Paleoceanography and Paleoclimatology

COMMENTARY
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Key Points:

- Timing is important for comprehending Earth's biological and climatic processes shaping evolution, extinction, and recovery
- Key climate proxy records of the last 100 million years are not sufficiently synchronized across regions
- A coordinated effort is needed to synchronize regional and global climate proxy records to unravel causes and consequences of climate change

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Timing Is Everything

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Abstract Deep ocean sediments document past environmental changes over space and time. The information gleaned from such deposits allows scientists to test climate models that are used to predict future climate change. However, the causes and consequences of changing climate can be unraveled only if geological data from different regions are synchronized in time so that lead-lag relationships can be properly established. Synchronization of geological archives across regions requires precise and accurate age models, but available age models are often not sufficiently accurate to rigorously test causality arguments. We therefore propose to launch an international, coordinated effort to revise and recalibrate the dating tools available to paleoclimatologists—that is, the local and regional information obtained from bio-, magneto-, and chemostratigraphy as well as radioisotopic geochronology—with the synchronizing tool of astrochronology. Cross-fertilization of expertise is needed to generate new age models for sediment records from which key climate events have been or can be reconstructed. We expected this initiative could make a significant contribution to the understanding of Earth history, biotic evolution, and particularly, Earth's climate history.

Plain Language Summary Geological records allow scientists to better understand how the natural climate system operates over time and space, but obtaining reliable information requires exact knowledge of the timing of past climate events. Currently, many important climate archives are not sufficiently well synchronized to confidently draw connections between data from different localities. Here we call to the international science community to launch the Time Integrated Matrix for Earth Sciences (TIMES) program with the aim to accurately synchronize age models for critical geological climate records of the last 100 million years.

1. Introduction

The expression of global climate change varies from region to region. Quantifying regional differences is critically important for understanding the climate system and improving estimates of future environmental and ecological response to climate change. Geological records are a prime target to validate climate and earth system models because they provide the opportunity to assess potential and complex consequences of elevated atmospheric CO_2 concentrations during past warm climates (Burke et al., 2018; Hollis et al., 2019; Lunt et al., 2021; Tierney et al., 2020). Offshore and onshore marine sequences, as well as lacustrine and terrestrial sediments, may harbor continuous successions of past environmental and climatic conditions on millennial to orbital time scales going back millions of years, in contrast to instrumental records that document the past one or two centuries at best. Marine sediments have been less disturbed by tectonics and surface processes than those on land and continental margins, allowing for exploration of sedimentary archives bearing detailed records of climate dynamics going back to the Late Cretaceous, the past 100 million years or so. Even older marine sedimentary sequences are unlikely to be recovered by scientific ocean drilling as continuous subduction of the sea floor has removed most of this material. Scientific ocean drill cores provide the fossil and mineral materials that have proven so useful for reconstructing past ocean conditions—temperature, pH, oxygenation, circulation, productivity, carbon storage and much more (e.g., Clark et al., 2024; Hess et al., 2023; Inglis et al., 2020; Lyle et al., 2019; Meckler et al., 2022; McClymont et al., 2023; Moretti et al., 2024; Rae et al., 2021; Rohling et al., 2024). These marine records of Earth history enable paleoclimatologists to investigate how ocean ecosystems changed in response to environmental perturbations, including fluctuations in paleo-atmospheric CO_2

(e.g., Anagnostou et al., 2016; Anagnostou et al., 2020; Boscolo Galazzo et al., 2014; Boscolo-Galazzo et al., 2021; Griffith et al., 2021; Henehan et al., 2020; Huber et al., 2018).

Geological climate records offer the opportunity to understand the temporal evolution and interaction of changes in different regions, which requires quantification and differentiation of driving processes. But the regional response of the climate system can only be deciphered if the geological data are synchronized in time using precise and accurate age models. Coordinated Universal Time (UTC) is used to regulate clocks and time, and therefore an invaluable tool for human interactions across regions. When studying the geological past, it is essential to have an equivalent to the UTC. This is the Geological Time Scale (GTS), which compiles and calibrates the temporal relationships between rocks and fossils around the world. Applying the latest GTS to paleoclimate records by building an age model thus should synchronize records across different "time zones."

The GTS is updated periodically to reflect ongoing efforts to calibrate geologic time through in-depth stratigraphic and geochronologic studies. The latest version, GTS2020 (Gradstein et al., 2020), exhibits critical improvements in chronological precision and accuracy. With an increasing number of highly resolved records, scientists aim to focus past climate reconstructions on shorter-term variability and rapid changes. Despite many major improvements, GTS2020 lacks the resolution to synchronize highly resolved regional climate archives on a global scale. It is the field of astrochronology (Hinnov, 2013; Laskar et al., 2020), as discussed below, that offers the opportunity to improve the chronology of paleoclimate records significantly, synchronizing them across regions.

As a multidisciplinary team of paleoceanographers, paleoclimatologists, and geochronologists, here we issue a call to action to establish a consistent astrochronological time frame, that goes beyond the capabilities of the GTS2020, and to synchronized age models for all key sedimentary climate archives across geographic regions. Due to its scale, such an endeavor will require international coordination and should encompass at least the past 100 million years, the interval with sufficient coverage by scientific ocean drilling records. In the following, we outline how an improved stratigraphic framework for this time period can be established.

2. The Building Blocks for an Accurate Age Model

For dating geological archives, and/or establishing an age model, diverse techniques are routinely used (Figure 1). Some methods allow for determination of numerical ages, whereas others provide relative ages. All these techniques have different levels of associated uncertainty. Most numerical ages are derived through radioisotopic geochronology, which involves the dating of rocks, minerals, and fossils based on the known decay rates of radioactive isotopes, including ^{40}K to ^{40}Ar, ^{40}Ar to ^{39}Ar, ^{238}U to ^{206}Pb, ^{235}U to ^{207}Pb, and ^{14}C to ^{14}N (Schmitz et al., 2020). Relative age estimates mostly come from biostratigraphy, based on the evolutionary and biogeographic changes in fossil assemblages over time (Gradstein, 2020). This method is comparatively fast and inexpensive. Uncertainties can be large because the appearance, dispersal and extinction of fossil marker species can be diachronous between different ocean basins and across latitudes. In addition, the rate of appearance or extinction, and thus the accuracy of age determination, varies over time.

