of the Oldest Ice dust signal. We then assess procedures for rapid dating of potential Oldest Ice sites, noting that the ability to detect dating errors is an essential feature. We emphasize that ongoing efforts to identify, recover, date, and interpret an Oldest Ice core should use care to avoid unfounded assumptions about the 40 kyr world based on the 100 kyr world.

1 Introduction

The marine sediment record shows that the climate system cycled through glacial and interglacial states with regular ~41,000 year (41 kyr) periodicity prior to 1.2 million years ago (Ma) in the so-called 40k world (Figure 1) (Lisiecki and Raymo, 2005). Between 1.2 Ma and 0.7 Ma, the periodicity of these cycles lengthened and became less regular while their magnitude increased, an event known as the Mid-Pleistocene Transition (MPT). Finally, from 0.7 Ma until the present, irregular ~100 kyr cycles have characterized the climate system, as seen in both marine sediment and ice core records.

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Our understanding of the MPT and the 40k world remains limited in large part because the continuous ice core record extends only 800 kyr into the past (Lambert et al., 2008), with a few discrete snapshots of older climate up to 2.7 million years old (Yan et al., 2019). A central question is *why* the transition happened, with implications for the fundamental mechanisms of the climate system; see Berends et al. (2021) for a thorough review. Clark et al. (2006) proposed that soft regolith eroded over repeated glaciations in the early Pleistocene, eventually exposing unweathered bedrock that allowed thicker ice sheets to grow and introduce nonlinear feedbacks. Tectonic activity may have lowered atmospheric CO_2 and led to more extreme glacial cooling (Raymo et al., 1988; Ruddiman and Raymo, 1988), though Honisch et al. (2009) question the role of CO_2 based on evidence that its atmospheric concentration during 40k-world interglacial periods did not change, a finding supported by Yan et al. (2019). McClymont et al. (2013) interpret gradual global decrease in SSTs across the MPT as evidence of a change in internal climate feedbacks. Chalk et al. (2017) suggest that both changing ice sheet dynamics and carbon cycle feedbacks played a role, while Willeit et al. (2019) emphasize the importance of both declining CO_2 and regolith removal. In a number of these cases, an abrupt increase in the duration of glacial cycles may have resulted from frequency locking of a slowly increasing internal period to insolation variations (Nyman and Ditlevsen, 2019). Beyond the driver of the MPT, related questions regarding the early and mid-Pleistocene include the history of Antarctic temperature before 800 ka and the role of carbon dioxide in large ice sheet dynamics (Fischer et al., 2013).

A 1.5 Ma continuous ice core would greatly advance our understanding of Quaternary climate and has been stated as a goal of the International Partnership in Ice Core Sciences. Several groups worldwide are already taking steps toward drilling an Oldest Ice core (Fischer et al., 2013; Goodge and Severinghaus, 2016; Van Liefferinge et al., 2018; Zhao et al., 2018). These efforts must contend with the unprecedented challenges of retrieving 1.5 Ma ice: the geothermal heat flux of the bedrock must not be high enough to melt the basal ice containing the oldest ice; the ice sheet must not be so thick that it insulates the geothermal heat and melts the basal ice; and the bedrock topography must not have disturbed the stratigraphy (Fischer et al., 2013).

Given the sparse coverage of geothermal heat flux and bedrock topography data across Antarctica, efforts to drill an Oldest Ice core require extensive reconnaissance work to increase the likelihood of selecting drill sites with intact 1.5-million-year-old basal ice. Several efforts are pursuing "rapid access drilling," a reconnaissance mode of exploration in which boreholes are quickly drilled or melted through the ice sheet without retrieving intact ice cores (Goodge and Severinghaus, 2016; Winebrenner et al., 2013). Rather than 5 or more years, these techniques require less than a single field season to reach the base of the ice sheet. Though the ice is not retrieved, indirect measurements such as borehole temperature and dust content may be made in conjunction with rapid access drilling. The dust content of ice is measured by optical logging, in which a light source is lowered through the borehole and the dust content of the ice determines the amount of light backscattered (Bay et al., 2001; Chan et al., 2017; Goodge et al., 2021). This technique allows for rapid dating of the ice by comparison to a well-dated reference record.

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While no Antarctic dust record exists beyond 0.8 Ma to serve as such a reference, the dust record from marine sediment cores around Antarctica extends as far back as 4 Ma (Martínez-Garcia et al., 2011) and has been proposed as a stratigraphic template for dating Oldest Ice (Wolff et al., 2022). With the exception of minor, intermittent contributions from local volcanos, the dust measured in Antarctic ice originates from Southern Hemisphere terrestrial sources, primarily South America, Australia, and New Zealand (Neff and Bertler, 2015). Some is deposited in the oceans and archived in marine sediments in the Southern Ocean before it reaches Antarctica. During glacial periods, exposure of continental shelves and reduced washout due to weakened rainfall as well as increased gustiness and aridity drives higher dust transport and deposition to both subantarctic marine sediments and Antarctic ice (McGee et al., 2010; Markle et al., 2018). Ice cores from across Antarctica appear to have a common dust (or calcium) signal through time, suggesting the use of dust as an ice dating tool (Baggenstos et al., 2018; Mulvaney et al., 2000).

