



Exploring the Cenozoic Earth system with extraterrestrial ^3He

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10 **Abstract.** A key method for contextualizing climate today and into the future is to draw upon the past. Marine sediments
accumulating at the bottom of the ocean serve as the only continuous archive of Earth's climate history spanning tens of
millions of years. From the earliest studies of marine sediments, reconstructed changes in the inputs of sedimentary
constituents such as volcanic glass, ice-rafted debris, particulates carried by rivers, desert dust, organic and inorganic
remnants of organisms and biological process, and even extraterrestrial material, have been used to discern past
15 environmental conditions. Specifically, it is the rate at which these different components of sediments from the bottom of the
ocean accrue over time that can provide unique and important insight into how Earth system dynamics operated in the near
and distant past. Traditional techniques for quantifying sediment mass accumulation rates (MARs) contain numerous
complexities that can lead to erroneous MAR determinations. Constant flux proxies (CFPs), particularly extraterrestrial ^3He
($^3\text{He}_{\text{ET}}$) delivered in interplanetary dust particles from space, are underutilized geochemical tools that alleviate these issues as
20 long as key assumptions can be constrained. In this perspective, we review CFP $^3\text{He}_{\text{ET}}$ as a CFP and outline its benefit for
understanding Cenozoic climate beyond the Quaternary. Ultimately, we suggest that the application of $^3\text{He}_{\text{ET}}$ is valuable for
providing the broader paleoclimate and paleoceanography communities with accurate records of Cenozoic Earth system
change from a MAR perspective.

1 Introduction

25 A variety of archives contain crucial information about the paleo-Earth System. However, many of these, such as tree rings
(e.g., Anchukaitis, 2017) and ice cores (e.g., Brook and Buizert, 2018; Jouzel and Masson-Delmotte, 2010), are restricted to
the mid-to-late Quaternary (~2.6 million year ago (Ma) to present). Additionally, while the application of new dating
methods has allowed for the use of speleothems (e.g., Harmon et al., 2004; McDermott, 2004; White, 2007; Wong and
Breecker, 2015) and corals (e.g., Felis and Pätzold, 2003; Kiessling, 2001; Lough, 2010; Thompson, 2022) as paleoclimate
30 indicators within and beyond this shorter timescale, these archives are spatially limited and typically only cover relatively
short intervals of time. Terrestrial deposits such as accumulations of loess or extensive lacustrine deposits can provide
information spanning several million years (Bird et al., 2020; Caves Rugenstein and Chamberlain, 2018; Cohen et al., 2022;



Ding et al., 2002; Guo et al., 2002; Maher, 2016; Williams et al., 1997), but are susceptible to hiatuses, usually have low resolution chronologies, and, like older corals and speleothems, are spatially limited. High resolution archives that are also temporally expansive are integral for understanding the modern Earth system, not least because several warm intervals of the Cenozoic (~66 Ma to present), such as the mid-Piacenzian Warm Period (mPWP; ~3.3-3.0 Ma), mid-Miocene Climatic Optimum (MMCO; ~17-15 Ma), and Paleocene-Eocene Thermal Maximum (PETM; ~56 Ma) are relevant for future, rapid climate change (Burke et al., 2018; Tierney et al., 2020).

Marine sediments, while not devoid of complications (one of which is the focus of this perspective), offer several solutions to the disadvantages mentioned above. Owing to a plethora of national and international coring efforts across the last several decades (Becker et al., 2019; Normile and Kerr, 2003; Ocean Sciences Board, 2011; Robinson et al., 2024; Smith et al., 2010) marine sediments from a wide swath of every major ocean basin are available. By combining these extensive coring programs with comprehensive and robust stratigraphic work, and accounting for the nature of sedimentation processes in the ocean, recovered marine sediments constitute (mostly) continuous archives of paleoenvironmental change (Becker, 2014). The temporal coverage of these records depends on location-specific rates of accumulation, but can span up to tens-of-millions of years. For shorter cores, or longer cores from regions characterized by rapidly accumulating sediments, material collected typically only encompasses portions of the Quaternary or short windows of time within older intervals. However, the resolution of these cores, in conjunction with ever-improving analytical techniques, can provide insight into seasonal and inter-annual processes, thus overlapping with observational records and data from other archives. Taken together, marine sediments are likely the only archive that can offer information at high resolution about the Earth System across the Cenozoic from a global perspective.

There are numerous organic and inorganic materials found within sediments at the bottom of the ocean that can provide insight into the larger Earth System. These include (but are not strictly limited to) *i*) fossils and organic matter related to organisms living within the water column and in the sediments, *ii*) terrigenous material from land transported via rivers or wind, *iii*) volcanic detritus, *iv*) biominerals, *v*) authigenic mineral precipitates, *vi*), hydrothermal inputs, and *vii*) material from space (Li and Schoonmaker, 2003). Quantitative assessments of how certain sediment constituents vary through time can offer crucial knowledge regarding past changes in terrestrial environments (e.g., Crocker et al., 2022), atmospheric and ocean circulation (e.g., Adkins, 2013; Frank, 2002; Rea, 1994), ocean chemistry and biology (e.g., Ravizza and Zachos, 2003), and nutrient cycling (e.g., Deutsch and Weber, 2012; Tagliabue et al., 2017), among others. Specifically, it is the accumulation rate of certain sediment constituents that can offer valuable insight into the characteristics of Earth's atmosphere, oceans, and landscapes in the past.

An inherent property of marine sediments that contain multiple constituents is that, unless the input rate (i.e., mass accumulation rate (MAR)) of each can be independently determined, it is difficult to know if changes observed in the concentration of a specific component are driven by shifts in its own input, or that of another component. The latter scenario



65 is referred to as “dilution” and is one major issue of solely relying on concentrations to develop records of past changes in the Earth System (Anderson and Winckler, 2005; Bacon, 1984; Tyson, 2001). In fact, aside from studies focusing on isotope or organic compound ratios of bulk sediments or specific sedimentary components, knowing the MAR of sediments and the material that they are comprised of such as dust (e.g., Rea, 1994), organic matter and its bi-products (e.g., Schoepfer et al., 2015), and extraterrestrial material (e.g., Farley, 1995), are crucial for developing a comprehensive interpretive framework.

70 While reconstructing sediment MARs is a promising and widely used approach for evaluating past climates, there are important caveats that need to be considered if we are to push the boundaries of our paleoclimate knowledge. In any instance, do the sediment MARs we use actually reflect the MARs we need to answer our specific question? The primary reasons why the answer to this query might be “no” are associated with 1) the resolution at which we can determine sediment fluxes and 2) horizontal movement of sediment at the bottom of the ocean. The latter process can prove particularly
75 troublesome, because in many cases Earth scientists need to know the MAR of material that is raining from above, and not what is being gained or loss via lateral sediment transport in the deep ocean. If those working with marine sediments cannot be confident that they are using a sediment MAR that fits their need, then another question arises. Can we trust our interpretations, at least from a MAR perspective, of what marine archives say about ocean-atmosphere-landscape conditions, both today and in the past?

80 The most widely used method of calculating marine sediment MARs uses linear sedimentation rates (LSRs), which are derived from a record’s age model. While the depth-age tie-points constituting the age model are independently determined, the calculated LSRs can be influenced by both resolution limitations and horizontal sediment transport. Over the last several decades, new approaches have been developed to address these complications. Termed “constant flux proxies” (CFPs), these geochemical tools have provided key insights into how the Earth System behaved in the past that would have otherwise
85 remained elusive using the traditional sediment MAR method (Costa et al., 2020; McGee and Mukhopadhyay, 2013). The two primary CFPs used for marine sediment flux studies are thorium-230 (^{230}Th) and extraterrestrial helium-3 ($^3\text{He}_{\text{ET}}$). While the former has been much more widely applied, the 75,584±110-year half-life of ^{230}Th (Cheng et al., 2013) limits its applicability to the last ~400-500 thousand years (kyr). $^3\text{He}_{\text{ET}}$, as a stable isotope, is thus the only CFP that can provide insight into marine sediment MARs (and thus the Earth system from a MAR perspective) beyond the late Quaternary. This
90 makes $^3\text{He}_{\text{ET}}$ the only reliable method for confidently reconstructing past changes in the MAR of all components of marine sediments on these timescales unless *i*) a marine sediment record has an age model constrained at a similar resolution to the timescales being studied, and *ii*) horizontal sediment redistribution by ocean bottom currents can be ruled out.

Ee aim to achieve the following goals in this work:

- 1) Provide a detailed background on the age model-based method for determining MARs of marine sediments and the
95 caveats associated with this approach.



- 2) Describe CFPs and their utility, with a specific focus on $^3\text{He}_{\text{ET}}$.
- 3) Emphasize the importance of using the CFP $^3\text{He}_{\text{ET}}$ to study past changes in climate using marine sediment archives and highlight two examples: one from the Pliocene North Pacific and the other from the early Cenozoic Southern Ocean.
- 100 4) Lay out important remaining uncertainties related to the application of $^3\text{He}_{\text{ET}}$ in marine sediments, and detail future work to address these issues.

By fulfilling the objectives listed above, we aim to provide a compelling argument for Earth scientists to more fully utilize $^3\text{He}_{\text{ET}}$ to discern accurate fluxes of materials found within marine sediments to study the Cenozoic.