Changes in Earth's magnetic field, and in particular flips of its dipole from magnetic north to magnetic south and vice versa, have been recorded in the rocks through the geological past (Ogg, 2020). The irregularly alternating sequences of normal (north) and reversed (south) polarity have been documented in seafloor magnetic anomaly profiles and sequences on land. This barcode-like pattern has been calibrated in time and is known as the Geomagnetic Polarity Time Scale (GPTS, Figure 1). Magnetostratigraphy refers to the documentation of these flips in individual sedimentary successions and their correlation to the GPTS. The benefits of using these features for global correlation is that the process of a reversal is completed within a few thousand years, and thus is geologically synchronous across the globe. But reversals are statistically random and therefore the barcode-like pattern is irregular, providing a repetitive signal but with very unevenly placed age datums. In addition, sedimentary sequences can be condensed or contain a gap in time, an unconformity, making the alignment of the barcode-like pattern to the GPTS difficult or even impossible. Therefore, magnetostratigraphy is commonly combined with biostratigraphy because each biostratigraphic zone is defined by non-repetitive bioevents and spans a specific portion of the GPTS (Figure 1).

Both biostratigraphy and magnetostratigraphy function as a relative correlation tool for sediments from different locations. As neither technique provides a numerical age, magnetostratigraphic age calibration has depended

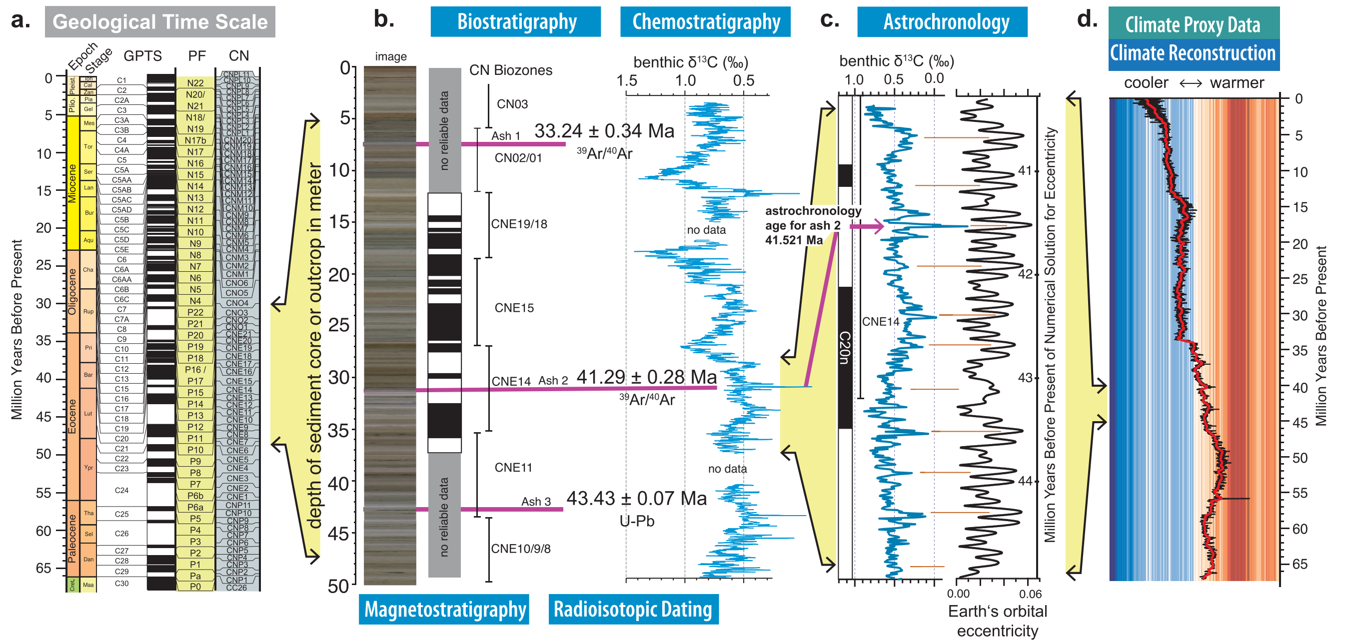

Figure 1. Schematic overview of techniques to create and improve age models for geological records and their use in paleoclimate reconstructions: (a) Epochs, stages, Geomagnetic Polarity Time Scale (GPTS), planktonic foraminifer zones (PF; Wade et al., 2011), calcareous nannofossil zones (CN; Agnini et al., 2014) for the last 67 million years as defined in the Geological Time Scale (2020; Gradstein et al., 2020); (b) synthetic geological record spanning 50 m with given chronostratigraphic data; (c) tuning of the geochemical record to the orbital solution of eccentricity (Laskar et al., 2011) provides astrochronological ages for ash layers, bio- and magnetostratigraphy improving the initial age estimates; (d) any proxy data from the particular geological record can then be compared to records from other regions contributing to global climate reconstructions and testing climate model results.

primarily upon radioisotopic ages of ash layers (e.g., Cande & Kent, 1992). Based on the first-order correlations between biostratigraphic datums and magnetostratigraphy in boreholes as well as land sections, a magneto-biochronology has been developed and is now incorporated in the GTS (e.g., Berggren et al., 1995). Because ages for biostratigraphic events are determined by their relative position in a particular magnetic polarity chron, they depend on the age calibration of the GPTS. Due to the irregular spacing and variable resolution of the biostratigraphic events, magnetic field reversals and radioisotopic age determinations, these approaches are collectively insufficient overall to produce age models for climate records that allow comparison between different regions with an accuracy of a few thousand years. Past chemical changes in seawater elemental and isotopic composition, and derived patterns therein, provide another powerful tool to align and date geological archives. Common methods study changes in the strontium, osmium, sulfur, oxygen and carbon isotope compositions and are known as chemostratigraphy (see respective chapters in Gradstein et al., 2020). Variations in the oxygen and carbon isotopic composition of marine carbonate fossils allow regional and global correlation with a temporal resolution of a few to several thousand years over the past 100 million years or so (Bornemann et al., 2023; Lisiecki & Raymo, 2005; Voigt et al., 2012; Westerhold et al., 2020).