Previous work relied on a single marine sediment core from site ODP 1090 in the southern Atlantic Ocean and focused on its similarities to the ice core dust signal during the past 800 kyr (Martínez-Garcia et al., 2011; Wolff et al., 2022). However, the critical time period for using marine dust to date an Oldest Ice core is 800 kyr – 1.5 Ma, i.e., before and during the MPT when the climate system is known to have been different. Here we build on the concept of marine dust as a stratigraphic template for Oldest Ice by comparing the ODP 1090 dust record to a new higher-latitude 1.5 Ma marine dust record from the southern Atlantic Ocean and benthic $\delta^{18}O$ (Wolff et al., 2022; Weber et al., 2022; Lisiecki and Raymo, 2005). We examine changes in the agreement of these two records from the 40 kyr world to the 100 kyr world. Finally, we demonstrate how marine dust records can be used with rapid drilling and optical dust logging, and we suggest other visual pattern-matching strategies that may assist in dating these sites in conjunction with rapid access drilling and borehole optical logging.

2 Data description

As templates for the Oldest Ice dust record, we use the two oldest subantarctic marine dust records and the global benthic $\delta^{18}O$ stack and compare them to the two oldest continuous Antarctic ice core dust records (Figures 1-2).

2.1 EPICA Dome C (EDC)

The European Project for Ice Coring in Antarctica Dome C (EDC) ice core was drilled from 1993 to 2004 at 75.1 °S, 123.35 °E and covers the past 800 kyr (Lambert et al., 2008). Dust content was measured by both Coulter counter and laser sensor, which agreed well; we use the laser data, as they are measured at higher resolution. The EDC3 age scale was primarily generated by an ice flow model using independent age markers to constrain model parameters (Parrenin et al., 2007).

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2.2 Dome Fuji (DF)

The Dome Fuji (DF) ice core was drilled at 77.31 °S, 39.70 °E in two sections: the first in the 1990s representing the past 340 kyr and the second in the 2000s ending at 720 ka. We use the first record until the second record begins at 296 ka, when we switch to the second record because of its higher time resolution. Dust microparticles were measured with a laser particle counter. The DFO2006 age model is based on aligning isotopic records to EDC records on the AICC2012 chronology (Dome Fuji Ice Core Project Members: et al., 2017; Fujii et al., 2003).

2.3 Scotia Sea, International Ocean Drilling Program Site U1537 (U1537)

A new 1.5 million year old record of magnetic susceptibility as a dust proxy was recently published from a marine sediment core drilled in 2019 at 59.11 °S, 40.91 °W in the Scotia Sea in the southern Atlantic Ocean (Weber et al., 2022). The age scale was established by synchronizing magnetic susceptibility to the EDC dust flux on the AICC 2012 time scale from 0-800 ka, and to the LR04 benthic $\delta^{18}O$ stack from 800 ka – 1.5 Ma, with additional tie points based on magnetic reversals.

2.4 Southern Atlantic Ocean, Ocean Drilling Program Site 1090 (ODP1090)

A 4 million year old marine sediment core was drilled in 1997 at ODP site 1090 in the southern Atlantic Ocean at 42.91 °S, 8.90 °E (Martínez-Garcia et al., 2011). The age scale for the past 800 kyr is based on visual correlation of X-ray fluorescence iron measurements as a dust proxy to the EDC dust record on the EDC3 chronology. The original ODP Site 1090 age model is used for the period 800 ka to 2.9 Ma, based on alignment of benthic $\delta^{18}O$ to the LR04 benthic $\delta^{18}O$ record, which in turn is tuned to orbital forcing.

2.5 LR04 Benthic Stack (LR04)

While benthic $\delta^{18}O$ is not a direct proxy for Antarctic dust, the timing of glacial-interglacial fluctuations is common between the two as the growth and decay of ice sheets regulates both 1) the $\delta^{18}O$ and temperature of the global oceans, which determines the $\delta^{18}O$ of calcite of benthic foraminifera, and 2) the aridity (due to temperature) and circulation of the atmosphere, which influences the production and transport of dust. The 5.3 million year old LR04 stack includes 57 globally distributed benthic $\delta^{18}O$ records aligned using an automated graphic correlation program (Lisiecki and Raymo, 2005). The LR04 age model was tuned to a simple model of ice volume based on summer insolation at 65 °N.

3 Comparison of dust records

To assess the degree to which the dust signal in marine sediments represents an Oldest Ice dust signal, we first correlated each pair of dust records over the common time period, 14.1 – 715.9 ka (Table 1). We put the records on a common timescale by interpolating them to 100-year timesteps and normalized them to unitless values between 1 and 10. The strong correlation

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between DF and EDC ice dust (R = 0.72) indicates that the dust signal is consistent across the East Antarctic Plateau. The correlation between the marine dust records is also strong over this period (R = 0.73), suggesting that the marine dust signal is consistent throughout the mid-to-high latitude southern Atlantic Ocean after the MPT. Each ice record matches with each marine dust record to a similar degree, with correlation strengths falling with the range of 0.68-0.78 (Table 1). For comparisons to the LR04 benthic $\delta^{18}O$ signal, we used the logarithm of the dust records to represent the nonlinear relationship between glacial conditions and dust flux (Shaffer and Lambert, 2018). The relationship between LR04 and EDC, U1537, and ODP1090 is strong over the common time period (R = 0.74-0.76), while the correlation with DF is slightly weaker (R = 0.64).

However, the time period where marine records are actually required to extend the existing ice dust record is 800 ka – 1.5Ma, across the MPT and into the 40k world when the climate system is understood to be different from the 100k world. The new U1537 record allows us to examine the robustness of the marine dust record into the pre-MPT period. A rolling correlation with a 200 kyr window demonstrates that the relationship between U1537 and ODP1090 weakens beyond 800 ka, the target Oldest Ice period (Fig. 3, R = 0.35 over 800 kyr – 1.5 Ma). On the other hand, U1537 dust continues to agree closely with LR04 benthic $\delta^{18}O$ over this time period (R = 0.73).