2 MARs from an age model perspective

- 105 The most commonly used approach for the determination of MARs of bulk marine sediment (and in turn any sediment component) is only reliant on knowing the ages (t_n and t_{n-1}) of two depth horizons (z_n and z_{n-1}), where n refers to a given horizon with a known depth and age, and sediment dry bulk density (DBD; typically in g cm^{-3}) between these depth horizons. To start, LSRs (typically in cm kyr^{-1}) are calculated via:

$$LSR = \frac{(z_n - z_{n-1})}{(t_n - t_{n-1})} \quad (1)$$

- 110 Subsequently, the LSR can be converted into a MAR (typically in units of $\text{g cm}^{-2} \text{kyr}^{-1}$) using the sediment DBD with the equation:

$$bMAR = LSR * DBD \quad (2)$$

We hereafter refer to any MAR derived using the age model as ‘bulk’ MARs (bMARs). As this method was increasingly embraced, key problems related to this approach were identified, and a potential solution provided (Bacon, 1984).

- 115 Specifically, two prominent issues plague bMARs. The first is the dependence on an age model itself to calculate bMARs. Because changes in sediment MARs can occur between age model tie points, fluxes of constituents measured at higher resolution than the identified depth-age horizons contain inherent uncertainty and could ultimately prove inaccurate (Fig. 1) (Francois et al., 2004). In addition to missing changes in sedimentation rates between tie-points, gaps in sediment accumulation may also go unaccounted for using the age model-based approach, again biasing these interpolated bMARs
- 120 (Dott, 1983; Sadler, 1981, 1999). For cores with high resolution age models, these issues become less relevant. However,



many cores, particularly those that cover longer time intervals, tend to rely on dating methods that produce tie points with hundreds of thousands to millions of years between them (e.g., magnetostratigraphy and biostratigraphy).

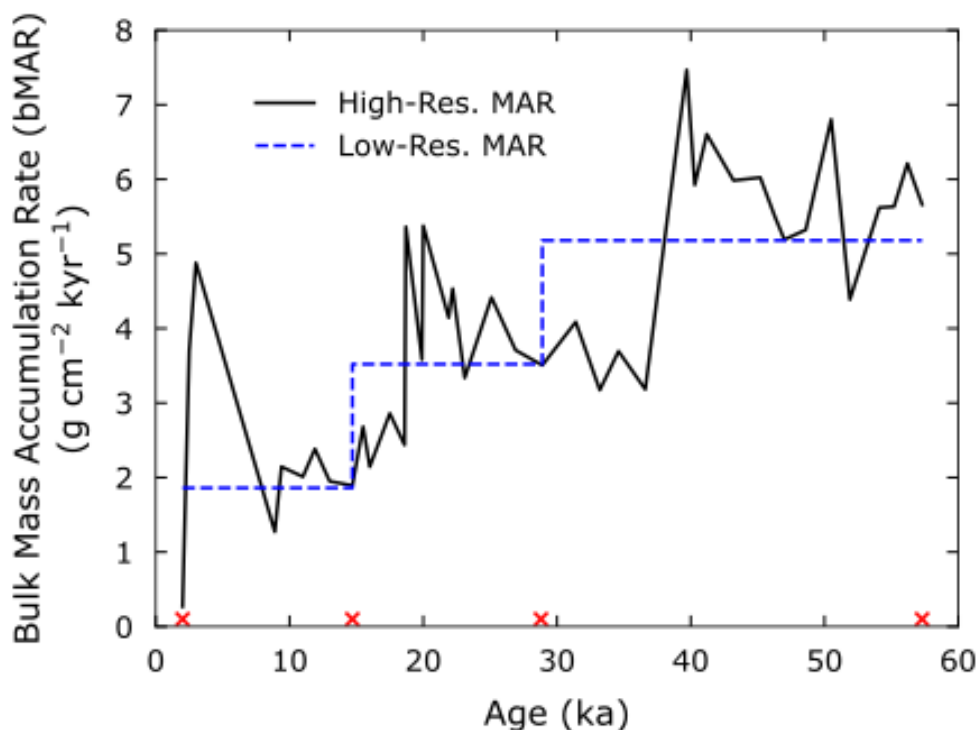


Figure 1: Simple representation of bMAR dependence on the resolution of the available age model. The two lines are separate estimates of bMAR over the last ~60 kyr for a marine sediment core in the North Pacific (Abell et al., 2023; Kinsley et al., 2022). The black line represents a sediment bMAR determined using a benthic oxygen isotope statistical tuning approach (Ahn et al., 2017). The red crosses are four selected age model tie-points for the same interval, and the blue dashed line is the sediment bMAR based on this lower-resolution age model.

A second process that leads to uncertainties in age model-derived bMARs is the net movement of sediment laterally via ocean currents during or after deposition at the seafloor (Dubois and Mitchell, 2012; Frank et al., 1999; Johnson and Johnson, 1970; Watkins and Kennett, 1977). This horizontal sediment redistribution can result in net material transport to a site (focusing) or net transport away from a site (winnowing). In many applications, these age model-derived bMARs are assumed to reflect the rate of material transported vertically downwards to the site (vMAR):

$$bMAR = vMAR \tag{3}$$

However, syndepositional lateral sediment advection can complicate records relying on age model-derived MARs, such that:



$$bMAR \neq vMAR \quad (4)$$

From the bMAR, the MARs of specific sediment constituents (MAR_X) are determined via:

$$bMAR_X = [X] * bMAR \quad (5)$$

140 where $bMAR_X$ is the MAR of sediment component X based on the age model-derived bMAR and [X] is the fraction of component X in the sediment sample.

An additional uncertainty arises for $bMAR_X$ when using age model-derived sediment bMARs because any perceived variability in $bMAR_X$ between age model tie-points will be driven solely by changes in the concentration of X. Put another way, combining high-resolution concentration data with lower-resolution bMARs is not equivalent to high resolution $bMAR_X$. In fact, the potential impacts of dilution by different sediment components become relevant again for this scenario.

145 3 CFPs and getting at the true vertical MAR

CFPs are invaluable for circumventing the inaccuracies originating from age model resolution and lateral sediment transport for age model-derived sediment bMARs. Specifically, CFPs allow for the direct quantification of marine sediment vMARs. In doing so, they can provide improved constraints on a range of dynamics spanning every component of the Earth system.

3.1 Setting the scene: ^{230}Th as a CFP

150 Marine geochemists recognized over four decades ago that one could take advantage of the chemical behavior of certain radioactive isotopes of uranium (U) and Th in seawater to independently determine marine sediment vMARs (Bacon, 1984; Suman and Bacon, 1989). U is conservative with nearly constant concentrations within the ocean (~3% change in concentration per salinity unit difference from 35) (Owens et al., 2011), and ^{234}U decays to produce ^{230}Th at a known rate, the latter of which is quickly adsorbed onto particulate matter, which sinks through the water column and delivers this ^{230}Th ,
155 known as $^{230}\text{Th}_{\text{xs}}$, to the seafloor. This constant production and deposition of $^{230}\text{Th}_{\text{xs}}$ in marine sediments means that its concentration within said sediments ($[^{230}\text{Th}]$) is only reliant on its production rate (β), which scales with water depth (z), and dilution by other sediment constituents. This dilution is driven by the vMAR of the sediment, so $^{230}\text{Th}_{\text{xs}}$ concentrations scale inversely with sediment vMAR. We note that there are additional sources of ^{230}Th that contribute to the total measured ^{230}Th , such as ^{230}Th stemming from detrital or authigenic components in the sediments, that are accounted for to produce $^{230}\text{Th}_{\text{xs}}$.
160 Finally, ^{230}Th decay through time must be considered, and the concentration of $^{230}\text{Th}_{\text{xs}}$ is adjusted to reflect time since deposition ($^{230}\text{Th}_{\text{xs},0}$). For additional details on this specific method, see Francois et al. (2004) and Costa et al. (2020). $^{230}\text{Th}_{\text{xs},0}$ is related to sediment vMAR via:



$$[{}^{230}\text{Th}_{xs,0}] = \frac{\beta * z}{vMAR} \quad (6)$$

This equation can be rearranged to solve for sediment vMAR:

$$165 \quad vMAR = \frac{\beta * z}{[{}^{230}\text{Th}_{xs,0}]} \quad (7)$$

Going one step further, the vMAR of any sediment constituent is then found via:

$$vMAR_X = [X] * vMAR \quad (8)$$

${}^{230}\text{Th}$ can be measured on any given sample, meaning that the resolution of a ${}^{230}\text{Th}_{xs,0}$ -derived vMAR record is only limited by the sampling resolution, not the resolution of the age model. We stress that the ages of samples are still reliant on the core's age model, so the determination of ${}^{230}\text{Th}_{xs,0}$ (i.e., the ${}^{230}\text{Th}$ concentration corrected for decay and detrital/authigenic components) is inextricably linked to the available age model. Additionally, it has been shown that, for most settings and within the ~30% uncertainties of the assumed constancy of the ${}^{230}\text{Th}$ burial rate, ${}^{230}\text{Th}$ likely travels with horizontally redistributed sediments in nearly the same proportion as the originally deposited material (Costa et al., 2020; Francois et al., 2004; McGee et al., 2010; Tomchovska et al., 2025). This characteristic of ${}^{230}\text{Th}$ is why CFP-derived MARs are considered to reflect vMARs, not bMARs. There are certain locations where this assumption has been called into question (Lyle et al., 2005, 2014). Generally, however, provided that the $[{}^{230}\text{Th}]$ of laterally transported sediment is the same as the sediment of the site of interest, then horizontal sediment redistribution will not bias ${}^{230}\text{Th}$ -based MARs (Kretschmer et al., 2010; Mollenhauer et al., 2011).