The observation that highly resolved sedimentary and isotopic signals show remarkably cyclical variability eventually gave rise to the most precise and accurate dating method applicable to continuous sedimentary records: astrochronology (Laskar, 2020). Astrochronology has revolutionized the construction of the Geologic Time Scale. It builds on the subtle, quasi-periodic changes in Earth's inclination axis and its orbit around the Sun, caused by the gravitational interaction of larger bodies in the Solar System. These changes affect the amount and distribution of incoming solar radiation on Earth, driving climate changes on the surface of the planet. These orbital frequencies are known as "Milankovitch cycles," after the Serbian mathematician Milutin Milankovitch, who established the connection between Pleistocene ice age cycles and changes in orbital parameters (Milankovitch, 1941). Milankovitch cycles show characteristic rhythms caused by modifications in the precession of the equinox (21,000 years), the tilt of Earth's spin axis (41,000), and the eccentricity of Earth's orbit around the Sun (100,000 and 405,000). Those cycles, if recorded in sediment or ice cores, are the basis for cyclostratigraphy (Drury et al., 2021; Hilgen, 2010; Hilgen et al., 1991).

Cyclostratigraphy uses the identified astronomically forced cycles of known periods as a metronome to establish relative durations within sedimentary successions. To demonstrate that cyclic variations in a geological data set are related to orbital cycles, the studied interval needs an initial estimate of its duration, which typically comes from independently dated bio-magnetostratigraphy or radioisotopic ages of ash layers (Figure 1). This initial age foundation can identify unconformities and allows for the correlation to long-term numerical solutions of Milankovitch insolation quantities, where every point has an absolute age, turning cyclostratigraphy into exceptionally accurate astrochronology (Hinnov, 2013). Astrochronology can date sedimentary archives with unprecedented accuracy, precision and resolution, which cannot be achieved by any other dating method. Thereby, astrochronology is widely applicable to stratigraphic records, and not limited to sporadic ash horizons amenable to radiometric dating.

Astrochronology has had a profound impact on numerous geoscience fields. For example, the intercalibration of astronomical and radioisotopic ages helped to reduce the absolute uncertainty of the $^{40}Ar/^{39}Ar$ method from ±2.5 to ±0.25% (Kuiper et al., 2008). This means that the age uncertainty of a 50 million year old Eocene record, could be reduced from ±1.25 million years to ±125,000 years. However, the fundamental issue of the intercalibration of astronomical and radioisotopic geochronometers is still not fully resolved (see 3.3). In our opinion it is astrochronology that can provide the age models needed to synchronize geological climate proxy data at the critical resolution needed to reconstruct climate variability on orbital time scales (Figure 1) and to decipher the sequence of events across regions.

3. Age Model Inconsistencies

Despite major advances over the last 50 years to improve the Geologic Time Scale, synchronizing data from different regions on a global scale remains extremely challenging. For the Plio-Pleistocene, the last 5.33 million years, a stack of 57 globally distributed marine carbon and oxygen isotope records functions as the global timekeeper for all other paleoclimate records (LR04, Lisiecki & Raymo, 2005). The LR04 stack combined chemostratigraphy with astrochronology, providing a very accurate reference curve. New marine oxygen isotope records can be synchronized in time, correlating the distinctive pattern in the oxygen isotope data to the LR04 target with an uncertainty of 5,000 years or less. This approach achieves the level of synchronization required to connect records from different regions, and puts these records into a global context, a prerequisite to investigate causality arguments and determine leads and lags in climate processes. Using a probabilistic stacking method, 180 globally distributed marine oxygen isotope records have been synchronized (Ahn et al., 2017). To account for ocean basin differences of several thousand years in the timing of oxygen isotope changes, regional stacks now have been constructed for the Atlantic and Pacific oceans covering the last 2.7 million years (Lisiecki & Stern, 2016; Zhou et al., 2024).

Prior to 5 Ma, the patterns in the marine oxygen isotope records are harder to resolve because of the reduced amplitude of the signal. Furthermore, the number of undisturbed and completely recovered drill cores beyond 5 Ma is limited and not many high resolution records have been generated. To date, no stacked carbon and oxygen isotope reference record with a highly accurate astrochronology like the LR04 stack has been established to span the geological past older than 5 Ma. Beyond 5 Ma, marine carbon isotope records are currently the best option to correlate records from different regions at the resolution of a few thousand years (e.g., Cramer & Jarvis, 2020). However, over the last decades, progress has been made to compare and integrate marine sedimentary archives with successions on land, to define a complete cyclostratigraphic framework without any unconformities. Correlation to long-term numerical solutions of Milankovitch insolation quantities allowed the construction of astrochronological age models covering the Cenozoic Era and parts of the Late Cretaceous (e.g., Holbourn et al., 2005, 2014, 2015, 2018, 2021; Batenburg et al., 2014; Drury et al., 2021; Kim et al., 2022; Liebrand et al., 2016; Wilkens et al., 2017; Westerhold et al., 2014; Zeebe & Lourens, 2019). These efforts culminated in an astronomically tuned deep-sea benthic foraminifer carbon and oxygen isotope reference record that cover the entire Cenozoic by stitching, not stacking, together 14 scientific ocean drilling records—the Cenozoic Global Reference Benthic foraminiferal Carbon and Oxygen Isotope Data set (CENOGRID, Westerhold et al., 2020).