The disagreement between marine dust records raises the question of which to use for dating Oldest Ice. We suggest that U1537 is likely more representative than ODP1090 of Oldest Ice dust. U1537 is located much closer to both Antarctica and southern South America, one of the primary sources of glacial dust to East Antarctica (Delmonte et al., 2008; Li et al., 2008). In contrast, ODP 1090 is located about 11,000 km further east and nearly 20° further north (42.91 °S), in the mid-latitudes rather than high latitudes (Fig. 2). Based on these criteria and discussed further in Sect. 5, we suspect that ODP1090 and U1537 are responding to latitudinally variable climate signals, and that U1537 more closely represents the Antarctic dust pattern.

We recommend that U1537 be used for dating Oldest Ice instead of ODP1090 and will use it throughout the rest of this study. While a composite record could be developed incorporating both ODP1090 and U1537, it would likely decrease the predictive ability of U1537 for dating Oldest Ice. Though not a direct comparison to dust, LR04 agrees closely with U1537, and there may be advantages to using both as reference records for the purposes of peak matching, with LR04 representing the broad shape of lower frequency variability and U1537 providing more detailed higher frequency variability.

3.1 Improving visual pattern matching

This approach relies on visual pattern-matching that takes advantage of the common pacing between the sequence of peaks in the marine and ice dust records. While the glacial-interglacial pattern of dust is consistent between EDC, U1537, and LR04 on established age scales, some dust peak tie points may be ambiguous, and differences in shorter-term variability may make identifying common peak shapes more difficult.

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We briefly explore a collection of techniques that may aid in visual pattern-matching (Fig. 4, Table 2). These include using the logarithm of the records (Fig. 4d-f), smoothing with a 20 kyr running mean (Fig. 4b and e), and taking the derivative of the smoothed records (Fig. 4c and f). The logarithmic EDC and U1537 dust records were more strongly related than the original normalized records (R = 0.80, compared to 0.74). Smoothing increased the correlation strength between U1537 and EDC for both normalized (R = 0.92) and logarithmic records (R = 0.93); however, we caution that smoothing over time relies on an initial age scale constructed for a dust-depth record (see Section 1), and over-smoothing may dampen the distinctive peak shapes that are used for pattern-matching. In contrast, smoothing barely increased the correlation strength between LR04 $\delta^{18}O$ and logarithmic EDC dust (R = 0.76), and their derivatives were more weakly related than the original normalized records.

4 Application to Rapid Dating of Oldest Ice Sites

4.1 EDC example

Here we use the optically logged EDC dust record as an example of how to rapidly date potential Oldest Ice sites (Fig. 5a). The EDC borehole was logged in January, 2010 with a logging speed of ~25 cm s^{-1} over a ~6 hour round trip (The IceCube Collaboration, 2013). Despite turbid borehole fluid, the optical log of the borehole demonstrates similar features to the laser sensor measurements of the ice core. Bubbly ice above 1250 m interacts with the light source differently from clear ice and is not shown here.

To simulate the case of an Oldest Ice site optical log where the basal age is uncertain, we first applied the Nye 1D ice flow model to put the dust-depth record on an initial age scale and visually identified dust peaks in the compressed deep ice (Dansgaard and Johnsen, 1969) (Fig. 5b-c). We identified local maxima of the smoothed records as tie points and linearly interpolated the age between these tie points to produce a revised age model (Fig. 5d). We also demonstrated the use of a dynamic time warping (DTW) algorithm (Fig. 5d), which has been used to establish time scales for other optical logs and may be considered as a tool for dating Oldest Ice (The IceCube Collaboration, 2013). With the start and end tie points assigned, DTW calculates the Euclidian distance between corresponding points of two input time series and stretches the time series by repeating points to minimize the sum of distances (Micó, 2022). While more sophisticated approaches are available to establish age scales, these represent two simple techniques that enable age estimations in the field where decisions may need to be made quickly.

4.2 Identification of dating errors

The ability to identify dating errors is important for dating potential Oldest Ice sites, where ambiguities may arise in aligning ice and marine dust peaks, especially in deep, old, highly compressed ice. We investigated the effects of incorrect alignment of the oldest (deepest) peak on the dating methods described above using an artificial 1.5 Ma Oldest Ice dust record that mimics the common timing but different amplitudes between marine and ice dust peaks.

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The artificial dust record was created by smoothing the U1537 dust record with a 20 kyr running mean and scaling the smoothed record by random factors between 0.4 - 0.7 linearly interpolated between 500 kyr intervals. Random noise was added at 2 kyr intervals scaled by the amplitude of the smooth artificial dust, and the resulting record was normalized between 1 and 10. The amplitude of the noise was adjusted such that the artificial record correlated with the original U1537 record with R = 0.76, comparable to the correlation strength of U1537 with DF and EDC over the past 800 kyr (Table 1). This artificial record was put on a depth scale using the Nye model and interpolated to 20 cm resolution (Fig. 6a).

Then we dated the artificial record as described in Sect. 5.1: we used the Nye model in the other direction with different ice thickness and accumulation parameters to stretch and compress the dust record sufficiently to identify distinct peaks, which we visually matched to the modeled ice dust record (Fig. 6b). We interpolated ages between tie points, and we used the start and end tie points as inputs to the DTW algorithm. Though the start and end tie points matched the original ages of the artificial record, the DTW algorithm misaligned peaks in the period from 700 ka to 1.5 Ma, i.e., through and before the MPT, such that the peaks in the artificial record appeared older than they originally were (Fig. 6c, top). Aligning the logarithmic artificial record with logarithmic U1537 via DTW avoided these errors (Fig. 6c, middle), while the alignment between the logarithmic artificial record and the LR04 benthic stack resulted in one peak that appeared too young (Fig. 6c, bottom). While these errors do not affect the end age of the DTW alignment, which is assigned as an input, we note that the DTW algorithm is overall less accurate over the MPT and pre-MPT period with less extreme glacial cycles than the post-MPT period.