Under the assumptions described above, Costa et al. (2020) quantified sediment redistribution for the Holocene and Last Glacial Maximum using available ${}^{230}\text{Th}_{xs,0}$ -derived vMARs. Specifically, these authors calculated sediment focusing factors (Ψ) (Suman and Bacon, 1989), defined as:

$$\Psi = \frac{\rho_{avg} * [CFP_{avg}] * (z_n - z_{n-1})}{P_{CFP} * (t_n - t_{n-1})} \quad (9)$$

where ρ_{avg} is the average dry bulk density, $[CFP]_{avg}$ is the average CFP (either ${}^3\text{He}_{ET}$ or ${}^{230}\text{Th}_{xs,0}$) concentration, P_{CFP} is the production rate of the CFP, $(z_n - z_{n-1})$ is the sediment thickness, and $(t_n - t_{n-1})$ is the elapsed time, all between two dated sediment horizons. Put more simply, the focusing factor can roughly be thought of as the 'excess' or 'missing' sediment in a given interval compared to what was delivered vertically. Values for Ψ that are less than 1 indicate winnowing, while value greater than 1 indicate focusing. As an example, a value of 0.5 implies that half of sediment delivered vertically is transported away, while a value of 2 means that only half of the total sediment comes from sediment delivered vertically.



Costa et al. (2020)'s compiled results highlighted the extensive nature of marine sediment reworking and characterized its spatial and temporal variability on a global scale (Fig. 2). The focusing factor distributions, specifically the high proportion of focused sites, also illustrate the paleoclimate community's propensity to retrieve samples from regions with thick sediment sequences. While intuitive and necessary, seeking material from these settings immediately increases the potential for these sediments to be impacted by sediment redistribution. In sum, the potential for ^{230}Th to produce high resolution records of sediment fluxes that are corrected for syndepositional sediment redistribution make it a vital tool for studying past climates using ocean sediments.

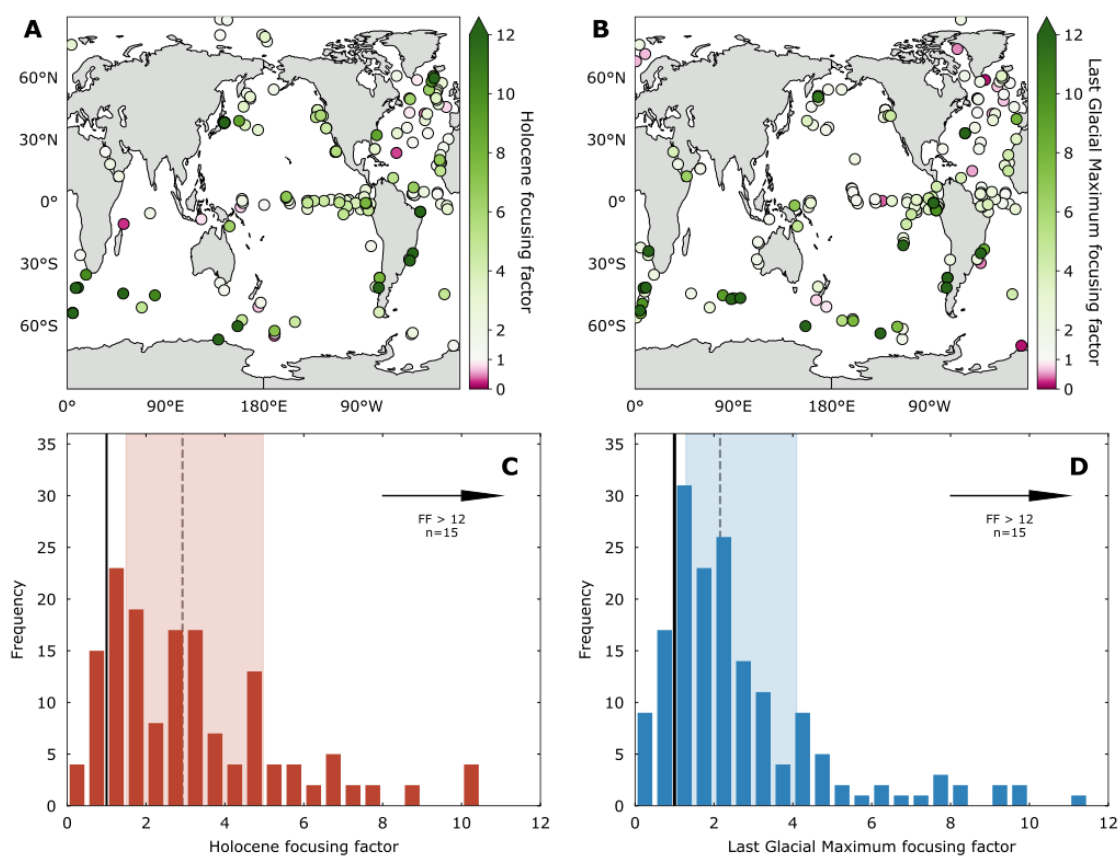


Figure 2: Sediment focusing based on the $^{230}\text{Th}_{\text{xs},0}$ method. **A)** Holocene (5-0 ka) focusing factors. **B)** Last Glacial Maximum (23.5-18.5 ka) focusing factors. **C)** Histogram of Holocene focusing factors. Solid black line indicates a focusing factor of 1 (i.e. $\text{bMAR} = \text{vMAR}$). Dashed gray line indicates the median focusing factor. Light red region represents the interquartile range. **D)** Same as C, but for the Last Glacial Maximum focusing factor data. All focusing factor data is from Costa et al. (2020).



3.2 Accurate MARs in deeper time: ${}^3\text{He}_{\text{ET}}$ as a CFP

In the 1960s, Merrihue (1965) pointed out that at least some He, particularly ${}^3\text{He}$, found in marine sediments likely came from a source outside of Earth. Later work determined that this extraterrestrial ${}^3\text{He}$ (${}^3\text{He}_{\text{ET}}$) is contained in micrometer-scale “space dust”, commonly referred to as interplanetary dust particles (IDPs), and can be found in numerous archives across the planet (Farley et al., 2021; McGee and Mukhopadhyay, 2013; Peucker-Ehrenbrink et al., 2016; Schlosser and Winckler, 2002; Taylor et al., 2016). This extraterrestrial component of marine sediment ${}^3\text{He}$ is deconvolved from terrestrial ${}^3\text{He}$ (${}^3\text{He}_{\text{terr}}$) using assumed helium isotope ratio values for these two sources ($({}^3\text{He}/{}^4\text{He})_{\text{ET}}$ and $({}^3\text{He}/{}^4\text{He})_{\text{terr}}$) and the sample’s helium isotope ratio ($({}^3\text{He}/{}^4\text{He})_{\text{meas}}$) (McGee and Mukhopadhyay, 2013) via the equation:

$$[{}^3\text{He}_{\text{ET}}] = [{}^3\text{He}_{\text{meas}}] * \frac{1 - \frac{({}^3\text{He}/{}^4\text{He})_{\text{terr}}}{({}^3\text{He}/{}^4\text{He})_{\text{meas}}}}{1 - \frac{({}^3\text{He}/{}^4\text{He})_{\text{terr}}}{({}^3\text{He}/{}^4\text{He})_{\text{ET}}}} \quad (10)$$

Marcantonio et al. (1995) proposed using this noble gas isotope of space dust found within marine sediments as a CFP to determine the $v\text{MAR}$ of said sediments. Specifically:

$$v\text{MAR} = \frac{F_{{}^3\text{He}_{\text{ET}}}}{[{}^3\text{He}_{\text{ET}}]} \quad (11)$$

where $F_{{}^3\text{He}_{\text{ET}}}$ represents the flux of ${}^3\text{He}_{\text{ET}}$ to Earth. This value has been independently constrained for the late Quaternary using ${}^{230}\text{Th}$ as well as ice cores to be $0.8 \pm 0.3 \text{ pcc cm}^{-2} \text{ kyr}^{-1}$ (McGee and Mukhopadhyay, 2013). We discuss in section 6 the uncertainties regarding this value during earlier intervals of Earth’s history.