While the CENOGRID records represent the most complete and highly resolved sedimentary archives, they encompass only a small subset of existing paleoceanographic records. Many geochemical proxy-based paleoclimate reconstructions have been generated from records that are not part of CENOGRID. To synchronize records that are not included, each record would require an equally highly resolved carbon and oxygen benthic foraminiferal isotope record. That by itself is an enormous and maybe unrealistic task, not only due to the labor required, but also because many important records lack well-preserved calcareous microfossils. More importantly, producing these chemostratigraphic data alone will not solve the problem of synchronization because there are substantial issues with respect to age model construction that must be addressed first. For example, bio- and magnetostratigraphic datums, as well as radioisotopic numerical ages of ash layers, provide essential, independent constraints that help anchor Milankovitch cycles in cores that have been recovered and/or sampled discontinuously. But despite significant advancements over the past few decades, in our opinion the GTS 2020 (Gradstein et al., 2020) continues to exhibit inconsistencies in bio- and magnetostratigraphic datums, largely due to the lack of proper synchronization of key records and data sets. Because bio- and magnetostratigraphic age datums and radioisotopic numerical ages form the basis for the initial age determination of the sedimentary archive, their inconsistencies hamper the construction of sound astrochronologies for these sediment cores. The three examples below illustrate representative age inconsistencies and their complexity, which must be resolved if we want to synchronize geological data from different regions and improve our understanding of the drivers of climate and associated ecosystem changes.

3.1. Primary Data Quality and Reliability

As described above, an astrochronologic framework can be constructed if highly resolved lithological and/or geochemical records provide evidence for the presence of Milankovitch cycles. But construction efforts are often hampered by uncertainties in the initial age constraints. For instance, most of the age models constructed for scientific drilling cores are based on biostratigraphic data generated during the expeditions at sea, in a limited time frame with high workload. Such conditions may lead to age model errors, and resolution is typically low. Shipboard scientists do not always have strong expertise in the specific time intervals of the recovered sediments, which increases the potential for misinterpretation. Moreover, due to the shortage of biostratigraphic specialists and funding, more detailed biostratigraphic frameworks are not always developed post-cruise. Finally, the approach and concepts for taxonomy and biostratigraphy have evolved significantly over the last decades, so that to our opinion some previously published data sets require a concerted revision.

One example demonstrating that a robust astrochronology requires high-resolution, reliable biostratigraphy comes from Ocean Drilling Program (ODP) Site 1,085, drilled in 1,713 m water depth 250 km west of the Orange River mouth (Namibia, South Africa, Figure 2). During the expedition, calcareous nannofossil and planktonic foraminiferal datums were used to make an initial biostratigraphic age model for the earliest Pliocene to middle Miocene (4–14 Ma, Wefer et al., 1998). Those datums were then used as a starting point to construct a highly resolved astrochronology for a benthic foraminiferal carbon and oxygen isotope record (Westerhold et al., 2005). Due to apparent mismatches between that record and CENOGRID, a revision of the shipboard age model using state-of-the-art biostratigraphic concepts was made (Gastaldello et al., 2024). The revised calcareous nannofossil biostratigraphy shifted age assignments by up to 800 kyr (Figure 2). Because of this revision, the published astrochronology of the frequently used carbon and oxygen isotope records from ODP Site 1,085 (Westerhold et al., 2005) is inaccurate between 7 and 11 million years ago. This is just one example that highlights the need to verify initial shipboard age estimates and check whether updates have been published, as these datums are the starting point for astrochronologies and magnetostratigraphy, or the basis for comparing records globally. In the 1970s and 1980s, initial biostratigraphies published in the Scientific Results volumes were continuously updated and refined in further investigations. An unfortunate outcome of easier access to sophisticated instrumentation in recent times is that geochemical results are obtained more quickly and hence published before the more time-consuming biostratigraphic studies can be completed. But the increasing number of geochemical records requires improvement of age models to unlock their true potential. Along these lines, we propose that a central open access repository for continuously updated age models is needed.

3.2. Consistency of Applied Age Models

Advances in analytical methods and availability of new geological records have led to improvements of the Geological Time Scale over the last few decades. The numerical magnetochronological ages are required to recalibrate biostratigraphic events, but there are still relatively few astronomically calibrated records with clear magnetostratigraphy for any given time interval, particularly in the Paleogene. The most recent GTS 2020 (Gradstein et al., 2020) selected some astronomically calibrated magnetostratigraphic records not suitable to recalibrate the age of bio-events. For instance, the Neogene interval between 18 and 20 million years ago used the

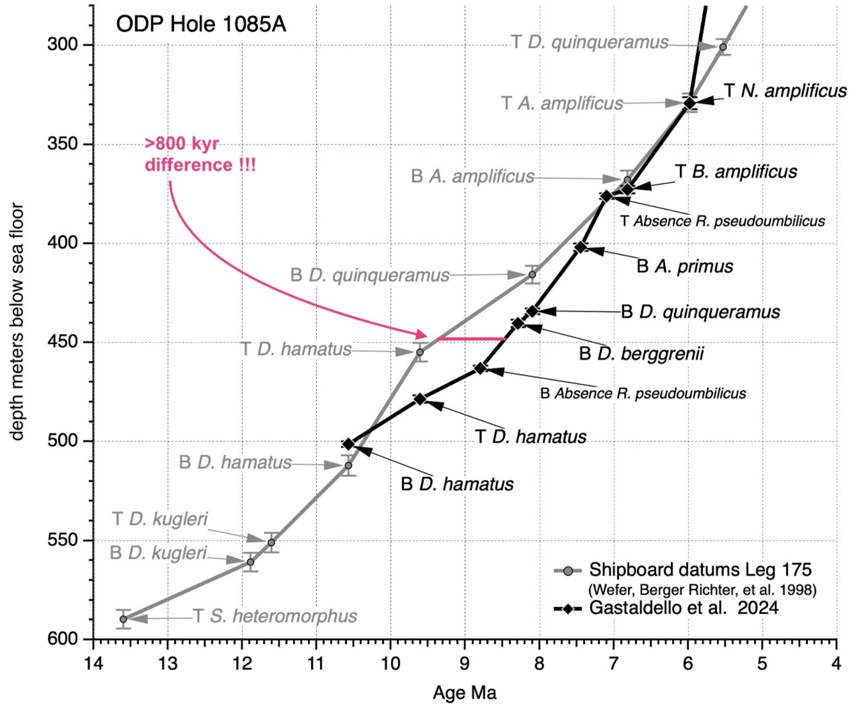

Figure 2. Drill depth versus age plot for ODP Hole 1085A. Biostratigraphy datums are from calcareous nannofossils obtained during Ocean Drilling Program Leg 175 in 1997 (Wefer et al., 1998) and revised datums from 2024 (Gastaldello et al., 2024) for the 300 to 600 mbsf depth interval. Such datums are frequently used as a starting point for astrochronologies or other age models: this plot shows that biostratigraphic datums need to be reevaluated for key scientific ocean drilling records. Note: error bars for depth axis (sample resolution), not for age-axis; T = Top of the event equal to the highest occurrence of a fossil, B = Bottom of the event equal to the lowest occurrence of a fossil.