Finally, we investigated whether errors in peak matching that result in incorrect end ages are identifiable using linear interpolation of manually aligned peaks and using DTW, as both approaches ultimately rely on an initial step of manual peak identification and alignment which is susceptible to error. We disregarded tie point 15A from the artificial record, matching tie point 16A to 15B, 17A to 16A, and so forth to induce an end age for the artificial record that is too young by approximately one 40 kyr glacial cycle (Table 3, -1). We disregarded an additional tie point, 18A, and shifted the subsequent tie points accordingly to induce an end age for the artificial record that is too young by two glacial cycles Table 3, -2). We repeated this procedure disregarding one (15B) to two (15B and 20B) peak tie points from U1537 to induce end ages for the artificial record that are too old (Table 3, +1 and +2). We linearly interpolated between the tie points for each incorrect version and applied DTW with the incorrect end tie points to compare the strength of the correlation between the resulting artificial records and U1537. For linear interpolation of manually aligned peaks, the correlation strength was highest for the correct alignment and decreased with additional misalignments (Table 3, rows 1-3). This pattern was consistent for the logarithmic artificial and U1537 records and for the logarithmic artificial record aligned with LR04 $\delta^{18}O$. However, because DTW adjusts the time series to minimize the disagreement between records, effectively optimizing the correlation, the correlation strength hardly varied for inputs with incorrect end tie points (Table 3, rows 4-6). Thus, dating errors are apparent when using linear interpolation of manually aligned peaks, but obscured when using DTW.

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5 Discussion

Our study comparing marine dust records and peak alignment techniques demonstrates that the very same climate features that motivate interest in the MPT and 40 kyr world require us to be cautious and critical in applying tools we have used for the 100 kyr world. Until very recently, the ODP1090 dust record was the only 1.5 million year old record in this region, and it has been used as a representative Southern Ocean dust signal with implications for biogeochemical cycling, justified by strong correlation with EDC dust over the past 800 kyr (Martínez-Garcia et al., 2011; Chalk et al., 2017). Yet the decreasing correlation strength with the new U1537 dust record beyond 800 ka suggests that the dust signal is spatially variable across the mid-to-high latitude southern hemisphere in the 40 kyr world, and high amplitude glacial dust peaks in U1537 back to 1.5 Ma complicate the hypothesis that increasing dust flux across the MPT contributed to increasing iron fertilization, CO_2 drawdown, and intensification of glacial cycles (Martínez-Garcia et al., 2011; Chalk et al., 2017).

This spatial variability in the marine dust signal may provide insight into early Pleistocene climate dynamics. The Southern Hemisphere westerlies, which transport dust from South American dust sources eastward to site ODP1090 and southeast to site U1537 and the Antarctic plateau, shift equatorward during cold periods and poleward during warm periods (Lee et al., 2011; Vanneste et al., 2015). The less intense glaciations of the 40k world may have resulted in less intensification and equatorward movement of the westerlies during glacial periods, with less dust transport at the lower latitude of ODP1090. This may contribute to the irregular pre-MPT dust signal in ODP1090 while distinct 40 kyr peaks are still present in U1537 that correspond to cycles in the LR04 benthic $\delta^{18}O$ stack (Fig. 1). Dust transport from South America to the eastern Atlantic Ocean may have also been suppressed under less glacial wind intensification and a warmer, wetter background state due to the 11,000 km distance, while transport to the much more proximal U1537 site was unaffected. Extending the Southern Ocean dust record further back in time at multiple sites would shed light on these spatial patterns, and modeling studies could help address the underlying dynamical questions.

The need for careful evaluation of techniques also applies to aligning age tie points. While the artificial record discussed in Section 2 is non-unique, and an actual Oldest Ice dust log may contain features that cannot be predicted using existing data, the misalignments using DTW and inability to identify these errors point to the limitations of this algorithm despite its successful employment for other younger optical dust logs (The IceCube Collaboration, 2013). Other potential peak alignment protocols may be similarly tested on artificial Oldest Ice records that simulate the irregular cycles of the MPT.

6 Conclusions

We have explored the use of marine records as stratigraphic templates for dating Oldest Ice, including the new U1537 marine dust record that is located closer to a primary dust source than previous records. We have shown that the U1537 dust record and the LR04 benthic $\delta^{18}O$ stack provide well-dated reference records resembling the expected pattern of Antarctic dust for the target period 800 ka -1.5 Ma. They may serve as tools for rapid dating of potential Oldest Ice sites as well as eventually dating a recovered Oldest Ice core in conjunction with other methods such as argon isotope dating of deep ice (Bender et al., 2008; Yan et al., 2019).

The rapid access optical dust logging technologies that are being developed for Oldest Ice site reconnaissance may further be used to evaluate the coherence of the dust signal across the East Antarctic Plateau in the 40 kyr world, independent of Oldest Ice exploration efforts. If the dust signal is consistent, as it is across multiple ice cores the 100 kyr world, it could be used to identify and reconstruct disturbed deep Oldest Ice cores that have been affected by folding. On the other hand, spatially variable dust signals may reveal differences in atmospheric circulation during the 40 kyr world and the MPT compared to the 100 kyr world. Disagreement between the U1537 and ODP1090 marine dust records already indicates that we have much to learn about the MPT and the 40 kyr world from paleoclimatic data. To this end, rapid dating of optically logged Antarctic dust records provides a useful tool in the effort to recover an Oldest Ice core.