Assuming $F_{{}^3\text{He}_{\text{ET}}}$ is constant over the period of interest, ${}^3\text{He}_{\text{ET}}$ can be applied in the same way as ${}^{230}\text{Th}$. However, unlike ${}^{230}\text{Th}$, which decays over time, ${}^3\text{He}_{\text{ET}}$ is a stable isotope and can hypothetically be applied in any interval, taking into account assumptions regarding helium retentivity (i.e., the capacity of a He-bearing mineral to retain that He through time). Because the application of ${}^{230}\text{Th}$ is limited to the last ~400-500 kyr, ${}^3\text{He}_{\text{ET}}$ opened to the door for studies of marine sediment fluxes prior to the latest Quaternary (Farley and Eltgroth, 2003; Marcantonio et al., 2009; McGee and Mukhopadhyay, 2013; Mukhopadhyay et al., 2001b; Murphy et al., 2010; O’Mara et al., 2022, 2024; Torfstein et al., 2010; Winckler et al., 2005). In fact, ${}^3\text{He}_{\text{ET}}$ has been identified in sediments from ~480 Ma (Patterson et al., 1998), potentially indicating its utility beyond the Cenozoic. Considering that age model resolution (and therefore $b\text{MAR}$ resolution) is typically lower in older strata, ${}^3\text{He}_{\text{ET}}$ -derived $v\text{MARs}$ become increasingly necessary as we seek to interrogate the sediment record in deeper time. Recent works also suggests that ${}^3\text{He}_{\text{ET}}$ may provide additional advantages to ${}^{230}\text{Th}$ in certain depositional environments because it is not impacted by heavy particle scavenging, nor is it reliant on knowledge of the sample age for decay corrections (Middleton

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et al., 2020; Pavia et al., 2024). Overall, $^3\text{He}_{\text{ET}}$ offers numerous advantages over the traditional age model-based approach to reconstructing marine sediment fluxes, particularly prior to the late Quaternary.

4. The state of $^3\text{He}_{\text{ET}}$ as a Cenozoic CFP



230 While there are ^{230}Th -derived MAR data covering a substantial portion of almost every major ocean basin for the Holocene
and Last Glacial Maximum, there are very few $^3\text{He}_{\text{ET}}$ marine sediment data prior to 400 ka (Figs. 3 and 4). In fact, many of
the published $^3\text{He}_{\text{ET}}$ data for the Cenozoic were not utilized to calculate vMARS, but were combined with age model-derived
MARs to either estimate an influx of $^3\text{He}_{\text{ET}}$ from space ($F_{3\text{He}_{\text{ET}}}$) (Farley, 1995; Farley et al., 2006; Farley and Patterson,
1995; Graham and Konrad, 2022; Marcantonio et al., 2009; Mukhopadhyay et al., 2001a; Patterson and Farley, 1998;
235 Winckler et al., 2004), or to determine the duration of a rapid climatic event (Farley and Eltgroth, 2003; Mukhopadhyay et
al., 2001a; Murphy et al., 2010). We note that the $^3\text{He}_{\text{ET}}$ data from these latter studies could still be used to determine marine
sediment vMARS (by assuming a value for $F_{3\text{He}_{\text{ET}}}$), but this method was not applied in the original work. Where deeper-time
 $^3\text{He}_{\text{ET}}$ data have been generated, most records are limited to short, targeted windows of interest (Farley and Eltgroth, 2003;
Marcantonio et al., 2009; Murphy et al., 2010), with little development of longer-term, multi-million year records.

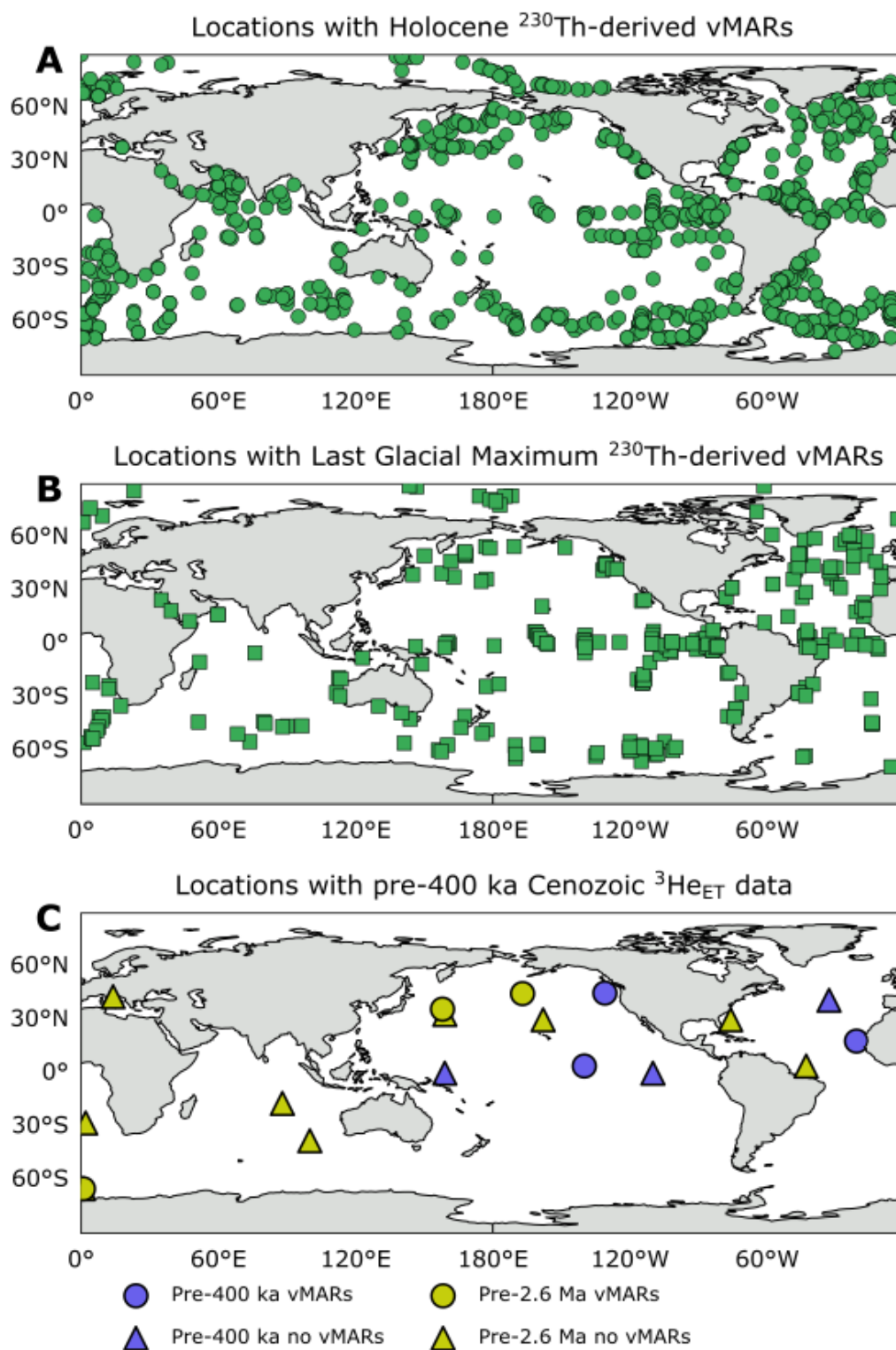




Figure 3: Available constant flux proxy data for various time intervals. A) Locations with Holocene (0-5 ka) ^{230}Th -normalized sediment vMAR data (Costa et al., 2020). B) Locations of Last Glacial Maximum (18-23 ka) ^{230}Th -normalized sediment vMARs (Costa et al., 2020). C) Locations with any marine sediment $^3\text{He}_{\text{ET}}$ (or just ^3He) data for the Cenozoic prior to 400 ka. No studies that produced $^3\text{He}_{\text{ET}}$ data from only 0-400 ka (i.e., the approximate range where ^{230}Th can be applied) are included here. Purple symbols indicate sites with $^3\text{He}_{\text{ET}}$ data that fall only within the Quaternary prior to 400 ka (Farley and Patterson, 1995; Middleton et al., 2020; O'Mara et al., 2022, 2024; Patterson and Farley, 1998; Winckler et al., 2005). Yellow symbols represent sites with at least some $^3\text{He}_{\text{ET}}$ data for the Cenozoic prior to the Quaternary (Abell et al., 2021, 2023; Abell and Winckler, 2023; Farley, 1995; Farley et al., 2006; Farley and Eltgroth, 2003; Graham and Konrad, 2022; Marcantonio et al., 2009; Mukhopadhyay et al., 2001b; Murphy et al., 2010). Circles with solid border indicate sites where $^3\text{He}_{\text{ET}}$ data have been used to calculate sediment vMARs (Abell et al., 2021, 2023; Abell and Winckler, 2023; Middleton et al., 2020; O'Mara et al., 2022, 2024; Torfstein et al., 2010) Circles with dashed borders represent sites where $^3\text{He}_{\text{ET}}$ data are not used to determine sediment vMARs. These studies either 1) determine an influx of $^3\text{He}_{\text{ET}}$ using the site's age model (Farley, 1995; Farley et al., 2006; Farley and Patterson, 1995; Graham and Konrad, 2022; Mukhopadhyay et al., 2001a; Patterson and Farley, 1998; Winckler et al., 2004) or 2) determine a flux of $^3\text{He}_{\text{ET}}$ using the site's age model and then calculate sediment accumulation rates and/or event durations using this value (Farley and Eltgroth, 2003; Marcantonio et al., 2009; Murphy et al., 2010).