magnetostratigraphic information from a deep sea sedimentary record, even though the original publication that generated the record considered the magnetostratigraphy inadequately resolved for improving the time scale (Liebrand et al., 2016). As a result, the Neogene GPTS2020 age (Raffi et al., 2020) for the dipole flip from C6 reversed to C6 normal differs by almost 200 kyr compared to both the Neogene GPTS 2012 (Hilgen et al., 2012) and the updated GPTS accompanying CENOGRID (Westerhold et al., 2020). Additionally, further inconsistencies are evident in the interval between 15 and 18 million years ago, where GPTS 2020 used the astronomically calibrated magnetostratigraphic record of Kochhann et al. (2016), which was not used to calibrate the CENOGRID GPTS. Such inconsistencies in recently published time scales make it difficult to calibrate bioevents and align records globally. We think that a more concerted and unified effort is needed to generate consistent, universally agreed upon age models.

To further illustrate the consequences of inconsistent age model applications, three examples are shown in Figure 3. The examples compare the global mean surface temperature derived from CENOGRID (Westerhold et al., 2020) with reconstructions of atmospheric CO_2 concentrations for the Middle Eocene Climate Optimum (MECO, ~40 Ma) and the Early Eocene Climate Optimum (EECO, ~50 Ma) from three ocean drilling sites (Figure 3a). The CO_2 estimates are based on the boron isotope proxy in planktonic foraminifera (Anagnostou et al., 2020; Henehan et al., 2020), whereas global surface temperatures have been estimated from deep-sea benthic foraminiferal oxygen isotope data (Hansen et al., 2013; Westerhold et al., 2020). The CO_2 estimates were originally published by Henehan et al. (2020) and subsequently included in the Cenozoic CO_2 Proxy Integration Project (CenCO_2PIP Consortium, 2023). For the CenCO_2PIP compilation some age models were updated, but in this case the numerical ages were kept as originally published. The relationship between variations in atmospheric CO_2 and global temperature is a critical question relevant to policy makers and the general public, so we believe that it is of utmost importance to verify the age models and ensure consistency.

In the first example (Figures 3b and 3c), atmospheric CO_2 reconstructions are from ODP Site 1,263 in the eastern South Atlantic. The estimates of global temperatures from CENOGRID at 40 Ma are also from ODP Site 1,263,

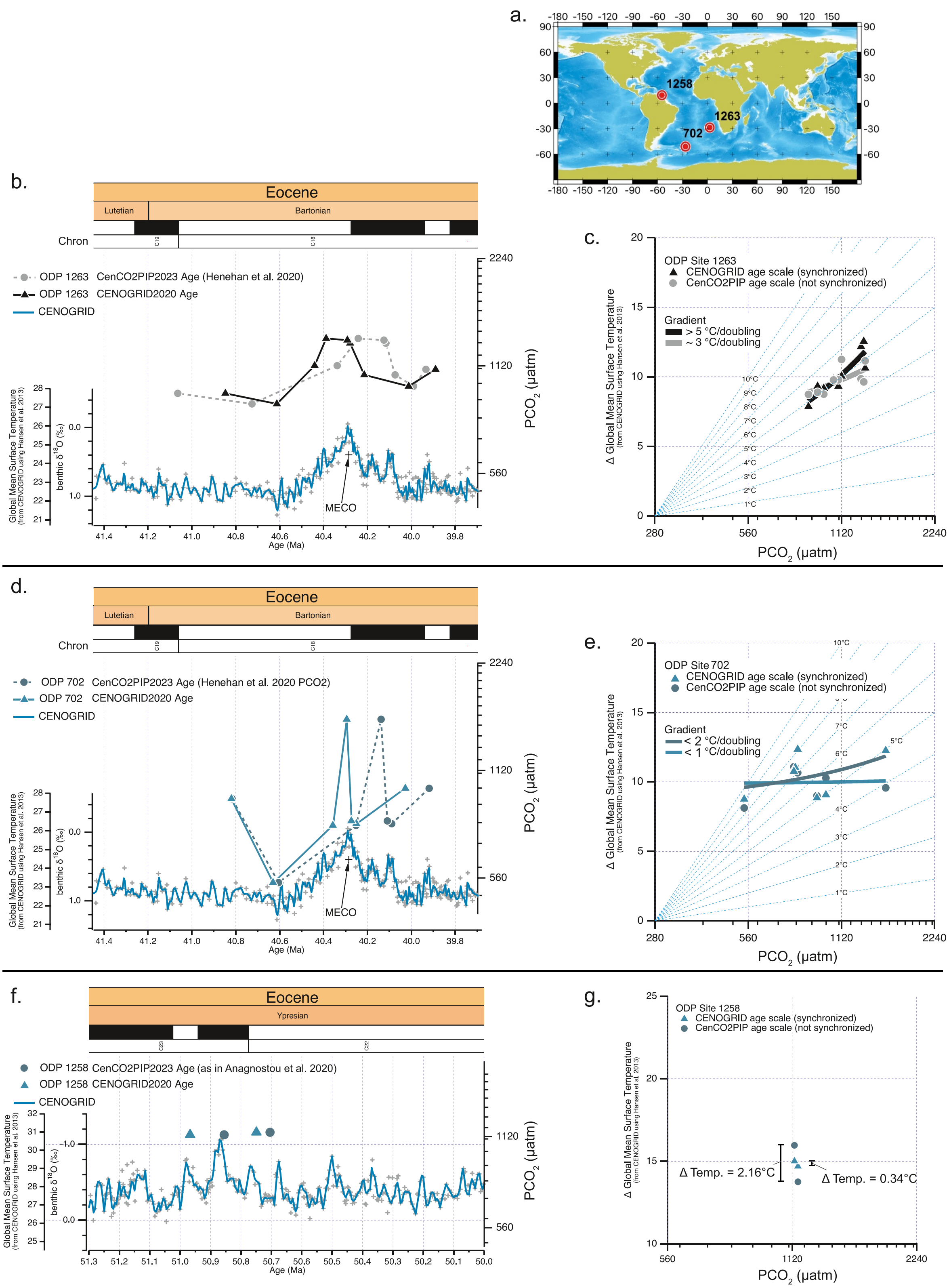
a.
1258
1263
702
b.
Eocene
Lutetian
Bartonian
Chron
ODP 1263 CenCO2PIP2023 Age (Henehan et al. 2020)
ODP 1263 CENOGRID2020 Age
CENOGRID
MECO
Global Mean Surface Temperature (from CENOGRID using Hansen et al. 2013)
benthic δ18O (‰)
PCO2 (µatm)
Age (Ma)
c.
ODP Site 1263
CENOGRID age scale (synchronized)
CenCO2PIP age scale (not synchronized)
Gradient
> 5 °C/doubling
~ 3 °C/doubling
Δ Global Mean Surface Temperature (from CENOGRID using Hansen et al. 2013)
PCO2 (µatm)
d.
ODP 702 CenCO2PIP2023 Age (Henehan et al. 2020 PCO2)
ODP 702 CENOGRID2020 Age
CENOGRID
MECO
e.
ODP Site 702
CENOGRID age scale (synchronized)
CenCO2PIP age scale (not synchronized)
Gradient
< 2 °C/doubling
< 1 °C/doubling
f.
Eocene
Ypresian
ODP 1258 CenCO2PIP2023 Age (as in Anagnostou et al. 2020)
ODP 1258 CENOGRID2020 Age
CENOGRID
g.
ODP Site 1258
CENOGRID age scale (synchronized)
CenCO2PIP age scale (not synchronized)
Δ Temp. = 2.16°C
Δ Temp. = 0.34°C