Code Availability

Code used in this study is available upon request.

Data Availability

EDC optical dust log data is available upon request. All other data was previously published.

Competing Interests

The contact author has declared that none of the authors has any competing interests.

Author Contribution

Jeffrey Severinghaus and Ryan Bay conceptualized the study, with new direction from Jessica Ng. Jessica Ng developed the dust record comparison methodology and performed the analysis. Ryan Bay and Delia Tosi produced the EDC optical dust log. Jessica Ng prepared the manuscript with contributions from all co-authors.

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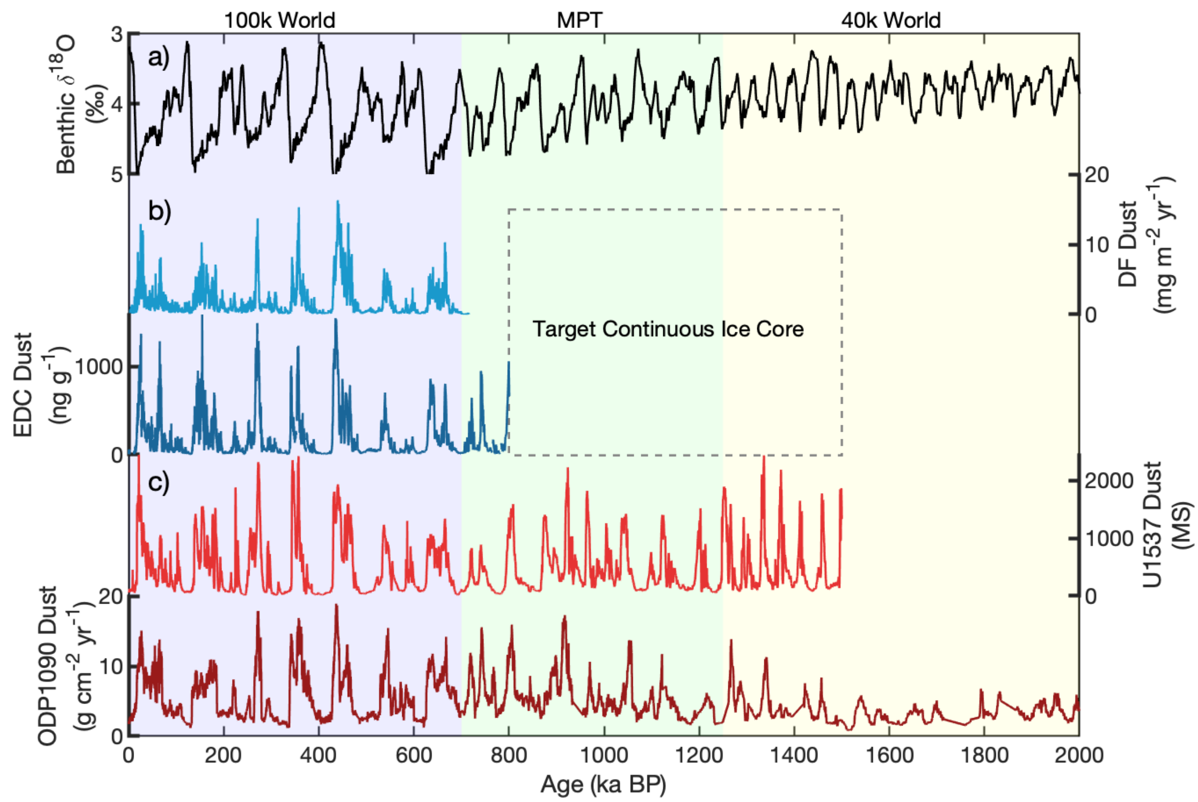

Figure 1: Time series of LR04 stack of benthic $\delta^{18}O$, ice dust records, and marine dust records used in this study shown to 1.5 Ma, the target Oldest Ice age. Colored panels indicate the 40k world (yellow), the Mid-Pleistocene Transition (green), and the 100k world (blue).

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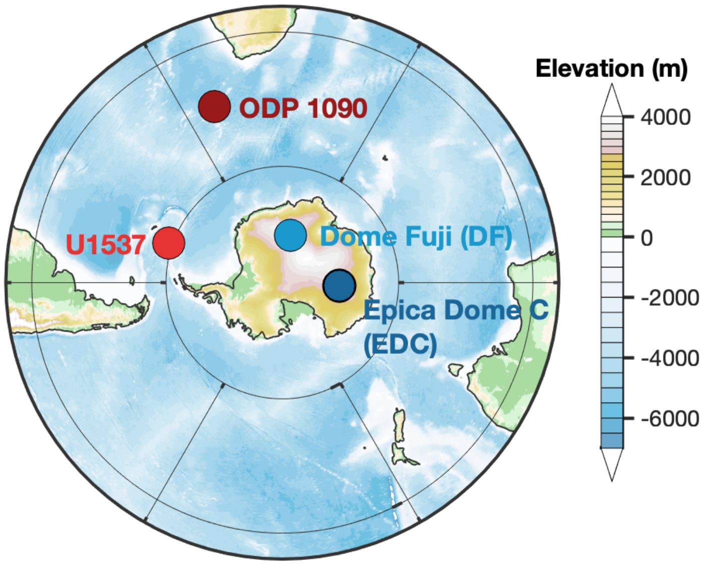

395 **Figure 2: Location of the four dust records used in this study. EDC (dark blue) was drilled at 75.1 °S, 123.35 °E; DF (light blue) at 77.31 °S, 39.70 °E; U1537 (red) at 59.11 °S, 40.91 °W; and ODP1090 (dark red) at 42.91 °S, 8.90 °E.**

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Table 1: Correlation coefficient R of ice dust, marine dust, and benthic $\delta^{18}O$ records over the common period 3.3ka – 715.9 ka. *Benthic $\delta^{18}O$ was correlated with the common logarithm of the dust records, which is more similar in shape to benthic $\delta^{18}O$ than the original dust records.