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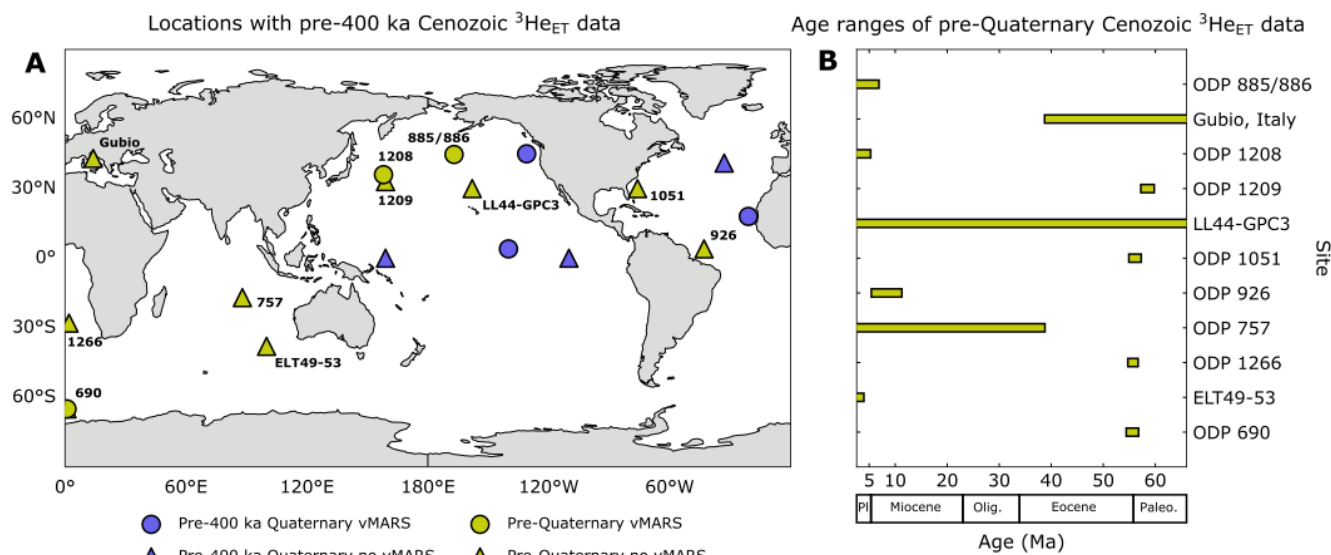


Figure 4: Spatial and temporal coverage of marine sediment $^3\text{He}_{\text{ET}}$ (or just ^3He) data for the Cenozoic prior to 400 ka. No studies that produced $^3\text{He}_{\text{ET}}$ data from only 0-400 ka (i.e., the approximate range where ^{230}Th can be applied) are included here. A) Spatial coverage of $^3\text{He}_{\text{ET}}$ data for the Cenozoic prior to 400 ka. Symbols are the same as Fig. 4C. Cores with pre-Quaternary Cenozoic $^3\text{He}_{\text{ET}}$ data are labeled. B) Temporal coverage of $^3\text{He}_{\text{ET}}$ data from the beginning of the Cenozoic to the Pliocene.

260 Considering all of these points, and acknowledging the large-scale, secular shifts in Earth's climate and landscapes documented across the Cenozoic (Molnar, 2004; Molnar and England, 1990; Mudelsee et al., 2014; Tierney et al., 2020; Westerhold et al., 2020), we assert that the CFP $^3\text{He}_{\text{ET}}$ may be one of the most vital yet underused tools for interrogating both



short- and long-term shifts in the Earth system from a marine sediment flux perspective. At minimum, we suggest that the paleoclimate and climate science communities could greatly benefit from further utilization of the $^3\text{He}_{\text{ET}}$ as a CFP.

265 5 Pre-Quaternary $^3\text{He}_{\text{ET}}$ case studies

To explicitly illustrate the impact of using $^3\text{He}_{\text{ET}}$ -derived marine sediment vMARs on our understanding of sediment MARs in the ocean, and in turn Earth's atmosphere, ocean, and terrestrial landscapes prior to the time window afforded by ^{230}Th , we present two case studies. The first draws on the findings recently described by Abell et al. (2021) and Abell and Winckler (2023) using Pliocene marine sediments in the North Pacific Ocean, while the second discusses how $^3\text{He}_{\text{ET}}$ has been used to reevaluate the role of ocean productivity during the PETM (Ma et al., 2014; Torfstein et al., 2010). In each example, we address in detail the similarities and differences between the MARs produced using age models (i.e., bMARs) and $^3\text{He}_{\text{ET}}$ (i.e., vMARs) in these works. We then highlight the influence that the CFP-derived sediment vMARs had on proxy flux records relevant to reconstructing past Earth system conditions. While each of these studies certainly contain their own assumptions, uncertainties, and caveats, our goal is to present them as examples of "stories still unwritten" within existing marine sediment cores. In doing so, we hope to stimulate the paleoclimate and paleoceanography communities to evaluate what we think we know regarding the paleo-Earth System from a marine sediment MAR perspective, and in turn pursue new hypotheses using this important proxy.

5.1 North Pacific sediment fluxes, dust inputs, and primary productivity in the Pliocene

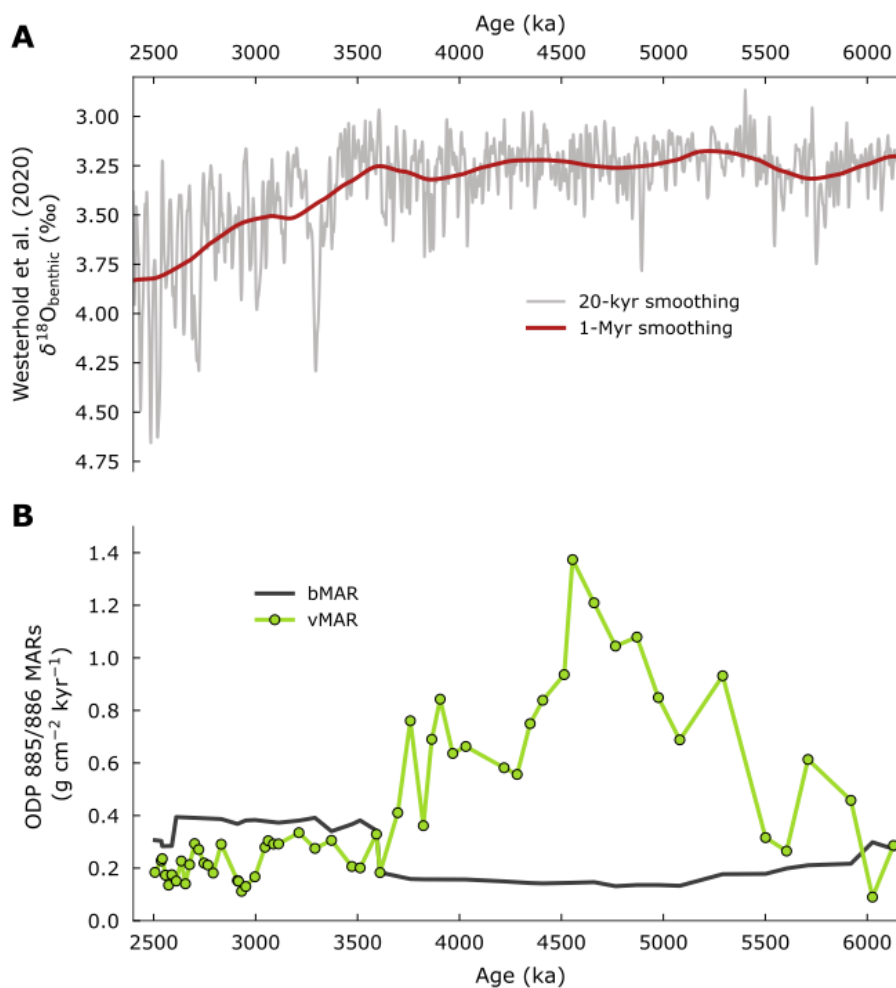
Both of the studies covered here primarily focused on the Pliocene (~5.3-2.6 Ma) sections of Ocean Drilling Program (ODP) marine sediment cores Sites 885/886 located in the central subarctic North Pacific Ocean (Rea et al., 1993). ODP Sites 885/886 contain biogenic opal, dust predominantly from Asia, and minor amounts of circum-Pacific volcanic material (Pettke et al., 2000; Rea et al., 1993, 1998; Snoeckx et al., 1995). Due to a lack of calcium carbonate, the age model (and in turn sediment fluxes) for the core are determined using a combination of magnetostratigraphy and biostratigraphy (Dickens et al., 1995; Morley and Nigrini, 1995; Rea et al., 1993). For much of the Pliocene and Quaternary, the resolution of the LSRs is on the order of several hundred thousand to millions of years, limiting our knowledge of sediment constituent bMARs on timescales less than this range. Additionally, several hiatuses within the Cenozoic have been suggested based on the core's stratigraphy (Rea et al., 1993). Any unidentified hiatus would further influence sedimentation rates. Finally, we note that early work suggested that certain sedimentation patterns at ODP Sites 885/886 are somewhat anomalous compared to other data produced at these sites, and even at other sites within the subarctic North Pacific (Dickens et al., 1995; Morley and Nigrini, 1995; Rea et al., 1993; Snoeckx et al., 1995). These interesting yet potentially problematic points related to the age model-derived LSRs and bMARs at ODP Sites 885/886 made them optimal targets for applying the $^3\text{He}_{\text{ET}}$ method. The production of CFP-derived vMARs may be even more timely considering the number of Pliocene dust, carbonate, opal, and



other flux datasets produced using these marine core sites (Bailey et al., 2011; Chen et al., 2024; Rea et al., 1998; Zhang et al., 2018, 2020, 2021).