Figure 3.

which should make the comparison of data straight-forward. During the MECO, global temperatures and atmospheric CO_2 increased over the course of 400–500 kyr. Direct comparison of temperature- and CO_2-changes should provide an estimate of how climate responds to an increase in CO_2 concentrations, and thus provide insight on the Earth System Sensitivity (EES) during the middle to late Eocene hothouse climate state (Westerhold et al., 2020). But as can be seen from Figures 3b and 3c, the result depends on the age model used comparing the data. We test this by applying the GTS 2012 age model (Gradstein et al., 2012) to the CO_2 data, as used by Henehan et al. (2020) as well as the CenCO_2PIP Consortium (2023), and plotting this against the surface temperature reconstruction with the CENOGRID age model (Westerhold et al., 2020). As a result, ESS is on the order of ∼3°C warming per doubling of CO_2. But when applying the CENOGRID age model to the CO_2 estimates from ODP 1263, ESS increases to >5°C warming per doubling of CO_2. The example shows that applying inconsistent age models to data from eve the same location can lead to significantly different data interpretations.

The second example (Figures 3d and 3e) shows age model effects on data from core sites that are not included in the CENOGRID reference. The CO_2 data (Henehan et al., 2020) are from ODP Site 702, drilled in the central area of the Islas Orcadas Rise in the South Atlantic. Plotting Site 702 CO_2 estimates using the GTS 2012 age model results in no gradient, suggesting no relationship between CO_2 and temperature changes across the MECO. But using the correlation of bulk carbon isotope data between ODP Sites 702 and 1,263 (Rivero-Cuesta et al., 2019), transferring the CENOGRID age model to Site 702, results in a ESS on the order of 2°C (Figures 3a and 3b). This estimate is lower than the 5°C from Site 1,263 which could be due to either the time resolution of the data or remaining issues in the transfer of the age model between sites. The example nonetheless demonstrates how an updated age model via carbon isotope correlations between CENOGRID and non-CENOGRID sites can generate improved data comparison across regions.

In the third example (Figures 3f and 3g), two CO_2 estimates from different depths in ODP Site 1,258, drilled on the Demerara Rise in the western equatorial Atlantic, are very similar yielding 1,135 and 1,157 ppm (Anagnostou et al., 2020). Almost equal CO_2 levels should be accompanied by almost the same temperature. Applying the CENOGRID age model for 1,258 samples, we find a 0.34°C difference in surface temperature reconstruction. But using the reported ages in Anagnostou et al. (2020) to extract reconstructed temperatures from CENOGRID for the CO_2 data points results in a difference of 2.16°C. This discrepancy is surprising because Anagnostou et al. (2020) in principle used the same age model (Westerhold et al., 2017) for their CO_2 reconstructions as CENOGRID. The deviation in this case stems from an erroneous depth and depth-to-age conversion of the samples in Anagnostou et al. (2020). The conversion of sampling depth in a core (in meters below sea floor) to age can be complex if multiple versions of a composite depth record for a drill site exist, especially if samples are not from the defined composite section, but from a parallel hole. Age models are consistent only with their intended composite depth models.

All three examples show that a consistently applied, synchronized astrochronology is of paramount importance to accurately reconstruct past climate and ecosystem dynamics. In our opinion a large effort beyond typical scientific collaborations is needed to eliminate inconsistencies and set standards for reproducible and updatable data.

3.3. Intercalibration of Numerical Dating Methods

For detailed climate reconstructions it is important that other rock archives, such as flood basalts, or less ideal, less cyclic, or incomplete marine successions are incorporated into the astrochronological framework. For those cases, the astrochronological method of synchronizing records cannot be applied, and other dating methods must come into play, most notably radioisotopic geochronology. At this point, the intercalibration of different numerical, that is, astronomical and radioisotopic, dating techniques becomes critical because these methods should produce the same age if the same geological (climatic) event is dated.