	DF	EDC	U1537	ODP 1090	LR04*
DF	x	0.72	0.76	0.68	0.64
EDC	0.72	x	0.75	0.78	0.74
U1537	0.76	0.75	x	0.73	0.76
ODP1090	0.68	0.78	0.73	x	0.76
LR04*	0.64	0.74	0.76	0.76	x

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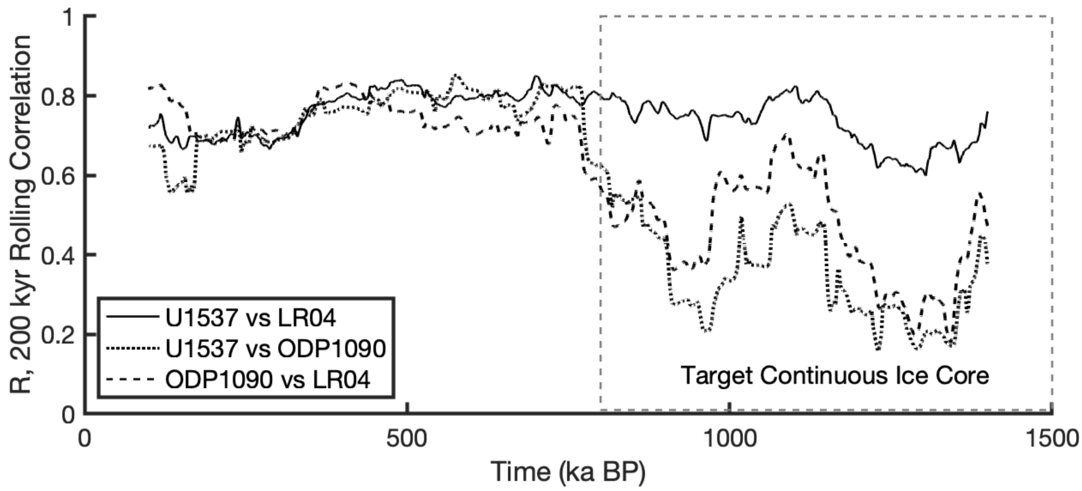

405 **Figure 3: 200 kyr rolling correlation of marine records with the first and last 100 kyr removed to eliminate edge effects: U1537 vs ODP1090 dust (dotted line), LR04 benthic $\delta^{18}O$ vs logarithm of ODP1090 dust (dashed line), and LR04 benthic $\delta^{18}O$ vs logarithm of U1537 (solid line).**

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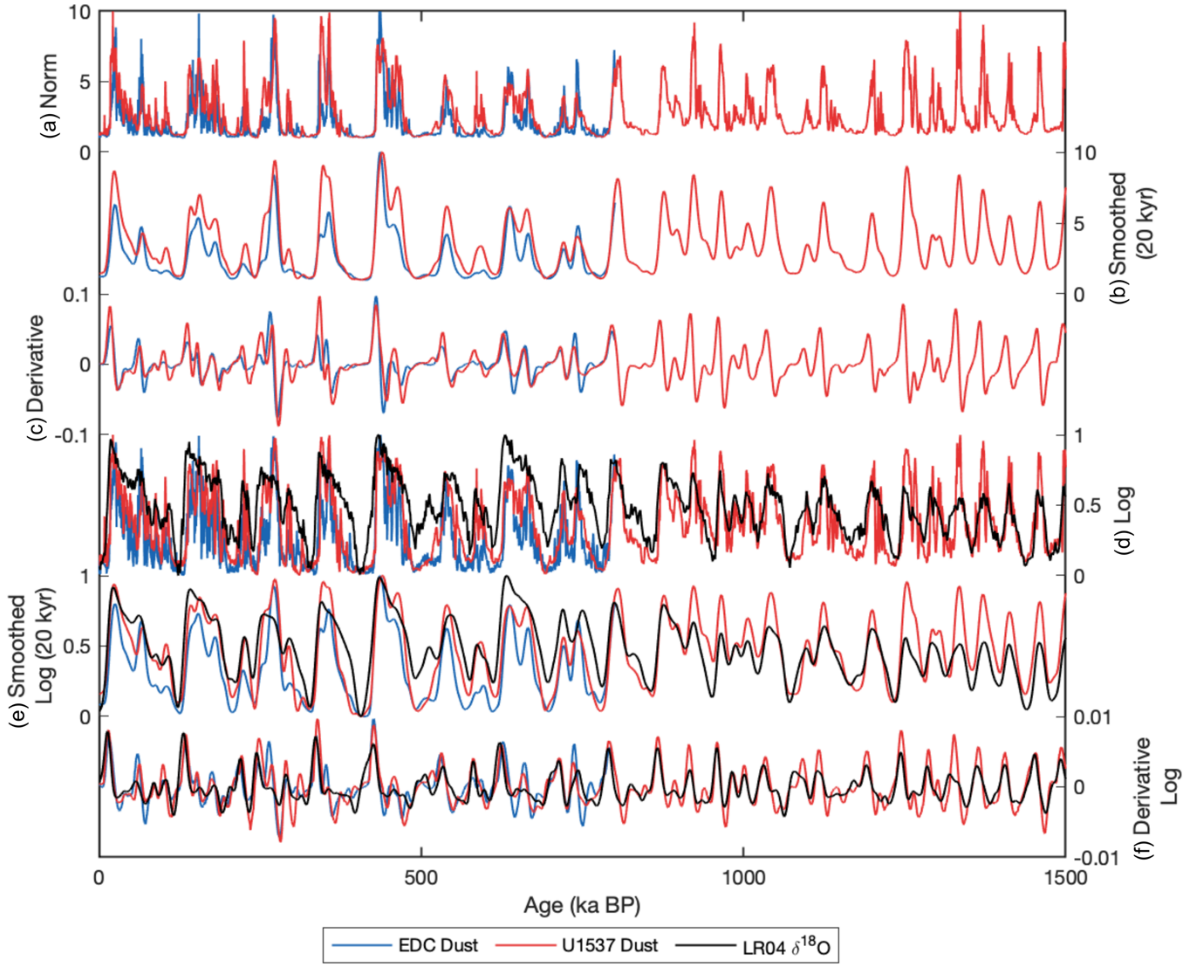