295 Together, the studies of Abell et al. (2021) and Abell and Winckler (2023) produced $^3\text{He}_{\text{ET}}$ -derived sediment vMARS spanning ~6.0-2.5 Ma at ODP Sites 885/886. For much of the Pliocene at ODP Sites 885/886, there are substantial discrepancies between the age model-derived bMARS and $^3\text{He}_{\text{ET}}$ -derived vMARS, particularly during the period of ~5.5-3.6 Ma (Fig. 5). Because of the discrepant bMARS and vMARS, sediment vMARS at ODP Sites 885/886 determined using $^3\text{He}_{\text{ET}}$ (Abell et al., 2021; Abell and Winckler, 2023) produce completely different dust and opal MAR records at these sites when
300 compared to earlier work (Fig. 6) (Rea et al., 1998; Snoeckx et al., 1995). As such, Abell et al. (2021) found no large increase in dust MARs during the mid-Pliocene, a feature evident in the initial work of Rea et al. (1998). Additionally, while Snoeckx et al. (1995) previously suggested low opal accumulation (a proxy for productivity) in the central subarctic North Pacific during the early and mid-Pliocene (~5-3.6 Ma), contrary to evidence from several other contemporaneous studies (Arnold et al., 1995; Barron, 1998; Dickens and Barron, 1997; Dickens and Owen, 1996), Abell and Winckler (2023) found
305 high vMARS of two productivity proxies in this interval (Fig. 6C and D). Abell and Winckler (2023) posited that this period of elevated export production could be attributed to North Pacific deep water formation, although this hypothesis is still heavily debated (Burls et al., 2017; Novak et al., 2024). Regardless of the driver, by reconstructing opal vMARS using $^3\text{He}_{\text{ET}}$ at ODP Sites 885/886 during the early and mid-Pliocene, Abell and Winckler (2023) found that opal accumulation at these sites is consistent with other datasets from these same cores (Arnold et al., 1995; Dickens and Barron, 1997; Dickens and
310 Owen, 1996) as well as many other ODP sites from the subarctic North Pacific (Barron, 1998). Finally, by comparing the Pliocene $^3\text{He}_{\text{ET}}$ -derived dust vMAR records from ODP Sites 885/886 to other another core with $^3\text{He}_{\text{ET}}$ -derived vMARS located in the North Pacific, Abell et al. (2021) showed that changes in atmospheric circulation, specifically the westerlies, occurred with the intensification of Northern Hemisphere Glaciation in response to shifts in Northern Hemisphere ice sheets and meridional temperature gradients.

315 We highlight the various paleoclimate-related findings of each of these individual studies in order to emphasize just how critical the use of the CFP $^3\text{He}_{\text{ET}}$ was to these datasets and interpretations. In the case of Abell et al. (2021), it allowed for the normalization of variable sediment accumulation histories and age model resolutions across independent (and quite distal) sites, and thus provided internally consistent comparisons. Uncertainties related to these core-specific characteristics that influence sediment MARs cannot be completely ameliorated without employing a CFP.



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Figure 5: Late Miocene, Pliocene, and early Pleistocene MARS at ODP Sites 885/886. **A)** Benthic oxygen isotope compilation of Westerhold et al. (2020). Gray curve is the 20-kyr smoothed record, while the red curve is the 1-Myr smoothed record. **B)** bMARs (Dickens et al., 1995; Rea et al., 1998) and vMARs (Abell et al., 2021; Abell and Winckler, 2023) for ODP Sites 885/886. To allow for direct comparison, LSRs and DBDs were interpolated to calculate bMARs for sample locations with $^3\text{He}_{\text{ET}}$ -derived vMARs. Uncertainty estimates on vMARs are removed for clarity (see original studies for uncertainties associated with $^3\text{He}_{\text{ET}}$ -derived vMARs).

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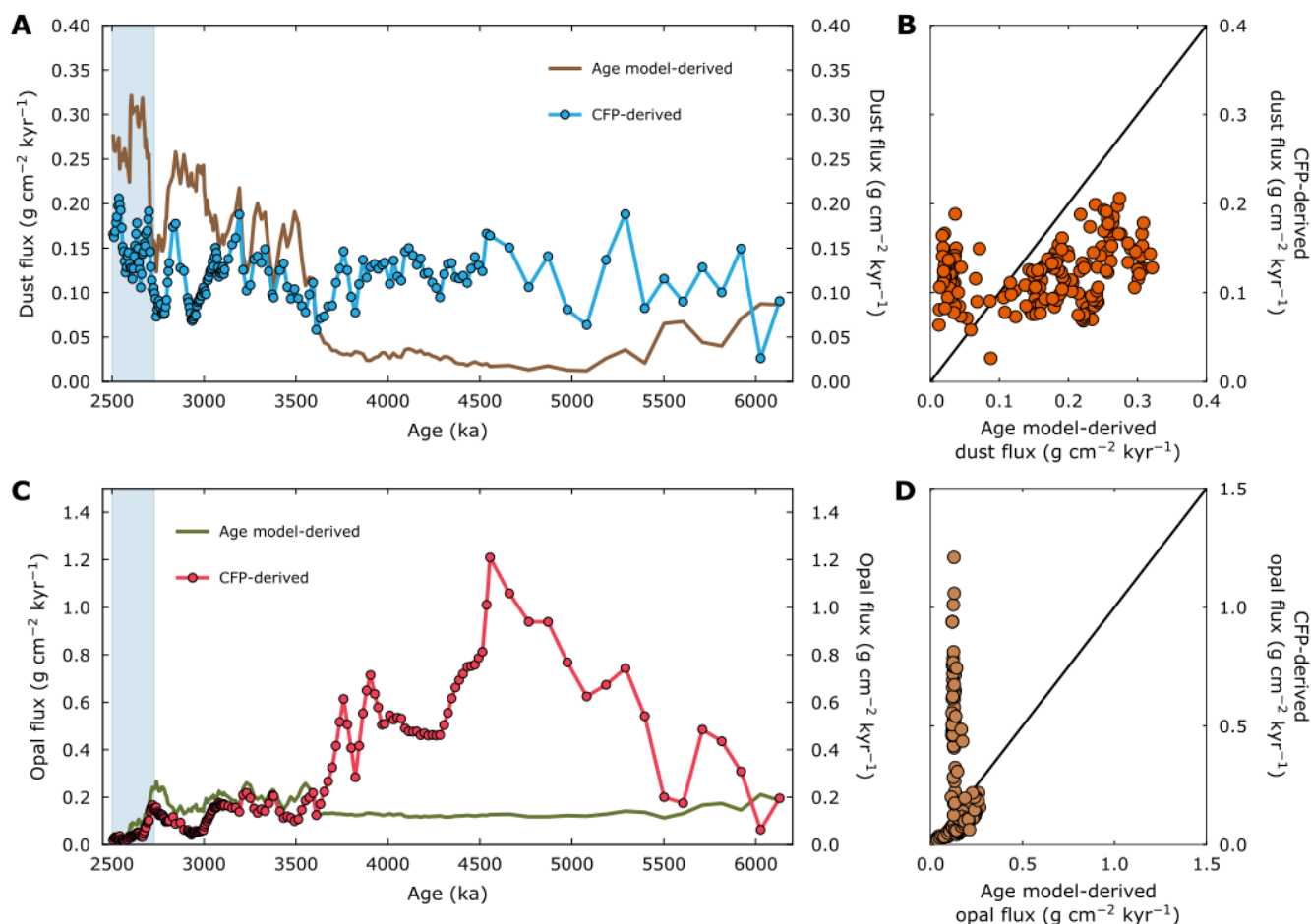


Figure 6: Pliocene dust and opal fluxes derived using different methods at ODP Site 885/886. **A)** ODP 885/886 Pliocene age model (brown line) and CFP-derived (blue line with circles) dust fluxes using a combination of Th, Al, Fe, and Ti concentrations as dust proxies (Abell et al., 2021; Abell and Winckler, 2023). Blue shading indicates the intensification of Northern Hemisphere Glaciation. **B)** Scatterplot of dust fluxes from A. Black line indicates a 1-to-1 relationship. **C)** ODP Site 885/886 Pliocene age model (green line) and CFP-derived (pink line with circles) opal fluxes (Abell and Winckler, 2023). Opal concentrations are determined assuming a two-endmember sediment composition system. Specifically, the concentrations of four detrital endmember element proxies (Th, Al, Fe, and Ti) are combined to calculate dust concentrations, and the dust concentrations are then subtracted from 100 to determine the opal concentrations. Blue shading indicates the intensification of Northern Hemisphere Glaciation. **D)** Scatterplot of opal fluxes from C. Black line indicates a 1-to-1 relationship. Uncertainty estimates on vMARS are removed for clarity (see original studies for uncertainties associated with ³He_{ET}-derived vMARS).