Figure 3. Three examples for the effect of asynchronized age models on climate sensitivity estimates for the Middle Eocene Climate Optimum and the Early Eocene Climate Optimum—for details see discussion in Section 3.2. (a) Map showing the location of the ODP drill sites. (b, d, f) Global mean surface temperatures based on CENOGRID (Westerhold et al., 2020) and estimates of CO_2 from boron isotope analysis (Anagnostou et al., 2020; Henehan et al., 2020; all in CenCO2PIP2023) vs. age. (c, e, g) Log scale CO_2 versus the global mean surface temperature difference from preindustrial, calculated from CENOGRID at the same age of the given data point as in CenCO2PIP2023 and adapted to the CENOGRID age model.

Numerical ages obtained through radioisotopic geochronology can produce highly precise and accurate age models on par with orbital-scale precision of astrochronology, but critical uncertainties remain that hinder intercalibration across all geochronometers. $^{40}Ar/^{39}Ar$ dating with its large internal uncertainty relies on the calculation of an age relative to that of a standard. The Fish Canyon sanidine (FCs), which is the most widely used standard in $^{40}Ar/^{39}Ar$ dating for the last 100 Myr, is calibrated by either an astronomical or U-Pb dating-optimization approach. However, these FCs ages are at present inconsistent, with the astronomically calibrated age of 28.201 ± 0.046 Ma (Kuiper et al., 2008) significantly younger than the U-Pb calibrated age of 28.294 ± 0.036 Ma (Renne et al., 2010, 2011). In addition, they show variable concordance with U-Pb ages; other studies relevant to this intercalibration issue, such as U-Pb zircon dating of the Fish Canyon tuff itself (Keller et al., 2018; Wotzlaw et al., 2013) and the age of Quaternary magnetic reversals (Channell et al., 2020), suggest an FCs age that is close to or even slightly younger than the astronomically calibrated age of Kuiper et al. (2008).

The discrepant ages for the FCs result in a difference of more than 200,000 years in the $^{40}Ar/^{39}Ar$ age for the K/Pg boundary (Sprain et al., 2018). The $^{40}Ar/^{39}Ar$ K/Pg age using the FCs age of Renne et al. (2010, 2011) exhibits greater consistency with the K/Pg boundary age of 66.02 Ma obtained by U-Pb zircon geochronology (Clyde et al., 2016). However, the most recent astronomical study dates the K-Pg boundary to 65.92–65.96 Ma (Zeebe & Lourens, 2022), which falls between the two possible $^{40}Ar/^{39}Ar$ K/Pg boundary ages. Additionally, $^{40}Ar/^{39}Ar$ and U-Pb dating of the Deccan Traps may suggest a different eruption history of larger lava flows relative to the position of the K/Pg boundary depending on which FCs age is used (Schoene et al., 2019, 2021; Sprain et al., 2019). Such problems thus hinder full understanding of the potential contribution of Deccan Traps activity compared to the effects of the asteroid impact on K/Pg extinctions (Hull et al., 2020).

Despite continued uncertainty in dating K/Pg boundary records, we think that radioisotopic dating has the potential to provide critical numerical estimates that may refine age models based on biostratigraphy, magnetostratigraphy, and cyclostratigraphy, when horizons with minerals amenable to dating are interbedded with strata from which climate proxy records have been generated. Indeed, U-Pb dating of ash layers in combination with Bayesian approaches (e.g., Keller et al., 2018; Schoene et al., 2019) can provide age models for stratigraphic sections that are not amenable to astrochronology because of unconformities (Kasbohm et al., 2021) and/or poor recovery of drilled sediments (Kasbohm et al., 2024). Kasbohm et al. (2024) obtained high-precision U-Pb geochronology data across the Miocene Climate Optimum (MCO, 14–17 Ma) using dated ashes from ODP Site 1,000 (Nicaragua Rise), accounted for poor core recovery due to rotary drilling, then applied Bayesian techniques to produce ages with uncertainties for a new bulk carbon and oxygen isotopic record from this site, as well as for the biostratigraphic datums. This work revealed good agreement between radioisotopic U-Pb and astrochronological age models for the MCO. To our opinion applying this approach to other, more continuous sedimentary records, especially those with detailed biostratigraphy, magnetostratigraphy, and astrochronology, should be among the central goals for future studies.

4. The Synchronization Challenge

The ability to constrain ages and temporal relations is fundamental to the formulation of causality arguments pertaining to Earth's history. Our comprehension of climate impacts on ecosystems, including species' evolution, extinction and recovery from perturbations, hinges on precise knowledge of exact dates and rates. We think that the acquisition of accurate chronological data is therefore of paramount importance for meaningful interpretations, in particular across regions.

What methodology can be employed to establish a uniform and precise temporal framework for geological records from different regions? The foundation for this approach was recently established with CENOGRID (Westerhold et al., 2020). Spanning the last 66 million years, this data set benefits from a complete astrochronological age model and forms the basic framework for synchronizing the chemostratigraphy of globally distributed marine records. However, correlating geochemical cycles in records that are not part of CENOGRID to individual Milankovitch cycles in the astronomical solution still represents a significant challenge, that cannot easily be done by individuals. Addressing this problem has been attempted by a handful of researchers (e.g., Holbourn et al., 2022, 2024), but despite significant improvements, these revised solutions have not yet benefited from collective stratigraphic expertise, and some concerns remain. We believe the overall task is of considerable magnitude and requires a concerted effort. To be effective, it requires outstanding expertise in the areas of data management and synchronization, as well as cooperation and interaction between the stratigraphy, geochemistry