Figure 4: Time series of EDC dust (blue), U1537 dust (red), and LR04 $\delta^{18}O$ (black) applying techniques to aid visual pattern matching. a) Normalized EDC and U1537 dust; b) smoothed EDC and U1537 dust; c) derivative of smoothed EDC and U1537 dust; d) LR04 $\delta^{18}O$ with logarithm of EDC and U1537 dust; e) smoothed LR04 $\delta^{18}O$ with smoothed logarithm of EDC and U1537 dust; f) derivative of smoothed LR04 $\delta^{18}O$ with derivative of smoothed logarithm of EDC and U1537 dust.

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Table 2: Correlation coefficient R of smoothed and otherwise treated EDC and U1537 dust records.

	EDC vs U1537						Log_{10} EDC vs Log_{10}LR04		
	Norm	Smooth	Derivative	Log	Smooth Log	Derivative Log	Norm	Smooth	Derivative
R	0.74	0.92	0.79	0.80	0.93	0.82	0.74	0.76	0.69

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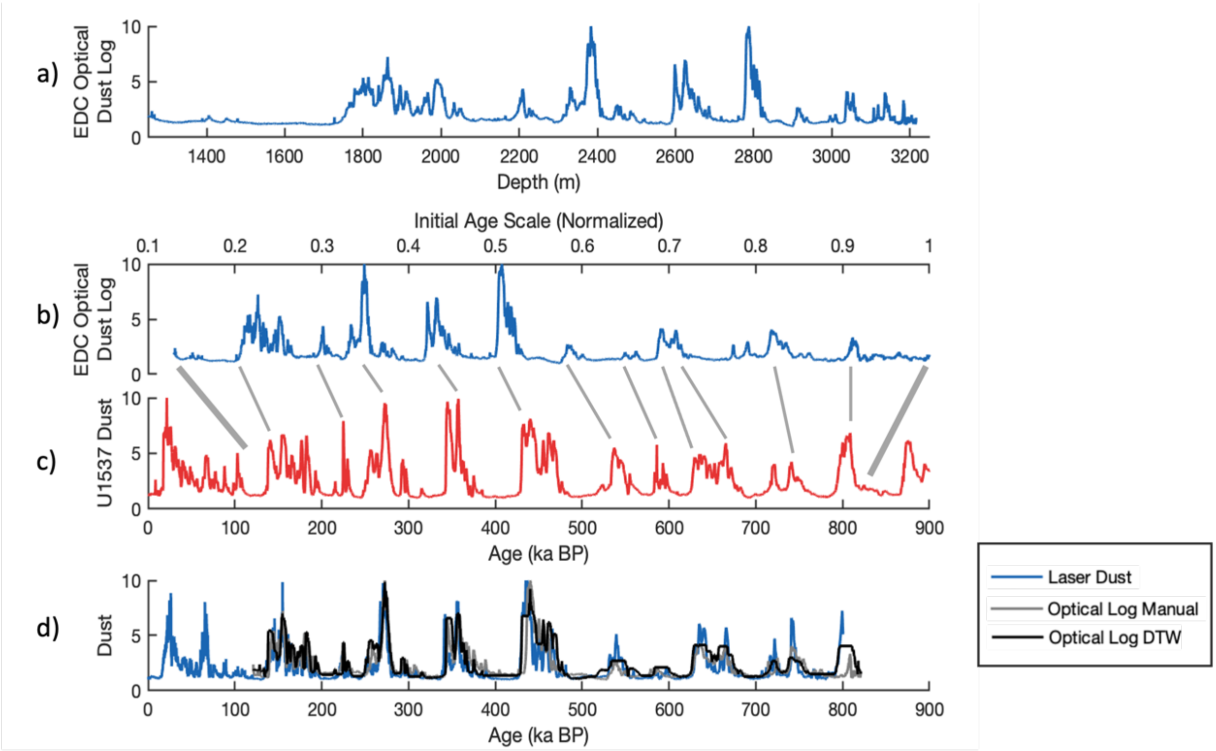

420 **Figure 5: Example of dating EDC optical dust log using marine dust record. a) Normalized EDC optical dust log signal vs depth. b) EDC optical log signal vs normalized age using Nye ice flow model to establish a preliminary age scale. c) U1537 marine dust record. Tie points with (b) are marked in gray. Thick gray lines indicate start and end tie points used for DTW. d) EDC optical log signal on revised age model linearly interpolated between tie points (gray) and on DTW age model (black). Laser dust data are shown in blue.**