5.2 The “productivity feedback hypothesis” for the PETM recovery



The PETM is a hyperthermal that occurred at ~56 Ma caused by an enormous input of carbon into the atmosphere-ocean system (McInerney and Wing, 2011). The exact cause, duration, and mechanisms of climate system recovery for the PETM are still debated. One specific driver previously posited is that the efficiency of the marine biological pump shifted in response to the large carbon perturbation, ultimately reducing atmospheric CO₂ and inducing a return to background conditions (Bains et al., 2000; Ma et al., 2014; Papadomanolaki et al., 2022; Stoll et al., 2007). While all proxies used to make inferences about the biological pump have inherent uncertainties, some of the best evidence of the productivity feedback mechanism comes from barite/excess barium present in marine sediments (Bains et al., 2000; Ma et al., 2014). These studies generally point to increased productivity during the onset of the carbon isotope excursion that is used to stratigraphically mark the onset and recovery of the PETM. Importantly, in the work of Bains et al. (2000) and Ma et al. (2014), barite/excess barium bMARs are assumed to represent the vertical rain rate of these proxies as indicators for productivity. Considering this assumption, additional information further constraining sediment vMARs through ³He_{ET} is crucial.

There are only two sites where published ³He_{ET} and barite/excess barium data exists for the entirety of the PETM, which are ODP Site 690 in the Southern Ocean and ODP 1266 in the South Atlantic (Bains et al., 2000; Farley and Eltgroth, 2003; Ma et al., 2014; Murphy et al., 2010). At ODP Site 690, Bains et al. (2000) used the age model-based sediment MARs to calculate barite MARs, and found increased productivity coincident with the onset of the carbon isotope excursion. However, by applying the ³He_{ET} data produced by Farley and Eltgroth (2003) as a CFP, Torfstein et al. (2010) found that barite MARs (and in turn productivity) did not increase until ~70 kyr after the onset of the carbon isotope excursion. As such, the latter study proposed the productivity feedback hypothesis cannot be invoked for the PETM. Interestingly, a similar yet less dramatic discrepancy exists between the barite/excess bMARs and vMARs at ODP Site 1266. Using the ³He_{ET} data from Murphy et al. (2010), Ma et al. (2014) found productivity peaks at ~80 and 125 kyr after the onset of the carbon isotope excursion. However, if the bMARs are applied, then the major increase in barite fluxes is observed earlier, at ~50 kyr post-onset of the carbon isotope excursion. Depending on how the productivity data are interpreted in the framework of the productivity feedback hypothesis, these differences in timing could lead to quite varied interpretations of the marine carbon cycle across the PETM. While this feedback mechanism would be (and is) debated even without considering the CFP data, this is just another example where ³He_{ET} can lead to substantial revisions of how we as Earth scientists view key climatic events within the Cenozoic.

6. Important caveats and uncertainties to consider when using ³He_{ET} as a CFP

While we have shown that ³He_{ET} can be important for reconstructing accurate marine sediment and paleoclimate proxy vMARs, this approach is not without its uncertainties and caveats. These can be encountered during measurement and subsequent quantification of the terrestrial and extraterrestrial components, or be related to assumptions made regarding the characteristics of ³He_{ET} delivery to Earth. We briefly detail each of these below.



370 When measuring typical sample sizes, the low abundance of the $^3\text{He}_{\text{ET}}$ -bearing IDPs in all but the slowest accumulating
marine sediments can lead to less-than-optimal reproducibility in replicates. This statistical uncertainty stemming from
sampling can be partially ameliorated by measuring several replicates for a given sample as well as leaching biogenic
sediment components (i.e., carbonates) to concentrate He-bearing sediment constituents (i.e., terrestrial and extraterrestrial
material) within a particular sample prior to analysis. A related artifact of IDP delivery to marine sediments in the presence
375 of rare, large IDPs. Referred to as the “nugget effect”, the inclusion of these IDPs in samples being measured can produce
anomalously high concentrations of $^3\text{He}_{\text{ET}}$ (Farley et al., 1997). As with the reproducibility issue, analysis of multiple
replicates per sample can help to identify and remove samples with these nuggets.

Post-measurement, one must then carefully consider which helium isotope ratios are used for the terrestrial and
extraterrestrial endmembers (Eq. 10). As initially pointed out by Marcantonio et al. (1998), if the helium isotope ratio of a
380 given sample falls near the terrestrial endmember value, then the determined $^3\text{He}_{\text{ET}}$ concentration will be highly sensitive to
the chosen terrestrial endmember value. Importantly, terrestrial endmember helium isotope ratios have been suggested to
span several orders of magnitude (Marcantonio et al., 1998; McGee et al., 2016). As such, we suggest studies employing
 $^3\text{He}_{\text{ET}}$ as a CFP perform sensitivity analysis on their chosen terrestrial endmember value to evaluate its effects on calculated
 $^3\text{He}_{\text{ET}}$ concentrations (Abell et al., 2023; Abell and Winckler, 2023; Marcantonio et al., 1998; Middleton et al., 2016;
385 O’Mara et al., 2022, 2024; Pavia et al., 2024, 2025).

To this point, we have described the carrier of $^3\text{He}_{\text{ET}}$ to marine sediments as IDPs (Ozima et al., 1984), predominantly those
of the smaller ($\sim 20\text{--}35\ \mu\text{m}$) size fraction of overall IDPs (Brook et al., 2009; Farley et al., 1997; Mukhopadhyay and Farley,
2006; Torfstein, 2012), although this is debated (Jull et al., 2007; Lal and Jull, 2005; Stuart et al., 1999; Stuart and Lee,
2012). Importantly, specific mineral phases have been implicated as the primary location where $^3\text{He}_{\text{ET}}$ is hosted in the larger
390 IDP, including (but not limited to) magnetic minerals such as magnetite, ilmenite, or ulvospinel, various silicate phases such
as olivine and pyroxene, Al oxides, diamond, and graphite (Darrah and Poreda, 2012; Fukumoto et al., 1986; Matsuda et al.,
1990; Mukhopadhyay and Farley, 2006; Stuart and Lee, 2012). Based on a suite of methods, including microscopy, grain
size separation, leaching, magnetic separation, and step heating, the magnetic and silicate phases are the most likely
candidates (Darrah and Poreda, 2012; Mukhopadhyay and Farley, 2006; Stuart and Lee, 2012). Currently, we lack a
395 quantitative determination of the partitioning of the $^3\text{He}_{\text{ET}}$ between these two mineral groupings. Because a silicate mineral
such as olivine or pyroxene is susceptible to diagenesis under different conditions than a magnetic mineral such as
magnetite, ilmenite, or ulvospinel, accurately characterizing the mineral host of $^3\text{He}_{\text{ET}}$ is essential. An example to illustrate
the consequences of an equivocal understanding of $^3\text{He}_{\text{ET}}$ in IDPs for $^3\text{He}_{\text{ET}}$ as a CFP is the impact of temporally varying
marine sediment porewater chemistry. If there are intervals of suboxia/anoxia (i.e., the interval where iron reduction occurs)
400 that lead to the dissolution of fine-grained magnetic minerals, then $^3\text{He}_{\text{ET}}$ being hosted in magnetite/ilmenite/ulvospinel could
be lost to seawater, biasing sediment $v\text{MARs}$ too high for these intervals. Silicate minerals would not undergo substantial



dissolution at these times. However, if porewaters became alkaline, then silicate minerals could undergo diagenesis while the mentioned magnetic minerals would likely survive intact. Future work could address these uncertainties either through processing collected IDPs with various leaching experiments or comparing $^{230}\text{Th}_{\text{xs0}}$ - and $^3\text{He}_{\text{ET}}$ -derived vMARS across intervals in marine sediments where known changes in sedimentary porewater conditions occurred.