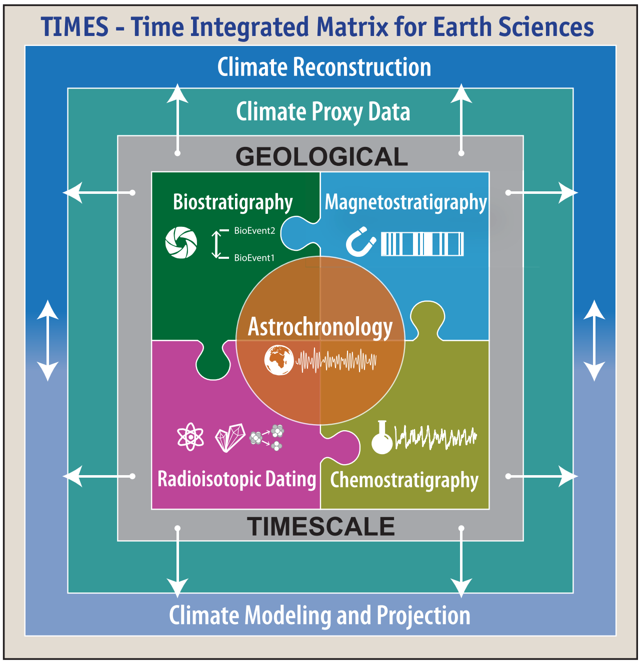

Figure 4. The Time Integrated Matrix for Earth Sciences program could function as a coordination network that aims to revise and recalibrate dating tools available to paleoclimatologists (bio-, magneto-, and chemo-stratigraphy as well as radioisotopic geochronology) with the synchronizing tool of astrochronology. TIMES should facilitate the interaction of proxy and modeling communities with the astro/geochronology community and advance the understand of Earth's climate history.

and geochronology communities. To our opinion an internationally coordinated effort is required to evaluate and, where necessary, recalibrate biostratigraphy, magnetostratigraphy, chemostratigraphy and radioisotopic dating using the synchronization tool of astrochronology. We think that the synthesis of climate proxy data with orbital and sub-orbital scale resolution is necessary to enable regional and global syntheses of spatial and temporal climate variability. Cross-pollination of expertise is required to establish new age models for published paleo-reconstructions from key sites.

In order to guarantee the long-term success of these endeavors, to our mind it is essential to implement strategies that facilitate the inclusive collaboration of the international community, provide support for early career researchers and foster a trusting and mutually respectful community. We therefore propose that an internationally coordinated program, the Time Integrated Matrix for Earth Sciences (TIMES, Figure 4), be established as an extension of the highly successful collaborative efforts of the International Ocean Discovery Program (IODP). To maximize scientific and intellectual gain, it is essential that this initiative is inclusive, allowing the collective knowledge of our diverse geoscience community to be harnessed, and the potential for innovation to be unlocked. We are confident that the gained knowledge will assist humanity in preparing for a warmer world, will help locate habitable regions for future generations, and thereby guide political decision-making.

The present moment is good for the commencement of this endeavor, as scientific ocean drilling efforts are transitioning into a new phase. In extension of the experiences gained from the PAGES PlioVar (McClymont et al., 2017) and PlioMioVar MioOcean Temperature Synthesis efforts (Modestou & Sosdian, 2023), the TIMES program could function as an umbrella for individual, more targeted projects. Networking schemes and programs to fund individual projects related to TIMES are already starting to evolve with the Ocean Drilling Legacy Assets Projects (LEAPs, (https://www.iodp.org/call-for-leap-proposals),), the IODP[3] Scientific Projects using Ocean Drilling ARChives (SPARCs, https://iodp3.org/proposals/, Camoin et al., 2024), and the Core Re-Discovery Program (ReCoRD, https://j-desc.org/en/record). Given the magnitude of the task and extensive collaboration, the TIMES science program will likely require a minimum 10-year time frame to be completed.

To our opinion TIMES should start with the identification of geological records from which data of high importance have been generated, and those from which little is known to date, but which bear promise to provide significant insights into the climate patterns of the last 100 million years or so. Establishing reliable and consistent age models for these records is the highest priority of TIMES, but this work will be complemented by surveys of previously recovered sediments to answer key scientific questions. International workshops and meetings should address a suite of guiding questions: Which are the key marine ocean drilling and land-based records to be included in the reference age framework? Which sites have produced key records that need a synchronized age model? What are the key locations for modeling studies that need better age constraints? How and where do we have to improve the building blocks of the Geologic Time Scale to establish consistent age models for pivotal geological climate proxy records?

In essence, we propose that TIMES should aim to refine and spatially expand the CENOGRID reference and extend it back in time. The collaborative development of high-quality age models will benefit the paleoceanographic community at large, and will offer substantial time savings and value for relatively modest financial outlay, particularly when compared to the substantial costs associated with the recovery of drilled sediments. Together, these efforts can facilitate the optimal utilization of the valuable sediment archives extracted by deep-ocean drilling over the past few decades, and can likely lead to the development of proposals for future scientific land and ocean drilling campaigns, as well as to new insights in Earth history.

In addition to efforts targeted at generating and refining key scientific findings, we envisage that TIMES should aim to define astrochronozones and astro-unit-stratotypes for the International Commission on Stratigraphy

(ICS), as well as regional reference records with bio-, magneto- and chemostratigraphy. In contrast to the ICS, which periodically updates the GTS according to new findings, TIMES could take an active approach, seeking out where age constraints are missing or need improvement, and setting an agenda for moving timescale calibration forward. Consistent astrochronologies for key proxy records should be made available to everyone and the intercalibration issues of Ar/Ar and U-Pb numerical dating methods should be solved. We think that a TIMES-Hub web interface has to be established to connect all efforts, functioning as an interchange of knowledge, newly developed methods and tools (e.g., an age uncertainty calculator). The TIMES-Hub should encompass an open access database and platform-independent software tools, complying with FAIR principles (findability, accessibility, interoperability, and reusability) and policies (e.g., Wilkinson et al., 2016; Stall, 2017; Khider, D. et al., 2019).

Finally, we think TIMES should train the next generation. During this critical decade when ocean drilling will differ significantly from the program as we have known it, since taking place on a much smaller scale, trainees will have very limited opportunity to obtain shipboard experience and make global scientific connections by participating in drilling expeditions. This is where TIMES can provide an interdisciplinary platform for mutual learning and networking. TIMES has to ensure gender balance at all levels of the program, engage researchers from diverse backgrounds, support early career researchers in their efforts, and be guided by principles of equity, diversity, and inclusion (EDI).

As timing is everything, our efforts should begin now, to calibrate temporal climate records to better understand Earth's past, influence policies to ameliorate our warming present, and train the next generation of scientists whose discoveries will shape the future.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data are available through Anagnostou et al. (2020), Henehan et al. (2020), Westerhold et al. (2020) and Gastaldello et al. (2024).

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