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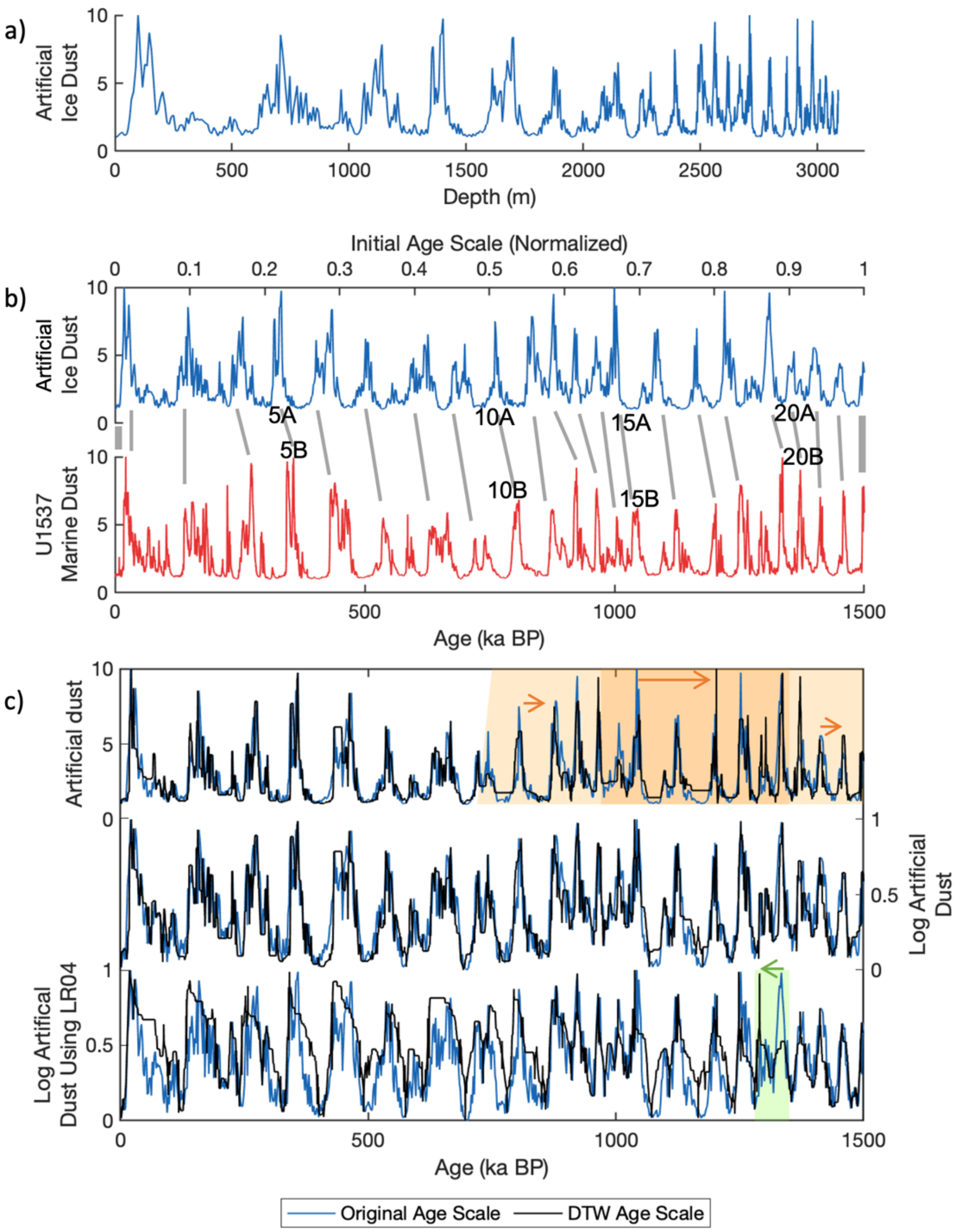

425 **Figure 6. Dating of artificial Oldest Ice optical dust log. a) Artificial Oldest Ice dust-depth record constructed using U1537 and Nye ice flow model. b) Numbered tie points between artificial record on a preliminary age scale using Nye model (top, blue) and U1537 (bottom, red). Thick gray lines indicate start and end tie points used for dynamic time warping. c) Comparison of DTW results (black) to original age scale (blue) of artificial record. Colored panels mark time periods with misaligned age tie points. Orange indicates that misaligned peaks appear too old; green indicates that misaligned peaks appear too young.**

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Table 3. Correlation coefficient R of U1537 and artificial Oldest Ice dust record dated by manual peak alignment and linear interpolation (Manual) and dynamic time warping (DTW) given peak alignment errors. +1 and +2 indicate intentional misalignment with peaks removed from U1537 such that the oldest artificial Oldest Ice age appears too old; -1 and -2 indicate misalignment with peaks removed from the artificial record such that its oldest age appears too young.

Artificial Oldest Ice	Reference	Method	Misalignment				
			-2	-1	0	+1	+2
Norm	Norm U1537	Manual	0.65	0.65	0.73	0.65	0.60
Log_{10}	Log_{10} U1537	Manual	0.65	0.68	0.75	0.67	0.64
Log_{10}	LR04	Manual	0.56	0.60	0.62	0.55	0.52
Norm	Norm U1537	DTW	0.980	0.980	0.978	0.978	0.978
Log_{10}	Log_{10} U1537	DTW	0.985	0.985	0.984	0.982	0.980
Log_{10}	LR04	DTW	0.974	0.975	0.976	0.974	0.975