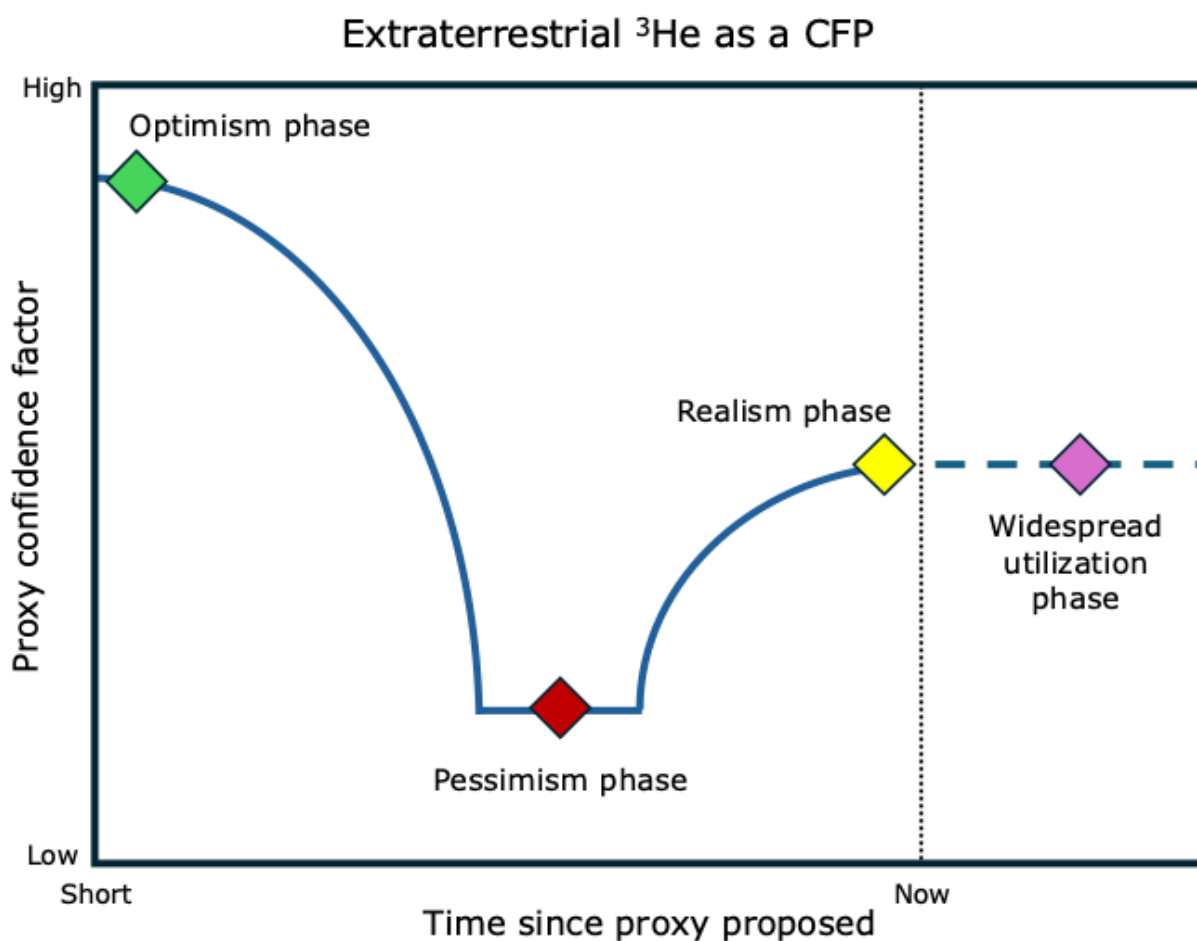
While numerous studies have compared $^{230}\text{Th}_{\text{xs0}}$ - and $^3\text{He}_{\text{ET}}$ -derived vMARS at sites with low to moderate levels of sediment redistribution and found minimal impacts, there have only been two studies that addressed the influence of intense sediment redistribution on $^3\text{He}_{\text{ET}}$ -derived MARs (McGee et al., 2010; Tomchovska et al., 2025). While both McGee et al. (2010) and Tomchovska et al. (2025) found sediment focusing to minimally impact $^3\text{He}_{\text{ET}}$ -derived vMARS, intense winnowing led to substantial discrepancies between $^{230}\text{Th}_{\text{xs0}}$ - and $^3\text{He}_{\text{ET}}$ -derived vMARS. However, because there is still debate over the effects of focusing and winnowing on ^{230}Th (Costa et al., 2020; Lyle et al., 2005, 2014; Marcantonio et al., 1995, 2014; McGee et al., 2010), and the findings of Tomchovska et al. (2025) are limited to one region of the ocean, more work is needed to assess the impacts on $^3\text{He}_{\text{ET}}$, particularly where winnowing is the dominant process.

Finally, while a plethora of studies have worked to determine $F_{^3\text{He}_{\text{ET}}}$ in the modern and late Quaternary (Farley et al., 2021; Fénisse et al., 2025; McGee and Mukhopadhyay, 2013), this value in deeper time is, at present, under constrained. The only available estimates for $F_{^3\text{He}_{\text{ET}}}$ prior to the Quaternary are calculated under the assumption that the archive used did not experience sediment redistribution (Farley, 1995; Farley et al., 2006; Farley and Eltgroth, 2003; Marcantonio et al., 2009; Mukhopadhyay et al., 2001a; Murphy et al., 2010). Considering that 1) one of the key advantages of using CFPs in the first place is to constrain sediment redistribution, 2) syndepositional sediment advection occurs in many places in the ocean and is time varying (Fig. 1), and 3) these studies yield regional differences in the $F_{^3\text{He}_{\text{ET}}}$ influx from space (see Fig. 5 in McGee and Mukhopadhyay, 2013), we argue that this assumption is problematic. An example that likely points to sediment redistribution impacting these past studies can be seen in the variety of proposed $F_{^3\text{He}_{\text{ET}}}$ values for the early Eocene, which range from <0.1 to ~ 0.7 pcc $\text{cm}^{-2} \text{kyr}^{-1}$, depending on the site (McGee & Mukhopadhyay, 2013; Farley & Eltgroth, 2003; Murphy et al., 2010; Mukhopadhyay et al., 2001b; Farley, 1995a). As present, for future studies relying on $^3\text{He}_{\text{ET}}$ to determine marine sediment fluxes, we suggest to either *i*) use the well-constrained late Quaternary $F_{^3\text{He}_{\text{ET}}}$ value, or *ii*) use both the late Quaternary value and another estimate from the period of interest and evaluate the dataset's sensitivity to the chosen value. Importantly, as long as $F_{^3\text{He}_{\text{ET}}}$ is constant over the period of interest, interpretations regarding relative changes in vMARS are still viable. Further constraints on the value of $F_{^3\text{He}_{\text{ET}}}$ for at least the late Neogene and Quaternary could be provided via combined analyses with other geochemical tracers that have known production rates. One example is meteoric ^{10}Be (Frank et al., 2002; Winckler et al., 2005), although ^{10}Be is not without its own complexities (Middleton et al., 2026; Savranskaia et al., 2024).

7. The future of $^3\text{He}_{\text{ET}}$ and our understanding of the Cenozoic Earth System from marine sediments.



In this perspective, we have described how CFPs applied to marine sediments have provided, and can continue to provide new, valuable information about the Earth system across (at least) tens-of-millions of years. With that being said, Fig. 5 clearly demonstrates that $^3\text{He}_{\text{ET}}$, the only viable CFP beyond the late Quaternary, has yet to be used beyond a handful of studies. We stress that this is not because $^3\text{He}_{\text{ET}}$ is new to the field of paleoclimatology or has not been well-studied as a proxy. To be clear, those who apply $^3\text{He}_{\text{ET}}$ as a CFP are quite aware of its inherent uncertainties and where further constraints are needed, which we have highlighted in the work. Using the Elderfield proxy confidence curve as a guide (Chase et al., 2018; Elderfield, 2002), the CFP $^3\text{He}_{\text{ET}}$ is thus well within the “realism phase”. Considering the unique benefits of the proxy illustrated by our review of several recent studies from both the late and early Cenozoic that utilize the CFP $^3\text{He}_{\text{ET}}$, we propose that the logical next step for this proxy is a “widespread utilization phase” (Fig. 7).





445 **Figure 7:** Elderfield proxy confidence curve for the CFP $^3\text{He}_{\text{ET}}$. Note that at this moment in time, we posit we are in the “realism phase” of the proxy, and the next goal would be its widespread utilization by the paleoclimate community. Based on Elderfield (2002) and Chase et al. (2018).

So, what is standing in the way of applying this influential method to every marine sediment core to develop both short- and long-term accurate records of changes in the Earth system across the Cenozoic? In a practical sense, the simple answers to this question at present are 1) a scarcity of laboratories making measurements of marine sediment noble gases, and 2) no single publication (to our knowledge) dedicated to describing $^3\text{He}_{\text{ET}}$'s utility to the broader Earth science community exists. 450 While the former is not amenable to a ‘quick fix’, we hope the information presented here serves to remedy the latter issue.

In summary, it is our opinion that without the application of $^3\text{He}_{\text{ET}}$ prior to the late Quaternary, key future questions regarding both short- and long-term shifts in the Earth system over the last ~66 Myr that can only be investigated from a marine sediment flux perspective, may go unanswered. Potentially even more problematic is that our current understanding of Earth's climate and landscapes based on fluxes in the ocean could be erroneous due to reliance on existing age model- 455 derived bMAR datasets. While our case studies focused on small spatial and temporal scales compared to the applicable range of $^3\text{He}_{\text{ET}}$, we stress that new findings stemming from the application of this CFP are not limited to just the North Pacific and Southern Ocean, nor just the Pliocene and PETM. As evidenced with ^{230}Th , processes influencing our ability to accurately reconstruct MARs in the ocean with traditional approaches are spatially heterogenous and change over time. As we attempt to peer back farther into Earth's past through the lens of marine sediment MARs, recognizing and correcting for 460 these uncertainties is paramount. Finally, with new deep ocean drilling heavily stymied for the foreseeable future (Means, 2023; Robinson et al., 2024), utilizing available marine sediment cores to address these and other questions is crucial. CFPs, and $^3\text{He}_{\text{ET}}$ in particular, provide a means to expand work on these irreplaceable archives while generating new information about the Earth system across the Cenozoic.

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470 **Author Contributions:** All authors contributed to the conceptualization of this perspective. J. T. A. compiled the published data and performed all analyses. J. T. A. wrote the initial version of the manuscript. All authors provided comments and revisions.



Data/Code Availability: All data needed to evaluate the conclusions in the paper are present in the Supplementary Data File and associated files deposited in a repository. Files containing the dust, productivity, mass accumulation rate, and focusing factor data from the original cited studies, as well as the code files for figure generation, are stored at Figshare.com via the link: <https://figshare.com/s/98d2296ab151f7c28d45>.

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